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STATE OF THE ART SURVEY ON SPACERS AND SPACER DAMPERS

**Working Group
B2.11**

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STATE OF THE ART SURVEY ON SPACERS AND SPACER DAMPERS

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STATE OF THE ART SURVEY ON SPACERS AND SPACER DAMPERS

Summary

ON BEHALF OF WORKING GROUP B2 (22) 11, TASK FORCE 05

Convenor: L. Cloutier

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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 items of hardware aimed at maintaining the geometry of the bundles to meet the requirements of electrical performance (For the purposes of simplicity, the term “spacer” is used generically to describe “rigid”, “articulated”, “flexible” or “spacer damper” types unless otherwise stated). 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.

WGB2-11-TF5 has produced a “State of the Art Survey on Spacers and Spacer Damper” in three parts:

Part 1 - “General Description” (Published as ELECTRA #209, August 2003)

Part 2 - “Technical Aspects” (CIGRE SCB2 Web Site)

Part 3 - “Experience with Current Practice” (CIGRE SCB2 Web Site)

PART 1 - “GENERAL DESCRIPTION”

A paper published in ELECTRA #209, August 2003, presented a first part of a State of the Art Survey on spacers and spacer dampers. Its objective was to give a general description of this item of hardware. It provided the reader with an extensive review of the different types of spacers and spacer dampers used on overhead transmission lines with bundled conductors. They can be of the “rigid”, “articulated”, “flexible” or “spacer damper” types. In the design of spacers, the selection and combination of materials must be based on considerations of the service life requirements in terms of mechanical loads, electrical loads and environmental attack. The material requirement and the selection criteria were reviewed and experience with commonly used materials extensively covered. A complete section reviews different types of clamping systems currently used.

The number and location of spacers are the subjects of frequent debate. It follows that 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 short-circuit forces and the bundle twisting due to ice loads.

PARTS 2 & 3 - “TECHNICAL ASPECTS” & “EXPERIENCE WITH CURRENT PRACTICE”

The study covered both the technical aspects and experience with current practice. Design characteristics for spacers in-

clude four different aspects: mechanical, dynamic, electrical and environmental. Due consideration must be given to clamping. Indeed, a spacer clamp should be capable of easy, reliable installation, preferably verifiable by ground based inspection and should provide a safe, reliable, non-damaging, long-term grip on the subconductor. Component parts should be secured and an energy storage mechanism is required to prevent loosening due to the effect of vibration, thermal cycling conductor and elastomer creep (in the case of elastomer lined clamps). All materials should be compatible with the conductor and avoid corrosion. The spacer should be designed to accommodate the mechanical loads arising from the effect of wind, ice and short circuit currents flowing in the bundle. The mechanical loads on the spacers under icing conditions may be in plane or out of plane, due to uneven ice accumulation on the subconductors. Bundle twisting may also occur under heavy ice accumulation or as the result of sudden ice shedding. The spacer should be capable of returning the subconductors to their equilibrium positions without having sustained damage or causing damage to the subconductors.

The most important spacer parameters determining their dynamic characteristics are the mass and inertia of the spacer components, the stiffness and the damping capacity of the articulations, and the arm angle. Depending on their type (rigid, articulated, flexible or spacer damper), spacers more or less incorporate a complete set of such parameters. The influence of each parameter depends on the type of vibration phenomenon involved. Moreover, wake-induced oscillation modes can be classified in two groups: breathing modes and rigid body modes; the modes are also influenced by the parameters.

Electrical characteristics are also an important aspect of the design of spacers and spacer dampers. If any components of a spacer are electrically insulated from all of the subconductors, these components will be charged capacitively by the energized phases. The resulting voltage difference between the subconductors and the insulated components may amount to many kilovolts and can lead to spark-over between components or to tracking across the surfaces of the insulating materials, especially if they become polluted. Such discharge activity will lead to radio interference and to degradation of the insulating materials, which can be avoided by ensuring that every component of a spacer is connected via a conducting path to a subconductor. This also avoids any possible safety hazards associated with trapped charge on the spacer components when the line is switched out, although such charges might be expected to leak away before any maintenance activity could be initiated. The spacer should be designed to limit visible corona, Radio Interference and Audible Noise discharges to specified values at the operating voltage of the line, multiplied by an agreed safety factor.

Finally, for environmental considerations, spacers should be capable of withstanding a wide range of service conditions without functional impairment. These include thermal cycling due to climate and current loading of the conductors and the effects of pollution, which can cause chemical, galvanic and electrolytic corrosion. If elastomers are used in the construction of the spacer, they should be chosen to have good fatigue endurance, controlled electrical conductivity and resistance to the effects of ozone, UV, oil and grease, pollutants and ageing under the range of conductor operating temperatures. Test methods were defined to properly assess the mechanical, dynamic, electrical and environmental characteristics.

Field measurements of wind-induced vibrations of bundled conductor lines are usually carried out to assess whether the anti-vibration system in use provides sufficient protection against potential damage to the conductors and accessories. An anti-vibration system is made up of a specific set of spacers, dampers, spacer dampers or a combination thereof, positioned along the span according to specified schemes. On occasions, field measurements are conducted to verify whether use of special devices such as aircraft warning spheres or anti-galloping devices does not impair the integrity of the line. They also serve to assess the comparative performance of various protection systems.

The state of the art survey included a review of the actual experience gained with current practice. It summarised the most common problems experienced with spacer damper systems as viewed by users. In addition, the results of a questionnaire prepared by this group revealed experience with conductor damage. The difficulties encountered with spacer damper systems may take different forms and be attributable to different causes and the document describes some of the most common problems.

Firstly, it should be noted that many of the problems arising in service could have been avoided by a better knowledge of the specific service conditions. There are not many problems for which a solution does not exist nowadays. The real difficulty is to establish the actual operating conditions of a specific transmission line. Usually, only an overview of the line is provided but this is not sufficient to identify specific locations where problems can arise.

The present trend for cost reduction has led to a significant loss of expertise in many utilities. This means that utilities are losing the capacity to carry out their own studies and as a result, they have to rely on suppliers to recommend the proper spacer damper system to use. On the other hand, the market has become more and more competitive so that suppliers have to offer cheaper solutions. With these two phenomena merging, it may be expected that problems will increase in the future.

A questionnaire entitled "Survey on Damage to Spacer and Spacer Dampers and/or Conductors in Bundled Conductor Lines", prepared by SC22(B2)-WG11-TF5, was circulated to the national members of CIGRÉ SC22(B2) for distribution to utilities within their regions in 1999. To improve the participation, some questionnaires were also sent by other members selected for their technical involvement in the subject under study. A total of 66 replies were received from 19 countries: 12 from Europe, 2 from North America, 2 from South America, and 1 each from Asia, Africa and Australia. However, the Task Force regrets that the experience of several countries operating long EHV transmission lines (e.g. Russia, India, China) could not be included in the results of the survey of field experience due to lack of response.

Damage to conductors represented 30% of the problems reported. Problems with spacer frames and spacer clamps each accounted for 28%, whilst 14% of the problems were related to spacer articulation mechanisms. It should be noted that

many of the conductor problems occurred as a consequence of clamping system failures; therefore these data should be viewed with this in mind.

The value of any questionnaire is dependent on the number of replies received and their scope in representing a true reflection of actual experience from around the world. In the case of this study, sufficient replies were received to yield some useful information but it is disappointing that some countries known to have significant experience did not respond.

In general, the analysis of the data supports much of what has been only anecdotal experience up until now so it may be concluded that this has been a worthwhile exercise. Perhaps surprisingly, the data did not show any correlation between either conductor spacing to diameter ratio (S/d) or maximum subspan length and reported damage. Nevertheless, members of the Task Force are confident that there is a relationship between these two parameters and damage related to wake induced oscillation. The Task Force believes that further investigation is indicated.

It is not surprising that the majority of problems occur at the clamp/conductor interface where inadequate clamp design or poor installation results in clamp loosening and the inevitable conductor damage, with complete failure in extreme cases. Metal to metal clamps are most commonly involved but elastomer lined clamps are not without their problems either. In the case of the latter, incorrect specification of the elastomer material, which then causes corrosion, can play a major role in the failure mechanism.

The scope for bad installation can be reduced by the clamp design and the incorporation of "fail-safe" features, permitting post-installation ground based inspection. Conductor failures due to accumulated damage arising from vibration induced bending stresses at in-span clamp locations appear to be restricted to very specific conditions not normally found on the majority of lines. Spacer dampers are generally recommended on a system basis, which includes in-span locations according to defined irregular subspan lengths. This is important in the control of subspan oscillation but less so in the control of aeolian vibration.

The results of the survey indicated that problems with spacers and spacer dampers can be relatively minor but extreme cases are possible, resulting in expensive and potentially disruptive damage to conductors and hardware alike. The spacer or spacer damper system can act in a "sacrificial role", needing replacement after a number of years but having protected the integrity of the line in the meantime.

THE COMPLETE STATE OF THE ART SURVEY INCLUDING ALL THREE PARTS IS PROVIDED AS A CIGRE BROCHURE IN THE NEXT PAGES.

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STATE OF THE ART SURVEY ON SPACERS AND SPACER DAMPERS

Part 1 - General description

1.1. 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.

1.2. 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.

1.2.1 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.

1.2.2 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), the bundle configuration 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 thence 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 a 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 [3].

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.

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, and may lead to very high amplitudes of oscillation.

1.2.3 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.

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, with ratios in the region of 12 or below being the most critical, 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.

1.2.4 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.

1.3. TYPE OF SPACERS

1.3.1 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.

1.3.2 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 1.3.2.1) or an elastomer-lined, rod-attachment type (Figure 1.3.2.2).

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.

1.3.3 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 1.3.3.1).

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.

1.3.4 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 1.3.4.1, 1.3.4.2 and 1.3.4.3.

A flexible spacer is 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 1.3.4.4).

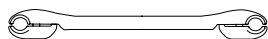


Figure 1.3.2.1: Clamp type

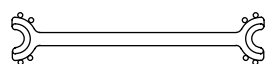


Figure 1.3.2.2: Rod-attachment type

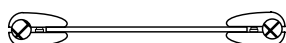


Figure 1.3.3.1: Articulated Spacer



Figure 1.3.4.1: Spring spacer

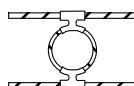


Figure 1.3.4.2: Ring spacer



Figure 1.3.4.3: Hairpin spacer

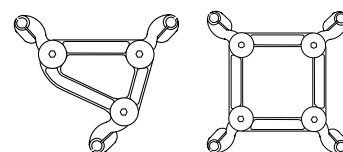


Figure 1.3.4.4: Spacer dampers

1.4. MATERIALS USED IN SPACERS

1.4.1 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.

1.4.2 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 temperatures.

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 anodising.

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.

Elastomers should be semi-conductive because 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 with too high a carbon content and, therefore, too high a conductivity are liable to burn out and to cause galvanic corrosion between the carbon in the elastomer and the conductor strands.

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 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.

1.4.3 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 of 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 of chrome-vanadium steel (50CrV4) or Ck75 unalloyed steel. They can be electroplated 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 cables. 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 of 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 ($> 200\text{ }^{\circ}\text{C}$) and very low temperatures ($< -30\text{ }^{\circ}\text{C}$). 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 (fluoro-carbon 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.

1.5. CLAMPING SYSTEMS

1.5.1 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 in-stalled over helical, factory-formed rods to provide an enhanced degree of conductor protection.

1.5.2 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.

The geometry of the cantilever clamp is such that it is less sensitive to changes in the conductor and errors in tightening.

1.5.3 Opposed hinge clamp

The opposed hinge clamp (Figure 1.5.3.1) is a heavy duty metal-to-metal clamp which, because of its hinge/conductor/bolt geometry, imposes a significantly higher grip on the conductor than the cantilever clamp (Figure 1.5.2.1) which has a conductor/bolt/hinge geometry. The opposed hinge clamp almost completely en-closes the conductor. The clamp keeper pivots on a detachable or captive hinge and is secured by a 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.

Because of the high mechanical advantage offered by the clamp geometry, the bolt installation torque for the opposed hinge clamp is generally about 50 to 75% of that of the equivalent cantilever clamp to avoid excessive localised clamping stresses in the conductor.

As an alternative to the bolt, a loaded coil spring may be used to exert a constant clamping force on the conductor.

1.5.4 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. 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 slip load achieved by elastomer-lined clamps is significantly less than with 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.

1.5.5 Helically-attached clamp

The helically-attached clamp is a bolt-less 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.

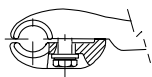


Figure 1.5.2.1: Cantilever bolted

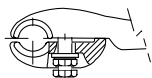


Figure 1.5.2.2: Break-away head

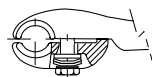


Figure 1.5.2.3: Belleville washers

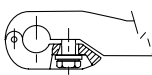


Figure 1.5.3.1: Hinged bolt

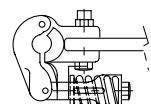


Figure 1.5.3.2: Coil spring loaded

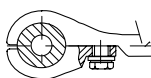


Figure 1.5.4.1: Cantilever bolted

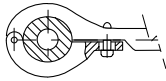


Figure 1.5.4.2: Hinged latching

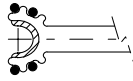


Figure 1.5.5.1: Elastomer-lined

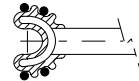


Figure 1.5.5.2: Elastomer-covered

1.6. CONCLUSION

Spacers represent an important item of overhead line hardware and are extensively used to ensure that bundled conductors provide reliable mechanical and electrical performance in service. Simple in concept, spacers form part of a complex electro-mechanical system exposed to the natural environment, requiring that their construction, installation and location along the span be properly specified. Spacer dampers have evolved in a variety of configurations and designs, making ingenious use of a number of different materials. Part 2 and Part 3 of this paper will develop the design aspects of spacers and spacer dampers, and report on present field experiences.

1.7. REFERENCES

- [1] Len Smith, "The Language of Rubber", Du Pont de Nemours SA, 1993.
- [2] CIGRÉ, Working Group 22.01, "A qualitative guide for bundled conductor spacer systems", 1979.
- [3] David Hearnshaw, "Spacer Damper Performance – A Function of In Span Positioning", IEEE T74-0618, 1974.

STATE OF THE ART SURVEY ON SPACERS AND SPACER DAMPERS

Part 2 – Technical aspects

2.1. INTRODUCTION

2.1.1 Technical Aspects

In a previous paper [1], a general description of the mechanical system formed by conductor bundles and spacers (spacer dampers) was presented. A thorough review enabled the state of the art concerning the current practices for the optimisation of the type and the position of spacers on a span to be presented. A classification for the various types of spacers and spacer dampers used on overhead transmission lines with bundled conductors was proposed.

