Maintenance 16

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Contents

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16.1 Introduction

This Chapter covers the description of maintenance of Overhead Transmission Lines (OHTL). Due to difficulties encountered by most Line Owners in building new OHTL and even with upgrading existing lines, the present Chapter is to understand issues and technologies related to the safe maintenance and operation of existing transmission lines. Since most of the world's power utilities' OHTL are approaching their design life or beyond, a good maintenance strategy is important to ensure their integrity.

The environment in which utilities operate has changed drastically in recent years. In the past, investment and maintenance decisions were often determined more by avoiding technical risks than by budget restrictions. The introduction of regulators and other new business drivers has changed this situation. Investment and maintenance cost must be well founded more and more and utilities have to apply modern asset management methods.

Traditionally, maintenance decisions on overhead lines have mainly been based on visual inspections. The results of visual inspections are normally entered into a maintenance management system. This way a valuable database is created. However, the basis of these maintenance methods is mainly qualitative and leaves room for inaccuracies. More importantly, it is hard to substantiate decisions regarding maintenance or replacement of components on the basis of a qualitative system. This Chapter describes how, with a combination of inspections, testing of samples and analysis, quantitative insight into the condition of components is obtained. The quantitative nature of the assessment results enables the asset manager to take intelligent and well-founded decisions regarding maintenance, refurbishment, upgrading, replacement, etc. of overhead lines.

Defects and failures occur in practice due to:

- Unforeseen external causes such as faults in an adjoining grid, extreme weather conditions, sabotage;
- Internal causes like wear, aging, deformation, poor construction or material;
- Operational aspects such as electrical overload, switching faults, improper functioning of protection and control.

Defects can lead to failures causing unforeseen unavailability of the line. Proper analysis of defects and failures can give a contribution to the development of strategies to maintain a sound condition of the overhead line.

16.2 Maintenance Strategy

16.2.1 Introduction

Formulating a transmission line maintenance strategy is dependent on the transmission line asset owners' drivers and constraints. Drivers could be a requirement to improve reliability and availability of the system, i.e., to meet System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI). Drivers could also be a requirement to satisfy new regulatory requirements, customer or user requirements (e.g., a new aluminum smelter customer or a wind farm generator). Constraints are typically budgetary or schedule constraints.

The maintenance strategy will be dependent on the asset owners' particular environment (i.e., coastal, desert, forest, etc.), existing condition of the assets and, perhaps most important, criticality of the existing transmission lines (e.g., lines from a nuclear power or must run plant).

Maintenance activities can be divided into three basic categories:

- Periodic normal maintenance,
- Preventative maintenance or component repair, and
- Emergency restoration or repair.

Each of these three areas can have its own maintenance strategy based upon the asset owner's drivers and constraints.

Periodic normal maintenance consists of activities such as:

- Vegetation management,
- Tower painting,
- Insulator washing.

These activities lend themselves to an economic risk analysis as outlined it Cigré TB 353 and used for the uprating and upgrading of transmission lines (see Chapter 18 – Uprating & Upgrading). The optimum time intervals between these activities can be determined based on risk assessment and cost evaluation (see Cigré TB 175 and 353).

Preventative maintenance or Component repair consists of activities such as:

- Damaged insulator replacement,
- Conductor repair,
- Hot splice replacement,
- Spacer and spacer-damper replacement,
- Repair of structural tower members or foundation repair,
- Correcting electrical clearance problems, etc.

These activities do not lend themselves to an economic "optimum time to do the work" analysis, but they can be prioritized and usually are dealt with in the near term. The driver for these items is the need to maintain system reliability, availability and capacity (i.e., hot conductor splices may reduce the maximum capacity of the line). If left unnoticed and unattended to, these items will eventually result in line failures with resulting economic consequences (Cigré TB 175).

Emergency restoration is usually a result of component failure and therefore line failure or the result of major storm damage, sabotage or delayed maintenance. The economic consequences of such a line failure are discussed in Cigré TB 175. Strategies to prepare for emergency restoration have been discussed in Cigré ELT-222-4. The purpose of the Cigré ELT-222-4 article is to help asset owners develop their own emergency response plan or strategy for their overhead transmission lines. The implementation of the plan should result in adequate material, manpower and equipment resources to address identified emergency situations. The key to the development of an adequate emergency response plan is for the asset owner and senior management to commit to a proactive long term plan for responding to anticipated emergency situations, and the formulation of a corporate policy on how the utility will respond to emergencies.

16.2.2 Steps in Developing a Maintenance Strategy

No matter what the maintenance activities are, they all share similar requirements that must be considered when developing a maintenance strategy.

16.2.2.1 Prioritizing the Transmission Lines

Some transmission lines are more important than others. Some lines can not be taken out of service without large financial and political penalties for the asset owner. These lines need to be identified and ranked in importance (i.e., risk and consequence).

16.2.2.2 Periodic Inspection of the Lines

All the lines need to be inspected. The time interval between inspections may be based on their priority ranking above. Inspections can be as simple as walking the right-of-way, climbing the structures and visually inspecting the components. Recently more sophisticated methods are available such as flying the lines with helicopters using high definition video cameras, LiDAR cameras and infrared cameras looking for such items as hot joints and splices or spacer-damper failures before significant conductor damage occurs. All transmission line components can be inspected in this way as well as the vegetation along the right-of-way and access roads. In recent years, real time transmission line monitoring equipment have been developed that measure critical maintenance parameters (e.g., conductor sag, vibrations, insulator contamination, etc.). This new equipment will need to be considered in an overall maintenance strategy, if not today then in the near future.

16.2.2.3 Data Base Management

Proper data base storage and retrieval systems are necessary, otherwise the results of the periodic inspections would be lost. The importance of having good and accurate data in the data base is discussed in Cigré TB 175. With this data deterioration trends can be used to catch problem areas early and avoid line failures. When line failures do occur, this data should also be gathered and maintained for proper asset management.

16.2.2.4 In-House or Outsourcing of Maintenance Work

A decision needs to be made as to which activities will be performed in-house and which activities will be outsourced. Few asset owners perform all of their maintenance activities (e.g., vegetation management along the right-of-way is typically outsourced). The risks and rewards associated with outsourcing of maintenance activities and the development of key performance indicators for evaluating outsourcing contractors are discussed in Cigré TB 201 and in Cigré TB 561.

16.2.2.5 Performing Live Work or De-Energized Work

Depending on the criticality or priority of a line, it may not be able to be taken out of service for extended periods of time to perform required maintenance. In this case, live working techniques may need to be implemented by the asset owner. Again, these may be performed in-house or outsourced, but in either case extensive planning is required as part of an overall maintenance strategy. If work can be done de-energized, planning and coordination with other organizations is required for a successful implementation of a safe maintenance program (see Cigré TB 561).

16.2.2.6 People, Equipment and Training

Depending on the maintenance activities that are planned to be performed by in-house personnel, consideration must be given to the technical skill levels and the numbers of maintenance personnel required. Training facilities and periodic retraining drills are an essential part of any successful maintenance program. The capital investment in specialized equipment, maintenance of the equipment and replacement of this equipment should also be part of the overall maintenance strategy. This equipment may include helicopters, robots or transmission line monitoring equipment which has not normally, in the past been associated with transmission line maintenance.

16.2.2.7 Outside Resources

Few asset owners have all the personnel and equipment to handle all of their maintenance activities, especially emergency restoration after large storms. Because of this, a successful maintenance strategy should also include a plan for sourcing additional outside personnel, equipment and line materials as required (see Cigré ELT-222-4). Mutual assistance between asset owners has been used successfully for this purpose; however, initial planning between different asset owners is required for successful implementation of the option.

16.2.2.8 Benchmarking and Continual Improvement

To implement a successful maintenance program the asset owner should compare his performance with other comparable asset owners. A plan for doing this should be considered as part of the overall strategy. After any major event (e.g., storm restoration) or periodically after normal maintenance activities, the asset owner should do a "lessons learned" with maintenance and engineering personnel involved in order to continuously improve the maintenance activities.

16.2.3 Conclusion

Formulating a successful transmission line maintenance strategy is dependent on the transmission line asset owners' drivers and constraints. The maintenance strategy will be dependent on the asset owners' particular environment, existing condition of the assets and, perhaps most important, criticality of the existing transmission lines.

No matter what the maintenance activities are, they all share similar requirements that must be considered when developing a successful maintenance strategy. They include:

- Prioritizing the transmission lines,
- Periodic inspection of the lines,
- Data base management,
- Considerations for in-house or outsourcing of maintenance work,
- Performing live work or de-energized work,
- Planning for people, equipment and training,
- Developing outside resources,
- Benchmarking and continual improvement.

The remaining sections in this Chapter will discuss some of these aspects in greater detail.

16.3 Condition Assessment of OHTL

A transmission line is regularly inspected in order to achieve updated information about the condition of the line as well as the immediate surroundings. Various inspection techniques have been developed to enable the condition of the OHTL to be assessed (Cigré TB 175). Inspections may be performed from a plane, a helicopter, a car, by foot patrols or by climbing the towers.

Condition assessment will enable transmission line asset owners to achieve greater efficiency when planning OHTL refurbishment's or more effectively to direct their maintenance activities, at a time when systems are ageing and consents for new lines are becoming increasingly difficult to obtain. The inspection should be performed so that the transmission line owner is provided with sufficient information to plan the maintenance of the OHTL.

The purpose of this section is to list common defects found in OHTLs and to list generic techniques that are currently available and can be used to find these defects in-situ.

This section is limited to the common defects which are found on conductors (phase and earth-wire) and fittings, insulators, supports and foundations on high voltage OHTLs.

This section does not deal with laboratory tests or problems that might occur in the right of way. It highlights those defects and inspection techniques, which an asset manager can use to establish or improve a basic inspection programme.

16.3.1 Conductor System Including Joints and Fittings

Conductor deterioration follows different patterns in different geographic areas. Deterioration such as conductor corrosion (internal and external), conductor broken strands, defective or loosened spacers, missing or drooping vibration dampers, lightning strikes, etc. (Cigré TB 175) may happen.

For the last decade numerous failures of conductor joints have been reported, the reasons for which have included asymmetrical installation of the aluminum sleeve as well as accelerated ageing and deterioration of the contact surface in the joint due to an increased electrical load (Cigré TB 216).

As the transmission grids around the world age, there is increased need for a consistent method and guide of evaluating “aged” fittings for inspection and testing, and for their replacement (Cigré TB 477).

16.3.1.1 Conductor Corrosion

Conductor deterioration follows different patterns in different geographic areas. Some factors should be kept in mind when considering the effects of location of internal and external corrosion.

For example, prevailing weather pattern in the area of interest. Airborne industrial pollution can be carried several kilometers or more downwind from its source. In this situation, all conductors in the effluent plume are likely to be affected. If the primary source of pollution is an industrial complex with a very tall smokestack the corrosive effluent will be carried farther than if the smokestack is short.

Also, corrosion at joints and clamps is generally not representative of the overall condition of the conductor because corrosive effluent will tend to concentrate in these places.

Technical Background – Internal Corrosion

Internal corrosion is caused principally by industrial and salt pollution environment in the presence of moisture. Original conductor grease levels, together with condition and thickness of the galvanizing coating of the steel, will determine rate of corrosion.

Zinc Corrosion

Salt and industrial pollution will act as an electrolyte when combined with prolonged wetting of the conductor. This will form corrosion cells once the zinc layer has been breached.

In the first instance, the zinc will protect the aluminum from corrosion by sacrificial galvanic action. However, after the steel is exposed the galvanic cell forms between steel and aluminum.

Corrosion of the zinc coating is temperature dependent and is a maximum between 60-70 °C. Above this temperature, the rate of corrosion decreases.

Aluminum Corrosion

When aluminum and unprotected steel (either by design or after the loss of protection such as grease or zinc or aluminum cladding) are in a conductor the aluminum is sacrificial. The rate of corrosion is high when there are marine and industrial pollutants present. The aluminum and its corrosion products eventually cause the conductor to "bulge". Reduction in the aluminum section leads to a loss of mechanical strength and electrical conductivity. In severe cases, this causes a transfer of current to the steel and subsequent failure due to overheating. It is possible that all the outside strands of the conductor appear intact whilst the inner aluminum wires have severed completely.

When internal conductor corrosion has started, it continues at a uniform rate until the surface area of steel becomes greater than that of aluminum. At this point, the corrosion rate increases exponentially.

Steel Corrosion

It is possible in non-polluted areas, for the unprotected steel to act as the anode, resulting in loss of section of the steel without loss of aluminum section. No external indication of this process of deterioration will be visible until the conductor fails in tension.

