

TECHNICAL REPORT



INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE

**Radio interference characteristics of overhead power lines and high-voltage equipment –
Part 3: Code of practice for minimizing the generation of radio noise**

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IEC TR 18-3:2017

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INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE

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Part 3: Code of practice for minimizing the generation of radio noise**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION
INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE

**RADIO INTERFERENCE CHARACTERISTICS
OF OVERHEAD POWER LINES
AND HIGH-VOLTAGE EQUIPMENT –**

**Part 3: Code of practice for minimizing
the generation of radio noise**

FOREWORD

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CISPR 18-3, which is a technical report, has been prepared by CISPR subcommittee B: Interference relating to industrial, scientific and medical radio-frequency apparatus, to other (heavy) industrial equipment, to overhead power lines, to high voltage equipment and to electric traction.

This third edition cancels and replaces the second edition published in 2010. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) localisation system of spark discharges which might contain frequency components up to 3 GHz;
- b) information regarding equations for predetermination of the radio noise level from HVDC overhead power lines.

The text of this technical report is based on the following documents:

DTR	Report on voting
CIS/B/655/DTR	CIS/B/676/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the CISPR 18 series can be found under the general title *Radio interference characteristics of overhead power lines and high-voltage equipment*, on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued later on.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This Technical Report is the third of a three-part series dealing with radio noise generated by electrical power transmission and distribution facilities (overhead lines and substations). It contains recommendations for minimizing the generation of radio noise emanating from high-voltage (HV) power systems which include, but are not restricted to, HVAC or HVDC overhead power lines, HVAC substations and HVDC converter stations, hardware, etc., in order to promoting protection of radio reception.

The recommendations given in this Part 3 of the CISPR 18 series are intended to be a useful aid to engineers involved in design, erection and maintenance of overhead lines and HV stations and also to anyone concerned with checking the radio noise performance of a line to ensure satisfactory protection of radio reception. Information on the physical phenomena involved in the generation of electromagnetic noise fields is found in CISPR TR 18-1. It also includes the main properties of such fields and their numerical values. CISPR TR 18-2 contains recommendations for methods of measurement for use on-site or in a laboratory. It furthermore recommends procedures for determination of limits for the radio noise from HV power systems.

The second editions of CISPR 18-1, -2, -3 underwent thorough edition in the maintenance work. The purpose of the maintenance work was to review for update in the measurement conditions, terminology, and the lateral profiles of radio noise, etc. Other updates belonged to the description of HVDC systems and to the upper edge measurement frequency.

The review for this third edition of CISPR 18-3 focused on the following issues:

- a) description on gap noise locating system involved in the expansion of upper measuring frequency from 300 MHz to 3 GHz;
- b) collation of predetermination formulae of radio noise level for DC power lines involved in update on DC description.

The CISPR 18 series does not deal with biological effects on living matter or any issues related to exposure to electromagnetic fields.

Considering

- a) that the radiation of electromagnetic energy from overhead power lines causes interference,
- b) that the level of this noise may be reduced by the design and lay-out of a line,
- c) that when defects cause unusually high levels of interference there is need to detect and locate these faults,

this document recommends as CODE OF PRACTICE for minimizing the generation of radio noise that the latest edition of CISPR Publication 18-3, including amendments, be used as guide for minimizing the generation of such noise caused by overhead power lines.

CISPR TR 18-1 describes the main properties of the physical phenomena involved in the production of 123 disturbing electromagnetic fields by overhead lines and provides numerical values of such fields.

In CISPR TR 18-2 methods of measurement and procedures for determining limits of such radio 125 interference are recommended.

This CISPR TR 18-3 forms a "Code of Practice" to reduce to a minimum the production of radio noise by power lines and equipment.

NOTE The recommendation above is based on CISPR RECOMMENDATION No. 57.

RADIO INTERFERENCE CHARACTERISTICS OF OVERHEAD POWER LINES AND HIGH-VOLTAGE EQUIPMENT –

Part 3: Code of practice for minimizing the generation of radio noise

1 Scope

This part of CISPR 18, which is a technical report, applies to radio noise from overhead power lines and high-voltage equipment which may cause interference to radio reception, excluding the fields from power line carrier signals.

The frequency range covered is 0,15 MHz to 3 GHz.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-161, *International Electrotechnical Vocabulary (IEV) – Chapter 161: Electromagnetic compatibility*

CISPR TR 18-1:___¹, *Radio interference characteristics of overhead power lines and high-voltage equipment – Part 1: Description of phenomena*

CISPR TR 18-2:___², *Radio interference characteristics of overhead power lines and high-voltage equipment – Part 2: Methods of measurement and procedure for determining limits*

ISO IEC Guide 99, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*

NOTE Informative references are listed in the Bibliography.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-161 and the ISO IEC Guide 99 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

¹ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

² Under preparation. Stage at the time of publication: CISPR/RPUB 18-2:2017.

4 Practical design of overhead power lines and associated equipment in order to control interference to radio broadcast sound and television reception

4.1 Overview

This clause provides guidance on the techniques that may be applied during the design, construction and operation of high voltage overhead power lines and associated equipment in order to keep the various types of radio noise described in this document within acceptable levels.

4.2 Corona on conductors

During line design, consideration should be given to the geometric parameters of the line, in order to ensure that radio noise due to conductor corona will not exceed a specified acceptable level. The most important parameters are conductor diameter and number of conductors per phase. Other parameters that could be varied, such as distance between phases, height of conductors above ground or spacing of sub-conductors in the bundle, have a smaller effect. In practice, they are usually determined by mechanical or insulation requirements.

The quantitative laws that determine the level of radio noise caused by conductor corona are discussed in 4.3 of CISPR TR 18-1:³, and in Clause 7. These laws normally apply to both stranded and smooth conductors, since the surface unevenness caused by stranding does not, in general, substantially change the noise level, especially when conductors are damp or wet. The existence of scratched or broken strands or deposits of extraneous substances such as dirt or insects on the surface, on the other hand, may lead to severe localised corona discharges, due to high local voltage gradients. This may considerably increase the noise level of the line. For these reasons, it is necessary to avoid damage to the conductor surface during construction. It should be handled with great care in transportation and erection and suitable techniques should be used to avoid contact of the conductor with the ground or other objects during stringing. It is also advisable to avoid external greasing of the conductor for protection during transportation and tensioning; when the conductor is loaded, the increase in temperature, especially in hot weather, will cause this grease to run to the outside, gathering dirt and leading to areas with high local gradient and consequent radio noise. When the steel core or inside layers are greased for corrosion protection, a type of grease should be selected that will not migrate to the surface of the conductor even at the highest temperature.