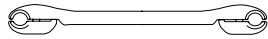


Figure 2.1.1.1: Rigid type



Figure 2.1.1.2: Articulated type



Figure 2.1.1.3: Flexible type

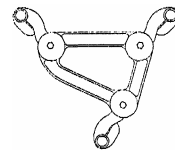


Figure 2.1.1.4: Spacer damper type

The important aspects of material selection for spacers were addressed and finally, a review of the different clamping systems, designed to satisfy specific conditions, allowed the transmission line engineer to be presented with a clearer picture of the practical choices facing him.

In this second part, more technical aspects are presented. After reviewing the design characteristics for spacer, the methods developed for spacer testing are reviewed and typical field measurements are described. Finally, a brief summary of the analytical basis and the computational methods developed to date for spacer application highlights the complexity of the problem and the importance of continuing to pursue better solutions for the control of conductor bundle motion.

In a last part, the actual experience gained with current practice will be reviewed. The results of a questionnaire prepared by this group will reveal practical experience with bundled conductors equipped with spacers and spacer dampers.

2.2. DESIGN CHARACTERISTICS FOR SPACERS

2.2.1 Mechanical characteristics

2.2.1.1 Clamping

A spacer clamp should be capable of easy, reliable installation, preferably verifiable by ground based inspection and should provide a safe, reliable, non-damaging, long-term grip on the subconductor. High, localised clamping stresses should be avoided and the clamp conductor groove should be smooth and free from irregularities. The clamp should be smoothly profiled to minimise Corona and RIV discharges at specified voltages. Component parts should be secured and an energy storage mechanism is required to prevent loosening due to the effect of vibration, thermal cycling conductor and elastomer creep (in the case of elastomer lined clamps). All materials should be compatible with the conductor and avoid corrosion.

The carbon content of any elastomeric component, such as clamp liners, needs to be low enough to prevent any galvanic corrosion of aluminium conductors but also high enough to prevent burning (tracking) due to a too high resistance being present (that aspect is reviewed in more length in section 2.2.3.1). Such considerations may also apply to other interfaces between elastomeric elements and aluminium components within, for example, spacer dampers.

2.2.1.2 Articulation

The spacer may incorporate articulation to accommodate relative transverse and longitudinal movements between subconductors of the bundle arising from unequal ice-loading, differential creep and the effect of wind without sustaining damage to itself or causing damage to the subconductors. The degree of articulation is limited by mechanical stops.

The spacer damper incorporates a mechanism that provides the necessary articulation and the enhanced flexibility and damping required for the control of wind-induced aeolian vibration and subconductor oscillation.

2.2.1.3 Mechanical Strength

The spacer should be designed to accommodate the mechanical loads arising from the effect of wind, ice and short circuit currents flowing in the bundle. The mechanical loads on the spacers under icing conditions may be in plane or out of plane, due to uneven ice accumulation on the subconductors. Bundle twisting may also occur under heavy ice accumulation or as the result of sudden ice shedding. Spacers should have mechanical stops to limit the degree of movement between subconductor clamps under these conditions. The spacer should be capable of returning the subconductors to their equilibrium positions without having sustained damage to itself or causing damage to the subconductors.

One important design load for spacers is due to short-circuit electro-mechanical forces [2]. The clashing of subconductors due to strong attraction forces inside the bundle induce large deflections on subconductors resulting in large subconductor tension increases. Depending of spacer type, components of these forces, acting towards the centre of gravity of the bundle, induce compression loads and/or bending moments in the components and/or clamp arms of the spacer. It is well known that compression forces can reach up to 16 kN and above for a short-circuit current near 50 kA [3]. The compression load depends not only on short-circuit current, but also on the initial tension in the subconductors, the subconductor diameter and subconductor spacing as well as subspan length. The greater the subconductor spacing, the greater the load will be. A subspan length of 30 meters and over will not induce significant change in the spacer compression loads. For lower values, as the spacer compression will increase significantly, it is recommended to evaluate properly the effect using published methods [4].

2.2.2 Dynamic characteristics

2.2.2.1 Generalities

The most important spacer parameters determining their dynamic characteristics are the mass and inertia of the spacer components, the stiffness and the damping capacity of the articulations, and the arm angle. Depending on their type (rigid, articulated, flexible or spacer damper), spacers more or less incorporate a complete set of such parameters.

The influence of each parameter depends on the type of vibration phenomenon involved. Moreover, wake-induced oscillation modes can be classified in two groups: breathing modes and rigid body modes; the modes are also influenced by the parameters.

One of the most obvious effects of any spacer is the introduction of coupling between the subconductors. Coupling means that the movement of one subconductor is transferred partially or totally to the other(s). It is generally accepted that such interaction has a positive effect in reducing the vibration or oscillation levels.

2.2.2.2 Definitions

In order to understand the properties of the different spacer types, it is necessary to first define certain parameters and terms relevant to spacers.

- **Breathing modes:** modes of vibration whereby subconductors move out of phase alternately moving closer and then farther from each other (e.g.: subconductor oscillation) (Figure 2.2.2.1);
- **Rigid body modes:** modes of vibration whereby subconductors move as a whole either in translation or in rotation, keeping their separation constant (e.g.: rolling, snaking, vertical galloping) (Figures 2.2.2.2, 2.2.2.3 and 2.2.2.4);

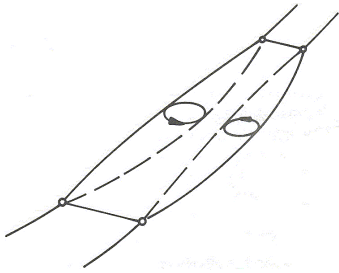


Figure 2.2.2.1: Subspan or breathing mode [6]

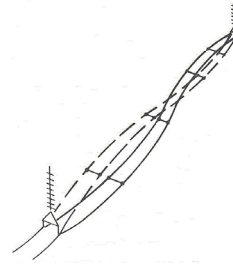


Figure 2.2.2.3: Horizontal galloping or snaking [6]

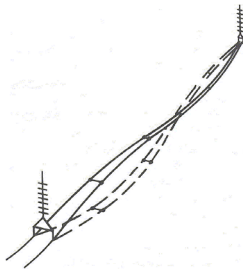


Figure 2.2.2.2: Vertical galloping [6]

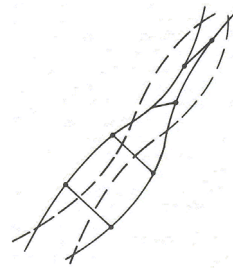


Figure 2.2.2.4: Rolling or twisting [6]

- **Sprung mass (or inertia) e.g. suspended mass:** mass (or mass moment of inertia) of the central frame plus the dynamically equivalent arm mass (or inertia) at the connection with the frame (applicable to spacer dampers);
- **Unsprung mass (or inertia):** equivalent arm mass (or inertia) at the clamp;
- **Stiffness:** ratio of force to translation (or torque to rotation) at one point.

2.2.2.3 Rigid Spacer

This type of spacer has no articulation, hence has a very high stiffness with no damping capacity. With rigid spacers, the damping of vibrations has to come from the conductor itself or from dampers. Such spacers tend to force nodes of vibrations at the spacer clamp. It is preferable that mass and inertia of spacers be kept as low as possible to prevent entrapment of vibrations within subspans. In such a case, end dampers may not be efficient and severe bending stresses may arise at spacer clamps.

2.2.2.4 Articulated Spacer

Articulated spacers differ from rigid spacers as clamps are designed to provide some movement. Such movement favours interaction between adjacent subspans on the same subconductors. With unequal subspan lengths, this may have a positive effect in the control of subspan oscillations. For aeolian vibrations, clamp movement may contribute to reduce the local bending stresses in the subconductors. However, the effect of the total mass and inertia should be the same as for rigid spacers.

2.2.2.5 Flexible Spacer

Flexible spacers are designed to maintain the bundle subconductor spacing while minimising the interference of the spacer with subconductor movements. To attain these two objectives, a compromise has to be made. The spacer has to be stiff enough to maintain the bundle geometry without permanent deformation of the spacer under fault level accepted for the line, while being flexible enough to allow vibrations and oscillations to pass through. As with rigid and articulated spacers, the mass and inertia have to be kept to a minimum. Moreover, the geometry of hairpin spacers should be optimized to avoid any undue rubbing where the rods first contact the conductor.

2.2.2.6 Spacer Damper

For low frequency rigid body modes, such as snaking, rolling or galloping, the spacer characteristics have no obvious effect. At these frequencies the effect of mass and inertia are not significant. As all subconductors move as a whole, the damping mechanism is not operating. However it has been noted from field tests that some spacer damper systems are more sensitive than others to rolling and snaking. No explanation has been provided for such behaviour.

The various spacer damper design parameters that are relevant have been listed in the Table 2.1.

	Breathing modes (out of phase)	Rigid body modes (in phase)
Wake-induced oscillations	Stiffness, Arm angle	
Aeolian vibrations	Stiffness, Damping, Unsprung mass, Arm angle	Stiffness, Damping, Sprung mass and inertia, Arm angle

Table 2.1: Spacer damper design parameters

Wake-induced oscillations:

A low **stiffness** is favourable to the interaction between adjacent subspans and to the reduction of the conductor stresses at the spacer clamps. However, too low a stiffness may cause the two subspans to react as a single long subspan, thus increasing the sensitivity to subspan oscillations. Moreover, under severe oscillations, spacer dampers with a low stiffness may exhibit large arm movements conducive to wear and fatigue of the damping mechanism.

The contribution of **damping** derived from the articulation has not been demonstrated to attenuate subspan oscillations. To really be effective, it is considered that the damping should be significantly higher than the usual.

The **arm angle** is important as it affects the apparent stiffness in the horizontal plane. A horizontal arm arrangement makes the spacer damper very rigid in this plane.

Aeolian vibrations:

For aeolian vibrations, **mass**, **stiffness** and **damping** cannot be considered independently. Indeed, a spacer damper can be considered as a damped spring-mass system. The resonant frequencies of the spacer damper depend on all those parameters. It is recognised that the resonant frequencies should be in the range of the most damaging vibration frequencies of the subconductors.

For breathing modes, the sprung mass has a minor effect, as the movement of the frame is small. In this case, the damping mechanism operates directly from the arm movements.

For rigid body modes, where all conductors move in phase, the **sprung mass** (or **inertia** for torsional modes) plays an important role. It is through the reaction of this mass that movement is induced in the damping mechanism. If this mass is too low, the spacer damper will move as a whole and no damping will be provided.

In practice, several modes of vibration may be active simultaneously and may be different for each subconductor. The importance of the above parameters also depends on the type of bundle. A horizontal bundle of two conductors is the most difficult to control with respect to aeolian vibrations. In that case, the mass and inertia of the central body is particularly critical.

In all cases, the unsprung mass should be as low as possible in order not to force harmful conductor bending at the spacer position.

The arm angle can also contribute to the attenuation of aeolian vibration. An angled arm forces the conductor to vibrate in an angled direction with respect to the vertical. This may reduce the wind energy input and favour the interaction between the subconductors.

2.2.3 Electrical characteristics

2.2.3.1 Conductivity

If any components of a spacer are electrically insulated from all of the subconductors, these components will be charged capacitively by the energized phases. For example, the central frame of the spacer may be insulated from the arms and clamps by elastomeric bushes. The actual voltage achieved by these insulated components will depend on their capacitances and the stray capacitances to earth. The resulting voltage difference between the subconductors and the insulated components may amount to many kilovolts and can lead to spark-over between components or to tracking across the surfaces of the insulating materials, especially if they become polluted. Such discharge activity will lead to radio interference and to degradation of the insulating materials, which can be avoided by ensuring that every component of a spacer is connected via a conducting path to a subconductor. This also avoids any possible safety hazards associated with trapped charge on the spacer components when the line is switched out, although such charges might be expected to leak away before any maintenance activity could be initiated.

The elastomeric components that are commonly employed in spacer dampers, or that are used to line the clamps of some

spacers and spacer dampers, usually contain fine carbon particles in order to achieve suitable values of various mechanical properties (stiffness, damping, etc.). The carbon has the additional benefit of making the elastomer conducting. However, the large separation between aluminium and carbon in the electrochemical series may lead to corrosion of the aluminium conductor strands or spacer components in contact with the elastomer. The extent of the corrosion will depend on the amount of carbon in the elastomer and the pollution of the service environment.

The suitability of a carbon-loaded elastomer for use in spacers is commonly assessed by measuring its electrical resistance. Too low a resistance may lead to severe corrosion; too high a resistance may lead to radio interference and tracking problems. If any additive other than carbon is used to achieve the required electrical and mechanical characteristics of an elastomer, then similar considerations apply.

Suitable electrical conductivity between the spacer components and one or more subconductors can also be achieved by shunting the insulating elements with metallic elements, such as braids or brushes. The charging requirement can be met by ensuring that the components are electrically connected to only one subconductor. If the spacer forms a conducting path between two or more subconductors, then any voltage imbalance between the subconductors will lead to current flowing through the spacer components. Such currents may be significant under some fault conditions, for example, galloping faults, and the conducting components forming the path must be capable of carrying these currents without burning out.

2.2.3.2 Corona, Radio Interference and Audible Noise

The spacer should be designed to limit visible corona, RI and AN discharges to specified values at the operating voltage of the line, multiplied by an agreed safety factor. The critical area for discharge lies outside the bundle periphery defined by straight lines joining adjacent subconductors. All spacer component surfaces in this area should be smoothly and correctly profiled and be free from asperities. Fixing bolts or other locking devices should be shielded by appropriately shaped spacer components.

2.2.4 Environmental Considerations

Spacers should be capable of withstanding a wide range of service conditions without functional impairment. These include thermal cycling due to climate and current loading of the conductors and the effects of pollution, which can cause chemical, galvanic and electrolytic corrosion. If elastomers are used in the construction of the spacer, they should be chosen to have good fatigue endurance, controlled electrical conductivity and resistance to the effects of ozone, UV, oil and grease, pollutants and ageing under the range of conductor operating temperatures.

The spacer should be designed such that audible noise arising from its exposure to the wind is minimised. In particular, internal cavities formed by hollow castings, for example, in the central frame of the spacer, may be excited as Helmholtz resonators. This can only occur if the cavities have significant apertures connecting them to the outside world in such a way that the wind can blow across the mouth of the aperture. Such resonators can give rise to a whistling sound, which is close to a pure tone loud enough to be a public nuisance.

2.2.5 Sampling of previous specifications

The survey "sample of previous specifications", provided in Annex 2.A at the end of the document, is a condensed summary of existing specifications for spacer and spacer damper worldwide. It is representative of all climate and environmental conditions.