Inspection Techniques – Generic Description

Visual Inspection (Ground or Helicopter)

Unlike the OHL Corrosion detectors, visual inspection will not detect the problem at an early stage. As corrosion becomes more advanced, an experienced line inspector will detect the conductor bulging due to the corrosion products being several times the volume of the aluminum and possible discoloration of several strands. Where there is only a single layer of aluminum stranding over the steel core, the bulging is not so evident but in these cases, the corrosion products are visible between the strands.

OHL Corrosion Detector (OHLCD) - Eddy Current

This OHLCD is only suitable for detecting corrosion in ACSR and AACSR conductors. It works in an indirect manner by detecting the loss of galvanizing from the steel strands of the conductor. Loss of galvanizing can be detected by inducing eddy currents into the conductor from a coil that clips around the conductor. The resultant magnetic field is measured with a second coil that is sufficiently sensitive to detect the disturbed field in regions where the galvanizing has been attacked.

The detector will detect corrosion, even where it occurs over a length of a few centimeters. It cannot make a quantitative judgment on the actual loss of aluminum section. It is advisable to take conductor samples at locations indicated by the non-destructive test to determine the extent of corrosion and to test the residual strength of the conductor. These additional tests performed on conductor samples may improve the knowledge of residual life expectancy (e.g., bending and torsion tests on wires).

When conductors are to be tested, the instrument is carried up the tower, the vibration dampers and where applicable, spacers are removed and the two trolleys attached to the conductor. The equipment is then remotely guided along to the next tower and back. Readings are transmitted to a ground station where they can be analyzed with a computer and the results displayed in a form of a corrosion chart. Survey rates of between 6 and 10 spans a day is achievable depending on access. This OHLCD cannot be used where an optical cable has been wrapped on the ground wire.

When planning the deployment of this equipment, the choice of spans to determine the most severe corrosion can be made on evidence for sources of pollution. This is possible, provided an effluent stream map is available showing prevailing wind flows and industrial areas. Alternatively, a survey that is evenly distributed and comprises at least 10 % of the route may indicate the average condition.

OHLCD can also be used on ground wire made of galvanized steel by adding to the sensing head a plastic shell with adequate number of aluminum wires fitted in it.

OHL Corrosion Detector - Steel Core

This OHLCD detects a loss in steel cross sectional area. This area is measured by generating and receiving 2,000 pulses per second: the highest amplitude of every 20 pulses received is recorded on the in built computer, which compiles the data at 100 points per second. This information can be printed later by the computers graphing program. Survey rates of between 6 and 10 spans a day is achievable depending on access and time of year.

This equipment is sufficiently sensitive to indicate loss of steel to levels, which are much less than any likely critical amount.

It is advisable to take conductor samples at locations indicated by the non-destructive test to determine the extent of corrosion and to test the residual strength of the conductor. These additional tests performed on conductor samples may improve the knowledge of residual life expectancy (e.g., bending and torsion tests on wires).

The detector can be applied to the conductor either by hand from a trolley, or a helicopter. It runs across the conductor span by a number of means, i.e., motorized tug, helicopter or gravity.

When planning the deployment of this equipment, the choice of spans to determine the most severe corrosion, can be made on evidence for sources of pollution. This is possible, provided an effluent stream map is available, showing prevailing wind flows and industrial areas. Alternatively, a survey that is evenly distributed and comprises at least 10 % of the route may indicate the average condition.

The OHLCD is only suitable for detecting corrosion in ACSR and AACSR conductors. It cannot be used where an optical cable has been wrapped on the ground wire.

Technical Background – External Corrosion

Aluminum Corrosion

Sulphurous pollutants cause pitting of the surface where solid impurities are deposited on the outer surface of the conductor. Small corrosion cells are then set up when moisture is present. Normally this type of corrosion is evenly spread on the outside of the conductor and does not reduce strength to the same extent as internal corrosion.

Where a helix coil has been applied over the aluminum strands and under a suspension clamp or spacer, serious corrosion of the helical bars could occur in addition to corrosion of the conductor strands. This has been found to occur on routes close to the coast. The only method available in this situation is to dismantle the clamp or spacer and visually examine the condition of the conductor underneath.

Research has shown that the most serious attack occurs in the narrow crevices. Narrow crevices are formed between rubber and helix coils due to the deep impressions made by the helix coils in the rubber. Rubber contributes to the attack of the aluminum helix coils as well as the aluminum conductors. This is because seawater acids and other particles adhere to the aged rubber surface and because the rubber retains moisture.

Copper Corrosion

This form of corrosion is due to the combination of H_2S gas in the atmosphere and moisture.

The concentration of H_2S in the atmosphere in order to produce this corrosion can be very low, making it very difficult to detect and to eliminate. The most frequent sources are marshy or swampy areas, sewers and certain industrial processes.

The corrosion is usually even across the conductor, with a very thick film of dark grey/black copper oxide as shown in Figure 16.1.

16.3.1.2 Wind Induced Damage

Technical Background

Overhead lines are affected by wind induced oscillation in three ways (Aeolian vibration, Sub conductor oscillation, and Galloping).

In general, the forms of damage can be seen as:

- Drooping/missing/slipped vibration dampers,
- Missing nuts from suspension clamps or hardware,
- Split pins missing or displaced from their normal positions in cotter (clevis) pins, etc.,
- Corona rings or insulator strings displaced from their proper positions,
- Broken outer conductor strands, usually emanating from the ends of the suspension clamps,
- Broken inner conductor strands (Figure 16.2),
- Aircraft warning markers moved or missing from conductors or support wires,
- Loose or broken tower members,
- Severe wear of suspension hardware.

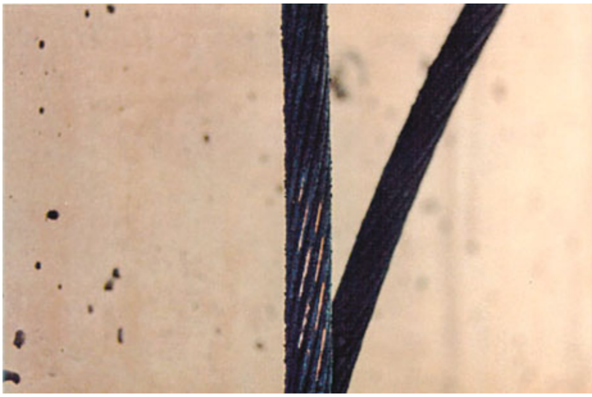


Figure 16.1 Corrosion of Copper Conductor.

Figure 16.2 Broken Inner Conductors Strands.

Aeolian Vibration

Aeolian vibration arises when the wind blows over individual conductors and induces high frequency vibration by the creation of vortices downstream of the conductor. This can create vibration amplitudes of the order of one conductor diameter with frequencies in the range of 5-150 Hz. It occurs predominantly when the wind is perpendicular to the line and in open flat terrain. Often the noise is first indication that there is Aeolian vibration.

Aeolian vibration may cause fatigue of the conductor strands after millions of vibrations. The risk of damage occurring is dependent upon the local wind climate as well as the conductor composition (capability of self-damping of the conductor, resistance to fatigue of the wires).

The point, at which damage occurs on conductors suffering from this wind-induced motion, is usually where the conductor is secured in a fitting, most often a clamp.

Sub Conductor Oscillation

Sub conductor oscillation (SCO) is also caused by wind-induced instabilities due to change in wind load on the leeward sub conductor. In this case the problem occurs on conductors with spacers and is worst with quad bundles, although it may also occur to a lesser extent on twin bundles. This form of vibration occurs at frequencies of about 1 Hz, but with amplitudes equal to the sub-conductor spacing and has resulted in “clashing” in some locations. The modes of oscillation are complex and numerous for quad bundles with horizontal, vertical and rotational forms. SCO is strongly reduced by providing a sufficient number of spacers with corresponding wind characteristics and unequal subspans between spacers.

Damage resulting from this wind-induced motion usually occurs where conductors are secured in a fitting, most often a spacer. The oscillations cause bending of the aluminum strands of the conductor and after tens of millions of cycles, fatigue failure of the outer and inner aluminum strands can occur.

Dynamic bending caused by sub conductor oscillation or Aeolian vibration is at a maximum in the external strands but the maximum damage occurs between the second and outer layers. This wear results in the formation of lens shaped markings on the second layer and undersides of the outer layer strands. Wear will be visible throughout the length of the conductor, with more wear being exhibited adjacent to the fitting. This ultimately results in cracks caused by fretting fatigue.

In the worst cases, observed on ACSR, all the aluminum strands in the conductor can fail and the consequent flow of current in the steel core causes melting and conductor failure.

Galloping

Galloping of overhead line conductors is a large amplitude (1 m to 10 m) predominantly vertical, low frequency (0.1 Hz to 1Hz) wind induced oscillation. Galloping usually depends upon the simultaneous existence of specific meteorological conditions in the presence of wind that may lead to the formation of an ice profile, displaying peculiar aerodynamic characteristics required for galloping (There are known cases where galloping has occurred without the presence of ice).

Galloping can cause damage to conductors in mid span where flashover between phases has melted the outer aluminum layer. The conductor damage is indicated by burn marks, which are dark regions around the flashover locations and globules of melted metal on the outer surfaces. Sometimes this may be accompanied by an increase in audible and Corona noise at the line section.

Galloping will also cause excessive wear to fittings, loosened spacers, and damage to tower members and insulators.

The main problem, as with conductor corrosion, is the identification of vulnerable sections of line to inspect for incipient damage in time to effect repairs. The first breaks in conductors occur under clamps and spacers and are not detectable by any practical techniques tried to date. However, in good conditions it may be possible to detect broken conductor strands protruding from the clamp by use of visual techniques.

Damage to suspension clamps and associated fittings can occur in areas subjected to wind induced motion. The worn surfaces are usually very difficult to see from the ground and may even be missed in a climbing or helicopter inspection. In time this wear can be sufficient to reduce the remaining strength of the supporting hardware to dangerous levels (see Figure 16.3) and to allow the conductor to drop.

Figure 16.3 Worn conductor hardware.

Inspection Techniques – Generic Description

VISUAL INSPECTION (GROUND OR HELICOPTER)

Stabilized Video Camera (Helicopter Use)

The camera is a suitable method to survey a line from a helicopter and examine all fittings in a relatively short period.

Provides pictures at a long distance allowing the majority of OHTL components to be examined. The images are recorded and can be analyzed later. Broken strands wear on fittings, defective or loosened spacers and missing or drooping dampers can be detected by this method.

RADIO FREQUENCY/MICROWAVE EMISSION DETECTOR

Overhead lines in good condition emit a predictable electric field, which in turn produces a continuous predictable Corona pattern. Distortions in the standard pattern indicate the presence of abnormalities. When defective, different line elements will create unique (distorted) Corona patterns. By recording and analyzing these Corona patterns, defective elements can be identified and their condition determined.

The sharp ends of broken strands of conductor generate Corona emission that can be detected with a helicopter-mounted detector. However, broken strands that do not protrude cannot be detected by this method. In one particular case, there were up to 20 broken strands, which were only identifiable, when the clamp was opened.

In some instances, Corona is generated from sources, which are not critical e.g., flashover damage on arcing horns. Previous experience and follow up examination of the suspect spans with high quality binoculars or a tripod- mounted telescope, is required to identify conductor damage at an early stage. The most practical method of identifying "fatigue related" damage at spacer positions is to target sections of line which are most at risk to sub conductor oscillation and then survey these sections (or all the line) with the detector. The line must be energized during this survey.

Where Corona is observed in a particular section, the line should be subsequently flown with a stabilized video camera, visually examining each spacer position.

Irregular Corona can also be detected and located with the use of a "Night Vision Binocular".

Gauges

Gauging can be used to measure wear providing the components are uniform in their dimensions.

Radioactive Isotopes

Radioactive isotopes can be used to expose sensitive film to detect broken strands. It is mainly used dead line but can be carried out live line. Experience has shown this method to be unreliable and should be used with caution.

16.3.1.3 Lightning Strike Conductor Damage

Ground wires are installed at the top of high voltage lines to protect the conductors from lightning strikes. However, although they are designed to have a good level of resistance to lightning impact, phase conductors may suffer damage during particularly severe strikes.

The damage varies from pitting of the outer surface, to melting and breakage of outer strands with consequent reduction of the mechanical strength of the conductor.