4.3 Corona on metal hardware

Radio noise due to corona on metal hardware, such as suspension clamps, dead-end clamps, yokes, guard rings, horns, spacers, etc., can be controlled. Appropriate shapes and dimensions may be specified during the design stage in order to avoid points of high voltage gradient. All edges and corners should be well rounded, bolt heads should be rounded or shielded and sharp points and protrusions should be avoided. It is also important that the protective galvanized finish on hardware be smooth, particularly at points of maximum voltage gradient.

Guard devices are sometimes installed to protect an insulator string from the destructive effects of a power arc and to improve the distribution of the potential along the string. They also contribute to the reduction of the level of radio noise from the conductor clamps, since they screen sharp points or protrusions on the clamps. The type and dimensions of the guard devices should be chosen in such a way that they do not themselves produce radio noise. For example, the use of simple horns should be avoided at voltages exceeding about 150 kV, and the diameter of tubes forming guard rings should be sufficiently large to ensure that no corona occurs during rain.

³ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

Present knowledge seems to indicate, however, that it may be relatively difficult to design guard rings suitable for rainy conditions, even if they are made of multiple tubes. In which case, it may be necessary to devise special arrangements for the yoke so that the string is screened directly by the conductor bundle and is protected from power arcs by suitable devices on the sub-conductors of the bundle.

As in the case of conductors, it is important to avoid damage to the hardware during manufacture, transportation, construction and maintenance by handling them with great care at all times.

4.4 Surface discharges on insulators

4.4.1 Clean or slightly polluted insulators

The radio noise produced by these insulators under dry conditions can be controlled by:

- the use of insulators of suitable design, especially as regards their geometry and the characteristics of the material at the more critical areas, or
- the use of guard devices designed to improve the distribution of voltage on the surface of the insulator or along the insulator string.

In insulator design, the use of conducting glaze, for example, improves the distribution of the surface voltage gradient on the insulator. In the design of a guard device, a metal ring as close as possible to the insulator, or to at least the first two or three insulators at the line end of an insulator string, may considerably improve the voltage distribution on the insulator or along the insulator string and reduce radio noise. The ring, however, shall remain compatible with other requirements such as insulation withstand, protection of the insulators from power arcs, screening of the clamps, etc. (see 4.3).

The radio noise produced in damp weather, fog or rain is usually more difficult to control than the noise under dry conditions. It is, however, seldom a critical factor in line design, since the increase in noise due to water droplets on the insulators is usually less important than the corresponding increase in noise produced by the conductors.

4.4.2 Very polluted insulators

Under dry conditions, in addition to the phenomena that cause noise on a clean insulator, other phenomena of the corona type may occur due to surface unevenness created by pollution deposits, as mentioned in 6.1 of CISPR TR 18-1:___⁴. Under these conditions even careful design of the various parts of an insulator may be of little benefit. Stress control devices suitable for improving the voltage distribution on the insulator or along the insulator string, however, may considerably improve the radio noise performance.

When the polluted insulator surface is wet, radio noise is generated by sparks across the dry bands, created by the leakage currents, as discussed in 6.1 of CISPR TR 18-1:___⁵. Occasionally, this noise has very high frequency components. It may affect both sound and television reception and is difficult to control. The only practical remedy is to limit the leakage current activity on the surface of the polluted insulator. This may be achieved by:

- a) diminishing the voltage stress on the insulator – for example by using a longer surface creepage path than is necessary for electrical withstand;
- b) using special types of insulators such as those made of organic material or coated with semi-conducting glaze, or designs with a longer creepage path such as fog type units, special shapes, etc.;
- c) coating the insulators with silicone grease.

⁴ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

⁵ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

4.5 Spark and microsparks due to bad contacts, commutation effects

Remedial measures for eliminating or reducing these types of radio noise are described in Clause 5 and in 8.4 of CISPR TR 18-1:___⁶ respectively.

4.6 Defects on power lines and associated equipment in service

Even if all possible precautions have been taken during design and construction of a power line or substation to keep radio noise within acceptable limits, defects may occasionally occur during operation, resulting in intolerable noise. This may be caused by breakage of strands on the conductors, damage to clamps or insulators or accumulation of pollution on conductors and insulators. In general, these defects shall be eliminated in order that the power system may operate properly, whether or not they are sources of radio noise. In fact, the occasional noise caused by such defects may result in detection and location of potential power system faults.

These abnormal noise sources may be located by various instruments such as radio noise measuring sets, television receivers or ultrasonic and optical detectors. Location will often be easier when the noise affects television reception, since at very high frequencies longitudinal attenuation along the line is very high. When only low and medium wave frequencies are affected, location of the noise source may require the recording of the longitudinal attenuation of the radio noise field strength, combined with optical, ultrasonic or ultraviolet devices, as discussed in Clause 5.

5 Methods of prediction of the reference level of an overhead line

5.1 General

This document has been written to provide the engineer in the field with the theoretical and practical background necessary to deal with radio interference problems. Technical aspects have been dealt with in Part 1 and many of the aspects discussed are dealt with in this clause in a simplified manner to bring together the theoretical and practical issues.

The reference level of a line is the strength of the radio noise field at a reference frequency of 500 kHz and at a direct distance of 20 m from the nearest conductor of the line. Where the voltage gradient in the air at the surfaces of the conductors of a normal line is greater than about 12 kV/cm to 14 kV/cm, depending on conductor diameter, the radio noise performance of the line is determined by the performance of the conductors. The number and diameter of the conductors per phase of a proposed line are often decided by the current-carrying capacity required or by economic considerations and usually a prediction of the reference level is required for a particular weather condition. If a line is designed with the conductors at a high surface gradient, very little can be done to reduce the noise level once the line has been constructed.

Figure B.14 of CISPR TR 18-1:___⁷ gives the correction to be applied to a radio noise level relating to a measurement frequency other than 500 kHz.

Where the voltage gradient in the air at the surfaces of the conductors of a line is less than about 12 kV/cm, the radio noise level is usually determined by the insulators and hardware. In this case the radio noise performance of the line is inherently good and it is usually desirable to preserve this good quality by selecting insulators and hardware of a matching quality. Most of the methods of prediction or predetermination are concerned with the conductor noise and do not apply to lines where the conductors are at a low surface gradient. None of the methods applies to sparking sources at loose or imperfect contacts.

⁶ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

⁷ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

5.2 Correlation of data given elsewhere in this publication

This subclause contains information about the correlation of the radio noise voltage at the line and the resulting radio noise field strength at ground level at a certain lateral or direct distance slant to the respective line.

a) Methods relating to noise from conductors

Subclause 5.3 of CISPR TR 18-1:___⁸ gives a survey of methods of prediction or predetermination for AC lines, both analytical or semi-empirical and empirical or comparative.