2.3. TEST METHODS FOR SPACERS

2.3.1 General

Spacers are used to maintain subconductor spacing under all conditions within prescribed limits.

To ensure a proper performance of the spacers during their lifetime, spacers should fulfil the following criteria:

2.3.2 Mechanical characteristics

2.3.2.1 Clamping

To avoid spacer clamp loosening or slippage, the clamping characteristics should be verified by a clamp slip test (longitudinal and torsional), breakaway bolt test and clamp bolt tightening test. The tests shall be performed using the conductors for which the clamps are designed.

2.3.2.2 Mechanical strength

In service, spacers should withstand mechanical loads imposed on them due to environmental or short circuit conditions. To simulate this, load compression and tension tests as well as simulated short circuit tests should be carried out.

2.3.3 Dynamic characteristics

2.3.3.1 Flexibility

To demonstrate the ability of the spacers to accommodate any expected relative movement or displacement of the subconductors during normal working line conditions, without damage to the conductors or spacers, a longitudinal, vertical, conical and transversal flexibility test should be carried out.

2.3.3.2 Fatigue

This test shall be performed to verify the fatigue behaviour of spacers subjected to alternating motions or simulated vibrations occurring in service. A subspan oscillation test and an aeolian vibration test are the most representative tests.

2.3.3.3 Damping

Tests to determine the damping properties of spacer dampers shall be performed. There are different methods specified, such as the stiffness-damping method, stiffness method or damping method. Damping and stiffness characteristics shall be measured before and after the fatigue tests.

2.3.4 Electrical characteristics

2.3.4.1 Corona and Radio Interference

Corona and radio interference voltage tests should be performed to verify the electrical behaviour of spacers in service conditions. A representative standard is [5].

2.3.4.2 Electrical resistance

The purpose of this test is to verify that the conductivity of the various components is such that potential differences and current flows do not result in degradation of spacer components or damage to the subconductors.

2.3.5 Resistance to environmental attacks

Spacers are used world wide under completely different environmental conditions and levels of pollution. To verify the resistance of the elastomer to various environmental conditions i.e. ozone, UV, extremes of temperature and salt spray, appropriate tests for elastomers should be carried out.

2.4. FIELD MEASUREMENTS

2.4.1 General

Field measurements of wind-induced vibrations of bundled conductor lines are usually carried out to assess whether the anti-vibration system in use provides sufficient protection against potential damage to the conductors and accessories. An anti-vibration system is made up of a specific set of spacers, dampers, spacer dampers or a combination thereof, that are positioned along the span according to specified schemes. On occasions, field measurements are conducted to verify whether use of special devices such as aircraft warning spheres or anti-galloping devices do not impair the integrity of the line. They also serve to assess the comparative performance of various protection systems.

2.4.2 Measurement Parameters and Points

In addition to aeolian vibration, which is well known in the context of single conductor lines, bundled conductors are also affected by a range of wake-induced oscillations including subspan oscillations, snaking, rolling and horizontal galloping [6]. Accordingly, both of these classes of wind-induced vibration are usually investigated in the field.

In comparison to single conductor lines, the number of critical points on bundled lines that may be suitable for measurement increases significantly. Not only are suspension clamps regarded as potential locations for conductor damage due to wind-induced vibrations but also all clamps or attachment devices of all spacers and dampers.

2.4.3 Measurement Methods

Aeolian vibrations have been measured simultaneously at several suspension and spacer clamps along test spans [7]. Usually, by virtue of the so-called bending amplitude method [8], the quantity measured has been the differential displacement between the conductor and the clamp at 89 mm from the last point of contact. Although originally recommended for application solely for metal-to-metal suspension clamps, the bending amplitude method has nevertheless been applied to measurements at metal-to-metal spacer clamps using lightweight sensors seated on the clamps. Alternatively, whenever spacers employed elastomer-lined clamps or helically attached clamps, the equivalent "inverted" bending amplitude [9] has been measured by means of sensors seated directly on the conductor in the close vicinity of clamps.

Regarding the measurement of wake-induced oscillation, no technology has yet received universal acceptance. Whether

the subconductor gross displacement, the differential displacement at the antinodes or the subconductor bending at spacer and suspension clamps should be measured is not clear either from a damage-oriented or an oscillation control point of view.

Test lines may also be used to assess the severity of aeolian vibration and wake-induced oscillation on bundled lines equipped with given types of spacers or spacer dampers [10, 11].

In many cases, when testing operating lines, investigators have had recourse to direct visual or video-aided observations. Indicators such as deformation rings have been used to determine maximum subconductor differential displacement. Commercial bending amplitude recorders have not been used currently to measure wake-induced oscillations for they may not respond adequately at the low frequencies involved.

In contrast, tests with several motion sensors, such as accelerometers mounted on one subconductor in every subspan along a complete span, have been carried out on a test line in order to assess the overall susceptibility of bundled conductor-spacer systems to wake-induced oscillations [7].

Measurements on real lines, before operation, have been carried out by means of relative displacement transducers such as LVDT's or potentiometers. In such cases, the measurement is taken at a certain distance from the spacer clamp and the antinode relative displacement is computed from this.

It is worth noting the experience that has been obtained through the instrumentation and monitoring of the dynamic behaviour of an existing line under operating conditions [12].

2.4.4 Interpretation

Interpretation of aeolian vibration measurements by the bending amplitude method is the same, regardless of whether they were made at suspension and spacer clamps on bundled conductors or suspension and damper clamps on single conductors. Often, the maximum bending amplitude recorded over a certain interval of time is simply compared to a preset admissible amplitude such as the conductor fatigue endurance limit [13]. Alternatively, CIGRÉ SCB2 WG04 and WG11 TF2 have proposed a method [14] of approximate assessment of the conductor lifetime on the basis of the recorded overall spectrum of amplitudes and frequencies.

Interpretation of wake-induced oscillation measurements is less clear. However, it may be as simple as checking that the subconductors in any subspan do not come (too often) too close to each other for a given range of wind velocities. On the other hand, whenever several sensors have been used for the field tests and several records are available, interpretation may be based on the total energy of oscillation [7] over a span as a function of wind conditions (velocity and azimuth angle).

2.5. ANALYTICAL BASES AND COMPUTATION METHODS

2.5.1 Introduction

Analytical tools and computational methods have been developed to help in the understanding of the phenomena encountered in conductor dynamics together with the objective of proposing efficient solutions to restrain conductor motion to acceptable levels. This section, however, will only give a picture of certain tools and methods that have proved their usefulness.

2.5.2 General

As already noted in Part I, Section 1.2 : 'Number and location of spacers', the main problems of wind excited vibrations connected with overhead transmission line bundles are aeolian vibration and instability phenomena due to wake effects and ice formation. The dynamic behaviour of the bundle - and then the bundle response to the above phenomena - is influenced by the type of bundle, its geometry (spacer spacing, tensile load), the spacer type and the span length. To control these phenomena, different solutions can be used, including spacer dampers, spacer plus dampers or a combination of twin articulated spacers. In case of galloping, anti-galloping devices may be used [15-18].

If the spacer is not rigid, its damping capability may play an important role in controlling aeolian vibration and, to a lesser degree, subspan oscillation. In the case of the latter phenomenon, spacer damping is generally not sufficient to suppress subspan oscillation [19] and will not suppress full galloping.

From the analytical point of view, the spacers should be modelled through their geometric and inertial characteristics (body + arms) and through the elastic and damping properties of the hinges connecting the body to the arms. These properties are frequency and amplitude dependent and are evaluated by means of forced vibration tests in the laboratory. Low amplitude tests in the range 5 to 100 Hz are used in the case of aeolian vibration, while high amplitude - low frequency (around 2 Hz) tests are used for subspan oscillation. Tests may be performed on the single elastic element or on the complete spacer.

The analytical modelling of the bundle strongly depends on the type of problem to be simulated and solved [20].

Depending on the need to simulate vortex-induced vibration [19, 21, 22], wake-induced oscillation [23], galloping, large displacement dynamics [16, 24] or, finally, impact loading (such as the failure of a conductor, the detachment of an ice formation or a short circuit), different techniques may be adopted.

The structural modelling of the spacer/bundle system is more complex than in the case of the single conductor, due to the presence of the spacers, which may be rigid, flexible or spacer dampers, depending on the nature of the connection between the body of the spacer and the arms. The choice among the three types depends on the problem that the spacers are required to solve.

The structural modelling of the bundle can be based on a Finite Element Method (F.E.M.) [15, 25] or on the transfer matrix method [21]. Both these approaches allow for the computation of the bundle natural frequencies and modes of vibration when the structural model can be linearised in the vicinity of a static equilibrium position.

When large displacements need to be simulated, a convenient approach is the schematisation through a F.E.M. and the integration in the time domain of the equations of motion [15, 24].

The choice of the type of structural model and of its degree of refinement depends on the type of problem to be simulated.

2.5.3 Aeolian vibration

For the case of vortex shedding, the usual approach is based on an energy balance between the energy input from the wind and the energy dissipated by the system of conductors, spacers and eventually, dampers [21]. The same considerations as for the single conductor hold true: the computation of the natural frequencies and modes of vibration can be performed neglecting the sag effect, because the first modes of vibration are not excited, and simplified end conditions can be assumed.

The energy input from the wind is obtained by wind tunnel tests in a smooth flow on a pair of cylinders [26-30]: curves similar to those of the single conductors can be obtained and can be used for certain ranges of subconductor spacing to conductor diameter ratio. Also, in this case, curves related to different levels of turbulence are available.

Additional information and more complex modelling are needed for a complete picture not only of the steady state (maximum) amplitudes of vibration but also of the transient conditions.

2.5.4 Wake-induced oscillation

The second important phenomenon, besides vortex shedding, is the large amplitude vibration due to wake effects known as subspan oscillation. This is essentially an aeroelastic phenomenon due to the interaction between the elastic system and the fluid, which can be classified as a flutter type instability.

On the upwind subconductor there is only the drag force, whilst the forces on the downwind subconductor depend on its motion, its relative position with respect to the windward conductor and the wind distribution. Referring to a generic pair of conductors in the bundle at a generic time, the relative velocity on the upwind conductor determines the wake direction, which propagates rapidly on the downwind conductor. The reduced velocities are high enough to allow the use of the quasi-steady theory. The drag (C_D) and lift (C_L) coefficients for the downwind subconductor depend on the relative position between the upstream and downstream subconductors. These coefficients have been derived from wind tunnel tests performed on two cylinders, with one in the wake of the other.

The range of frequencies covered by this phenomenon for classical bundles, is 1 to 2 Hz and the first mode of vibration of the subspans (the section of bundle between two spacers) is excited. Subspan oscillation occurs with relatively high wind speed (10 to 30 m/s).

Subspan motions are characterised by a flutter type instability phenomenon, which can be approximated, for classical bundles by taking into account a constant wind speed.

The simulation of the wake-induced oscillation and the computation of the amplitude of vibration, both in turbulent and non turbulent wind, can be performed by a F.E. approach integrating the equation of motion in the time domain [25] or by a modal approach in which the natural frequencies and modes of vibration are computed by a F.E.M.

Simulation of the wake-induced oscillation can also be performed in the frequency domain using an Energy Balance: in this case, the input wind energy is computed as a function of the elliptical orbit amplitude of the relative motion. The Energy Balance obviously considers steady state conditions and allows only for the evaluation of the limit cycle amplitudes of oscillation in a non turbulent wind [23].

2.5.5 Galloping

Just like single conductors, conductor bundles may be subjected to ice galloping and this problem can be treated using a 3D F.E. model of the bundle in order to exactly reproduce the effects of the adjacent spans, the type and geometry of the insulators, the sag (geometrical non-linearity) and the real tension distribution along the conductors. The bundle can be modelled using beam elements reproducing the inertial and elastic behaviour of the bundle itself, taking into account also the influence of the spacers, through suitable aerodynamic coefficients, measured in a wind tunnel with different ice profiles [15, 31].

Also, in this case, the effects of the end fittings, the constraints and the adjacent spans play an important role and should be introduced in the model.

This phenomenon may also occur coupled to subspan oscillation.

2.6. CONCLUSION

As established in Part 1, spacers and spacer dampers both represent important pieces of hardware in a transmission line. In this paper, design characteristics were reviewed and test methods for the assessment of the mechanical, electrical and environmental characteristics suggested. Field measurement methods were presented to assess the actual dynamic behaviour of conductor bundles. Moreover, computational methods are used to predict the response of bundles and assist in the interpretation of field measurements. Despite the progress achieved, the reader will appreciate that a great deal remains to be done. Part 3 will report on current practice, field experience and on the results of a survey of utilities' experience with the use of spacers and spacer dampers.