16.3.1.4 Conductor Joint Defects

Technical Background

Incorrectly Constructed Joints

Most joints used on ACSR have been of the compression type although bolted joints are used in jumpers. Overheating of these joints arises from inadequate compression along the length of the joint, mainly due to either poor design or installation problems. This will allow moisture penetration and result in oxidation of the internal aluminum surfaces between the joint and conductor. The resistive aluminum oxide reduces the paths for current flow and may cause micro arcing within the joint. Moreover, the resistance of the joint can increase due to the reduction of the contact pressure as a consequence of ice formation inside the joint, thermo-mechanical stresses, conductor vibrations, etc.

The consequence of this deterioration is that the joint becomes warm which further increases the rate of oxidation. Over a period of time, the joint resistance will increase resulting in excess current flowing in the steel core of the conductor. This can then overheat and rupture.

Instances have been reported where the non-oxide grease has been omitted, the wrong dies have been used for compressing the joints and the conductors have been only partially inserted into the joints.

Mid span joints are typically bolted parallel groove type, compression type and wedge type clamps. Overheating of these joints occurs primarily due to improper preparation and installation of the joint. Bolted parallel groove and compression type clamps seem to be most susceptible to overheating caused by high resistance due to corrosion, while wedge type clamps appear to be less so.

Corrosion has been discovered in mid-span joints after initial tests indicated excessive resistance. The corrosion is concentrated in the area where the steel core enters the steel joint sleeve. In addition mechanical failure of joints can occur where the joint has not been centralized correctly over the conductor. As discussed in Cigré TB 216, the failure of a joint is usually a result of an increased resistance due to corrosion, leading to an unacceptable increase in temperature and unstable mechanical conditions. Very few joints have been reported to display failure resulting purely from mechanical loads.

The reported events involving basically mechanical failures have occurred on joints that have been asymmetrically installed, where the ingress of the aluminum layers of an ACSR at one end of the joint has been less than 2,5 times the conductor diameter.

Detection of asymmetrically installed aluminum sleeves on ACSR conductors can be performed by a reluctance test. Detection of asymmetrically installed aluminum and steel sleeves on ACSR can be performed by a radiographic test.

Mechanical failures of ACSR joints caused by corrosion of the steel core on ACSR conductors, causing mechanical failure of joints, have not been reported so far. However, intense corrosion of the steel core has been detected in the vicinity of the steel sleeve. Detection of this corrosion can be performed with a boroscope test.

A.C. Corrosion

Resistance measurement and experience, has shown that potential differences which exist between the strands of overhead line conductors can cause premature failure of the conductor by interstrand arcing or a.c. corrosion of the aluminum and steel strands. The risk of failure may be increased where the potential differences between the strands are present at an early stage after installation.

A likely cause of potential difference between strands is faulty termination in which one or more strands may make poor contact at the terminations. It may also be due to one or more broken conductor strands.

At conductor positions adjacent to unstable terminations that are of very high resistance and probably dissipating sufficient power to be detectable by thermovision surveys, a.c. corrosion may have been initiated. This is likely to be accompanied by a mechanical and electrical failure of the joint itself.

The voltage differences due to broken strands are large enough to promote a.c. corrosion. Current transfer to other strands will also occur in the region of reduced strand cross section where this has occurred due to wear, fretting or corrosion.

Main Reasons for the Failure of Joints

The main reasons for the failure of joints have been identified as follows: corrosion of the aluminum contact surfaces, improperly cleaned conductors, and asymmetric installation of the aluminum sleeve and steel sleeve (on ACSR). All these reasons for failures can be attributed to an increased resistance across the joint. The total resistance across the joint consists of the conductor resistance, the sleeve resistance and the contact resistance. Only the latter will change with time in service.

Since the stranding creates a non-homogenous conductor and the compression of the joint does not completely eliminate the voids between strands, water, sometimes contaminated, will penetrate the joint. The water will then remain in the cavities until it evaporates through the air gaps inside the conductor. This will take time, depending on the temperature in the joint and the humidity in the surrounding atmosphere.

The water will, during the time inside the joint, change the oxygen content along the route, creating differences in potential. The difference in potential will create crevice corrosion in the aluminum, inside the joint. The time it takes for the water to dry influences the severity of the crevice corrosion.

Corrosion of the steel core is generally a result of galvanic corrosion. It has been observed that when the temperature of the galvanized steel core rises above 60 °C, the protective role of the galvanizing with respect to the steel can be reversed. The steel then "protects" the galvanizing.

Inspection Techniques

The electrical resistance of a joint is the main factor for assessing its condition. It can be determined using temperature measurement methods, resistance measurement methods or both.

It is not possible to detect the asymmetrical installation of joint sleeves using a temperature measurement method since the temperature distribution in the aluminum will be too uniform.

When using a resistance measurement, an asymmetrical installation of the aluminum sleeve results in too small a difference in the obtained resistance value to be detectable. Calculations of the change in resistance over a joint indicate that an asymmetry of 20 mm will give the same increase in the resistance as a temperature increase of 1 °C and a doubling of the contact resistance gives an increase of 10 °C at maximum conductor design temperature.

Detection of asymmetrical installation of the aluminum sleeve on ACSR conductors can be performed by a reluctance test.

Detection of asymmetrical installation of the aluminum sleeve on AAC, AAAC and of the steel sleeve of ACSR conductors can be performed by a radiographic test.

Detection of steel core corrosion in the vicinity of a steel sleeve can be performed by visual inspection with a boroscope.

These different test methods are described in detail in the following sections. Some of them are performed live line, such as temperature measurement tests, and others with the circuit dead, such as the radiographic (X-ray) tests.

Temperature Measurement Tests

The reliable measurement of joint temperature is highly dependent on the current flowing through the joint. Since the thermal conductivity of aluminum is very high, the temperature will be equalized along the joint. It would therefore be difficult to detect joints that have an unacceptable contact resistance at one end, but a lower resistance at the other end. Also, the higher resistance at one end will not be detected if the resistance is measured across the entire joint. To increase the chance of detecting defective joints, the current flow in the overhead line should be increased as much as possible. The temperature detection along the joint gets more difficult under some ambient conditions when the heat generated in the joint is transferred to the surroundings e.g., rain, snow or high wind velocities.

Infrared photography detects heat radiated in the infrared spectrum. Detected temperatures at the joint are compared with detected temperatures at the conductor. The resolution is normally 1 °C. Infrared photography can be performed from the ground (see Figure 16.4) or from a helicopter (see Figure 16.5). In the following sub-sections both methods are described.

Measurement of temperature by infrared photography can be a time-saving method enabling a utility to get a good indication of the condition of the joints along a line.

Figure 16.4 Thermographic inspection performed from the ground.

Figure 16.5 Thermographic inspection performed from a helicopter.

The infrared energy measured by the instrument pointed at the object of interest is the sum of the energy emitted, in a specific wavelength window, by the object itself and of the ambient energy radiated by the surroundings and reflected by the object towards the instrument. The latter, in the case of very reflecting objects (with low emissivity coefficient), can be a considerable proportion of the total measured energy and it is essential to accurately determine its value in order to determine the actual amount of energy emitted by the object. The surface structure will also influence the radiated energy.

A joint over-temperature is usually detected by comparing the brightness of the joint, with the unaided eye, on the screen with a suitable reference. This reference is usually the ground, the other half of the joint or the conductor when airborne surveying is used. In order to detect the over-temperature, the joint must appear brighter than the reference on the screen. Due to the lower emissivity of the joint compared with the ground, a fault-free joint appears darker than the ground, because the radiation from the cold sky is partly reflected from its surface. The colder the appearance of the sky and the lower the emissivity of the joint, the darker the joint appears on the screen. Therefore the less overcast the sky, or the higher the cloud ceiling, the higher the over-temperature needed for the joint to appear bright. Consequently a defective joint becomes more difficult to detect without making point measurements. In order to generalize the diagram the radiation temperature of the sky is plotted on the horizontal axis as an under-temperature when compared with ambient or the ground. The plotted curves show the critical joint over-temperature above ambient that is needed for the joint to appear brighter than the ground, on the screen, for different emissivities.

When a thermographic inspection is performed from the ground, the situation is different. The joint is always shown on the image as brighter than the sky in the background. Therefore it is not possible to visually detect joints with an over-temperature. Instead, the temperature of every joint must be measured with a camera having a sufficiently high resolution and compared with other joints.

Resistance Measurement Method

Various devices are available which can be used live line or with the circuit dead.

Measurement made by this method is more direct than infrared thermography and is not subject to emissivity, weather, current loading and background conditions. Although it is a time consuming activity, it can be useful to confirm the initial IR survey.

The lightweight live line devices are designed to attach directly to the high voltage line by the use of an insulated stick and read the resistance of any joint directly in micro ohms. They can also be designed to simply indicate "good" or "bad" for a given joint.

By pressing the two electrodes against the joint so that the connection under test is between the two, a resistance measurement can be obtained from the display panel in a matter of seconds. It calculates resistance by measuring AC current in the line and the voltage drop due to the resistance of the section under test.

The resistance should be measured from the conductor, in the vicinity of the joint, to the centre of the joint. The resistance measurement should be taken for each half of the joint since the degradation along the joint could be different. It has been observed that out of all joints with an increased resistance, around 10 % have unacceptable degradation over just one half of the joint.

The ratio of joint- to conductor resistance is widely spread over the range of conductors used, even for the same design of joint, e.g., 10 to 45 % for one type of joint. These circumstances indicate that it is not practical to use the ratio of joint- to conductor resistance as a criterion for the interpretation of results.

It is recommended that the joint resistance R_{joint}, is classified according to three reliability levels for each combination of conductor and joint using the same parameters as in the current carrying capacity calculation for conductors. For the interpretation of results, all resistance values should be translated to the same temperature, for example 20 °C. Out of the calculated resistance values for the joint, the maximum value should be used for comparison with the appropriate acceptance criterion.

Reluctance Tests

The aim of the reluctance test is to detect the asymmetrical installation of the aluminum sleeve on ACSR conductors by measuring the magnetic resistance (reluctance) of the joint. The asymmetry of the aluminum sleeve versus the steel sleeve should be detected by the use of a magnetic detector. The detector should be thoroughly calibrated for the actual type and size of joints with the aim of giving a proper detection of each end of the steel joint. It should be taken into consideration that the compression joint might be bent so that the steel core is not concentric inside the aluminum sleeve. Furthermore, the increased distance from the outer surface to the steel sleeve should be taken into account when the aluminum sleeve has an uncompressed section in the middle.

The transducer should slowly be carried along the joint axis and when the ends of the steel joint are detected, those points should be marked.

Radiographic (X-ray) Tests

The aim of the radiographic test is to detect asymmetrical installation of the aluminum sleeve on AAC, AAAC, ACAR, and ACSR conductors as well as the asymmetrical installation of the steel sleeve on ACSR conductor cores.

The X-ray film should be placed on the top of the joint. The exposure should be selected in such a way so as to allow the detection of the end of the steel core within the steel sleeve. Because it may be difficult to detect the ends of the aluminum sleeve, the ends of the aluminum sleeve should be marked with straps of lead.

The X-ray tube should be hung beneath the conductor at a distance such that a suitable exposure time and beam angle will be maintained.

Boroscope Test

The aim of the boroscope test is to detect corrosion of the steel core in ACSR conductors, in the vicinity of the steel sleeve.

If the joint has been filled with grease during installation, the boroscope test is not useful. Before detection, a hole, with an appropriate dimension for the lens, should be drilled through the aluminum sleeve in the immediate vicinity of each end of the steel joint. It should be noted that the wire strands of the steel core must not be damaged by this procedure.

The detector should be equipped with an internal light for illumination of the zone to be inspected. After the inspection has been performed, the drilled holes should be sealed with aluminum plugs.

The interpreter should be aware that the image of the surface of the steel core will depend on the type of corrosion protection applied to the steel sleeve, i.e., red lead paint, zinc-rich paint, hot dip galvanising, oil rich paste, or other treatments.

Acceptance Criteria

To reach a higher degree of confidence in the joints on an old transmission line, a set of acceptance criteria should be determined, as shown in Cigré TB 216. The criteria could be given for three levels of reliability, reflecting the importance of the line in terms of its sensitivity to outages, the occurrence of line crossing points and the risk to people beneath the line. The transmission line owner should state the requirements for the reliability of the particular section of the line where the joints are installed.

Since there is the ability to run standard conductor types (ACSR, AAC, AAAC and ACAR conductors) at temperatures up to 100 °C and many countries assume a maximum normal design temperature of less than 75 °C the resistance of the joint will be the triggering value for immediate replacement. In that case the expectation of future increases in current loading should be taken into account.

