STATE OF THE ART SURVEY ON SPACERS AND SPACER DAMPERS: PART 1 - GENERAL DESCRIPTION

1. INTRODUCTION

The use of multi-conductor bundles in high voltage overhead transmission lines to transport economically large amounts of energy has been established for several decades. Conductor spacers rapidly became important pieces of hardware aimed at maintaining the geometry of the bundles to meet the requirements of electrical performance. However, their role soon evolved as a more important component of a complex mechanical system subject to a range of environmental conditions. The response of a conductor bundle to wind excitation ranked highly in the concerns of transmission line engineers. It led to the design of spacer dampers together with the problem of properly distributing them in a given span. Several solutions are now proposed as an adequate spacer system design. Considerable knowledge has been acquired concerning the material requirements and selection criteria, including the use of clamping systems that provide a safe and reliable long-term grip on the conductors, while maintaining the quality of easy installation.

This paper presents the first part of a State of the Art Survey on spacers and spacer dampers. In a second paper, technical aspects, such as design requirements, test methods and field measurements, will be presented, together with the analytical basis for spacer application. Finally, a third paper will present experiences with current practice and the results of a recent questionnaire to survey damage to spacers, spacer dampers and conductors.

2. NUMBER AND LOCATION OF SPACERS

The optimisation of the type and the position of the spacers in a span is made with respect to problems of wind-excited vibrations: mainly instability phenomena (sub-span oscillations) and aeolian vibrations; other phenomena are ice galloping and wake-induced galloping (without ice), the last being a very rare occurrence. The optimisation of the type and design of the spacer must also take into account the short-circuit forces and the bundle twisting due to ice loads.

2.1 Aeolian vibrations

In this case, the parameter of interest is mainly the number of spacers, whilst their location is not so important. Because of the wave length values involved in this phenomenon (some metres at the maximum), tolerances in spacer positioning make sub-span lengths automatically different, one from another. As a result, whatever the spacing, it is practically impossible that - for any mode of vibration of the conductor - all the spacers are at nodes of the deflected shape and give no contribution to the energy dissipation. The optimisation of the spacer location with respect to aeolian vibrations is not useful: it is much more important to optimise the spacer type and its characteristics (stiffness and damping of the elastic elements, geometry and inertia of the parts).

It would be possible, from the aeolian point of view, to avoid spacers and to use dampers close to span ends; however, this solution obviously cannot maintain the bundle geometry along the span.
2.2 Instability problems: sub-span oscillation

In this case, the parameters of interest are the location of the spacers along the span (ratio between the lengths of two adjacent sub-spans) and the maximum sub-span length. Even if the type of spacer has some influence on the phenomenon and is important for the prevention of damage caused by sub-span oscillation to the conductors, the spacer location remains paramount.

Spacing is very important because sub-span oscillation is an instability phenomenon resulting from the coupling between two types of vibration mode of the bundle, one having a horizontal component of motion and one having a vertical component. Most commonly, the vertical component is provided by torsional modes of the bundle.

Torsional modal frequencies are mainly influenced by the overall span length and, to some extent, by the end conditions; the horizontal modal frequencies are mainly controlled by the sub-span lengths.

A change in the values of the sub-span lengths produces a change in the horizontal modal frequencies and hence in the coupling between the modes: so the problem can be controlled to some extent.

It is well known and agreed, that a span divided into equal sub-spans is more easily subjected to oscillation than a span divided into unequal sub-spans. This is because the equal sub-span length defines an horizontal frequency for which all the sub-spans vibrate at the same time, with a vibration mode which can easily be coupled to a torsional mode.

Some common modes of sub-span oscillation for quad bundles involve a combination of horizontal and vertical modes: these are less influenced by unequal sub-spans since both frequencies depend on sub-span length.

The instability mechanism is complex as it depends, in general, on the horizontal and torsional modal frequencies which are initially different (structural terms) and are made equal by the wind action, thus giving rise to a typical flutter-type instability.