The analytical method relies on the results of measurements carried out on a short length of sample conductor in a test cage and involves highly complex analyses. The sample conductor can be tested with any desired surface condition and the radio noise voltage measured by a circuit given in 4.5 of CISPR TR 18-2:___⁹. However, for AC lines, a reliable prediction of the reference level due to conductor corona can be calculated only from the wet test in this method since in this case the number of individual corona sources per unit length is sufficiently high to represent a statistically satisfactory sample.

The simple comparative formulae referred to in 5.3 of CISPR TR 18-1:___¹⁰ rely on the results of radio-noise field strength measurements carried out on an existing line of similar design. These formulae take into account the effects of any difference between the reference and proposed lines such as the differences in surface voltage gradient or conductor diameter. If the design of the reference and the proposed lines are similar and the operating conditions, such as air pollution, etc., are also similar, a fairly accurate prediction may be obtained of the reference level to be expected from the proposed line due to conductor corona. The effects of weather may also be determined by taking measurements on the reference line in a variety of weather conditions.

In 5.4 and Annex B of CISPR TR 18-1:___¹¹ is given a catalogue of radio noise field strength profiles resulting from conductor corona for certain designs of single circuit overhead line. The profiles are correct when the value of the voltage gradient in the air at the surfaces of the conductors of the lines are sufficiently high to produce radio noise. The values of the field strength, at a measurement frequency of 500 kHz, are given for both heavy rain and average fair weather conditions, the heavy rain conditions producing a higher field strength of between 17 dB and 25 dB. The profiles show the attenuation of the field with distance normal to the lines for distances out to 150 m.

For DC lines, reference is made to 8.2 of CISPR TR 18-1:___¹² for the calculation of the noise level.

b) Method relating to noise from insulators and/or fittings

Subclause 6.2 of CISPR TR 18-1:___¹³ gives a correlation between the radio noise voltage generated by a hardware or component of a line, when measured in accordance with the procedure given in 4.5 of CISPR TR 18-2:___¹⁴, and the level of the reference field. This correlation applies where the line has a single noise source, for example a broken insulator, or where multiple sources are distributed uniformly along the line. The method, which includes a semi-empirical formula, is particularly useful where the conductors of a proposed line are to operate at a low surface gradient and a prediction is required of the reference level to be expected from the insulators of the line. When the measurement procedure according to 4.5 of CISPR TR 18-2:___¹⁵ is carried out on insulators, then they

⁸ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

⁹ Under preparation. Stage at the time of publication: CISPR/RPUB 18-2:2017.

¹⁰ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

¹¹ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

¹² Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

¹³ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

¹⁴ Under preparation. Stage at the time of publication: CISPR/RPUB 18-2:2017.

¹⁵ Under preparation. Stage at the time of publication: CISPR/RPUB 18-2:2017.

are usually in a clean and dry condition, since this condition is normally specified. But the procedure is not restricted to measurements on clean and dry objects and specially polluted sample insulators could be tested when damp and when dry and the results inserted into the formula to predict the reference level of a proposed line.

c) Methods relating to aggregate noise from the conductors, insulators and/or hardware

Subclause 5.2 of CISPR TR 18-1:___¹⁶ gives information on the use of test lines. Where conditions relating to a new design of line are such that they cannot be related to data available from an existing line, the expected performance is sometimes studied on a relatively short test line. Such test line studies are particularly useful when a new system, for operation at a much higher voltage than hitherto, is in the planning stage. The radio noise performance of the experimental line is monitored in a range of weather and atmospheric conditions so that the performance of the proposed line can be assessed under the conditions it will experience in service. This could also include the effects of insulator pollution. Other important data, such as corona loss and acoustic noise performance, can also be obtained from the test line at the same time.

In 5.4 of CISPR TR 18-2:___¹⁷ a method is given whereby the reference level of a line may be found which will protect a given broadcast signal strength at a given distance from the line for 80 % of the time with 80 % confidence.

5.3 CIGRÉ formula

A simple direct formula has also been evolved for predicting the level of the radio noise field strength to be expected from the conductors of AC lines. The formula, which is empirically based, gives the most probable level to be expected from aged conductors in fair weather at a direct distance D_0 of 20 m from the nearest conductor at a measurement frequency of 500 kHz. The formula is derived from lines operating at voltages between 200 kV and 765 kV and at maximum voltage gradients between 12 kV/cm and 20 kV/cm. Strictly seen, the formula gives the noise from one phase conductor or bundle of a line and the effects of the other conductors may be taken into account by a summation process. However, for a number of designs of lines within these ranges, it is found that only a small error is introduced if only the conductor producing the highest noise at the measuring point of a three-phase line is considered; usually this is the nearest conductor but not necessarily so in all cases.

The formula is

$$E = 3,5 g_{\max} + 12 r - 30, \quad \text{in dB}(\mu\text{V/m})$$

where

E is the level of the radio noise field strength in dB($\mu\text{V/m}$) at a direct distance D_0 of 20 m from nearest conductor of proposed AC line;

$g_{\max}$ is the maximum gradient of the RMS voltage at the conductor surface, in kV/cm;

r is the radius of conductor or sub-conductor, in cm.

This matter is considered in more detail in Annex A.

5.4 Determination of 80 % level

The 80 % level for a line may be predicted by calculation [2, 3]¹⁸ or, if the line exists, the 80 % level may be determined with a high degree of confidence, by measurement. Methods of determining the 80 % level are as follows:

¹⁶ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

¹⁷ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

¹⁸ The figures in square brackets refer to the Bibliography.

- 1) for an existing line, the 80 % level may be determined, with a high degree of confidence, from the all-weather distribution curve obtained by measurements made over a period of one year;
- 2) if the all-weather distribution curve is not available, or in the case of a proposed line, the results of measurements made on one line of similar design in a similar climate and pollution environment could be used;
- 3) from the figures mentioned in 4.3.4 of CISPR TR 18-1:___¹⁹ it is seen that, on average, the 80 % level for a line is 10 dB greater than the 50 % level. Therefore, if the 50 % level is known, the 80 % level may be estimated;
- 4) the 80 % level may be predicted by adding 5 dB to 15 dB, depending on the climate, to the fair-weather level estimated from the simple formula given in 5.3.

5.5 Conclusions

The particular method of prediction to use in the case of a particular proposed line will depend on whether the interest is in conductor corona or noise due to insulators and/or hardware that is whether the conductors are to operate at a voltage gradient greater than about 14 kV/cm or less than about 12 kV/cm. For voltage gradients in between these values, both the conductors and the insulators may contribute to the noise level of the proposed line.