As shown in Cigré TB 216, when the replacement of a joint must be performed, repair joints and extended joints could be used. The preparation of the old as well as the new conductor should include mechanical cleaning of the contact surfaces intended to be inserted in the aluminum sleeve in order to obtain a low contact resistance. It is also recommended that protective grease be applied. This should be brushed on with a steel brush at these surfaces before compression.

Also the contact surfaces of the aluminum sleeve should be prepared in the same manner. After installation of the joints a resistance measurement should be performed.

To eliminate poor workmanship and associated warranty claims, particular attention should be made to meticulous preparation as well as ensuring that all compression equipment is set to provide a consistent product replicating what was prepared during type registration.

16.3.1.5 Evaluation of Aged Fittings

Evaluation and testing techniques for a variety of fittings are discussed in detail in Cigré TB 477. The evaluation is divided into two parts:

- Evaluation of Aged String Hardware,
- Evaluation of Aged Conductor Fittings.

String fittings are defined as fittings that attach conductor fittings to the towers. Conductor fittings are components that are in direct contact with the conductor, and they are generally used to tension, support or join conductors. Aged fittings are defined as fittings installed for over 30 years (see Chapter 9 and Cigré TB 477).

The assessment of the state of overhead lines should therefore include the evaluation of whether conductor fittings and conductor at the point of application still comply with design characteristics and present requirements, respectively. Original specification and design criteria at the time of the line erection may differ from today's requirements, and should be noted. In some cases, relevant information will simply not be available.

Initial field inspection can be done with thermal cameras for joints and dead-ends to determine potential fittings that should be evaluated. For the purpose of conductor fittings evaluation, it is recommended to cut out a representative number of fittings samples with a sufficient length of conductor without opening the fittings (see Chapter 9 and Cigré TB 477).

16.3.2 Insulators

16.3.2.1 Technical Background – Porcelain and Glass Insulators

General

There have been occurrences where loss of the split pin and washer from the dowel pin at the earth end of suspension insulators has resulted in failure of insulator strings. This has been more evident on towers with smaller vertical loads. Broken insulator sheds can result from vandalism and defects induced during the manufacturing process.

Porcelain

The main cause of failure to suspension and tension porcelain insulators is corrosion of the steel pin in the cap and the pin assembly. Surface leakage currents are concentrated at the pin, causing a higher current density in this area and consequent dry band formation around the pin base. Partial discharges bridge these dry bands resulting in severe spark erosion and after rapid removal of the galvanizing, natural corrosion of the pin occurs until the remaining cross sectional area can no longer support the load. Additionally the expansive corrosion products create a tensile, hoop stress, which leads to radial cracks in the porcelain.

Defective insulators will be more susceptible to failure during a pollution or lightning flashover as the arc passes through the cap of the punctured unit causing it to split open and precipitate a line drop. Most failures of this type have occurred at the line end of suspension strings where the voltage across the sheds is highest.

Glass

With glass insulators, the discharges erode the glass and pin and after fairly minor surface damage, the imbalance in the internal mechanical stresses in the toughened glass causes the shed to shatter completely. Cigré TB 306 provides guidance to utilities and engineers who are in charge of the maintenance of transmission lines on how to check the state of insulators and how to decide on the safe time for replacement.

16.3.2.2 Inspection Techniques

The inspection techniques listed below can be used for porcelain and glass insulators:

- Visual Inspection,
- Insulator Voltage Drop Measurer,
- Electric Field,
- Infrared Thermography,
- Radio Frequency/Microwave Emission Detector.

Generic Description – Insulator Voltage Drop Measurer

Incipient radial cracks that occur in porcelain insulator sheds and which can initiate tensile fracture, can be detected by application of a 30 or 50 kV test voltage at ground level. As this requires extensive outage duration, 1 kV to 10 kV meters have been developed for testing in-situ, dead line or live line. This method is time consuming and the reliability of the results is dependent upon the weather, pollution and humidity levels.

Generic Description – Electric Field

There is a measurable electrical field existing between the energized and grounded end of an insulator string. When one or more of the insulator sheds is defective or leaking current, the electric field will be reduced. The measuring equipment is applied over the insulator string and the electric field over each shed is measured. There is no electrical contact between the device and insulator. The measurements are then downloaded to a computer, which analyses the results to identify the location of defective insulator sheds.

Generic Description – Infrared Thermography

The infrared camera, operated from a helicopter or from the ground, can be used to identify defective insulators. The technique can identify defects under favorable conditions where head cracks (incipient defects produced within the porcelain during manufacture, or as result of damage during transport) result in warmer insulator caps.

However, the differentiation between warm insulators and cracked insulators is not always great enough for it to be completely reliable and therefore this method should be used in conjunction with the electric field or voltage drop measurer.

16.3.2.3 Technical Background – Composite Insulators

Composite insulators have become a highly developed alternative to conventional insulators in all transmission level voltage classes for AC and DC applications around the world. The assessment of line components, which includes insulators, insulator sets, conductors, dampers as well as towers, foundations, etc., is a well established philosophy in terms of line maintenance.

An essential issue that limits an even wider application of composite insulators in some countries is the concern about the assessment of their conditions in service and especially before the application of live line working (LLW) techniques. The diagnostics is easier for LLW, since its aim is to identify only large conductive or semi-conductive defects which may be critical during the specific linemen activity. A well chosen combination of available diagnostic methods make it possible to identify the absence of critical defects of composite insulators and to carry out LLW safely on overhead lines equipped with composite insulators, in a similar way as it is for ceramic and glass insulators.

For composite insulators, degradation can occur through premature ageing or internal manufacturing defects and it is not possible, using current technology, to choose a single technique that will detect all types of defective insulators with a satisfactory degree of confidence. A combination of two or more techniques has in practice, been proven to be the most effective means of identifying defective composite insulators in service. The inspection techniques listed below can be used by utilities on live lines on composite insulators:

- Visual inspection,
- Night vision equipment,
- Electric Field Measurements,
- Directional wireless acoustic emission,
- Infrared (IR) thermography,
- Ultra-violet (UV) detection,
- Combined IR- and UV-measurements (Multicam),
- High frequency high voltage measurement tool.

The high frequency high voltage tool is applied using a hotstick and has two spring-loaded electrodes separated by approximately six inches (152 mm – adjustable depending on the insulator design) as shown in Figure 16.6.

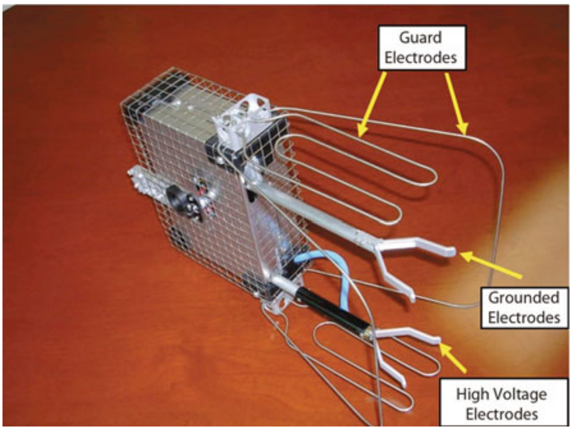


Figure 16.6 Recently introduced high frequency/high voltage tool showing high voltage electrode, grounded electrode and guard electrodes.

Ten prototypes of the tools are being tested in 2014 by utilities in the United States, Canada and Australia. After these field trials, the tool is expected to be available commercially. Considerable effort has been made to make the tool light and field-rugged and successful testing up to 345 kV has been completed. At 500 kV, the length of the hotstick results in high mechanical cantilever loads for the operator and a crawling robot which can take the tool as a payload is being developed by EPRI as described in Section 16.6.2.4.

16.3.3 Supports

16.3.3.1 Steel Structures Condition

Technical Background

The main factors, which affect the rate and onset of steel structure corrosion, can be categorised into two groups: environment factors and protection factors.

Environment Factors

The following factors affect the rate and onset of steel structure corrosion:

- Prevailing Weather Conditions,
- Tower Altitude,
  - Affecting pollution flux & time of wetness
- Fertilisers,
- Brushwood,
- Pollution Levels,
  - Industrial
  - Coastal.

Protection Factors

The following factors affect the rate and onset of steel structure corrosion:

- Surface Protection Quality,
  - Preparation and weather conditions
- Painting Policy,
  - Frequency and time of first paint
- Tower Access,
- System Access.

All of the above factors contribute to the time before onset of corrosion and to the rate at which it progresses. In most circumstances, it will be a combination of two or more factors. Any combination of the above factors will lead to a variety of support steel conditions (see Figure 16.7).

If the first painting is delayed until significant loss of galvanising has occurred and the steelwork has become corroded, extensive preparation may be required before painting. This work may involve grit blasting or replacement of certain tower members. Inevitably, this will reduce the overall life of supports.

Figure 16.7 Corrosion at tower joints.

Most supports are constructed using galvanised steel members, which may be pre painted prior to erection or painted some time after erection. A few supports are manufactured from "Corten steel", which is a steel alloy with a special low rate of surface corrosion. However, Corten appears to be more susceptible to high rates of corrosion at joints, in areas close to the coast and in areas subjected to high levels of humidity.

In addition to corrosion of the steel, the support members can be subjected to buckling due to soil movement, loose bolts or broken members. Excessive wind movements are the normal cause of loose bolts and steel breakage. These can be detected by visual examination or "rapping" the support with a hammer to detect loose components.

Inspection Techniques

The inspection techniques listed below may be used to assess the steel structure condition:

- Visual Climbing Inspection,
- Binoculars,
- Telescope,
- Camera,
- Electronic Paint & Galvanising Thickness Measurement,
- Cross Hatch Cut Test.

Generic Description – Visual Climbing Inspection

For the purposes of the inspection, each support is subdivided into zones according to the height and design of the support. Steelwork condition is assessed against standard photographs showing steelwork at various stages of deterioration. Each zone is then given a score accordingly.

Generic Description – Electronic Paint & Galvanizing Thickness Measurement
Measurement of non-ferrous metal paints (e.g., chromium, copper, zinc, etc.) or plastic coatings on steel, can be carried out by means of instruments using magnetic induction. With paint or plastic coating, or on non-ferrous structures, measurements are possible using instruments, which employ eddy currents (this technique can also be used for the measurement of ferrous and non-ferrous metal coating on steel.

Generic Description – Cross Hatch Cut Test
This is the method by which the adhesion values for the paint on the support members as specified in standards EN-ISO 2409 or ASTM-D-3359, can be ascertained.

16.3.3.2 Reduction in Stay Wire Tension and Stay Wire Corrosion

Technical Background
Stay wires are subjected to elongation due to the numerous oscillations whilst under tension. These oscillations result in mechanical fatigue of the cable wires, causing minor separation of the strands and thus, a relaxation and/or lengthening of the cable, which can result in mechanical damage to the support. It is therefore necessary to verify the tension of the stays on a regular basis and in some cases, to carry out re-tensioning.

Under certain conditions, i.e., the presence of moisture and oxygen, these stay wires will corrode.

Inspection Techniques
The inspection techniques listed below may be used to assess the stay wire condition:

- Hydraulic Method,
- Vibration Method,
- Deflection Method,
- Corrosion Detector.

Generic Description – Hydraulic Method
Measurement of the tension related to the pressure measured on jacks fixed to the stays anchorage devices. Allows simultaneous re-tensioning if required.

Generic Description – Vibration Method
The tension is determined by timing the reflected travelling pulses on the cable. The generation of the initial pulse and timing is computer controlled. The device is calibrated by comparing the timing and tension with cables of known tension. The equipment is light and easy to operate.

Generic Description – Deflection Method
Measurement of the perpendicular effort required to initiate a calibrated deflection between two points and calculation of the corresponding tension in the stay. The equipment is light and easy to operate.

Generic Description – Corrosion Detector

This device is based on magnetic induction process, which measures the variation of the magnetic flux at the defect location. These variations are identified on the signal records and then compared to signals related to typical defects of various magnitudes (corrosion, broken strands).

16.3.3.3 Corrosion of Anchor Rods

Technical Background

Overhead transmission lines supported by stay wires are sometimes anchored to the earth with rods. Under certain conditions, i.e., the presence of moisture and oxygen, these rods will corrode along their length.

Inspection Techniques

The inspection techniques listed below may be used to assess the corrosion of anchor rods:

- Ultrasonic Pulser and Receiver,
- Potential Measuring.