Given a certain span length with a certain number of spacers, the ratio between the lengths of adjacent sub-spans must be optimised. If this sub-span ratio is much lower than unity, adjacent sub-span lengths are very unequal and the long sub-spans may be unstable at relatively low wind speeds. This is especially the case for very long spans with many torsional modes in the frequency range of sub-span oscillation. In any case, long sub-spans are unsafe because, as the length increases, not only does the frequency decrease - together with the critical wind-speed for instability - but the associated vibration amplitude increases.

A sub-span ratio around 0.85 to 0.9 is generally agreed (literature, experimental tests and analytical simulations) to be the optimum solution.

Regarding the end sub-spans, these are generally shorter than the others: a good value for the ratio between the lengths of an end sub-span and the adjacent one is between 0.55 to 0.65.

2.3 Other instability problems: galloping with ice

Spacer type, number and spacing do not have a great influence in controlling this phenomenon. However, short sub-spans (20 to 30 m) at the ends do increase the bundle torsional stiffness and, as a result, achieve two goals: a partial contribution to detuning bundle torsional and vertical modes of vibration, and a reduction in the risk of static, torsional collapse.

2.4 Maximum sub-span length

The maximum sub-span length depends on the wind speed and on the type of terrain typical of the site. It is also dependent on the oscillation amplitude allowed by the specifications issued for the specific project.

The bundle configuration has a great influence on the performance of the line. All configurations of bundles experience sub-conductor oscillation to a greater or a lesser degree. For example, the diamond quad bundle is stable at low wind speed. However, due to the blow out angle, it may become unstable at extreme wind speeds, leading to very high amplitudes of oscillation.

Analytical simulations and measurements on real spans lead to a limit on the maximum sub-span length. This limit is related to specific conditions: for instance, with a ratio between bundle separation and conductor diameter of the order of 15 to 17 and a site characterised by medium/high wind speeds (> 20 to 25 m/s), this value should be around 65 m.

In non-severe conditions maximum sub-span lengths around 80 m have been used without problems. It is not easy to set a general specification: knowledge of the wind statistics typical of the site, combined with the parameters set for the project, assist in selecting the correct solution, taking into account, the number of cycles expected at the various strain levels predicted by the computation, together with the conductor and spacer fatigue limits.

3. TYPE OF SPACERS

3.1 General

This section gives a classification for the various types of spacers and spacer dampers used on overhead transmission lines with bundled conductors.

Typical conductor bundles comprise two, three or four sub-conductors. In particular cases, bundles with six or eight sub-conductors have also been used. There is no need to distinguish between the number of sub-conductors to arrive at a concise classification of spacers and spacer dampers.

A spacer or spacer damper typically consists of a central frame and conductor clamps that are connected to the central frame. The particular properties of the central frame, the conductor clamp - as well as the properties of the connection between the central frame and the conductor clamps - will be used in the following to classify the various types of spacers and spacer dampers. Where rigid or articulated spacers are used then vibration dampers are also generally employed.

It is recognised that the history of
spacers and spacer dampers has seen a wide variety of designs. It will always, therefore, be possible to find exceptions to any general classification. However, the classification introduced here should be suitable for the majority of spacers and spacer dampers. The figures provide examples of each type.

3.2 Rigid spacer
A rigid spacer restricts the distances between the conductor clamps to the nominal values of the sub-conductor spacing. The clamps do not allow for any significant movement of the sub-conductors with regard to each other compared to the conductor diameter. A rigid spacer can either have a metallic type of clamp (Figure 3.2.1) or an elastomer-lined, rod-attachment type (Figure 3.2.2).

Rigid spacers with metallic clamps are almost exclusively used as jumper spacers. In the jumper, the mechanical tension of the conductor is very low and, with the exception of short circuit loads, significant dynamic stresses will not occur at the spacer clamps in service. The rigid clamps can therefore be accepted in this particular case. Rigid spacers with elastomer-lined clamps were introduced more than thirty years ago.