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Annex 2.A: Sample of previous specifications

Specification		A	B	C	D	E	F
Elastomer	Resistance & characteristics	1-20 MΩ at 100 V / 50 Hz	Min. 1 MΩ	Max. 1.5 MΩ (110 V / 60 Hz) Ozone : 500 h / 50 ppHM Weatherometer: 20% elong ./. 60°C 160 h	Conductive Ozone : 70 h / 60°C 50 ppHM	Conductive	Conductive
	Environmental factors	-20 to 75°C UV Ozone Pollution	-10 to 90°C UV Ozone Atmospheric contents Life > 40 years	0 to 85°C UV Ozone	-5 to 75°C UV Ozone	-40 to 100°C UV Ozone	0 to 90°C UV Ozone
Electrical property	Corona, RI	>340 kV (400 kV) >240 kV (275 kV) >110 kV (132 kV)	No evidence of corona at phase to earth voltage RIV : Max. 6 dB lower than at 15% higher gradient	Depends on height RIV: 200 μV at specified test voltage or 400 μV at specified test voltage x 1,1	> 346 kV 200 μV at 303 kV	Extinction volt- age not less than 266 kV	
	Short circuit			50 kA / 0.25 s	40 kA 4 cycles		40 kA 6 cycles
Static displacements and loads	Longitudinal displacement	Min. ±25 mm					
	Vertical displacement	Min. ±50 mm					
	Conical displacement	Min. 20°		After dynamic fatigue test: 10 ⁶ cycles 2°			
	Tension loads	5 kN for 1 minute	Twin : 10 kN Triple : 11 kN Quad : 10 kN horizontal and vertical and 12.5 kN diago- nal Hex :6.5 kN	12.5 kN		5.91 kN for 1 minute	10 kN
	Compression loads	5 kN for 1 minute		12.5 kN		5.91 kN for 1 minute	10 kN
	Clamp slip	5 kN (max. 0.5 mm slip)	Metal clamp: min. 6 kN (max. 0.5 mm slip) Elastomer clamp: min. 2 kN (max. 1.5 mm slip)	Metal clamp: min. 7 kN (max. 0.5 mm slip) Elastomer clamp: min. 3 kN (max. 1.5 mm slip)	Metal clamp: min. 4.5 kN (max. 0.5 mm slip) Elastomer clamp: min. 2 kN (max. 1.5 mm slip)	Metal clamp: 4.5 kN longitudi- nal Elastomer clamp: 1 kN longitudinal	2 kN

Annex 2.A: Sample of previous specifications (continued)

Specification			A	B	C	D	E	F
Dynamic movements	Fatigue test	Aeolian vibration	Twin : 10^8 cycles at 20 Hz and 0.4° Triple/Quad: 10^8 cycles at $f=10-50$ Hz and $\pm 150 \mu\text{m/m}$	Highest f: between 5-40 Hz 10^7 cycles or : 10^7 cycles from 20-30 Hz and $y=3$ mm p-p Fatigue test: min. 4 Hz ± 40 mm 2×10^6 cycles	Laboratory test : $f = 5-50$ Hz / ± 3 mm 10^6 cycles afterwards a rotational slip test (min. 65 Nm) afterwards heat cycle tests ($5^\circ\text{C} - 60^\circ\text{C}$)	Vertical : 10^6 cycles / ± 3 mm at highest $f=5-50$ Hz	± 3 mm at resonant frequency between 5-40 Hz 10^8 cycles	Vertical 10^7 cycles / ± 2.5 mm 20 Hz
		Subconductor oscillation	Twin: 10^7 cycles at 1-5 Hz, $y=2d$ p-p Triple/Quad: 2×10^7 cycles at ± 260 N	5×10^4 cycles at ± 25 mm or displacement resulting from 250 N static force and min. 2 Hz	Fatigue test: min. 4 Hz, 10^7 cycles at ± 38.1 mm conductor displacement or 3.75 W dissipation or 95% of total stop to stop displacement	Longitudinal: 10^6 cycles at ± 25 mm cond. displacement / 2 Hz Vertical: 10^7 cycles at 4 Hz ± 38 mm or 3.75 W or 95% Conical: 10^6 cycles at 2-5 Hz and 2°	2×10^6 cycles at ± 25 mm or 226 N force at min. 2 Hz 10^7 cycles at min 4 Hz and ± 37 mm or 95% of total stop to stop displacement energy dissipation min 15 W/s	Longitudinal: 5×10^4 cycles at ± 25 mm 2×10^6 cycles at ± 15 mm 2 Hz Torsional: 10^7 cycles at ± 300 N 2 Hz
		Logarithmic decrement	Twin : min. 0.5 Triple/Quad : min. 1		According to tender regulation			
	Verification tests			- Field test - Aeolian test Strain: max. $200 \mu\text{m/m}$ p-p	Field test : Aeolian vibration test: max $300 \mu\text{m/m}$ p-p Subspan test	$200 \mu\text{m/m}$ p-p + subspan oscillation Field tests required	$152 \mu\text{m/m}$ p-p subspan oscillation 4 weeks field test required	Aeolian $200 \mu\text{m/m}$ p-p min. 14 days

p-p : Peak-to-peak value.

STATE OF THE ART SURVEY ON SPACERS AND SPACER DAMPERS

Part 3 – Experience with current practice

3.1. INTRODUCTION

The use of multiconductor bundles prompted the design of spacers, which are intended to maintain the geometry of the bundle. They rapidly evolved into spacer dampers to provide more adequate control of bundles subjected to a range of environmental conditions. A spacer damper system is generally defined as spacer dampers with specified in-span locations. However, where rigid or articulated spacers are used, vibration dampers are also generally employed to complete the spacer damper system. The first two parts presented a general description of a conductor bundle system and some important technical aspects related to the design of spacers and spacer dampers.

In this paper, the actual experience gained with current practice is reviewed. It summarises the most common problems experienced with spacers damper systems as viewed by users. In addition, the results of a questionnaire prepared by this group reveal experiences with conductor damage.

3.2. CURRENT PRACTICE AND FIELD EXPERIENCE

3.2.1 General considerations

The difficulties encountered with spacer damper systems may take different forms and be attributable to different causes. This section of the document describes some of the most common problems.

Firstly, it should be noted that many of the problems arising in service could have been avoided by a better knowledge of the specific service conditions. There are not many problems for which a solution does not exist nowadays. The real difficulty is to establish the actual operating conditions of a specific transmission line. Usually, only an overview of the line is provided but this is not sufficient to identify specific locations where problems can arise.

The present trend for cost reduction has led to a significant loss of expertise in many utilities. This means that utilities are losing the capacity to carry out their own studies and as a result, they have to rely on suppliers to recommend the proper spacer damper system to use. On the other hand, the market has become more and more competitive so that suppliers have to offer cheaper solutions. With these two phenomena merging, we can expect that problems will increase in the future.

3.2.2 Specification and evaluation of spacer damper systems

Purchasers of spacer damper systems have to write technical specifications that should reflect the expected operating conditions. These specifications should prescribe a given performance level with regard to wind-induced vibration and oscillation control. It is quite easy to call for vibration levels under the given operating conditions to remain below the endurance limit of the conductor. However, it is not so easy to prove that a given spacer damper system fulfils this requirement.

Computer methods exist to calculate the aeolian vibration levels occurring in bundles, but their validity is still questioned. TF1 of WG11 is currently discussing and evaluating the available models and a higher level of confidence should be gained in the future. Despite these limitations, computer models may be helpful in evaluating spacer damper systems on a comparative basis. On the other hand, there is no proven method to predict subspan oscillations. Laboratory tests cannot reproduce the most important parameter, which is action of the wind. Full scale outdoor tests, although reflecting real life accurately, have practical limitations rising from high cost and long time delays. Vibration and oscillation measurements can be done on existing lines to evaluate spacer-conductor systems. Such information can be used when purchasing spacer systems for new lines, provided the line characteristics are sufficiently similar.

This problem, combined with the current economic pressures makes it very difficult for the utility engineer to ensure that he installs the most appropriate system to maintain the geometry and damping of his bundled line.

3.2.3 Problems with spacer dampers in service

The problems observed with spacer damper systems can be related either to the design of the system or to the materials.

3.2.3.1 Design Related Problems

Inadequate Performance with regard to Vibration or Oscillation Control

Several conductor or spacer damper in service problems are caused by the spacer damper system's inability to control vibration and oscillation adequately. Unfortunately, this aspect is the most difficult to control and verify.

Fatigue of the Spacer Damper Damping Mechanism

Whenever vibration or oscillation levels are not well controlled, damage to the damping elements of the spacer damper may occur. Several instances have been reported in the past. In the most severe cases, it has been necessary to replace or refurbish spacer dampers on entire sections of lines. Usually, fatigue damage is a long-term process. However, experience has shown that uncontrolled oscillations may lead to spacer damage within a few months.

Damage to Conductors

The most critical damage related to spacer damper systems is certainly that affecting conductors. Two types of damage have been reported: wear and fatigue.

Wear has certainly been the most common problem. This type of damage is usually related to clamp loosening. Frequently, wear has been so extensive that the conductor failed. Clamp loosening may be attributed either to faulty installation or to the effect of conductor vibration and/or creep.

Conductor fatigue at spacer clamps is less common, since the bending stress levels are usually much lower at these points than at suspension points. However, a few major problems have been reported in the early eighties. On a long river crossing, a combination of spacer dampers plus Stockbridge dampers set up near suspension points had been used. It appeared that vibration levels at the suspension point were well controlled while there was severe in-span vibration activity that eventually led to strand fatigue failures. A further analysis showed that use of quite heavy spacer clamps had promoted the entrapment of vibrations within subspans.

Mechanical Damage to Spacer Damper

Besides the damping mechanism, other components of spacer dampers may be damaged in service. In some cases, severe arm-to-frame contact due to excessive oscillation has caused damage to either the frame or the arms.

Failure of spacer dampers due to mechanical overload has also been experienced. Overloading may be induced by severe differential icing or ice shedding or by dynamic stresses due to short-circuits.

3.2.3.2 Material Related Problems

Corrosion of conductor surface

Damage to conductors due to corrosion has been reported. It was associated with the use of elastomer lined clamps operating under adverse conditions. This effect appeared to be promoted by the use of an inappropriate elastomer material having a low electrical resistivity.

Corrosion of spacer damper components

Spacer damper components are generally made of aluminium alloy. In contaminated areas, some alloys may be subjected to corrosion. Such corrosion is usually superficial and does not impair the spacer damper's function. There could be, however, some cases where corrosion has a significant impact on spacer damper reliability.

3.3. SURVEY OF FIELD EXPERIENCE

3.3.1 Introduction

A questionnaire entitled "Survey on Damage to Spacer and Spacer Dampers and/or Conductors in Bundled Conductor Lines", (see annex 3.B) prepared by SC22-WG11-TF5, was circulated to the national members of CIGRÉ SC22 for distribution to utilities within their regions in 1999. To improve the participation, some questionnaires were also sent by other members selected for their technical involvement in the subject under study. A total of 66 replies were received from 19 countries: 12 from Europe, 2 from North America, 2 from South America, and 1 each from Asia, Africa and Australia. However, the Task Force regrets that the experience of several countries operating long EHV transmission lines (e.g. Russia, India, China) could not be included in the results of the survey of field experience due to lack of response.

3.3.2 General Information

The information received has been used to analyse the behaviour of in-service spacers and spacer dampers and to discuss the field experience reported to outline practical experience that will be worth taking into account for maintenance purposes or for the construction of new lines. It is based on the operating experience of 85 000 circuit km of lines with voltages from 64 to 765 kV and operated for 2 to 68 years. The average service time of the lines is 23 years. The study indicates that the average time to the first failure is 10 years (see Figure 3.A.2). The first failure however can actually occur in the first year or

as late as 30 years or more of operation, according to the operating conditions.

The representativeness of the replies has been expressed in Figure 3.A.3 (annex 3.A), where the circuit km of lines from the replies are compared on a logarithmic scale with the total circuit km of lines above 220 kV per continent for all utilities as found in reference [1]. Except for Asia, where the number of replies was extremely low, the response for all the other continents represents 2 to 24% of the total circuit km of lines.

Existing types of spacer appears to be well covered in the replies with 44% spacers dampers, 27% flexible spacers, 18% articulated spacers and 11% rigid spacers.

3.3.3 Reported Problems with Spacer Systems

3.3.3.1 Most significant problems

Damage to conductors represents 30% of the problems reported. Problems with spacer frames and spacer clamps each account for 28%, whilst 14% of the problems are related to spacer articulation mechanisms. It should be noted that many of the conductor problems occur as a consequence of clamping system failures; therefore these data should be viewed with this in mind.

The distribution of various types of problems in relation to the bundle type is shown in Figure 3.A.15.

Problems with clamps:

The Bolted metal clamp is the most widely used clamping system (49 respondents) and it is not surprising that most of the clamp problems reported concerned this type of clamp. From the 39 problems reported, conductor wear, conductor fatigue and clamp loosening are the most common. However, 6 cases of complete conductor failure are reported. Bad installation, bad design and vibrations are identified as the main causes of those clamp problems.

Elastomer lined clamps are used by 5 respondents. Two cases of conductor breakage and two cases of conductor wear have been reported. Incorrect installation and corrosion have been identified as the direct causes of the damage.

Problems with spacer articulations

Many spacer dampers use elastomer as damping elements that is why most of the problems with articulations are associated with the elastomer elements. From the 27 replies concerning spacer dampers, 19 elastomer problems are reported. Insufficient damping capacity, corrosion, bad design, bad material and sub-conductor oscillations are some of the causes identified.

Problems with frame

The number of problems with spacer frames is almost as significant as for clamps. Deformation, wear, fatigue and cracks, in decreasing order of number of occurrence, are the problems reported. Considering the number of replies received, frame problems seem to be more frequent on triple bundle spacers. However, if the length of lines represented for each bundle type is taken into account, spacer frame problems are twice as frequent on twin and quad bundles than on triple.

Vibration problems

Vibration or oscillation is reported 12 times as the cause of spacer problems. These cases are almost equally divided between twin and quad bundles. No case was reported on triple bundles. One obvious question is whether there is any relation between the vibration problems and the type of spacer system used. Spacer dampers and flexible spacers are involved in 5 vibration cases each although in this survey there are more reports about spacer dampers (27) than flexible spacers (17).

3.3.3.2 Importance of spacer problems

Considering that the questionnaire was asking specifically for information about problems with spacer systems, it is not possible from these results to have a clear picture of the real importance of those problems. A mini-questionnaire (see annex 3.C) issued after the first one was intended to evaluate the relative importance of the lines with problems with respect to the total transmission system. Unfortunately, only 11 of the first respondents have returned the second questionnaire and it is not possible to make direct connection between the two sets of replies.

From the replies to the second questionnaire, it appears that the percentages of lines with problems are as follows: 4% for twin bundle lines, 11% for triple and 23% for quad. When asked for the importance of the problem on a qualitative scale, the replies are as follows:

IMPORTANCE	No of replies
No	1
Fair	1
Moderate	3
High	2
Very high	4

The number of spacers affected by problems varies widely. In some cases it is only a few units that are defective. In other cases, spacers had to be replaced on entire lines. Replacement of conductors was also necessary when wear or fatigue damage was too extensive.

3.3.3.3 Discussion

The value of any questionnaire is dependent on the number of replies received and their scope in representing a true reflection of actual experience from around the world. In the case of this study, sufficient replies were received to yield some useful information but it is disappointing that some countries known to have significant experience did not respond.

In general, the analysis of the data supports much of what has been only anecdotal experience up until now so we may conclude that this has been a worthwhile exercise.

Perhaps surprisingly, the data did not show any correlation between either conductor spacing to diameter ratio (S/d) or maximum subspan length and reported damage. Nevertheless, members of the Task Force are confident that there is a relationship between these two parameters and damage related to wake induced oscillation. The Task Force believes that further investigation is indicated.

Not unexpectedly, the responses indicated that twin bundle lines were the most common (Figure 3.A.21) but had the least incidence of problems whereas quad bundles were second in order of usage but had the highest incidence of problems. Triple bundles were least used but were second in order of problems experienced, suggesting that there are properties unique to the triple configuration that may render it more problem prone.

Taken together, the use of flexible and articulated spacers predominated with spacer dampers being a close second and rigid spacers being by far the least used. It is probable that this reflects the predominance of twin bundles, where it is somewhat less common to use spacer dampers.