Generic Description – Ultrasonic Pulser and Receiver

This non-invasive technique eliminates the need to excavate, which is the only other alternative to fully assess their condition. The extent of corrosion can be categorized into three groups:

- No Corrosion (Good),
- Moderate Corrosion (Moderate),
- Excessive Corrosion (Excessive).

The system is compact and lightweight, consisting of an Ultrasonic Pulser and receiver together with a PC-based data collection and processing system.

Successful application requires a smooth, flat surface for coupling the probe to the anchor rod. This may require the grinding of a flat surface in the eyelet of the rod at right angles to the longitudinal axis in order to properly direct the ultrasonic wave.

Generic Description – Potential Measuring

The potential of a metallic surface is measured in relation to a reference electrode (i.e., $Cu/CuSO_4$). Potential measuring will indicate if the zinc coating is still able to protect possible exposed steel areas.

Measurements that gives the depth dependent potential distribution, may indicate if anchor rods are exposed to local corrosion attacks. By following the potential growth trend, the lifetime of the construction may be estimated.

16.3.3.4 Wood Poles Condition

Technical Background

The main damage, to which wood poles are subjected, is the degradation of mechanical strength due to wear and decaying of the wood and to the action of insects and woodpeckers.

Decaying takes place mainly in the ground line zone where humidity, fungi, bacteria and pollutants may penetrate inside the pole through the natural cracks in the wood or through the passages created by insects.

The ground line zone extends from about 45 cm below ground line to about 15 cm above. This is due to the typical limit of oxygen below ground and to the reduction of moisture at heights above ground (water and oxygen are necessary elements for the decaying of wood).

In order to protect the pole from the above agents, the wood is treated prior to installation. Supplemental "in situ" treatments may be applied during the lifetime of the pole in order to prolong the life (Figure 16.8).

Figure 16.8 Typical Wood Pole Structure.

Inspection Techniques

The inspection techniques listed below may be used to assess the wood poles condition:

- Visual Inspection,
- Climbing Inspection,
- Excavation,
- Sound and Bore,
- Electrical Resistance Measuring Device,
- Wood Pole Strength Measuring Device,
- Penetration Measuring Device,
- Trained Dogs,
- Portable Ultrasonic Detector.

Generic Description – Sound and Bore

This method involves first repeatedly hitting the pole surface with a hammer from ground line to 15-20 cm above. The main purpose of this is to locate internal decay pockets by listening to the sounds and noting the feel of the hammer. Borings should be made in the sections where decay is suspected. For poles that sound completely solid, at least one boring should be made at a 45° angle near ground line. An experienced inspector will notice a change in resistance against the drill when it contacts decayed wood.

Generic Description – Electrical Resistance Measuring Device

The decay process, even in early stages, will develop negative ions that lower the electrical resistance of the wood tissue. By measuring the electrical resistance of the wood by this instrument it is possible to detect incipient decay. The measurement is carried out by slowly inserting a probe (which consists of a twisted pair of insulated wires with bare tips) into a bore in the pole. When a sudden drop (75 %) in the resistance reading occurs, incipient decay is located.

Generic Description – Wood Pole Strength Measuring Device

This instrument utilizes the correlation that exists between the bending strength of the pole and spectral analysis of sound waves travelling through cross sections at various locations along the pole. The relationships between these factors are held in a computer and are used for comparison to determine the strength of wood poles to be assessed.

This instrument is not a substitute for traditional inspection. It does not detect decay and the results obtained should be coupled with a physical evaluation of the pole (e.g., by sound and bore).

Generic Description – Penetration Measuring Device

Measuring the number of rotations of a probe needed to penetrate a given distance indicates the condition of a given wood type (more rotations are needed to penetrate a given distance in harder wood than in softer wood). This is achieved by rapidly rotating a probe into the wood and measuring the rate of progress.

Any type of wood can be tested whether it is hard, soft, wet or dry.

The results are stored on a computer for easy data collection and analysis. The data collected can be used to calculate the wood density.

Generic Description – Trained Dogs

Dogs can be trained to smell certain types of wood rot.

Generic Description – Portable Ultrasonic Rot Locator

A transmitter is screwed into the pole and emits an ultrasonic pulse three times a second. The probe of a hand held receiver is placed firmly against the wood to detect the ultrasonic pulse. If the wood is in good condition, a strong signal will be received. A weak signal indicates decay. Where decay is detected, the results can then be feed into a program, which will calculate the strength and determine the rot position.

16.3.4 Foundations

16.3.4.1 Technical Background

For the majority of foundations, constructed using the appropriate materials, there are no significant modes of degradation. Poor workmanship and design deficiencies do however, give rise to potentially serious problems. Uplift failures, where the pyramid block remains in the ground, can occur if the stub is insufficiently encased in the block or the cleating is inadequate. Corrosion of the tower steel stub can occur when moisture and oxygen are present. The corrosion is usually only found at the chimney/muff interface where poor construction has left the joint open and bare steel is exposed. Problems with ground conditions such as mining subsidence can also occur.

The main factors, which affect the rate at which the tower stub can corrode, are:

- Foundation Construction Quality,
  - Continuity of concrete, interface quality, concrete thickness
- Soil Types,
  - Clay, alluvial soils are worst due to water retention
- Ground Water Levels and frequency of change in level.

For more detailed explanation of foundation deterioration mechanisms refer to Section 3 of the Cigré SC22 WG07 Report on “Refurbishment and Upgrading of Foundations” reference CE/SC 22 GT/WG 07, 1999, 160 pages Ref. No.141.

16.3.4.2 Inspection Techniques

The inspection techniques listed below may be used to meet the following foundation criteria:

- Foundation Type and Dimensions
  - Visual
    - Above ground
    - Below ground

  - Surface Penetrating Radar
  - Acoustic Pulse Echo
  - Probing
- Foundation Condition
  - Visual
    - Above ground
    - Below ground (Figure 16.9)
- In-situ Concrete Strength Tests
  - Core Samples
  - Penetration Resistance Tests (Windsor probe)
    - Comparative Quality and Localised Integrity
      - Surface Hardness Measurement (Schmidt hammer)
      - Surface Penetrating Radar
      - Acoustic Pulse Echo
      - Hammer Test
    - Durability
      - Carbonation Tests
      - Corrosion Rate Measurement
      - Half-cell Potential
      - Resistivity Tests
      - Concrete Dust Samples
      - Sulphate and Acid Concentration in soil or ground water
      - Concrete Core Samples
      - Steelwork Measurement
      - Timber Strength
      - Ultrasound
- Ground Resistivity
  - Soil Resistivity Meter.

For further details, see Chapter 13 – Foundations.

Figure 16.9 Foundation condition below ground.

16.4 Use of Carts for In-Span Maintenance Work

16.4.1 Introduction

One maintenance method commonly employed by many line owners and operators is working in-span on the conductors, shield wires and even the OPGW of a transmission line, especially when the accessibility with alternative methods such as the use of bucket trucks, cranes or helicopters is difficult, problematic or restricted. Sometimes, the work makes use of carts or man-baskets (see Figure 16.10) and sometimes the work is done without any apparatus at all to support and transport the person(s) on the wires.

As line components age, concerns arise for the safety of in-span work insofar as it increases the mechanical tension in the conductor on which it rides and that may be weakened with age or by the damaging actions of attachments on the conductor. Carts are used for in-span work such as the repair or replacement of spacers, dampers, aircraft warning markers, etc.

Cigré TB 471 identifies the factors that affect the structural integrity of the aged conductor systems and therefore, the risks associated with the use of carts on aged conductors. Guidelines are given for developing criteria or rules for use of carts, for inspection and assessment of safe conditions as well as alternative methods for dealing with presumed or known unsafe conditions.

16.4.2 Technical Considerations

Before working in-span on a wire, it was felt essential to know or to measure the present condition level of the wire, of its joints (compression or otherwise) and the insulators and fittings. The condition is generally unseen or difficult to quantify as damage is typically due to lightning, arcing, galloping, fatigue, corrosion, ageing and vandalism (bullets). The condition of the conductor at invisible places, such as under existing aircraft warning markers, and inside connectors is a major concern.

Figure 16.10 Cart used on a horizontal twin bundle.

Prior to carting, a specific engineering analysis can be carried out to establish its effect on line tension, and also check for adequate clearances. If necessary, the wires in question would be closely inspected by helicopter. An inspection may also involve the removal of a sample section of conductor for laboratory (external) analysis.

It is important to understand that the point load of persons on a span of wire generate a tension increase in the wire that can be 300 % to 500 % of the point load weight depending on the length of the span, the location in the span of the load and so on.

Minimum safety factors for using carts are considered useful to allow the possibility of sending a second (emergency) cart to help an imperilled one. Alternative emergency solutions are sometimes planned (especially when the accessibility from ground is difficult or impossible). Safety can be increased by using safety ropes to secure the insulators and hardware on both sides of the span to be traversed. A safety rope can also be tied to other phases. The clearance to the nearest live phase is calculated in advance.

Once the wire is aged, the work is to inspect and repair the conductor and the hardware and connections attached to it. Carts can carry one or more persons. These carts are supplied by manufacturers or are custom built by the user. They come in many sizes and weights. As described in Cigré TB 471, cart design, fabrication and usage are without many national or international standards, except standard BS EN 50374 applicable to all European manufacturers.

16.4.3 Sources of Tensile Strength Loss with Time

The tensile strength loss in the conductor, OHGW or OPGW, and in its tension-carrying connectors (end fittings, strain insulator assemblies and splices) is of interest in this Section.

Consider the suspension assemblies at structures. Compared to the issue of wire tension increase and integrity, this is an easy subject to understand and manage. As noted the tension increase is limited to the actual, gross weight of the cart and/or people placed on the wire.

This assembly is made up of the structures attachment plate, the hole(s) in it that support the assembly and all parts of the assembly. Rolled steel parts of this assembly tend to weaken only by loss of material through wear or corrosion. Either action is discoverable by visual inspection. Forged or cast metal parts and ceramic insulator parts are capable of weakening with time by micro-cracking—that is to say, invisible actions.

It is advantageous that most transmission lines and systems have a great number of these assemblies and load-carrying problems with them, i.e., failure of any of their parts, have a reasonable chance of showing up statistically before cart usage on them is considered.

Barring the development and collecting of statistical performance data, the risk associated with a failure of such an assembly caused by the use of a cart is only a matter of chance. Cart users must decide whether to operate under the conditions of "chance" or to do the data-gathering work beforehand to form a basis for risk assessment. The action that can be taken to mitigate the risk—known or unknown—is to tie the conductor off to the structure support above and by-pass the assembly that is not trusted.

Consider the conductors, including the tension-carrying connections such as end fittings, strain assemblies and in-span splices. Work by others and common knowledge within the industry allow the listing of sources of tensile strength loss in conductors and their tension carrying connectors. These are:

- *Core corrosion*: Steel, the most common core material does oxidize with time in selected environments. It is accelerated by industrial or sea coast environments. It has also shown to be a problem in self-damping conductors where the intentional gap (airspace) between the core and aluminum can fill with water at mid-spans causing loss of material in that location sufficient for breakages to be recorded at some utilities. Excepting these conditions, steel cores tend to retain strength for respectable periods of time.
- *Partial core breakages*: The strands of conductor cores can be broken over time from Aeolian vibrations. This will occur at structure support hardware or at point masses in–span such as marker balls. Generally, core strand fatigue failures are rarer than breakages in the aluminum strands caused by the same action. The brittle cores on the new high temperature conductors can be fractured during installation if the installation procedures are poorly executed. If not realized at the time, this can set up a future event when the conductor is tensioned to a higher value. This type of event has no recorded data to allow measurement of frequency of occurrence and is to be considered as very rare and eventually revealed by the natural tension fluctuations in the wire.
- *Aluminum strand breakages*: Aluminum strands are easily fractured in partial numbers by Aeolian vibration if the wire is not properly equipped with vibration dampers. Each broken strand is a calculable percentage loss of strength. Generally, the most likely location for broken strands to exist is under hardware attached to the conductor or in the layers of strands beneath the outer layer. This makes finding these broken strands nearly impossible by simple visual inspections. Various techniques do exist to look into these hidden places and these techniques are worth employing from time to time to track any progressions of strength loss caused by vibration.
- *Lightning damage*: Lightning strikes can burn aluminum strands. The result tends to be a large area that is clearly heat damaged. Lightning strikes damage steel strands of ground wires with much less visible evidence and much greater strength loss. The visible damage to steel strands can be as small as 1-2 mm but the instant, extreme heating changes the metal to Martensite—a brittle material. It is common to see several of the typical seven strands completely severed in brittle fracture at more than one location in most spans on a line. All tensile load in the wire is carried in the remaining, intact strands and failure will occur when the tensile strength of those remaining strands is exceeded. If two strands are fractured by a previous lightning strike, then the strength of the OHGW, while appearing to be intact and or full tensile capability, is actually reduced to 5/7th of its original strength. This is not an uncommon condition for steel OHGWs.