3.3 Articulated spacer
An articulated spacer restricts the distances between the conductor clamps to the nominal values of the sub-conductor spacing. However, it allows for rotation of the conductor clamps around a well-defined axis in relation to the central frame (Figure 3.3.1).

Articulated spacers are used on twin, triple and quad bundle lines. Sub-span lengths can be relatively short in these installations. Care to minimise wear must be taken in the design of the articulation.

3.4 Flexible spacer/spacer damper
A flexible spacer allows for large displacements of the conductor clamps with regard to each other in the plane perpendicular to the conductor axis. Elastic properties are typically incorporated into the spacer design to ensure that the spacer will restore the bundle’s nominal configuration when the external loads are removed.

The flexibility in the spacer can be achieved in a number of ways. Typical specimens are shown in Figures 3.4.1, 3.4.2 and 3.4.3.

Flexible spacers are called a spacer damper if large displacement of the conductor clamps results in significant energy dissipation either within the connection between the central frame and the conductor clamps and/or in the central frame itself (Figure 3.4.4).

4. MATERIALS USED IN SPACERS

4.1 General
In the design of spacer dampers, flexible spacers, articulated spacers and rigid spacers (hereinafter called simply “spacers” when the subject applies to all), the basic criteria for the selection of materials and combination of materials must be based on considerations of the service life requirements in terms of mechanical loads, electrical loads and environmental attack.

There are some materials that have been used for many years in spacer technology, giving satisfactory results. The list includes:

- aluminium alloys
- galvanised steel
- galvanised malleable cast iron
- stainless steel
- zinc aluminium alloys
- neoprene and some other types of elastomers

New materials, such as resin-bonded materials, foamed structural plastics and so on, have not yet been introduced into spacer technology and their employment in the near future cannot be anticipated.

4.2 Material requirements and selection criteria
Spacer materials [2] should have adequate mechanical strength over the whole range of service temperatures. They should withstand the thermal cycling dictated by the climate and by the current loading of the conductors. Typical problems are: elastomer deterioration at high temperatures, especially in rubber-lined clamps, hardening of elastomers and embrittlement of steel at low temperature.

Spacer materials should be resistant to: chemical corrosion caused by humidity and airborne pollutants, galvanic corrosion due to contacts between dissimilar materials in the presence of an electrolyte, and electrolytic corrosion caused by voltage difference between metal surfaces bridged by an electrolyte.

Galvanisation of steel components should provide favourable resistance to chemical corrosion. Aluminium and zinc alloys have a natural corrosion protection that can be further improved, when necessary, by surface treatments like anodizing.

Grease coating or painting is not considered reliable for long-term corrosion protection.

Galvanic corrosion can best be
avoided by reference to the galvanic series. If two or more dissimilar materials are to be in contact in the spacer, they should not be too far apart in this list and, where possible, the material with the greater surface area should be made anodic.

In any case, the selection of materials for application in areas with high atmospheric pollution should take into account the nature of the pollutants involved.

The spacer materials should have appropriate resilience to withstand impulsive loads, and the components subjected to fatigue and to rubbing should be formed from materials which have good resistance to these actions.

Corona discharges at the surface of spacers increase the presence of ozone which rapidly deteriorates organic materials if they are not suitably protected. These materials also need to be protected from ultraviolet radiation.

Non-conductive elastomers are liable to experience electrical discharges as a result of the pollutants coating the surface. Such discharges encourage a further growth of carbon deposit, leading to an escalating tracking situation and generating radio interference and audible noises.

Elastomers for spacers have to withstand contact with the oils and greases used in conductors and stringing machinery. In addition, the elastomers should not absorb rain water.

Damping elastomers used in spacer damper articulations should have large hysteresis losses, appropriate stiffness and good fatigue resistance over the entire range of service temperature.

4.3 Commonly employed materials

Aluminium-silicon alloys, generally of primary production, are currently employed for the cast components of spacers for aluminium-based bundled conductors. Current casting technology includes mainly gravity and pressure die casting. The most common aluminium-silicon alloy is the Al Si 12-ISO R 164, better known as LM6 (BS1490). The ductility of this alloy can be slightly improved by heat treatment, but it is normal practice to enhance the mechanical characteristics by modification of the melted alloy using metallic sodium, sodium salts or strontium.