Although the average time to spacer/spacer damper failure is about 10 years, problems must have been developing well before they became so evident. The primary cause of failures appears to be a combination of unforeseeably high levels of conductor vibration and/or oscillation combined with design shortcomings in the spacers and spacer dampers. Poor installation also has a part to play but it is difficult to prove this so long after the event with any certainty. A further factor must be the drive to achieve lowest 'first cost' rather than view the 'lifetime cost' of a system. This may be due in part to the fact that construction and maintenance budgets often come under separate areas of responsibility.

It is not surprising that the majority of problems occur at the clamp/conductor interface where inadequate clamp design or poor installation results in clamp loosening and the inevitable conductor damage, with complete failure in extreme cases. Metal to metal clamps are most commonly involved but elastomer lined clamps are not without their problems either. In the case of the latter, incorrect specification of the elastomer material, which then causes corrosion, can play a major role in the failure mechanism.

The scope for bad installation can be reduced by the clamp design and the incorporation of 'fail-safe' features, permitting post-installation ground based inspection.

Conductor failures due to accumulated damage arising from vibration induced bending stresses at in-span clamp locations appear to be restricted to very specific conditions not normally found on the majority of lines. Nevertheless, valuable design lessons can be learnt in that heavy clamps accentuate vibration entrapment in subspans and should be avoided.

Spacer dampers are generally recommended on a system basis, which includes in-span locations according to defined irregular subspan lengths. This is important in the control of subspan oscillation but less so in the control of aeolian vibration. The responses highlighted a significant number of spacer damper articulation failures but what is not clear is whether the cause was incorrect spacer damper location, inadequate design or a combination of both. The supplementary evidence of severe arm to frame contact in some cases indicates that excessive subspan oscillation has occurred and to this extent, the spacer damper system has failed in its primary purpose. In any event, prudence would dictate that the articulation/damping elements should be specified and designed to have as high a level of mechanical and environmental endurance as is practically and economically possible since they are, after all, the 'heart' of the spacer damper.

Whilst spacer failures due to mechanical overload have been experienced, this does not appear to be a major problem and can be designed for relatively easily.

The results of the survey indicate that problems with spacers and spacer dampers can be relatively minor but extreme cases are possible, resulting in expensive and potentially disruptive damage to conductors and hardware alike. The spacer or spacer damper system can act in a 'sacrificial role', needing replacement after a number of years but having protected the integrity of the line in the meantime.

3.4. CONCLUSION

Part 3 of this State of the Art Survey on Spacers and Spacer Damper contains an important contribution based both on the experience of the experts composing the TF5 and the results of a survey of utilities' experience.

That field experience, if used judiciously with the technical aspects and design characteristics presented in the two previous parts, should enable the transmission line engineer to correctly evaluate different spacer damper systems for adequate protection of a line. It should also provide the utility manager with the appropriate background to understand and evaluate the actual value of the different systems presented and their respective advantages for his application. Manufacturers should also benefit from this survey as they control the design of the spacer damper systems and very often the utilities rely on their recommendations for their applications.

Future work could include an investigation of the relationship between the important design parameters of conductor spacing

to diameter ratio and maximum subspan length and damage related to wake induced oscillation.

3.5. REFERENCES

- [1] ABS Energy and Power, "The T&D Report – World markets for transmission and distribution equipment 2000-2010", 2nd edition, Kilmichael House, United Kingdom, June 1999, 189 pages.

ANNEX 3.A. FIGURES

The following pages summarize through different graphs the information received from the questionnaire and the mini-questionnaire provided in annexes 3.B. and 3.C. respectively.

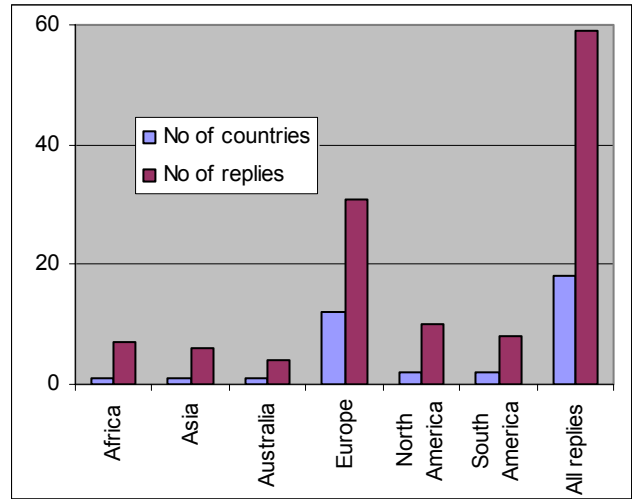


Figure 3.A.1: No of replies and countries

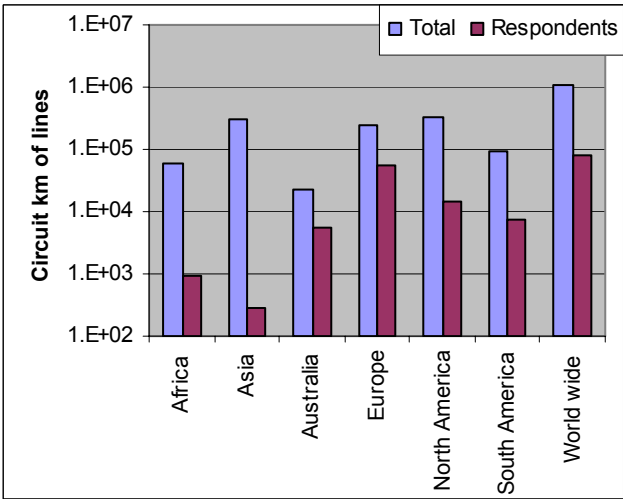


Figure 3.A.3: Circuit km of lines form respondents compared with total circuit km of lines above 220 kV per continent