- *Bolted fittings*: Bolted deadends are reasonably common. They are generally made of cast steel or aluminum and use U-bolts to hold the wire in a saddle shape of the casting. They are often of reasonably complex shape, including a "wave seat" to hold the wire in a bent position to assist with the grip. There have been cases where these types of fittings—those of a particular shape and application—have broken while in use at tensions well below the published rated strength. The point to understand is that great care and study should be made of these cast hardware components before relying on the manufacturer's claims. They can be complex entities with poorly defined or understood limits of use.
- *Compression fittings*: Compression splices and deadends are designed to transfer the full tension in a wire from the wire to something else. The industry is beginning to understand that the high temperatures that are being applied and the long years of service of these connectors are both leading to higher tensile failure rates with compression fittings than previously understood.
- *Flashover, galloping and vandalism* may happen.

16.4.4 Alternate Methods and Criteria for Cart Use

If there are any doubts about the condition of the components, work is done by an alternate method to in-span work such as:

- Lowering the damaged conductor to the ground,
- Lowering the damaged conductor to the level of another undamaged conductor,
- Using a bucket truck or a crane (depending on the conductor height),
- Using a helicopter (with or without live line working),
- Using robotics (see Section 16.6).

The natural environmental changes in temperature and the occurrences of wind and ice events can possibly generate tensions in the spans and weights on the support points comparable to those to be generated by in-span work. Thus, these natural events can be looked to as evidence that the spans have recently supported at least these loads. Finding evidence or proof of greater capability is much more difficult and generally not sought. Thus, the decision to work in-span will typically be made with only partial supporting data. The risk to be taken is a function of the organizations' willingness to take such risks.

16.5 Live Work Maintenance

Live work (work on energized circuits) has been carried out in different parts of the world for many decades. Live work is the preferred method of maintenance where system integrity, system reliability, and operating revenues are at a premium and removal of the circuit from service is not acceptable. Live work may also be beneficial in construction, upgrading and uprating.

Live work has been found to be a safe means of performing maintenance operations due to the additional planning and crew training required for live work. Most maintenance operations that are performed de-energized can also be performed using live work techniques.

This section describes the costs and benefits of live work versus de-energized methods. Examples of typical live work operations are given that are applicable to many asset owners. There is also a brief description of some of the technical requirements for implementing live work programs. For a more detailed discussion of the costs of developing an in-house live work programs and the outsourcing of live work, refer to Cigré TB 561.

16.5.1 Why Consider

16.5.1.1 Trends

Grids are getting older and need more maintenance. It will be more difficult to get the authorization to build new lines. There is consequently a need to increase capacity on existing facilities (e.g., replacing conductors). Increasing renewable generation (connection to the grid of wind farms, co-generation, solar farms, etc.) has impact on the availability of the network for scheduling maintenance.

16.5.1.2 Customers

There are difficulties and in some cases impossibilities to get outages of client feeders for de-energised work. Moreover, penalties may be claimed for undelivered energy (from power plant point of view).

16.5.1.3 Safety

With respect to the number and severity of accidents, live work has been found to be a safe way of performing maintenance operating. However it requires extensive training, qualification, and certification for each worker and supervisor.

16.5.1.4 Regulators

Regulators are requiring reliability and availability standards (i.e., respect of n-1 criteria, penalties for outages, etc.). Live work can help complying with these requirements.

16.5.1.5 Politics, Stakeholders

Performing live work on lines and substations to reduce customer outage time presents considerable advantages (public image, national consequences of outage, etc.).

16.5.2 What Can Be Done

Most maintenance operations that are performed de-energised can also be performed using live work techniques. To do so requires proper operating procedures that take into account the complexity of the task and technical standards referring to equipment, procedures, safety and quality assurance (see Cigré TB 561).

16.5.2.1 Complexity of Various Jobs

Live work has mainly been developed for overhead lines, fewer utilities are able to carry out live work in substations.

Table 16.1 gives a relative complexity rating of performing live working on overhead. The relative complexity is ranked as either low, medium or high (1, 2, 3), where:

- Low complexity work normally does not modify the electrical and mechanical characteristics of the structure and are often some distance away from the structures.
- Medium complexity work may modify the network configuration. These operations sometimes include connection/disconnection of electrical parts of the network.

Table 16.1 Live line work; Complexity of live work: Low, Medium, High (1, 2, 3)

		LINES	Complexity	Reference
Insulators	Change out	Suspension I-string	1	Figure 16.11
		Suspension V-string	2	Figure 16.12
		Dead Ends	2-3	Figure 16.13
	Testing		1	
	Cleaning and Washing		1	
	Splicing	Conductor	2	Figure 16.14
		Shield Wire	1	
Conductor & Shield Wire	Sampling & Testing		1-3	
	Repairing/Patch rod/ split sleeve		1	
	Replacing & Restringing		3	Case Study 16.1
	Relocating Phases		3	
	Installing OPGW		3	
Components	Communication device		2	
	Aerial Markers		1	
	Inter-Phase Spacers		2	
	Spacer-dampers		1-2	Case Study 16.2
	Corona rings		1	
	Suspension clamps		1	
	Jumpers		1	
Tower and Poles	Replacing tower		3	
	Replacing wood pole		2-3	
	Relocating		3	
	Refurbish, replacing steel members		2	
	Raising		2-3	
	Painting		1	

Figure 16.11 Changing 220 kV I-string insulator using bare hand techniques (Spain).

Figure 16.12 Changing a 500 kV V-String Insulator using Bare Hand Techniques (USA).

- High complexity work corresponds to the operations where the aim of the work will modify the network configuration. These operations include connection/disconnection of electrical parts of the network.

16.5.3 General Cost Comparisons

The feedback from utilities performing live work on overhead lines is that the cost is comparable to that in de-energised conditions. However, there will be a minimum additional cost of 1 or 2 more days for preparation of live work plans.

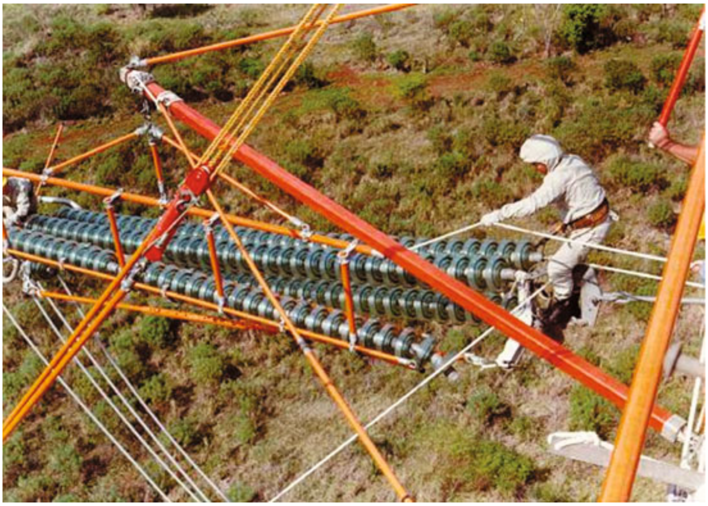


Figure 16.13 Changing 600 kV Insulator String using Bare Hand Method (Brazil).

Figure 16.14 Making a full Tension Conductor Splice (South Africa).

Table 16.2 gives a comparison of time required between live work and de-energised method and for different works.

Depending on whether live work program is carried out in house or outsourced, the Table 16.3 will give a general idea about the (in-house) costs for the utility of each stage in the live work program.

Referring to Table 16.3, the (in-house) costs for an in-house project will mainly depend on labour costs. In case of outsourcing the live work, total costs may be higher, because the fixed costs of the contractor will be calculated on the project. The level of these costs depends on the number of projects to be done, the situation in the market, short-time versus long-time contracts etc.

Table 16.2 Comparison of Time Required to Complete Live Line Work versus De-energised Work

	Bare hand method	
	225 kV	400 kV
Changing suspension insulators	From 5 to 15 % more	from 5 to 10 % more
Changing fitting and insulators	From 5 to 15 % more	From 5 to 10 % more
Changing wire components	30 % less	30 % less

Table 16.3 Comparison of Fixed Costs of In-house versus Outsourced Live Work

Item	In-house	Outsourced (In House Cost)
Preparing the conditions for a live work organisation	100 %	10 %
Feasibility study	At the beginning of the project	At each new situation.
Implementing a live work organisation	100 %	5 %
Validation of rules	100 % for initialising	100 % at each new situation
Training of teams	100 % for initialising	0 %
Training of system operating staff	100 % for initialising	100 % for surveying at each new procedure
Staff re-training	100 % (more or less due to the live work activity)	5 % for each new procedure
Purchasing tools	100 % for initialising	0 %
Regular testing	100 %	0 %
Tool repair	100 %	0 %

Case Study 16.1 (USA): Replacing & Restringing while Energised

The increase in capacity was accomplished by replacing the existing ACSR conductor with ACSS/TW (trapezoidal wire) and matching the design working tensions so that it would not be necessary to change out structures or anchors.

Due to system constraints the line could not be taken out of service for the extended period of time required for normal uprating. Therefore, the 52 km line, consisting of 234 H-Frame structures with the three phases in a horizontal configuration, was reconductored while energised. Work plans were developed to enable the sequential transfer of electric load between the three existing phases and a temporary transfer bus. Supplementary pole structures were constructed to support the energised temporary line. Rollers were installed on the de-energised existing phases to be reconductored. In this configuration, the induced voltages on the "de-energised" conductor ranged up to

30 kV, therefore, the equal potential stringing method was used to eliminate potential hazards to the line crews and public. Other procedures that were developed were:

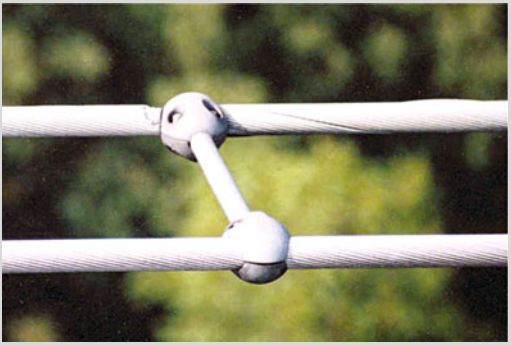
i. Tying off the existing and new conductor at night by insulating and isolating the conductor from the equipment.
ii. Transferring of large loads from existing conductor to the temporary line, and from the temporary line to the new conductor, using a mobile 345 kV breaker.

Installing rollers on the de-energised phase while the temporary line at the left is energised.

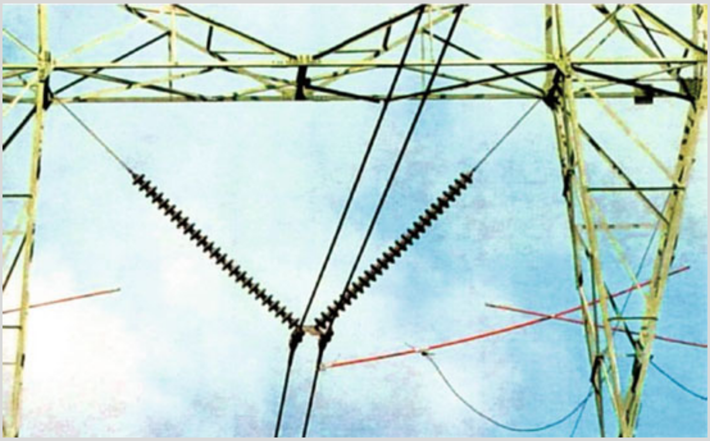
Mobile 345 kV Breaker.

Case Study 16.2 (USA): Spacer Replacement

This case study demonstrates how a spacer replacement programme could be completed live. The route is a 500 kV twin ACAR construction which has encountered spacer induced conductor damage.



Consideration was given to completing the work either de-energised or live. With circuit outage constraint charges at $75,000 per hour the decision was made to complete the work live with industry standard Portable Protective Air Gaps (PPAG) also fitted. The PPAG were installed on the towers at a distance of every 4 miles.



The work was completed over a 22 day period via a helicopter and this involved changing 6,208 spacers with a total cost of under $800,000 i.e., approximately 10 hours of outage cost.