Primary and secondary aluminium alloys with higher copper content (but no more than 1%) are employed for spacer components not in direct contact with the conductors. Copper improves the mechanical characteristics of the alloy but reduces the corrosion resistance.

For spacer components that are extruded or forged, aluminium-magnesium-silicon alloys type AA 6060 and AA 6063 are used. These alloys have an excellent corrosion resistance and can be submitted to heat treatments to improve their mechanical characteristics.

There are very few bundled lines equipped with copper conductors. For these lines, spacer components made of phosphor bronze or aluminium bronze are mainly used, in combination with copper alloy or stainless steel fasteners.

Galvanised steel is largely used for the elements of the clamp locking system and sometimes for other components. The zinc protection is generally achieved by hot dip galvanising, in accordance, for example, with ISO1471, except when spring steel is used. Bolts and nuts are made in low or medium carbon steel and are generally in accordance with ISO 898. The most commonly used are hexagonal head bolts of property class 8.8 and 6.8, together with hexagonal nuts of the appropriate class.

Belleville washers and other spring elements are made in chrome-vanadium steel (50CrV4) or Ck75 unalloyed steel. They can be electro-plated or mechanically galvanised in accordance with ASTM B695 or equivalent standard.

Stainless steel can be employed instead of galvanised steel in highly polluted areas: austenitic stainless steels (AISI 300 series) and ferritic stainless steels (AISI 400 series) are the most used.

Aluminium alloy bolts can be of type AA 7075 (high strength aluminium alloy bolts with mechanical properties equivalent to mild steel bolts of class 5.8) or AA 6101-T8.

Some spacers contain lengths of galvanised steel cable. Others employ or consist solely of helical rods made of aluminium alloy, generally of AA 6061-T8 type.

Inertial masses used in spacers are made either in galvanised, malleable cast iron or zinc alloy.

A number of synthetic rubbers have been used to date for spacer damper articulations and for clamp lining. Two broad groups can be identified: organic rubber and mineral rubber. The first is the most common while the second (silicon rubber) is employed in special cases involving resistance to high temperatures (> 200 °C) and very low temperatures (< -30 °C). However, it should be noted that silicon rubber has poor resistance to fatigue and abrasion.

Natural rubber (NR) of itself has poor resistance to ageing, ozone, UV radiation, oils and greases. However, with appropriate additives, it can be compounded to perform satisfactorily.

Synthetic rubber is prepared by reacting suitable monomers to form polymers; its elastomeric properties have to be developed by further compounding and the possible combinations are infinite [1]. Fillers, such as carbon black, silica, oils, waxes and fatty acids are used. Elastomer compounds are carefully formulated to fulfil all mechanical, chemical and thermal requirements. Organic rubber must be protected from the attack of ozone and ultraviolet radiation, while silicon rubber is not sensitive to these agents. The protection is achieved by means of special waxes that continuously migrate to the rubber surface creating a protective coating that restores itself after abrasion. However, the coating becomes discontinuous when the rubber is tensioned mechanically.

Rubber compounds can be either commercially available or specially formulated for the specific purpose. The former most common types are: Neoprene (chloroprene rubber), EPDM (ethylene-propylene rubber), NBR (nitrile rubber), FKM (fluorocarbon rubber), and VMQ (silicon rubber). Special compounds are a combination of two or more basic rubbers such as, for example, BR (polybutadiene rubber) and NBR, charged with appropriate fillers.
5. CLAMPING SYSTEMS

5.1 Introduction
A spacer clamp must be capable of easy installation on the conductor and provide a safe, reliable long-term grip. The design of such clamps should aim to:

- avoid high, localised clamping stresses - this is a function of clamp length, clamping force (bolt torque) and clamp geometry.
- avoid damage to the conductor due to clamping surface irregularities - the conductor contact surfaces must be smooth.
- minimise the possibility of incorrect installation.
- ensure that, if feasible, all components are captive - bolts may be peened or, if in a blind tapped hole, secured by an O-ring to the clamp keeper which itself may be secured to the body of the clamp by a tie or captive hinge.
- incorporate a stored-energy mechanism to prevent clamp loosening due to temperature cycling and conductor creep.
- exert an adequate, non-damaging long-term grip on the conductor - axial and torsional grip are often specified by the end user.
- be manufactured from a material that is compatible with the conductor and generally avoids corrosion.
- be profiled to minimise the possibility of corona and RI discharge at specified line voltages.
- be capable of ground level inspection to verify correct installation.
- preferably, be capable of being installed with hot line/helicopter techniques.

Elastomer-lined clamps generally have some range-taking capability whereas metal-to-metal clamps should ideally be matched to the conductor diameter in question, although a very limited degree of ranging is possible.

Metal-to-metal clamps may be installed over helical, factory-formed rods to provide an enhanced degree of conductor protection.

5.2 Cantilever clamp
The cantilever clamp is a metal-to-metal clamp secured by a captive, galvanised steel bolt bearing on a plain and split washer and secured by a captive, galvanised steel nut. Belleville washers may be used instead of the split washer to enhance energy storage and the nut may incorporate a locking mechanism, such as a nylon patch or ring. In this case it will be protected by a suitable anti-corrosion finish because galvanising is not feasible in these cases.

5.3 Opposed hinge clamp
The opposed hinge clamp is such that it is less sensitive to changes in the conductor and errors in tightening.

5.4 Elastomer-lined cantilever or hinged clamp
Clamp types described in sections 5.2 and 5.3 can also be used with an elastomer lining.

A widely used version of the elastomer-lined clamp utilises a boltless construction with an opposed, captive hinge and fastener. The clamp is lined with elastomer inserts which cushion and grip the conductor. The clamp is closed using a special tool and locked by a quarter-turn fastener or a latch. The clamp is not reliant on a bolt being correctly tightened, therefore there is no danger of conductor damage or clamp loosening arising from this source. The design is such that the elastomer remains under a predetermined degree of compression under all service conditions. A bolt may be used in place of the quarter-turn fastener.

The formulation of the elastomer is critical to the satisfactory long-term performance of the clamp. Essential properties include good resistance to ageing, pollution, environmental effects, ozone and grease. Compres-
sion set must be at a minimum to ensure that a positive grip is always exerted on the conductor. Electrical semi-conductivity must also be controlled within defined limits and there must be no corrosive interaction between the constituents of the elastomer, such as carbon, and the conductor strand material.

The slip load achieved by elastomer-lined clamps is significantly less than metal-to-metal clamps. This is acceptable because, if an exceptional event causes the elastomer-lined clamp to move, there will be no consequential damage to the conductor.

5.5 Helically-attached clamp

The helically-attached clamp is a boltless construction in which the conductor is cushioned in a U-shaped elastomer-lined clamp and securely held by helical, factory-formed rods. The clamp is generally elastomer-lined to protect the conductor, although some unlined clamps are in use. Correct installation may easily be verified from ground level. The rods must be manufactured from material which is compatible with the conductor strands. Essential properties of the elastomer include good resistance to ageing, pollution, environmental effects, ozone and grease. Compression set must be at a minimum to ensure that a positive grip is always exerted on the conductor. Electrical semi-conductivity must also be controlled within defined limits and there must be no corrosive interaction between the constituents of the elastomer, such as carbon and the conductor strand material.

The elastomer may be fully bonded to the clamp to prevent any ingress of pollutants and moisture whilst in service. The characteristics of the helical rods should be such that their ends are facing towards the centre of the sub-conductor bundle to minimise corona and RI discharge at specified line voltages.

The slip load achieved by helically-attached clamps is significantly less than metal-to-metal clamps. This is acceptable because, if an exceptional event causes the helically-attached clamp to move, there will be no consequential damage to the conductor.

6. REFERENCES