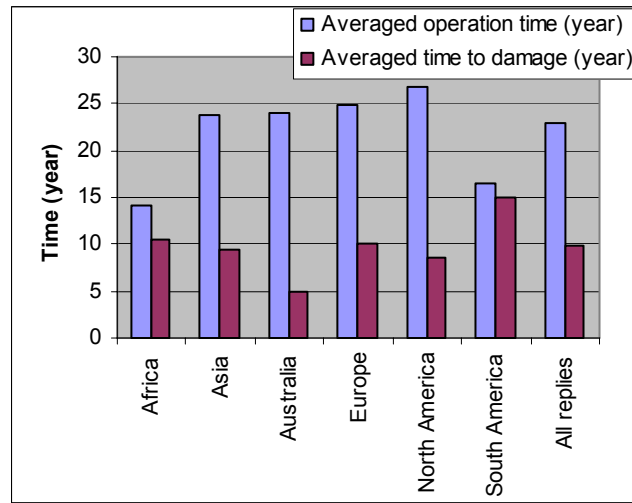


Figure 3.A.2: Averaged time to failure and averaged operation time on the lines

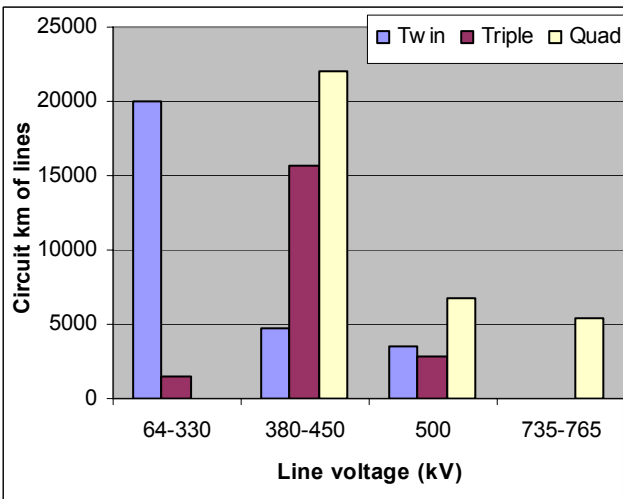


Figure 3.A.4: Line voltage

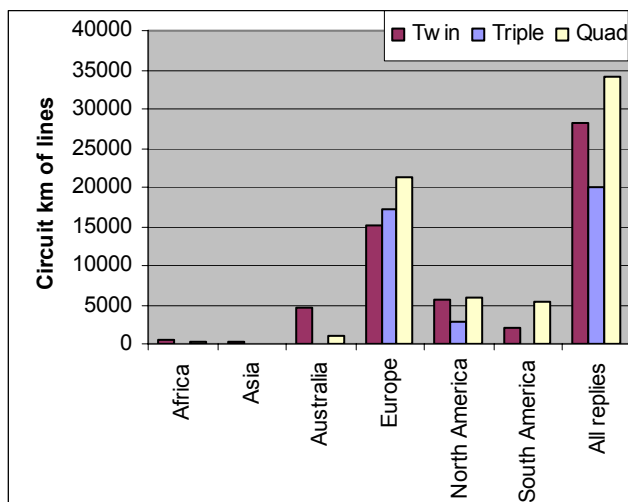


Figure 3.A.5: Total circuit km of lines from replies

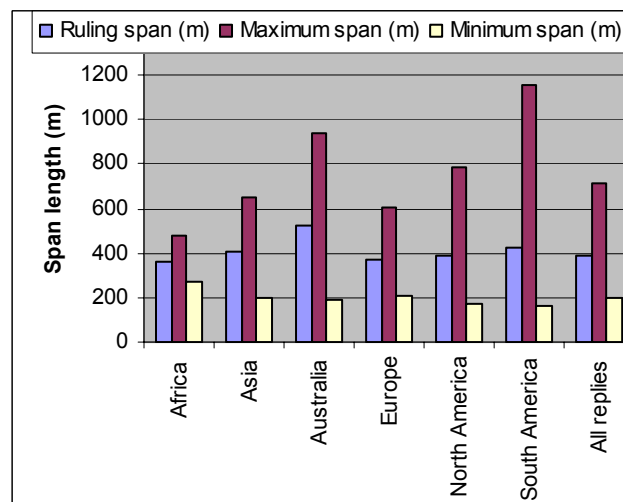


Figure 3.A.8: Averaged span lengths per continent

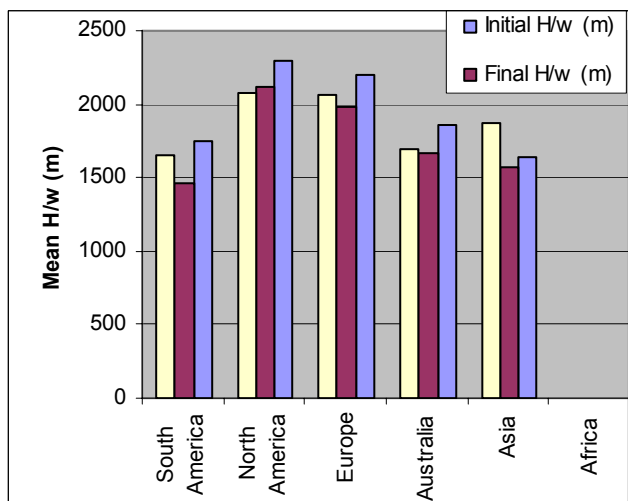


Figure 3.A.6: Averaged design tension parameter

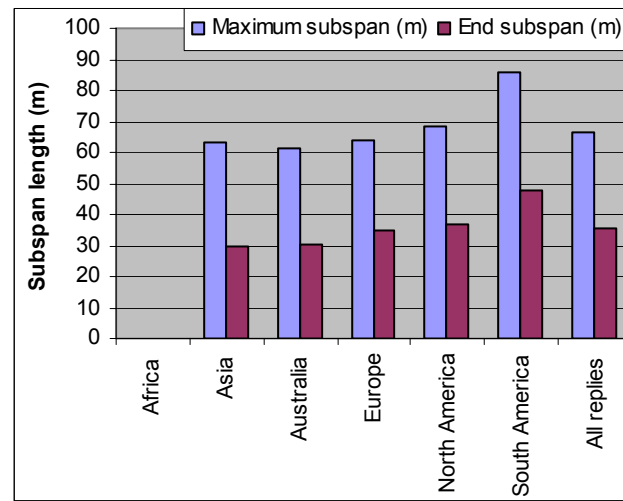


Figure 3.A.9: Averaged subspan lengths per continent

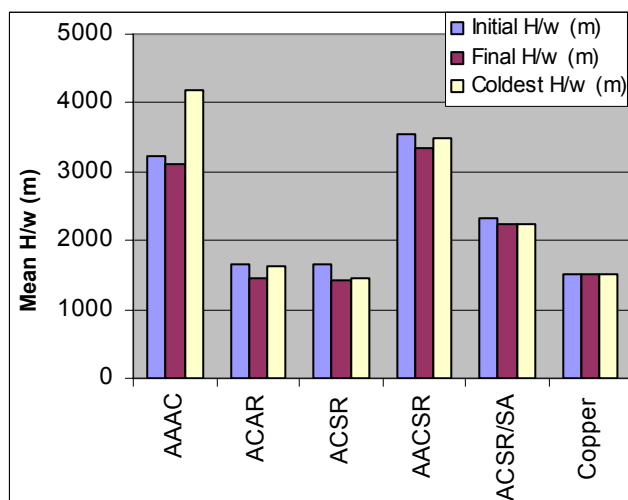


Figure 3.A.7: Averaged design tension parameter as a function of conductor type

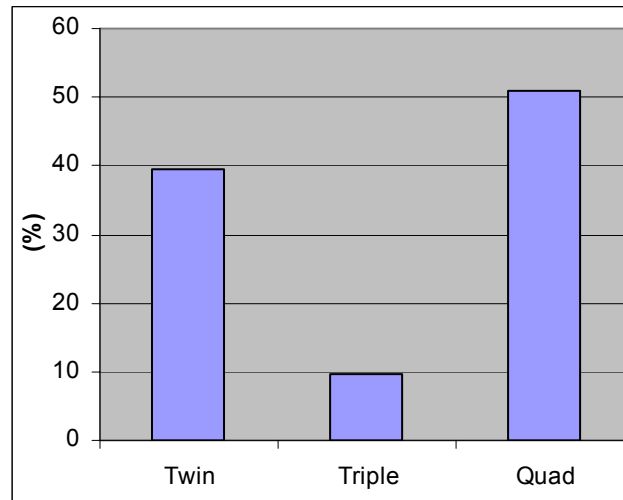


Figure 3.A.10: Percentage of circuit km of lines with problems

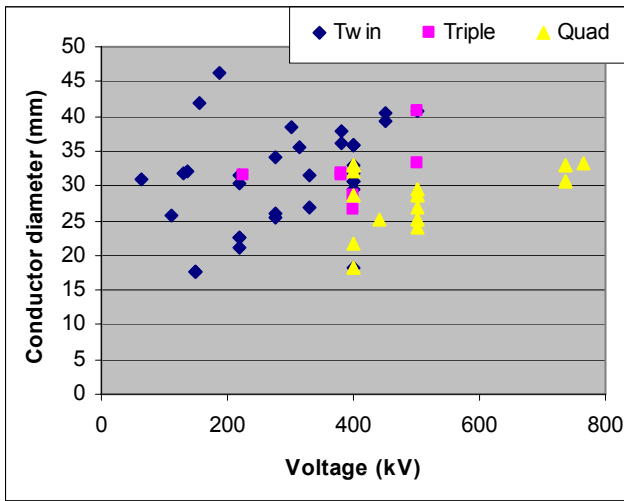


Figure 3.A.11: Conductor diameter

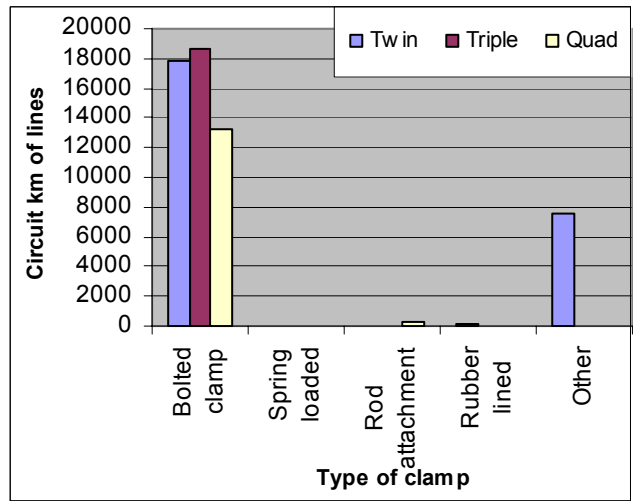


Figure 3.A.14: Clamp type

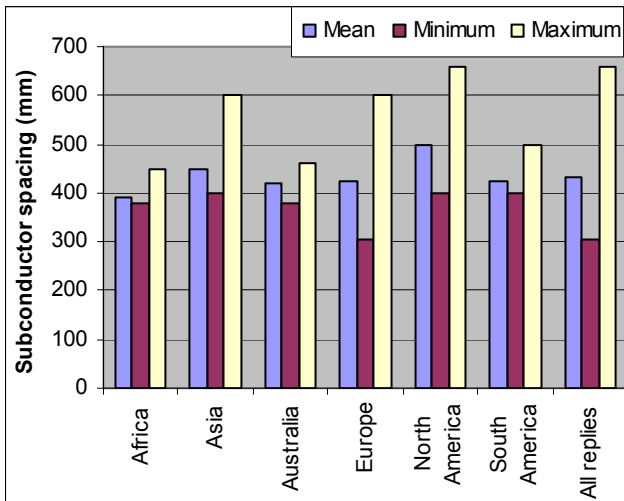


Figure 3.A.12: Subconductor spacing

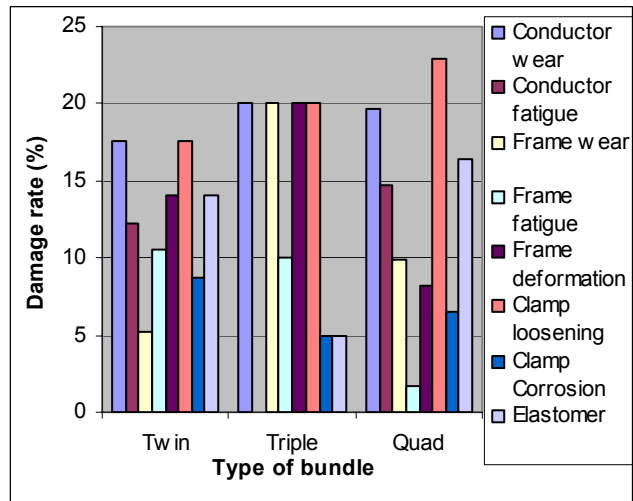


Figure 3.A.15: Type of damage as a function of type of bundle

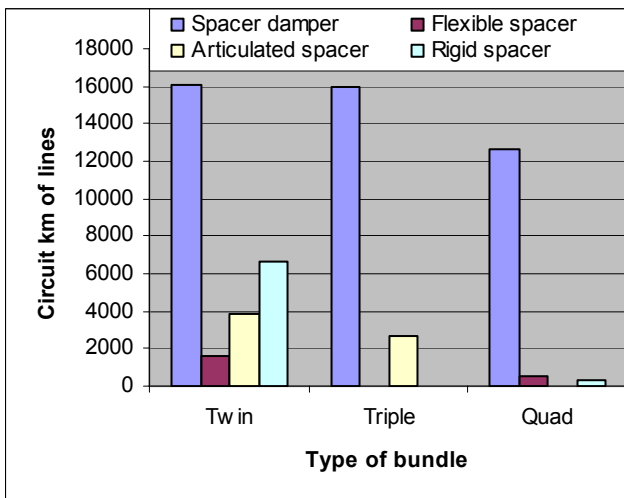


Figure 3.A.13: Spacer type

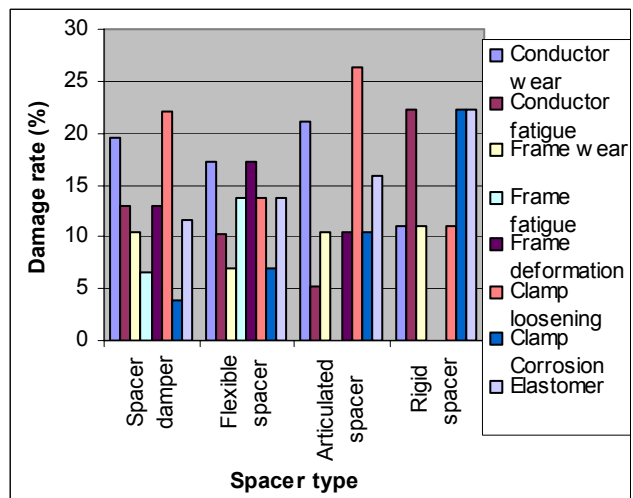


Figure 3.A.16: Type of damage as a function of type of spacer

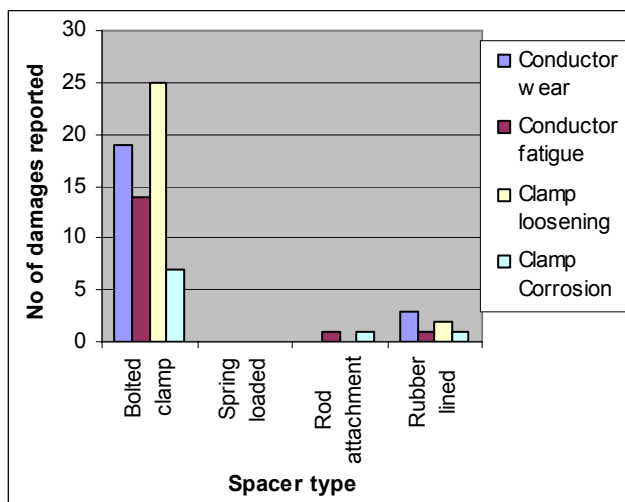


Figure 3.A.17: Type of damage as a function of type of clamp

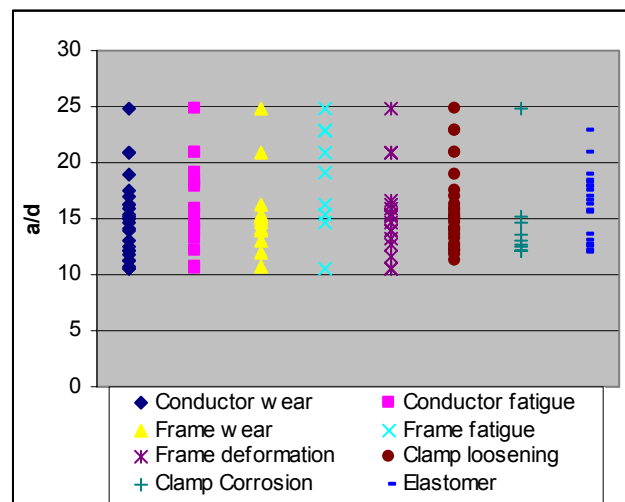


Figure 3.A.20: Type of damage as a function of subconductor spacing over conductor diameter (a/d)

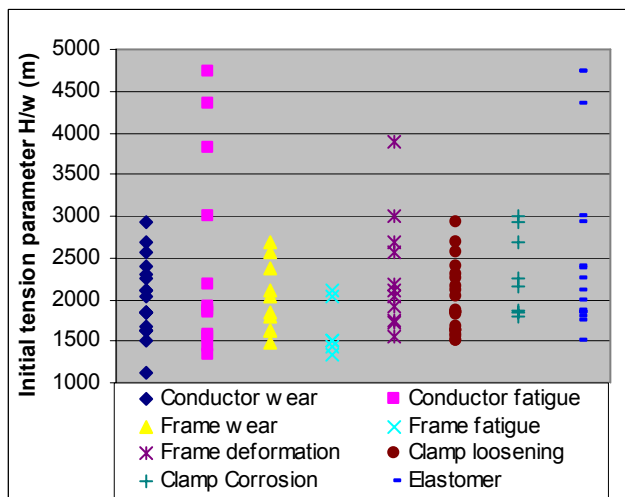


Figure 3.A.18: Type of damage as a function of initial tension

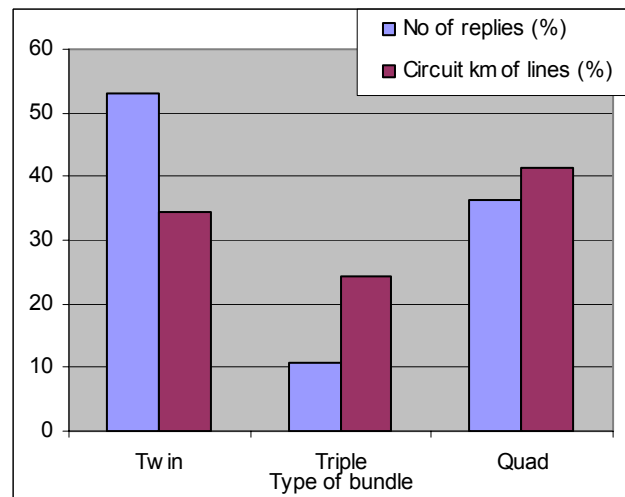


Figure 3.A.21: Replies distribution in term of bundle type

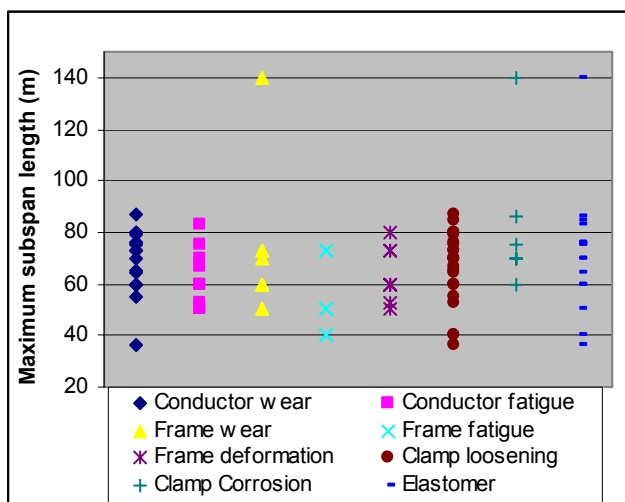


Figure 3.A.19: Type of damage as a function of maximum subspan length

ANNEX 3.B. QUESTIONNAIRE

The next nine pages of this annex contains the questionnaire entitled 'Survey on Damage to Spacer and Spacer Dampers and/or Conductors in Bundled Conductor Lines', prepared by B2 (22)-WG11,-Task Force 05 in order to obtain feedback from utilities for the preparation of the 'State of the art survey on spacers and spacer dampers: Part 3 – Experience with current practice'. This questionnaire was circulated to the national members of CIGRÉ SC22 for distribution to utilities within their regions in 1999. To improve the participation, some questionnaires were also sent by other members selected for their technical implications in the subject under study.

QUESTIONNAIRE FOR SURVEY ON DAMAGE TO SPACER AND SPACER DAMPERS AND/OR CONDUCTORS IN BUNDLED CONDUCTOR LINES

SCOPE:

Survey on damage to spacer and spacer dampers and/or conductors on bundled conductor lines.

The primary interest is in those lines exhibiting signs of damage and failures but information regarding lines which have been in operation without any reported problems are also of great interest as this will provide us with most useful information in our task to set up design recommendation for the future.

If you have experience from lines with different type of materials', please be kind to duplicate this form and complete those separately.

NAME OF COMPANY

.....
.....

ADDRESS

.....
.....
.....

TELEPHONE, FACSIMILE NUMBER AND E-MAIL ADDRESS

Telephone:
Facsimile:
E-mail:

NAME AND TITLE OF CORRESPONDENT

.....
.....

SECTION 1

1 TRANSMISSION LINE

1.1 Description

Voltage (AC or DC)

[kV]

Approximately length

Unit

Time in operation

[Year]

Any historical information, please attach

Time to the first damage report

[Year]

1.2 Conductor

Type (e.g. ACSR, AAAC, etc)

Area (Aluminium/Steel)

Unit

Diameter (OD/Core)

Unit

Stranding (Aluminium/Steel)

[Nos.]