The simple comparative formula referred to in item a) of 5.2, the catalogue of radio noise field strength profiles referred to also in item a) of 5.2 and the CIGRE formula given in 5.3 are all simple to use and, provided they are used within their inherent limitations, they should give reasonably accurate indications of the reference level to be expected from the conductors of a proposed line. It should be borne in mind that owing to the variable nature of radio noise and its dependency on the effects of weather, atmospheric conditions, pollution, etc., it is often difficult to measure the reference level of a line with any high degree of accuracy and reproducibility.

The method referred to in item b) of 5.2 relating to noise from insulators and/or hardware has not, as yet, become established practice for the case of specially polluted test insulators but the method would appear to have promise for this case. If a test line, referred to in item c) of 5.2, is available, together with the time required to carry out experimental work, the likely reference level from a proposed line may be obtained with a good degree of accuracy for the particular conductor, insulators and hardware proposed.

6 Preventive and remedial measures to minimize radio noise generated by bad contacts and their detection and location

6.1 General

Radio noise generated by sparking at bad, that is loose or imperfect, contacts occurs mainly in dry weather since in wet weather the comparatively small gaps involved usually became bridged with moisture.

6.2 Preventive and remedial measures

When constructing high voltage equipment it is important

- 1) to ensure that all fixing bolts are securely tightened, and
- 2) to bond conducting elements, as far as is possible, either to earth or conductor potential.

On distribution lines, bonding adjacent metal surfaces is important but bonding to earth or conductor potential is not required for spark suppression. If bonding to one side is not possible (for example at the pin and clevis, or ball and socket, couplings of an insulator string),

¹⁹ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

the adjacent conducting elements should have good metal-to-metal contact and the whole assembly should be well insulated from other metallic parts of the equipment. It should be borne in mind that even when equipment is new, galvanized metallic parts can have a corrosion coating of zinc carbonate. When the surfaces have weathered, additional oxides and sulphides may be present and an imperfect contact may result leading to the possibility of gap-type discharges. The phenomenon may occur when suspension insulator strings have inadequate mechanical loading.

The following preventive and remedial measures have been found to be effective:

a) Conductive grease and paste

A quick and economical method is the application of conductive grease to the socket or clevis area of insulators. This is a temporary cure, however, and it is necessary to re-apply the grease at a later date. The use of a copper paste, instead of conductive grease, promises to be a more lasting remedy but care shall be taken to ensure that the grease or paste does not find its way on to an insulating surface.

Ordinary, non-conductive grease applied to freshly galvanized surfaces will inhibit corrosion.

b) Bonding brush

The application of a bonding brush, with stainless steel bristles, is a temporary cure, lasting for some three to five years, by providing metal-to-metal contact in the pin and clevis, or ball and socket, area.

c) Bonding clip

Where pin and clevis type insulators are used, bonding clips can easily be installed in the pin and clevis area. It is especially important that these be installed in the conductor clamp connection with the line end insulator. There are several types of clip suitable for insertion between ball and socket which maintain sufficient pressure to break down the oxide film.

d) Permanent bonding

The best results are likely to be obtained with a permanent flexible bond across each individual metallic link of the insulator string, together with bonds from the earth end insulator to the cross-arm and from the conductor clamp to the line end insulator. The bonds should consist of stranded stainless steel or copper cable and can either be welded or fastened by screws. The cable should have a plastic covering to prevent bird caging of broken strands.

e) Metal weights for insulator strings with inadequate mechanical loading

In order to ensure good contact between the caps and pins of adjacent insulator units, the strings should be loaded with metal weights which are well-rounded to prevent corona discharges.

f) Spring and plastic washers

If a wooden construction is used, there is some merit in using spring or plastic washers. The spring washers are capable of preventing loose hardware on poles and cross-arms due to wood shrinkage. A plastic washer of acetate or nylon also improves tightness of the nuts. Where these "shake-proof"-type nuts or plastic washers are used, care should be taken to ensure that there are no insulating gaps between metallic parts. Such a washer is generally used only between a nut and a wood pole or arm.

g) Single insulator

The use of a single insulator has the advantage of having fewer possible radio noise sources.

h) Pin-type insulators with conducting glaze

With pin-type insulators, sparking may occur on the surface where the conductor rests in the top groove and at the tie-wire or stirrups in the side groove of the insulator. This problem may be overcome by using conductive paints or metallization of the insulator surface in the area of contact. These metallizing agents are effective only if applied

together with the glaze during manufacture of the insulator. In the case of pin-type insulators, if the pin screws directly into a threaded hole in the porcelain, the porcelain threads should be treated with conductive paint. As an alternative, a threaded metal insert can be cemented into the pin-hole; although the best solution is to purchase insulators with the pin-hole glazed during manufacture.

If a PVC insulated conductor is used, there is a possibility of local discharges occurring at the supporting insulators. These discharges can be avoided by wrapping the PVC with semi-conducting tape. For an 11 kV line, the tape should extend for 600 mm on either side of the insulator.

i) Plastic fasteners and insulated staples

The use of plastic fasteners or insulated staples to secure the earth wire to a wood pole will avoid sparking between the earth wire and its fasteners, particularly if the fasteners became loose or corrosion is present.

6.3 Methods of detecting and locating bad contacts

When bad contacts are present in a power line or substation, the detection and exact location of the radio noise source(s) are more important than the measurement of the resulting field strength. Practical methods for the detection and location of these bad contacts are described below. Measurements and observations should normally be made in fair weather.

Since a high voltage power line and associated equipment is often the source of different radio frequency fields, it is necessary to trace the radio noise by starting at the disturbed receiver. The first step in the investigation is to obtain an aural and/or visual indication of the radio noise, by using a loudspeaker or headphones and an oscilloscope or television receiver.

When tracing the source(s) of radio noise due to bad contacts it is better to observe the noise at the highest frequency perceptible because of the more rapid attenuation along the line. Whilst it is preferable that the apparatus used for tracing should cover the whole radio noise frequency range, few instruments are available that cover this spectrum. Few have been designed specifically for the location of sources of radio noise and, accordingly, it may be necessary to modify commercial apparatus to make it suitable.

The following apparatus will be found useful for locating bad contacts: a) to g) are conventional instruments and h) is a modern instrument employing recent digital signal processing techniques, which can estimate the Direction of Arrival (DOA) with high directional resolution.