16.6 The Use of Robotics and New Maintenance Techniques

16.6.1 Introduction

Strategic assets such as electricity transmission grids must be operated in a safe, predictable and reliable way. To do so, best practices in the operation and maintenance of transmission networks must evolve to respond to the changing context of pressured grid operators: operation and maintenance standards, laws and regulations, increasing loads, commercial exchanges, etc.

Nowadays, live-line work is a must for most maintenance operations, and the need to maintain system availability is a key factor in the introduction of robotics in this field. In order to maintain or increase the reliability of aging OHTL, new maintenance techniques are becoming available to assess and diagnose the condition of various OHTL components. Power line inspection and maintenance already benefit from developments in mobile robotics, which can reduce the potential risk to maintenance crews (e.g., live work), reach hardly accessible spans (e.g., river crossings), perform tedious labor faster, and decrease costs.

A comprehensive review of the state of the art in transmission line maintenance robot technologies have been presented by Toussaint et al. 2009 and in a Cigré TB entitled "The Use of Robotics in Assessment and Maintenance of OHL" to be published.

Most robotic technologies described here were published in CARPI 2010 and 2012 Conference Proceedings, where many papers were presented on power line robot design, simulations, subsystems and peripheral work (image processing, control and sensors).

16.6.2 Transmission Line Robotics

Robotic technologies have already proved to be a valuable means of inspecting certain systems, and robotic inspection is now considered to be a realistic approach for grid owners. A few major utilities have already introduced robotics into their maintenance practices, and several are funding projects to do so. Safety, efficiency, reliability and availability of equipment are the main factors driving this trend.

The expected increase in live-line work approaches has stimulated the development and use of robotic devices to minimize risk to field personnel safety and maintain power system reliability. This Section seeks to provide an overview and an assessment of the future possibilities for transmission line robotics. Four robot classifications are identified here:

- Ground-based robots,
- Line suspended robots,
- Aerial-based robots,
- Other types of robots (e.g., insulator robots).

16.6.2.1 Ground-Based Robots

The significant increase in live line work requirements within the OHLT industry has stimulated the development and use of robotic devices within the industry. The main benefits or aims of these devices are to increase safety to field personnel and minimize the risk to power system reliability when performing live line work. This section will look to review existing and developing robotic technology with respect to ground based robots.

In respect of ground robotics there is limited development in this area of robotics, with the main area for use focussing on the capture and control of energised conductors and carrying out tasks to provide safe working areas for linesman as well as keeping the lines energised during the projects. The development was driven to address specific live-line procedures, such as the replacement of rotten wood poles utilizing the existing hole (especially in rock) and reframing and re-insulating structures, which are typically difficult to execute with traditional live-line tools like hotsticks.

Much of the development has focussed around robotics arms for the manipulation and control of energised conductors. Examples of these being:

***LineMaster*™**

As shown in Figure 16.15, this is a robotic arm developed by Quanta Energized Services for remotely handling, moving and relocating energised conductors of varying voltages up to 500 kV.

Figure 16.15 Photo of the boom truck and LineMaster™ in action.

The robotic arm remotely captures and controls the energised transmission lines in a safe and efficient manner. The arm is controlled by a radio control device comprising of a portable transmitter and two receivers. The arm is powered via a hydraulic power source. There are two versions of the robotic arm which is generally mounted to a truck.

Main Features

- Operates by hydraulic actuator that attaches to conventional line trucks,
- Unit consists of adaptor, robotic arm and fibreglass segment,
- Robotic arm can extend up to +/−3 m (10 feet) and rotate 270 degrees,
- Primary unit models:
  - 227 and 454 kg (500 and 1000 lbs) lift
  - 2273 kg (5000 lbs), single-phase
  - 5455 kg (12000 lbs), three-phase
- Control is by ground-based safety spotter.

Benefits

- Enables upgrade relief to congested paths without adding to congestion by scheduling outages to perform work
  - Circuits most in need of relief are usually those difficult to schedule out of service
  - Reconductoring can increase thermal capacity
  - Structures beyond their expected service life can be repaired
- Enables reuse of existing rights of way
- Reduces matting and footprints in wetlands areas
- Reduces operational costs and delays of line switching and grounding
- Enables emergency repairs to generators (including nuclear plant substations) without plant outage
  - Avoid costs of shutdown, restart and replacement purchase power.

Three Phase Pick Robotic Arm

Developed for the capture and control of three conductors simultaneously, this technology is similar to that of the Quanta technology, however little technical specification available.

Single Pick Robotic Arm

Designed to handle higher conductor sizes and weights, which is used to remotely capture and control a single conductor at a time.

Significantly many of these technologies have been used extensively within the USA and South Africa.

Robotic Pole Manipulator

This is a design concept postulated in the academic paper compiled by Turner and Wilson 2010 titled System Development of a Robotic Pole Manipulator.

This concept was developed for wooden poles up to 16,8 m (55 ft) length. This is a truck mounted concept was identified and developed to eliminate injuries and near misses associated with the handling of power poles near overhead lines and in congested, urban environments.

In summary, the area of ground based robots is significantly restricted in terms of developmental paths. The main area focuses around ground manipulations of existing assets as well as the construction of new assets.

16.6.2.2 Line-Suspended Robots

The most used applications for robots suspended from the line are to perform visual inspection in transmission lines that cross difficult right of ways, such as large rivers or mountainous areas.

As described by Elizondo and Gentile 2010, line-suspended robot technology has been used since 2006 by Hydro-Québec IREQ (Canada) and since 2009 by Hibot (Japan). Development of this type of robot is active as more and more prototypes are being built and more players are expected to enter the market as service providers or technology users.

The robots or moving platforms are able to travel over the live or ground conductor of transmission lines within different conductor slopes (usually no more than 30-35 degrees) and many of them are able to pass through or cross over the following obstacles that are found attached to the conductors of transmission lines:

- Dampers for wind vibration (Stockbridge),
- Double suspension clamps with yoke plates and bundled conductor clamps,
- Single suspension clamp,
- Spacers for bundled conductor,
- Splices/sleeves,
- Warning spheres or aerial markers (sizes: 28, 56, 254 cm in diameter),
- Trunnion clamps.

Robots suspended from the line, can perform the following:

- Visual inspections by different types of cameras:
  - Live conductors and overhead ground wires and other transmission line components,
  - High risk vegetation encroachment in transmission line right of way by Light Detection and Ranging (LiDAR),
- Application of specialized sensors:
  - Measurements of electrical resistance in splices,
  - Recording of audible noise by a microphone,
- Temporary repairs/adjustments of transmission line components:
  - Mechanical clamp to repair broken conductor strands,
  - Motorized wrench for adjusting bolted assemblies,
  - Installation and removal of aircraft warning spheres or marker balls,

- Specialized applications:
  - De-icing,
  - Corrosion detection,
  - Electro-magnetic interference to identify arcing or nearby Corona,
  - Sensor reading systems to collect data from remotely installed devices strategically deployed,
  - Insulator cleaning.

Hydro-Québec IREQ has been developing different technologies to incorporate robots into transmission line maintenance practices. Their first technology, the LineROVer, was initially developed for de-icing, but also featured line inspection capabilities. A photo of the LineROVer is shown in Figure 16.16.

The LineScout was developed subsequently as shown in Figure 16.17. It has been designed to operate on two, four, or six conductor bundles and can cross

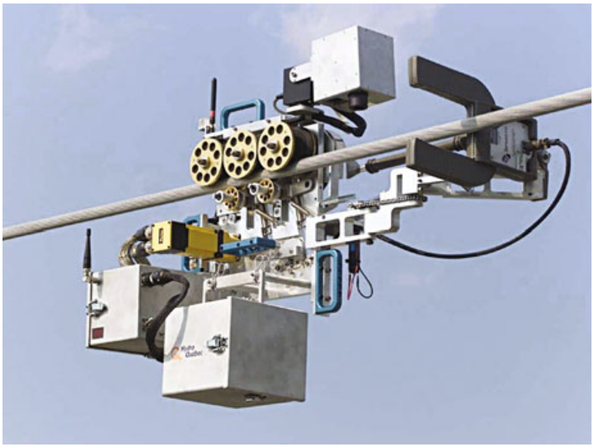


Figure 16.16 Photo of the LineROVer robot inspecting a transmission line.

Figure 16.17 Photos of the LineScout robot.

obstacles up to 0,76 m (30 inches) diameter found on conductors including warning spheres, spacer-dampers and single- and double-suspension clamps. Crossing dead-end structures and jumper cables was not included in the design specifications.

The LineScout was developed with active involvement of the linemen and line maintenance technicians from Hydro-Québec TransÉnergie. The main applications and capabilities of the LineScout robot are listed below:

- Visual inspections by four operator cameras. Defective transmission line components can be identified either through classical cameras or infrared technology.
- Application of sensors such as for the measurement of a compression splice's electrical resistance.
- Temporary repair of components. Using a universal electric torque wrench, components could be re-adjusted. Also, broken conductor strands can be temporarily repaired by installing a clamp.

The Expliner robot has been designed for remote inspection of energized high voltage transmission lines, up to 500 kV. It has the capability to cross the typical obstacles found in a transmission line, such as cable spacers and suspension clamps. The robot can reach the transmission line from an access cable, as shown in Figure 16.18.

The main application of the Expliner robot is to perform visual inspections by cameras. Defective transmission line components can be identified. It has been tested in facilities that represent the field conditions and on energized transmission lines. Even though the robot is capable of crossing obstacles typically found in transmission lines, completely autonomous control for the unit has not yet been achieved due to the unstructured environment and the variety of spacers and obstacles that need to be crossed.

16.6.2.3 Aerial-Based Robots

Routine inspections and asset condition assessment in many cases are carried out using helicopters with trained personnel to capture information for an intended

Figure 16.18 Expliner climbing to a transmission line.

purpose. As another tool to help meet customer requirements for availability and reliability, the application of robots to automate the inspection of transmission line assets is of increasing interest to electric power utilities, as this work is performed while the transmission lines are energized. Currently, electric power utilities are interested in investigating the technology of aerial based robots or unmanned aerial vehicles (UAV's) as it provide a unique perspective as they fly close to the transmission line to inspect the asset (Elizondo and Gentile 2010).

The current state of the art for aerial-based robots can be described as an autonomously controlled flying device that operates close to the transmission line assets (Elizondo et al. 2012). Overall, the development of UAVs is in its infancy stage for transmission line asset management. Over forty nine UAV models were reviewed by Elizondo et al. 2013; twenty five models classified as commercial UAVs and twenty four classified as military UAVs. Of the forty nine, there are seven UAV models, which have performed transmission line inspections. The focus of the majority of UAVs today is toward military applications.

Robots of this type have achieved autonomous operation as they have been able to verify their own position as they fly and wirelessly transmit images taken to ground. The main applications include:

- Visual inspections by different types of cameras:
  - Live and ground conductors and other transmission line components,
- Power line corridor monitoring and high risk vegetation encroachment:
  - Algorithms developed for individual tree crown detection and delineation,
  - Evaluation of machine learning techniques for object-based tree species classification,
  - Algorithm developed for automatic power line detection from aerial imagery and LiDAR point clouds.

Development of this type of robot is very active as more and more prototypes are being built and more players are expected to enter the market as service providers of technology users.

For instance, the electric power industry in Japan have faced severe challenges related to the industry deregulation which has resulted in additional efforts for the operations efficiency and cost reduction. This, among other conditions, has driven the development of an unmanned helicopter for the inspection of power transmission lines. The development was carried out by Chugoku Electric Power Co. which operates in the southwest region of Japan and has more than 8000 km of transmission lines.

This UAV is equipped with a GPS, camera and image transmission equipment and is able to fly in predetermined routes along the power transmission line. The robot verifies its own position as it flies and wirelessly transmits images taken to ground. A photo of the device flying along a transmission line is shown in Figure 16.19. The costs of this unmanned helicopter are about half when compared with the costs of a conventional manned helicopter.