Rated tensile strength

Unit

Mass per unit length

Unit

Special conductor, please provide details

1.3 Sub-conductors

Numbers of sub-conductors

Sub-conductor spacing

Unit

Sub-conductor configuration, please provide a dimensional sketch of the configuration

1.4 Device to maintain sub-conductor spacing. Details see Section 2.

Yes

No

1.5 Device to control wind induced vibrations. Details see Section 3.

Yes

No

1.6 Span length

Ruling

Unit

Maximum

Unit

Minimum

Unit

SECTION 1 (CONTINUATION)

1.7 Design practice

Initial design tension of rated tensile strength (RTS)		Unit	
Final design tension of RTS		Unit	
Design temperature		Unit	
Design tension of RTS at average temperature at the coldest month of the year		Unit	
Maximum design ice load		Unit	
Design wind speed		Unit	
Are all sub-conductors tensioned to the same value			[yes/no]
If no, please describe your practice			

1.8 If known, please describe weather conditions at time of failure or general prevailing conditions

Wind speed		Unit	
Direction of prevailing wind with respect to the line			[deg]
Amount of ice if present		Unit	
Other, please describe			

1.9 Line conditions

Terrain

1.9.1

Open sea; large stretches of open water	
Rural areas; open country with few low obstacles	
Low-density built-up areas; small town; suburbs; open woodland with small trees	
Town and city centres with high density of buildings; broken country with tall trees	

1.9.2 Presence of pollution

Industrial	
Agricultural	
Other, please describe	

SECTION 2

2 DEVICE TO MAINTAIN SUB-CONDUCTOR SPACING

2.1 Type of spacer/spacer damper, (See Annex A)

Spacer damper

Flexible

Articulated

Rigid

Other, please provide a sketch

2.2 Type of conductor clamp, (See Annex B)

Metallic, bolted

Metallic, coil spring loaded

Rod attachment

Rubber lined

Other, please provide a sketch

2.3 Material of

Clamp

Bolt

2.4 Type of damping mechanism employed in the spacer damper

Elastomer

Friction

Single articulated arm

Double articulated arm

Other, please indicate type

SECTION 3

3 VIBRATION DAMPER

3.1 Type of vibration damper if used in combination with spacers or spacer dampers

Stockbridge

Bretelle

Festoon

Impact

Other, please provide sketch

3.2 Numbers of vibration dampers per span

Please indicate the numbers

--

3.3 Location of vibration damper

One at end of the span

Both ends of the span

Further locations, please provide sketch

SECTION 4

4 SPACING SYSTEM

4.1 Describe the spacing system used to locate the spacers/spacer dampers

Equal spacing

Unequal spacing

Maximum subspan length

Representative end-subspan length

Other, please describe the system used

Unit

Unit

SECTION 5

5 SERVICE EXPERIENCE WITH BUNDLE CONDUCTOR LINES

From the following examples please indicate the problems you have experienced

5.1 Conductor damage

5.1.1 *At the clamp*

Complete failure

Wear

Fatigue

Other, please indicate

5.1.2 *In midspan*

Indicate location

Other, please indicate

5.2 Spacer frame damage

Deformation

Crack

Fatigue

Wear

Other, please indicate

5.3 Spacer clamp damage

Corrosion

Clamp loosening

Helical rod failure

Elastomer deterioration

Bellville/Spring washer

Other, please indicate

5.4 Spacer articulation damage

Elastomer element

Flexible spacer element, (See Annex A.2)

Pin joint (See Annex A.3)

Other, please indicate

SECTION 5 (CONTINUATION)

5.5 Any other bad service experience

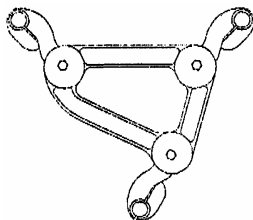
5.6 What do you think caused the problem

ANNEX A TYPE OF SPACER

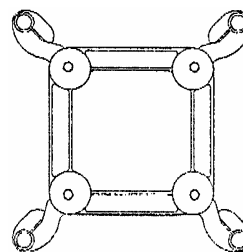
A.1 SPACER DAMPERS



A.1a - Twin bundle



A.1b - Triple bundle

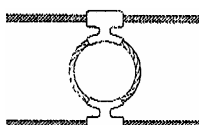


A.1c - Quad bundle

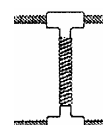
A.2 FLEXIBLE SPACERS



A.2a - Hairpin spacer



A.2b - Ring spacer

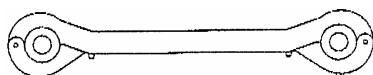


A.2c - Spring spacer

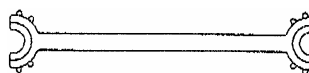
A.3 ARTICULATED SPACER



A.4 RIGID SPACERS WITH ELASTOMERIC LINED CLAMP



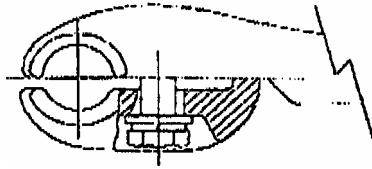
A.4a - Clamp Type



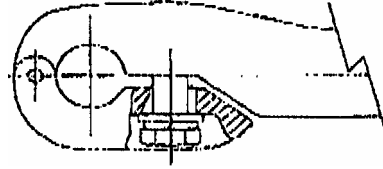
A.4b - Rod attachment Type

ANNEX B TYPE OF CLAMP

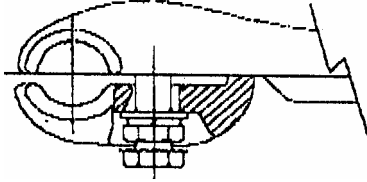
B.1 METALLIC CLAMPS, BOLTED



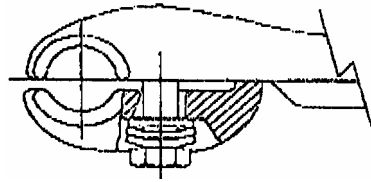
B.1a - Cantilever bolted type



B.1b - Hinged bolt type

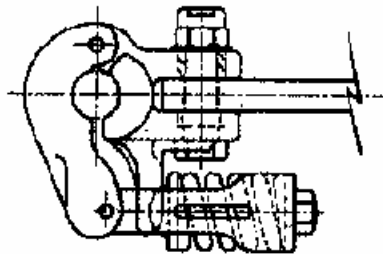


B.1c - Break-away head bolt

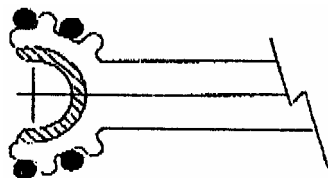


B.1d - Belleville washers

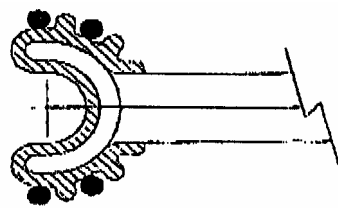
B.2 METALLIC CLAMPS, COIL SPRING LOADED



B.3 ROD ATTACHMENT

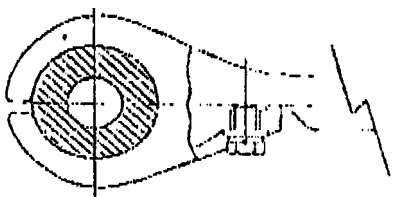


B.3a - Rubber lined type

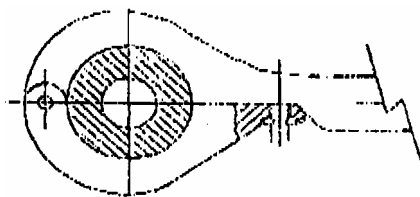


B.3b - Rubber covered type

B.4 RUBBER LINED



B.4a - Cantilever bolted type



B.4b - Hinged latching type

ANNEX 3.C. MINI-QUESTIONNAIRE

This annex contains the mini-questionnaire issued after the questionnaire provided in annex 3.B in order to evaluate the relative importance of the lines with problems with respect to the total transmission system.

1 Please provide the length of bundle lines in your system

Twin bundle		[km]
Triple bundle		[km]
Quad bundle		[km]
Others, please specify		[km]

2 Approximately how many kilometres of your bundle lines of the same configuration experienced the damage reported?

	Twin	Triple	Quad	Other
1 - 5 km				
5 – 10 km				
10 – 50 km				
50 – 100 km				
> 100 km, please specify				

3 On the line(s), which experienced damage at spacers, approximately what proportions of spacers were involved? Please reply for each line and give a numerical value of total numbers of spacers involved in the damage as indicated in the following boxes.

	Number of damage spacers			
	Twin	Triple	Quad	Other
< 0,1 %				
0,1 – 0,5 %				
0,5 – 1 %				
1 – 5 %				
> 5 %				

4 Please comment on the relative importance of damage at spacers to your company.

Not important	
Fairly important	
Of medium importance	
High importance	
Very high importance	

ANNEX 3.D. SUMMARIZED REPLIES

The following pages summarize through different graphs the information received from the questionnaire and the mini-questionnaire provided in annexes 3.B. and 3.C. respectively.