- a) A general coverage receiver (a.m.) tuneable from at least 500 kHz to 18 MHz.
- b) A VHF field strength measuring instrumentation fitted with a two-element broadband antenna and a VHF pre-amplifier: The audio output should be amplified sufficiently to feed a loudspeaker and an oscilloscope.
- c) An oscilloscope with sufficient intensity for use in full daylight, when used with a viewing hood, and a sweep frequency of approximately 500 Hz.
- d) An UHF field strength measuring instrumentation fitted with two interchangeable Yagi antennas (one array for 500 MHz and the other for 800 MHz): A moderate level audio output is required for a loudspeaker. RF pre-amplification is required and IF gain control is desirable. The whole assembly should be able to be carried by one man.
- e) A small radio frequency detector covering the frequency range MF to VHF but without automatic gain control.
- f) A small a.m. broadcast radio receiver without manual or automatic gain control and enclosed in a metal box: The receiver antenna can either be telescopic, to allow for variation in RF sensitivity, that is to adjust the RF gain, or, preferably, a ferrite rod mounted inside the metal box opposite a slot of similar length in the box side. The box is mounted at one end of an insulating tube, a few metres in length and having a diameter of approximately 3 cm to 6 cm. The output of the receiver loudspeaker is directed into the bore of the tube while, at the other end, a microphone is arranged to pick up the noise signal. The microphone output is then fed into an amplifier feeding the headphones or a

loudspeaker. This arrangement allows the receiver to be placed near to the source of the disturbance and, with care, can be used even when the radio noise is generated by high voltage equipment.

- g) The insulating properties of the tube and its length shall be such as to ensure observance of the safety rules appropriate to the system voltage.
- h) A sensitive ultrasonic detector with a parabolic reflector: In situations where the noise sources are numerous and are close together, for example in a substation, this can be a particularly useful instrument, but its use is restricted to fair weather conditions. It should be borne in mind that this instrument is also sensitive to corona sources.
- i) Radio-frequency (RF)-based DOA estimation system with high directional resolution (see Annex B): The system with an antenna array, e.g. consisting of four dipole antennas, a high-speed oscilloscope, and a computing device, e.g. a personal computer, in which a DOA estimation program based on digital signal processing techniques is installed, is available to locate the radio noise source due to bad contact, which can emit pulsed electromagnetic waves composed of wide spread frequency components, with high directional resolution [17, 18, 19].

A suggested procedure for locating a radio noise source or sources generated by bad contacts is as follows:

- i) Using the investigation apparatus, obtain an aural and/or visual identification of the noise signal at the disturbed receiver. Determine the frequency range of the noise by scanning the relevant part of the RF spectrum.
- ii) If broadband noise appears, use the highest possible frequency for tracking. If it is found, when moving along a power line, that the noise can be detected at progressively higher and higher frequencies, then the source is being approached. In the immediate vicinity of the source, the noise signal should be detected throughout most of the broadcast frequency bands. When the higher frequencies start dropping off, the source has been passed. Along the power line nulls may occur, at certain positions and at certain frequencies, due to standing wave patterns. For wood pole lines, a sledge hammer can be useful. If the base of the pole is struck with the hammer, noise due to bad contacts on that particular pole may either increase drastically or disappear temporarily. This assists in localizing the wood pole associated with the noise source.

A further method for locating bad contacts, particularly in a substation where several joints can be involved, is to direct a very fine water jet at each suspect metal joint in turn. To provide a high degree of insulation, a small volume of water, in a plastic container, is mounted at the end of a long rod or pole of insulating material. Two pipes enter the container, one which terminates in a nozzle to provide the fine water jet and the other which carries compressed air, via a valve, from the ground. The operator on the ground controls the water jet by means of the compressed air. After having located a bad contact, a similar device is often used to inject grease, of suitable consistency, into the defective joint.

- iii) If narrow band noise is detected, triangulation will best identify the source. Even here, however, at the source's location, the sparking noise will be detected over a broad range to 100 MHz. Narrow band noise may result from gap-type discharge causing resonance in a fitting or component.
- iv) If more than one noise signal exists, it may be necessary to use the oscilloscope to distinguish the sources. To determine if a noise source is due to bad contacts (sparking) or corona, the following information may be helpful:
 - a) oscilloscope or television pictures usually give clear indication;
 - b) noise above 30 MHz in fair weather is due to sparking;
 - c) if the noise occurs only in fair weather, it is probably due to sparking;
 - d) noise due to sparking predominates over corona noise on lines below about 70 kV.
- v) If the investigation indicated that the source is in a substation, a radio frequency detector, as described in item e) or a small a.m. portable radio receiver, without automatic gain control, should be used. The receiver should be placed near to the control wiring and

earth connection of each item of plant, in turn, so that the wiring may act as an antenna for the noise source.

- vi) In the case of a power line, when the tower involved has been identified, the measuring instrumentation described in item d) should be used to obtain further bearings. The tower should be scanned using both horizontal and vertical polarization of the antenna to determine whether or not the structure contains a source. If no noise field is detected, a further check should be made by tuning some 10 MHz above and below the measurement frequency (a null may occur at a particular frequency).
- vii) The last step to pinpoint the source should be carried out with the apparatus described in item f). It may be helpful to scan the insulators, either on the towers or in the substation, to prove that they are noise-free.
- viii) Low-level acoustic noise is often associated with sparking and gap-type discharges and the very narrow beam width of a sensitive ultrasonic detector, fitted with a parabolic reflector, will often be found useful in locating the source.
- ix) RF-based DOA estimation system, which can locate the position of the discharge existing within about 30 m from the system with high accuracy (elevation angles: error may be around 2°, azimuth angle: error may be around 3°), is available for temporally use or continual verification. In case of the continual verification, it can be a detector of deteriorated facility or associated equipment and parts.

In the case of temporal usage, the procedure to locate the radio noise source due to spark discharges are as follows;

- a) Using the investigation apparatus, obtain an aural and/or visual identification of the noise signal at the disturbed receiver. Determine the frequency range of the noise by scanning the relevant part of the RF spectrum;
- b) If broadband noise appears, use the highest possible frequency for tracking. Set up RF-based DOA estimation system where broadband noise is observed and locate the radio noise source;
- c) If narrow band noise is detected, at the source's location, the frequency spectra of the sparking noise will spread over a broad range to 100 MHz.

7 Formulae for predetermination of the radio noise field strength produced by large conductor bundles (more than four sub-conductors) and by tubular conductors

7.1 Basic principles

Subclause 5.3 reports a simple formula for the prediction of the radio noise field strength to be expected from the conductors of a line. The formula, which is empirically based, gives the most probable level to be expected from aged conductors in fair weather at a direct distance of 20 m from the nearest conductor at a measurement frequency of 500 kHz. The formula is derived from measurements performed near to lines operating at voltages between 200 kV and 765 kV and at maximum voltage gradients between 12 kV/cm and 20 kV/cm. The measurements were performed on lines with single conductors and conductor bundles up to four sub-conductors.

Methods of predetermination of the radio noise field strength produced by large bundles were developed in the frame of the projects of overhead lines at voltages equal to or higher than 1 000 kV, on the base of measurements on experimental spans or cages. They are based on the so called excitation function approach.