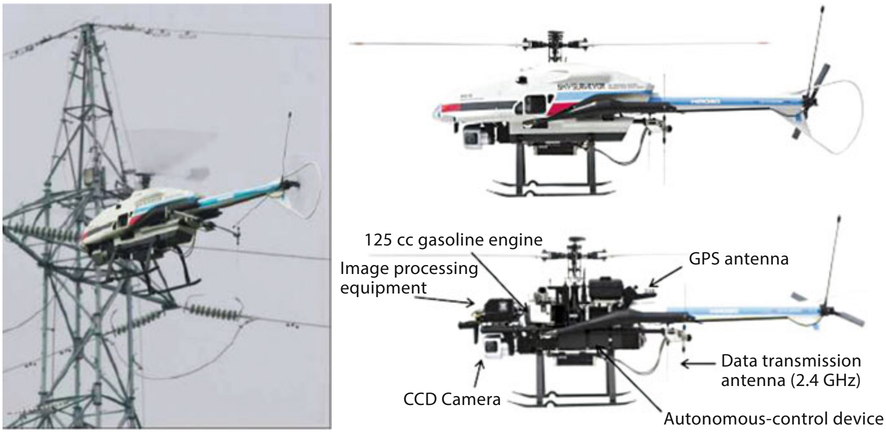


Figure 16.19 Unmanned aerial robot for transmission line inspections developed by Chugoku Electric Power Co. (Shimo 2006).

Figure 16.20 Live-line insulator cleaning robot developed by KEPCO 2006.

The limitations or barriers for aerial-based robots, which prevent them from wide deployment, are:

- Risk of sudden crash of the device,
- Unexpected environment changes like wind gusts,
- Invasion of privacy,
- Rules and regulations from aviation agencies,
    - In some countries, before using a UAV, a flight plan approval is required with associated time delay for approval process.

16.6.2.4 Other Types of Robots

Korea Electric Power Research Institute developed a robot for live line inspection of insulators (Cho et al. 2006) as shown in Figure 16.20. This robot was developed for 345 kV power transmission lines live-line insulator dry cleaning with brushes.

Korea Electric Power Corporation (KEPCO) developed a robot for live line inspection of suspension insulator strings as shown in Figure 16.21. The robot is measuring the insulation resistance and the voltage distribution along the insulator (Park et al. 2010).

As described in Section 16.3.2.3, the high frequency high voltage tool is usually applied for composite insulators using a hotstick. However, at 500 kV the length of the hotstick results in high mechanical cantilever loads for the operator and EPRI is developing a "walking beam" insulator crawling robot to operate under energized conditions, which can take the tool as a payload together with other inspection technologies. The objectives of the robot are to increase the repeatability of the measurement, reduce the mechanical stress on field personnel and increase safety. A version of this robot which is presently in testing is shown in Figure 16.22. For further information, refer to Cigré TB 545.

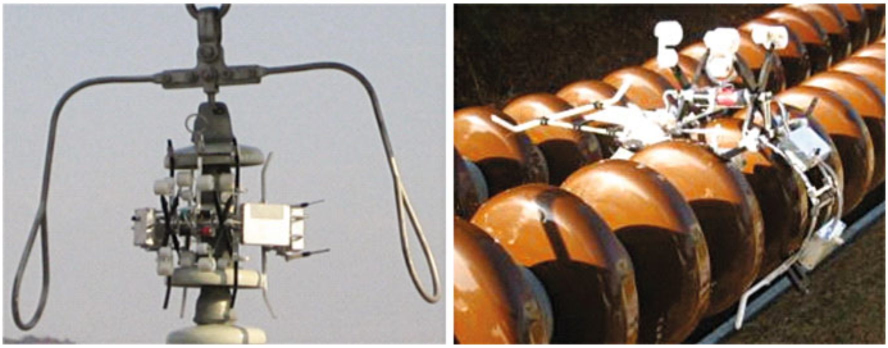


Figure 16.21 Live-line insulator inspection robot developed by KEPCO, 2010.

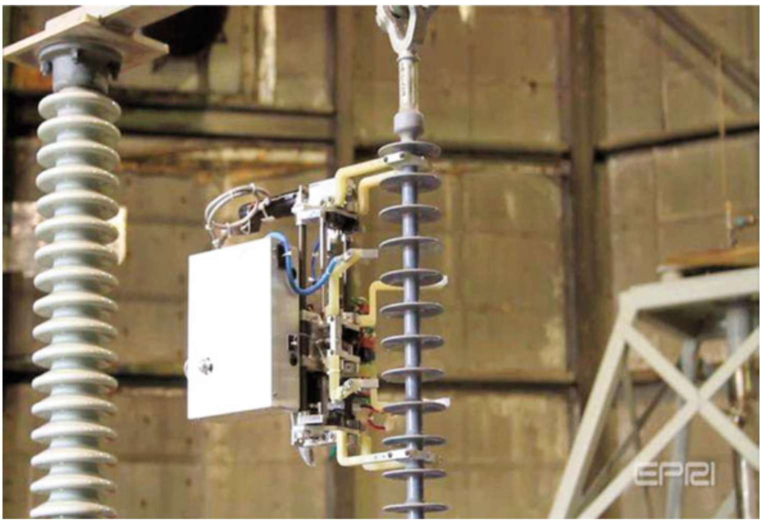


Figure 16.22 Technology demonstrator of the EPRI insulator crawling robot that is being investigated to replace the hand held operation.

16.7 Conclusion

Formulating a successful transmission line maintenance strategy is dependent on the transmission line asset owners' drivers and constraints. The maintenance strategy will be dependent on the asset owners' particular environment, existing condition of the assets and, perhaps most important, criticality of the existing transmission lines.

Inspection and maintenance activities are conducted to prevent degradation of an OHTL asset beyond a desired performance level. The time to perform these required maintenance activities in order to achieve a desired performance level of the OHTL is a critical question. Although failure of an OHTL is not desirable, total elimination of this risk may not be economically justifiable. A transmission line is regularly inspected in order to achieve updated information about the condition of the line as well as the immediate surroundings. Various inspection techniques have been developed to enable the condition of the OHTL to be assessed.

Condition assessment will enable transmission line asset owners to achieve greater efficiency when planning OHTL refurbishment's or more effectively to direct their maintenance activities, at a time when systems are ageing and consents for new lines are becoming increasingly difficult to obtain. The inspection should be performed so that the transmission line owner is provided with sufficient information to plan the maintenance of the OHTL.

One maintenance method makes use of carts for working in-span on the conductors and ground wires, especially when the accessibility with alternative methods such as the use of bucket trucks, cranes or helicopters is problematic or restricted. Carts are used for in-span work such as the repair or replacement of spacers, dampers, aircraft warning markers, etc. Guidelines are given for use of carts, for inspection and assessment of safe conditions as well as alternative methods for dealing with presumed or known unsafe conditions. Prior to carting, a specific engineering analysis can be carried out to establish its effect on line tension, and also check for adequate clearances.

Live work is the preferred method of maintenance where system integrity, system reliability, and operating revenues are at a premium and removal of the circuit from service is not acceptable. Live work has been found to be a safe means of performing maintenance operations due to the additional planning and crew training required for live work.

The expected increase in live-line work approaches has stimulated the development and use of robotic devices to minimize risk to field personnel safety and maintain power system reliability. There are three main classifications of robots: ground-based, those suspended from the line and aerial-based. Ground-based robots are designed to remotely capture and control energized conductors and execute tasks that are far beyond human capability from a mechanical and electrical stress perspective. Robots suspended from the line are designed to serve as the extended eyes and arms of the transmission lineman and their basic design function is to perform visual inspections. Development of aerial-based robots, which are designed to perform visual inspections, is very active as more and more prototypes are being built and more players are expected to enter the market as service providers of technology users.

16.8 Highlights

16.8.1 Maintenance Strategy

- Formulating a successful transmission line maintenance strategy is dependent on the transmission line asset owners' drivers and constraints. As described in Section 16.2, the maintenance strategy will be dependent on the asset owners' particular environment, existing condition of the assets and, perhaps most important, criticality of the existing transmission lines.
- No matter what the maintenance activities are, they all share similar requirements that must be considered when developing a successful maintenance strategy. They include:
  - Prioritizing the transmission lines
  - Periodic inspection of the lines
  - Data base management
  - Considerations for in-house or outsourcing of maintenance work
  - Performing live work or de-energized work
  - Planning for people, equipment and training
  - Developing outside resources
  - Benchmarking and continual improvement.

16.8.2 Condition Assessment of OHTL

- A transmission line is regularly inspected in order to achieve updated information about the condition of the line as well as the immediate surroundings. Various inspection techniques have been developed to enable the condition of the OHTL to be assessed. Inspections may be performed from a plane, a helicopter, a car, by foot patrols or by climbing the towers as described in Section 16.3.
- Condition assessment will enable transmission line asset owners to achieve greater efficiency when planning OHTL refurbishment's or more effectively to direct their maintenance activities, at a time when systems are ageing and consents for new lines are becoming increasingly difficult to obtain. The inspection should be performed so that the transmission line owner is provided with sufficient information to plan the maintenance of the OHTL.
- Conductor deterioration follows different patterns in different geographic areas. Deterioration such as conductor corrosion (internal and external), conductor broken strands, defective or loosened spacers, missing or drooping vibration dampers, lightning strikes, etc. For the last decade numerous failures of conductor joints have been reported, the reasons for which have included asymmetrical installation of the aluminum sleeve as well as accelerated ageing and deterioration of the contact surface in the joint due to an increased electrical load as described in Section 16.3.1.4.
- The main cause of failure to suspension and tension porcelain insulators is corrosion of the steel pin in the cap and the pin assembly. With glass insulators, the

discharges erode the glass and pin and after fairly minor surface damage, the imbalance in the internal mechanical stresses in the toughened glass causes the shed to shatter completely. Section 16.3.2 provides guidance to utilities and engineers who are in charge of the maintenance of transmission lines on how to check the state of insulators and how to decide on the safe time for replacement. For composite insulators, degradation can occur through premature ageing or internal manufacturing defects and it is not possible, using current technology, to choose a single technique that will detect all types of defective insulators with a satisfactory degree of confidence. A combination of two or more techniques has in practice, been proven to be the most effective means of identifying defective composite insulators in service.

- The main factors, which affect the rate and onset of steel structure corrosion, can be categorized into two groups: environment factors (prevailing weather conditions, pollution levels, etc.) and protection factors (surface protection quality, painting policy, etc.). Inspection techniques such as visual climbing inspection, electronic paint & galvanizing thickness measurement and cross hatch cut test are presented in Section 16.3.3.1.
- The main damage, to which wood poles are subjected, is the degradation of mechanical strength due to wear and decaying of the wood and to the action of insects and woodpeckers. Inspection techniques such as visual inspection, sound and bore, electrical resistance measuring device, penetration measuring device and trained dogs are presented in Section 16.3.3.4.

16.8.3 Use of Carts for In-Span Maintenance Work

- One maintenance method makes use of carts for working in-span on the conductors and ground wires, especially when the accessibility with alternative methods such as the use of bucket trucks, cranes or helicopters is problematic or restricted. Carts are used for in-span work such as the repair or replacement of spacers, dampers, aircraft warning markers, etc.
- Section 16.4 identifies the factors that affect the structural integrity of the aged conductor systems and therefore, the risks associated with the use of carts on aged conductors. Guidelines are given for developing criteria or rules for use of carts, for inspection and assessment of safe conditions as well as alternative methods for dealing with presumed or known unsafe conditions. Prior to carting, a specific engineering analysis can be carried out to establish its effect on line tension, and also check for adequate clearances.

16.8.4 Live Work Maintenance

- Section 16.5 deals with live work (work on energized circuits) that has been carried out in different parts of the world for many decades. Live work is the preferred method of maintenance where system integrity, system reliability, and operating revenues are at a premium and removal of the circuit from service is not acceptable. Live work may also be beneficial in construction, upgrading and uprating.

- Most maintenance operations that are performed de-energised can also be performed using live work techniques. To do so requires proper operating procedures that take into account the complexity of the task and technical standards referring to equipment, procedures, safety and quality assurance. Examples of typical live work operations are given in Section 16.5.2 that are applicable to many asset owners.
- The feedback from utilities performing live work on overhead lines is that the cost is comparable to that in de-energised conditions. Some comparisons of live work to de-energized work times and cost comparison of in-house verses outsourced live work are also provided in Section 16.5.3.

16.9 Outlook

- In order to maintain or increase the reliability of aging OHLs, new maintenance techniques are becoming available to assess and diagnose the condition of various OHL components.
- The expected increase in live-line work approaches has stimulated the development and use of robotic devices to minimize risk to field personnel safety and maintain power system reliability. Section 16.6 seeks to provide an overview and an assessment of the future possibilities for transmission line robotics. Four robot classifications are identified:
  - Ground-based robots (Section 16.6.2.1)
  - Line suspended robots (Section 16.6.2.2)
  - Aerial-based robots (Section 16.6.2.3)
  - Other types of robots (Section 16.6.2.4).

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