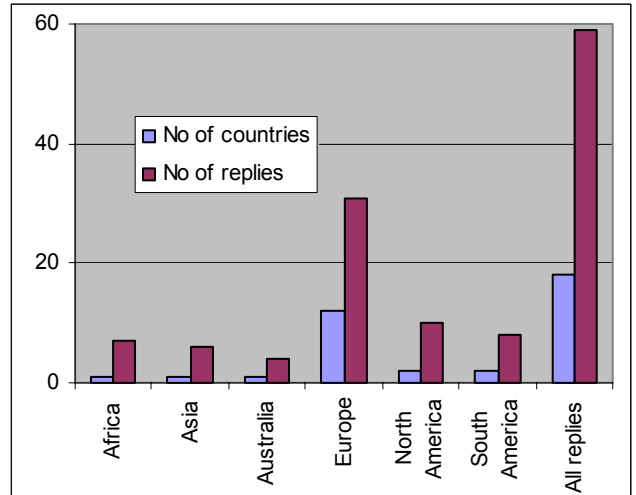


Figure 3.D.1: No of replies and countries represented

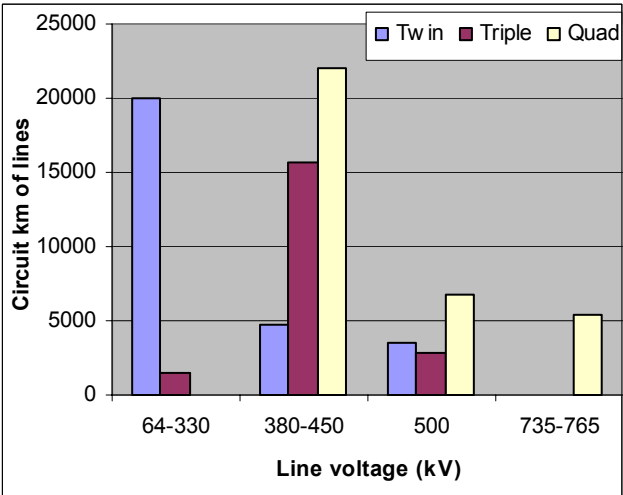


Figure 3.D.3: Line voltage

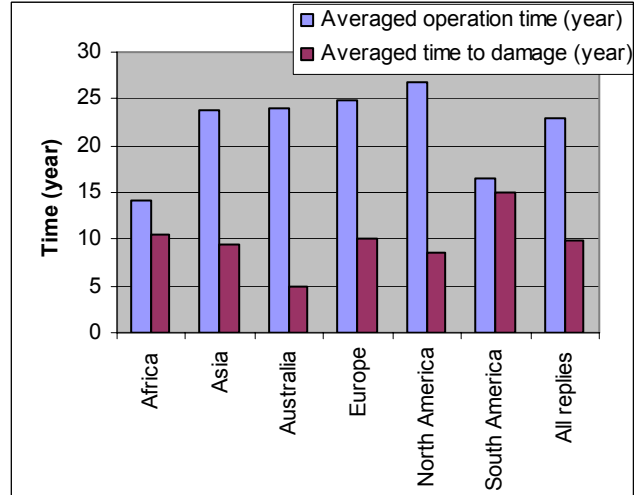


Figure 3.D.2: Averaged operation time of the lines

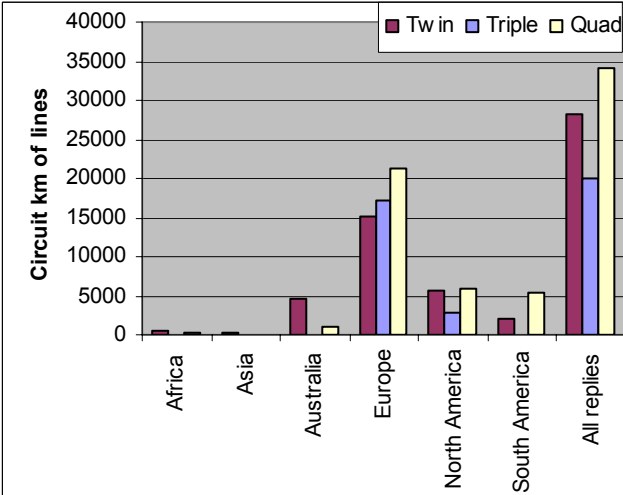


Figure 3.D.4: Total circuit km of lines from replies

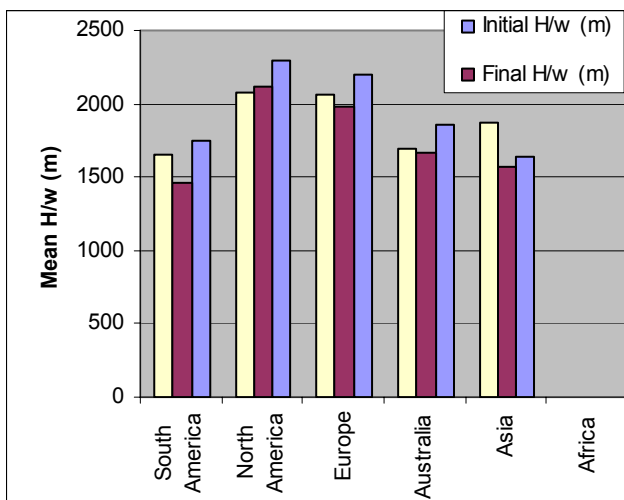


Figure 3.D.5: Averaged design tension parameter

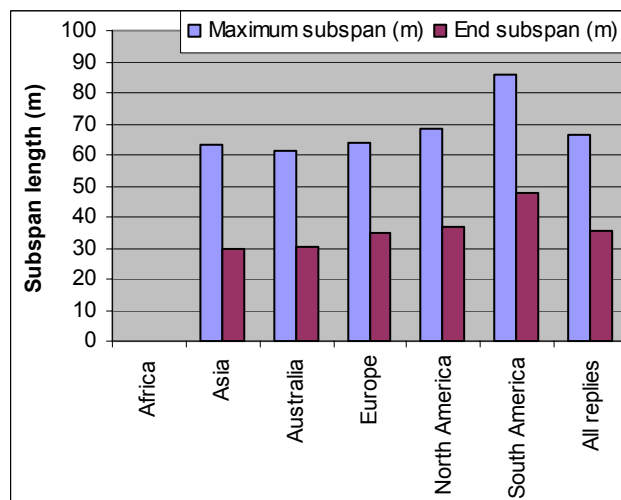


Figure 3.D.8: Averaged subspan lengths per continent

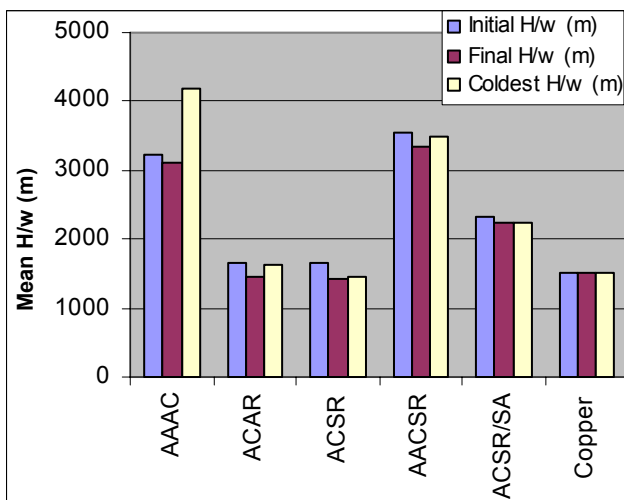


Figure 3.D.6: Averaged design tension parameter as a function of conductor type

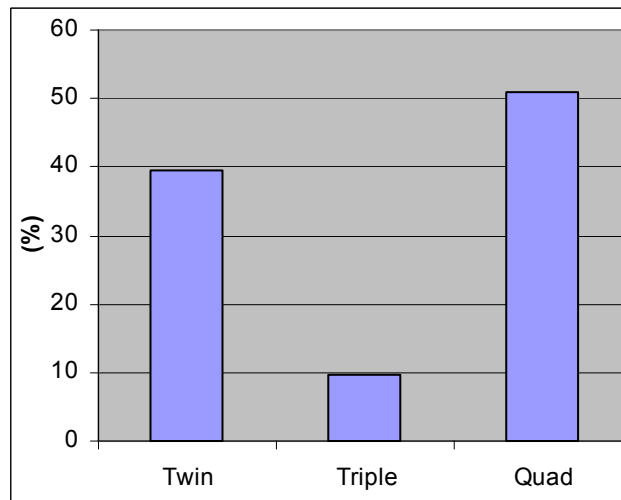


Figure 3.D.9: Percentage of circuit km of lines with problems

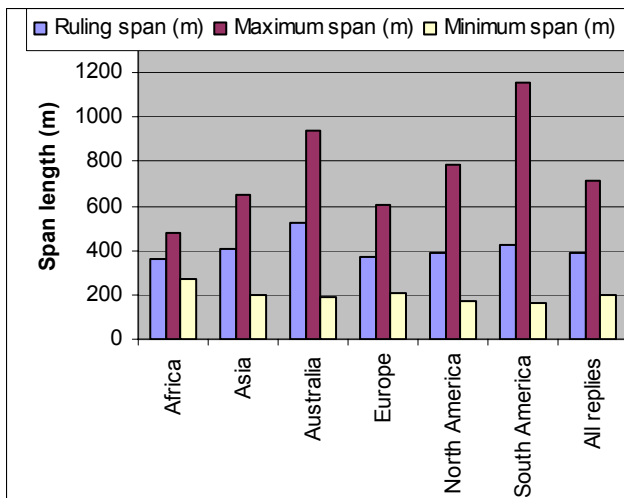


Figure 3.D.7: Averaged span lengths per continent

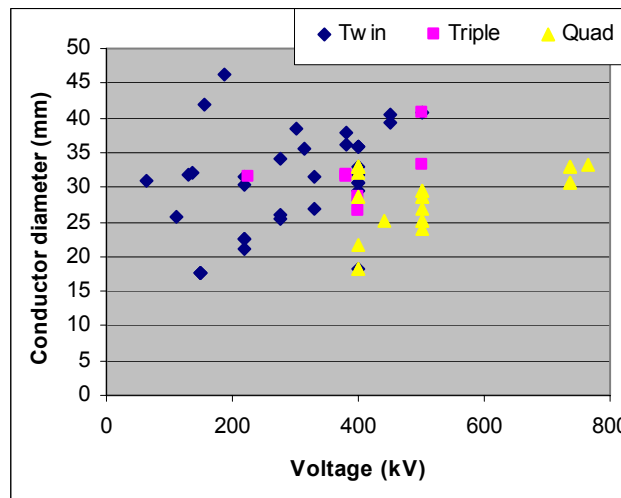


Figure 3.D.10: Conductor diameter

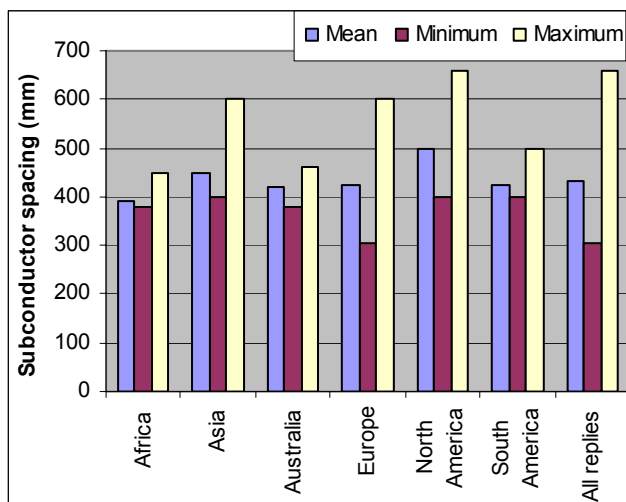


Figure 3.D.11: Subconductor spacing

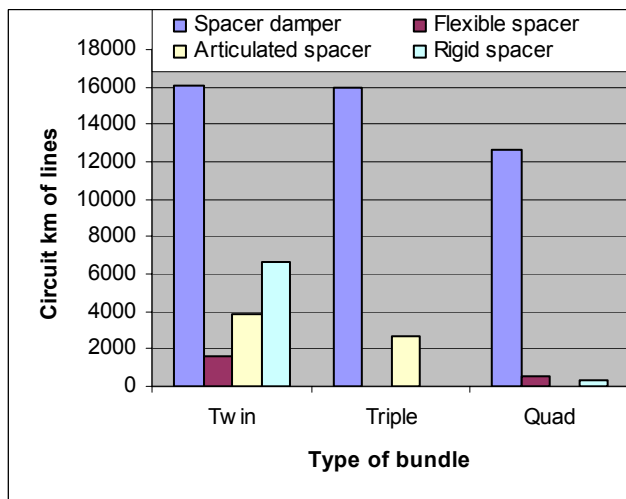


Figure 3.D.12: Spacer type

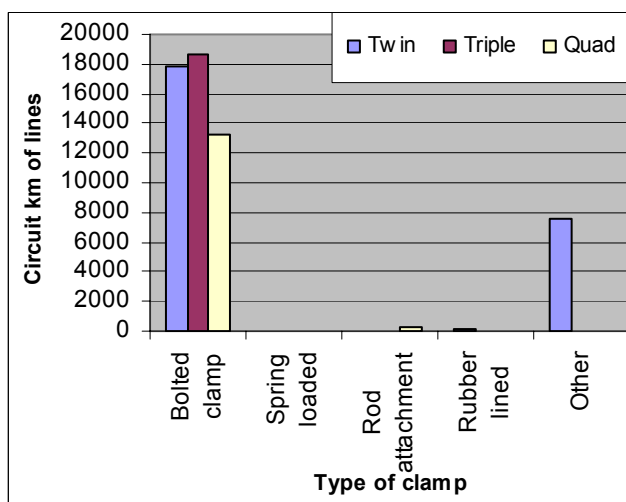


Figure 3.D.13: Clamp type

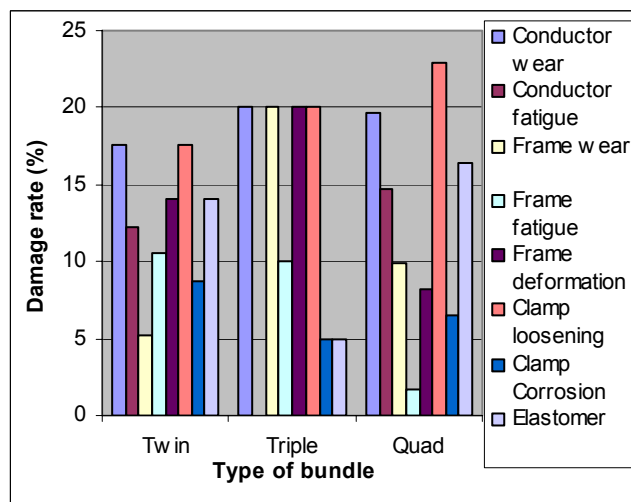


Figure 3.D.14: Type of damage as a function of type of bundle

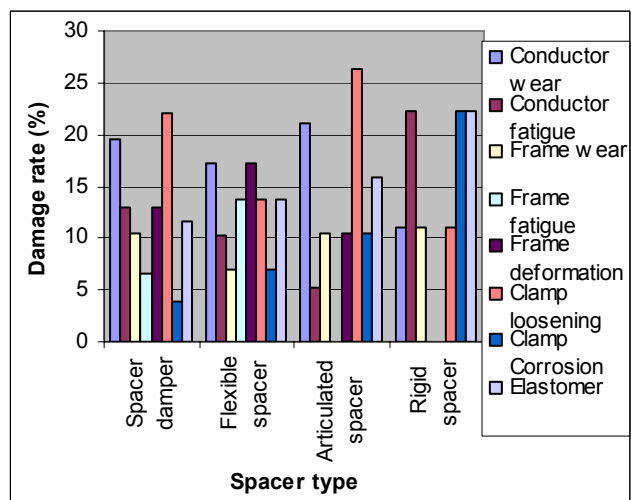


Figure 3.D.15: Type of damage as a function of type of spacer

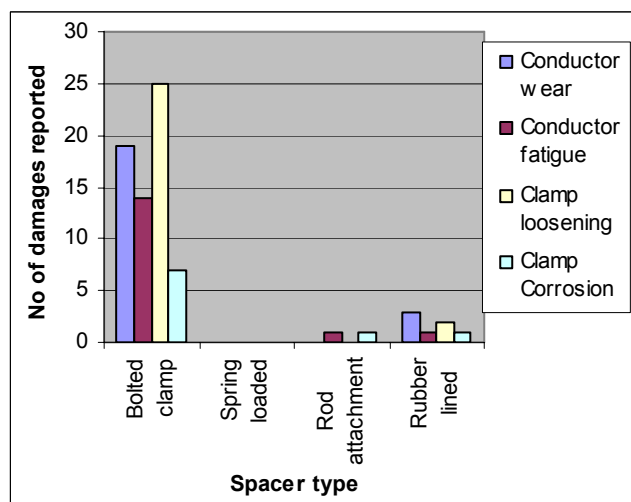


Figure 3.D.16: Type of damage as a function of type of clamp

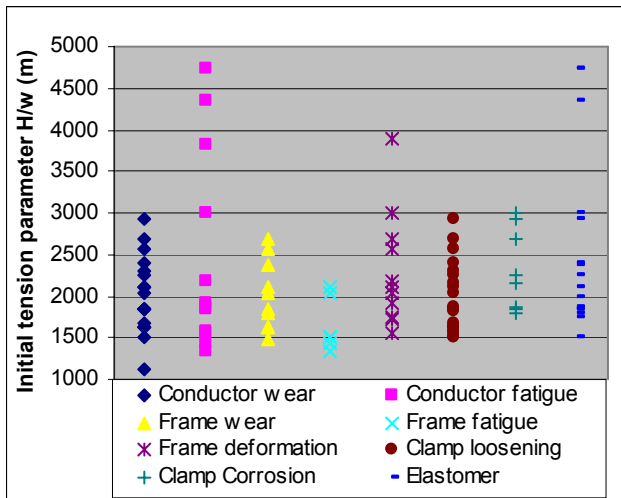


Figure 3.D.17: Type of damage as a function of initial tension

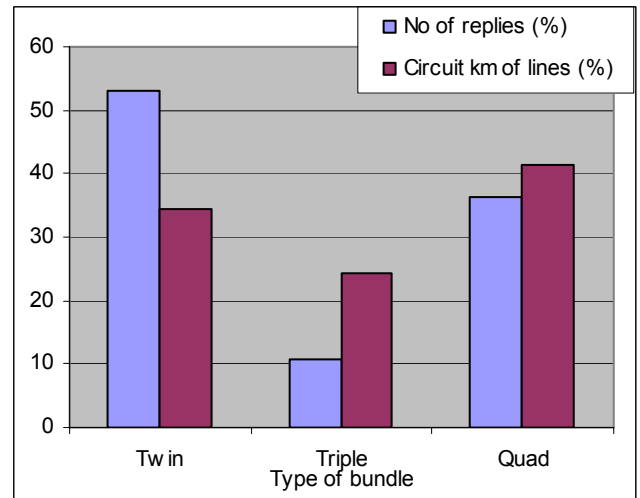


Figure 3.D.20: Replies distribution in term of bundle type

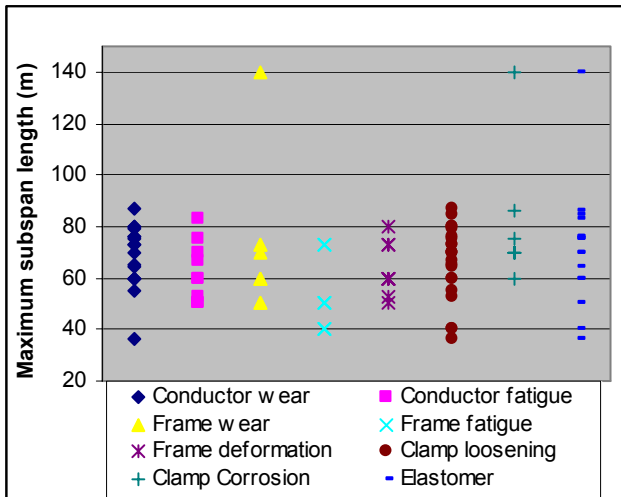


Figure 3.D.18: Type of damage as a function of maximum subspan length

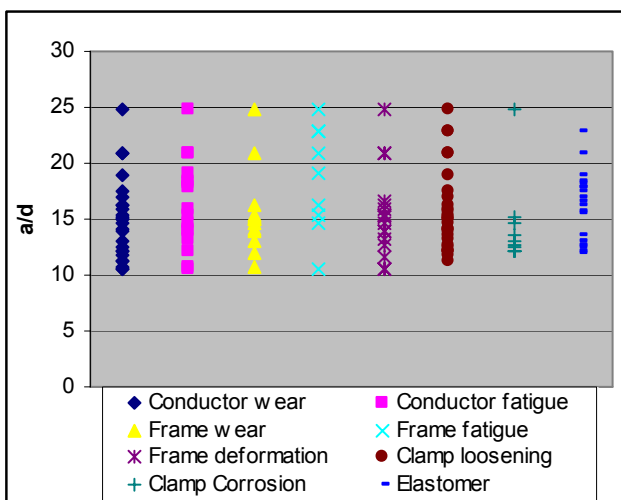


Figure 3.D.19: Type of damage as a function of subconductor spacing over conductor diameter (a/d)