The excitation function approach is based on the fact that the corona currents injected into a multiphase line depend not only on the intrinsic characteristics of the conductor under corona (its gradient, sub-conductor diameter, etc.) but also on the self and mutual capacitance of the multi-conductor system [4]. The radio noise currents are related to the intrinsic corona characteristics of the conductor (named excitation function I') through a relationship of the type:

$$|I| = |C| \times |I'| / (2 \pi \epsilon_0)$$

where

$|I|$ and $|I'|$ are the vectors of the phase radio noise currents and excitation functions of the conductors;

$|C|$ is the capacitance matrix.

The measurements of the radio noise current in a test configuration of known capacitance (cage or experimental span) allows the determination of the excitation function.

The approach based on the use of the excitation function and analytical methods to calculate the radio noise current propagation allows the predetermination of the radio noise field strengths for line configurations different from the ones tested.

Another important advantage of this approach is that the radio noise current measurement in a cage allows the determination of the excitation function under controlled ambient conditions (artificial rain corresponding to heavy rain) and for different conductor gradients, giving thus stable and reproducible results.

The predetermination methods based on the concept of excitation function was preferred for higher system voltages (voltages equal to or higher than 1 000 kV) where corona is generally more critical and its evaluation can be more accurate. Extensive research in this field has been performed in various countries: Canada (IREQ), Korea (765 kV Project), Italy (1 000 kV Project), Japan (CRIEPI), USA (GE/EPRI-Project UHV, AEP/ASEA, BPA), USSR (1 200 kV Project). These investigations principally consider the case of large bundles and the predetermination formulae given in this document are the result of the comparison and rationalization of a wide number of experimental results.

For tubular conductors, a similar approach was followed that led to the predetermination formulae for the excitation function given in this document. The experience gained in this field is much less than with large bundles and consequently the information provided in this document should only be used as a guide.

The investigations were made with the view of possible application to overhead lines at voltages equal to or higher than 1 000 kV, but the results can be applied to the cases of rigid tubular bus bars in high voltage substations. In this case, the guided field due to the currents injected into the lines connected to the substation is of importance (see 5.7 of CISPR TR 18-2: 2017).

7.2 Calculation of corona radio noise field strengths due to large bundles

7.2.1 Procedure for the predetermination of the radio noise field strength

On the basis of results of a comparative analysis of the various methods proposed in the literature [6 to 13], the following procedure is proposed for the calculation of the radio noise field strength at a given distance from the line for lines with symmetrical bundles and aged conductors:

- calculation of the excitation function of each phase in heavy rain by means of a semi-empirical formula (see 7.2.2);
- application of a correction factor to obtain the excitation function in other weather categories (see 7.2.3);
- determination of the radio noise field strength profile by means of complete or simplified analytical methods based on modal propagation (see 7.2.4).

²⁰ Under preparation. Stage at the time of publication: CISPR/RPUB 18-2:2017.

7.2.2 Calculation of the excitation function in heavy rain

The following formula for the calculation of the excitation function, in dB($\mu\text{A}/\text{m}^{1/2}$), in heavy rain is proposed:

$$\Gamma_{\text{h-r}} = 70 - 585/g + 35 \log(d) - 10 \log(n)$$

where

g is the average of the maximum gradients of the individual sub-conductors (in kV/cm);

d is the diameter of the sub-conductor (in cm);

n is the number of the sub-conductors in the bundle.

This formula gives satisfactory results in case of lines with conductors having a ratio between the sub-conductor spacing s and the sub-conductor diameter d higher than 10 to 15. At smaller s/d ratios, the actual excitation function may prove to be much higher than calculated especially in the case of bundles made of 10 or more sub-conductors.

NOTE A comparison between the different formulae for the predetermination of the excitation function was performed by CIGRÉ WG 36.01 [6]. The formula proposed in this subclause gives the upper envelope of the values that could be obtained with the other formulae and thus gives a conservative evaluation of the excitation function. For this reason, the formula is used only for pre-design purposes and for comparison between different line designs. The design of a line with large conductor bundles would imply a more accurate evaluation of the excitation function by means of measurements on experimental spans or on corona cages.

7.2.3 Correction factor to evaluate the excitation function in other weather categories

For other weather conditions (light rain, wet conductors, fair weather), various experimenters followed different approaches: some of them give formulae similar in structure to those given for the excitation function in heavy rain, but with different coefficients; some others propose correction factors to be applied to the heavy rain levels, constant or depending on the voltage gradients, bundle configuration and surface conditions of the conductors (in particular new and aged conductors).

As a guidance, if no more precise information is available from tests, the correction factors given in Figure 1 can be applied to the heavy rain excitation function to obtain the 50 % light rain value or the 50 % fair weather value.

If the 80 % all time excitation function value, $\Gamma_{80\%}$, is required to apply the indications of limits given in CISPR TR 18-2, the knowledge of the percentage of the different weather conditions (fair weather, rain, foul weather, etc.) as well as the statistical distributions of the radio noise under each such condition is necessary. Subclause 4.3.4 of CISPR TR 18-1: ²¹ shows how the statistical distributions are related to each other. As a rough indication, $\Gamma_{80\%}$ could be obtained by subtracting 10 dB to 15 dB from the heavy rain level in temperate climates.

7.2.4 Calculation of the radio noise field strength

7.2.4.1 General

The calculation of the radio noise field strength at a given distance from a three-phase line may be performed starting from the excitation function of each phase by means of analytical methods based on modal propagation analysis. Several computer programs were developed to perform this calculation. They may take into account the discontinuities of the line (change of configuration, interconnection to a substation, etc.). A simplified analytical method applicable to long lines is indicated in Annex C.

²¹ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

To allow a rapid evaluation of the radio noise field strength profiles, instead of the analytical methods, the method given below, which gives an acceptable approximation, can be used.

7.2.4.2 Rapid evaluation of the radio noise field of an overhead line

The evaluation of the radio noise field at a given distance from the line is made by applying to the excitation function a "field correction factor" to obtain the radio noise field strengths of a line of basic design at a given frequency and for a given ground resistivity. The radio noise field for the line under examination is then evaluated by introducing other correction factors to account for the differences between the actual line and that of the basic case.

The evaluation is performed in two steps.

Step 1

The radio noise field strength profile for a line of basic characteristics and under basic conditions (ground resistivity = 100 Ω m; frequency = 0,5 MHz) is evaluated by adding to the excitation function a "field factor". Field factors for three basic phase conductor configurations (flat, triangular and delta configuration) are given in the Figures 2, 3 and 4.

Step 2

The radio noise field strength profile for the actual line under consideration is evaluated by adding to the radio noise field strength of the basic case the correction factors given in Figures 5, 6 and 7 for each of the following parameters:

- ρ ground resistivity;
- f frequency;
- h minimum height above the ground;
- S spacing between phases;
- d sub-conductor diameter;
- n number of sub-conductors in a bundle.

NOTE Consideration of the external phase only does not unduly affect this simplified approach. A constant difference between the excitation functions of the central and external phases is assumed for all configurations: this assumption is not generally verified, but does not give deviations greater than 1 dB to 2 dB. An improvement in accuracy can be by considering the average value of the excitation functions.

7.3 Evaluation of corona radio noise field strength due to large tubular conductors

A procedure analogous to that suggested for the case of large bundle conductors (see 7.2.1) can be followed: the excitation function of each phase in heavy rain is evaluated by means of a semi-empirical formula and a correction factor is then applied to obtain the excitation function in other weather categories.

The following formula for the calculation of the excitation function, in $\text{dB}(\mu\text{A}/\text{m}^{1/2})$, in heavy rain is proposed:

$$\Gamma_{h-r} = -121 + 120 \log(g) + 40 \log(d)$$

where

- g is the maximum gradient on the conductor (in kV/cm);
- d is its diameter (in cm).

As regards the corrections to be applied to obtain the excitation function in other weather categories, the following indications may be useful, until further experience is obtained.

- The excitation function in light rain can be related to the one under heavy rain by means of the correction factor indicated in Figure 8, which is relevant to tubular conductors of 40 cm diameter. For other diameters, one should expect, as for bundle conductors, the correction increases as the diameter increases.
- As large tubular conductors have low electric gradients, the excitation function has insignificant values in fair weather conditions. The 80 % all-weather value of the excitation function thus depends very much on the climatic conditions. In moderate climates, this value may be obtained from the heavy rain value by applying a correction higher than that used for large bundles. For these areas, a correction of 15 dB to 20 dB is suggested until further information is available.

As regards the surface conditions, the following complementary information is available.

Tubular conductors are prone to accumulate more contaminant than bundle conductors, the effect of which may be sufficient to alter the excitation function. Tests have shown that the excitation function will not be altered by the effect of pollutants when the conductor is wet. When dry, the presence of solid particles on the surface may increase the radio noise to a value as high as for the same conductor in rain for the highest gradients, especially for low diameter conductors.

The formula given in this subclause may be utilized both for busbars or for line conductors.

In the case of busbars, the per unit length noise current I_0 can be obtained from the excitation function Γ by means of the matrix of capacitances of the busbar system (according to the first formula of Annex C). From I_0 , the total current I_t injected by the busbar is then obtained. The noise current injected into each one of the n lines connected to the substation, I , is derived by means of the following relationship (see 5.7.3 of CISPR TR 18-2:___²²):

$$I = I_t/n$$

so that its contribution to the line conductor noise can be evaluated with the criteria indicated in 5.7.4 of CISPR TR 18-2:___²³.

²² Under preparation. Stage at the time of publication: CISPR/RPUB 18-2:2017.

²³ Under preparation. Stage at the time of publication: CISPR/RPUB 18-2:2017.

8 Figures

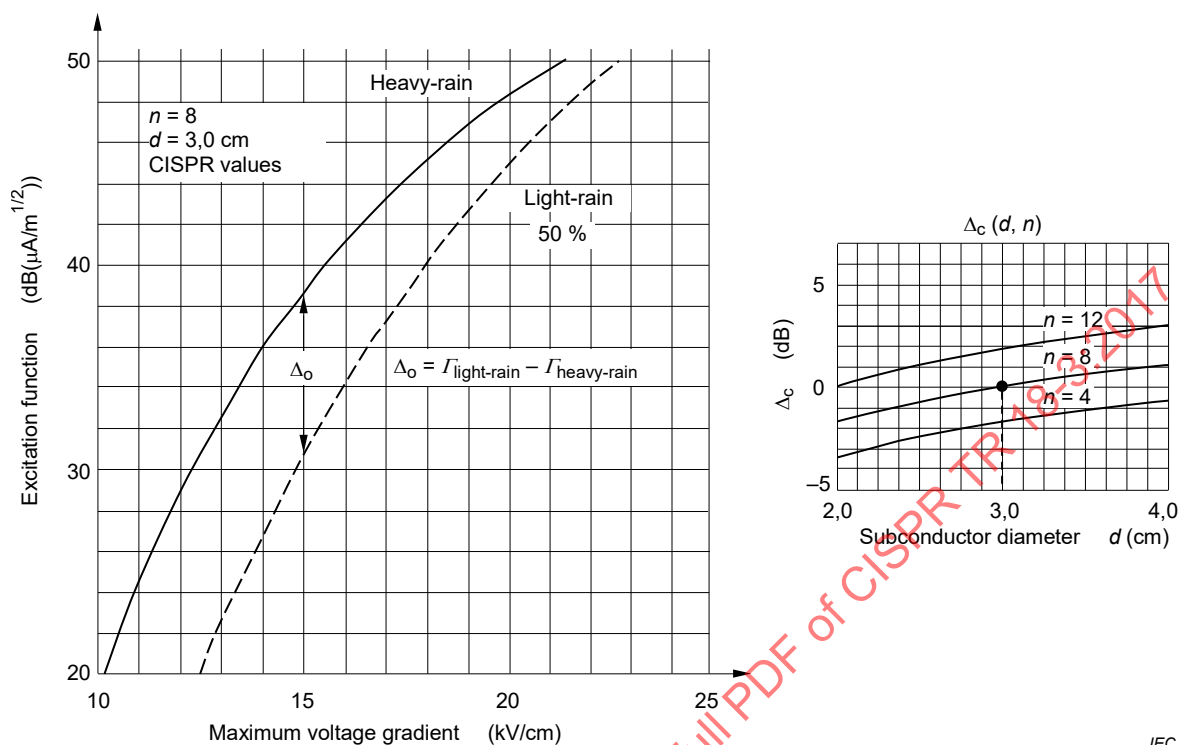


Figure 1 – Bundle conductors

Correction factors to be applied to the heavy rain excitation function to obtain the excitation function for light rain and for all-time weather conditions, as a function of the maximum gradient and number of sub-conductors:

$$I_{\text{light-rain}} = I_{\text{heavy-rain}} + \Delta_o + \Delta_c$$

The fair weather excitation function is obtained by subtracting 17 dB from the light rain excitation function.

$$I_{\text{fair-weather}} = I_{\text{light-rain}} - 17$$

In temperate climates, the 80 % value of the excitation function I for all-time weather conditions can be obtained by subtracting 10 dB to 15 dB from the heavy rain value.

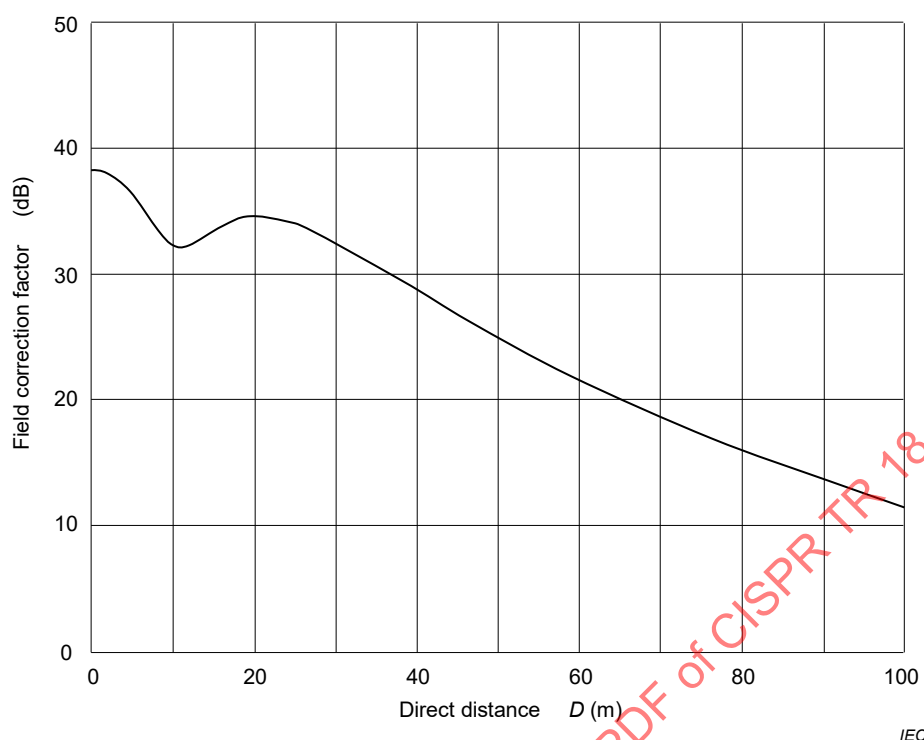


Figure 2 – Line with conductors in a flat configuration

Correction to be applied to the excitation function calculated for the central phase to obtain the radio noise field strength in dB(μ V/m) as a function of the direct distance D from the axis of a line having the following characteristics and consequent modal matrix and attenuation factors:

h = 20 m (minimum height above the ground)

S = 15 m (distance between phases)

d = 3 cm (sub-conductor diameter)

n = 8 (number of sub-conductors in a bundle)

s = 450 mm (bundle spacing)

ρ = 100 $\cdot \Omega$ m (ground resistivity)

f = 0,5 MHz (frequency)

$$|N| = \begin{vmatrix} 0,442 & 0,707 & 0,552 \\ -0,781 & 0,0 & 0,625 \\ 0,442 & -0,707 & 0,552 \end{vmatrix} \quad (\text{modal matrix})$$

$$\alpha_1 = 10 \times 10^{-6} \text{ Np/m}$$

$$\alpha_2 = 70 \times 10^{-6} \text{ Np/m} \quad (\text{modal attenuation factors})$$

$$\alpha_3 = 350 \times 10^{-6} \text{ Np/m}$$

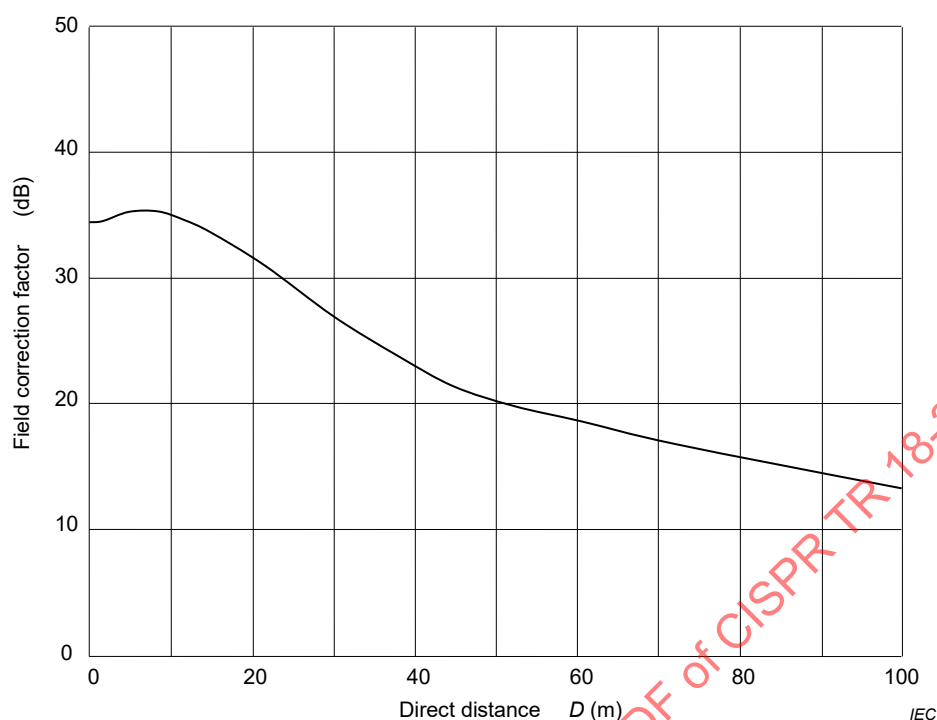


Figure 3 – Line with conductors in a delta configuration

Correction to be applied to the excitation function calculated for the central phase to obtain the radio noise field strength in dB(μ V/m) as a function of the direct distance D from the axis of a line having the following characteristics and consequent modal matrix and attenuation factors:

$h = 20$ m (minimum height above the ground of the lateral phases)

$h = 33$ m (minimum height above the ground of the central phase)

$S = 15$ m (distance between phases)

$d = 3$ cm (sub-conductor diameter)

$n = 8$ (number of sub-conductors in a bundle)

$s = 450$ mm (bundle spacing)

$\rho = 100 \Omega \cdot \text{m}$ (ground resistivity)

$f = 0,5$ MHz (frequency)

$$|N| = \begin{vmatrix} 0,412 & 0,707 & 0,574 \\ -0,812 & 0,0 & 0,583 \\ 0,412 & -0,707 & 0,574 \end{vmatrix} \quad (\text{modal matrix})$$

$$\alpha_1 = 10 \times 10^{-6} \text{ Np/m}$$

$$\alpha_2 = 25 \times 10^{-6} \text{ Np/m} \quad (\text{modal attenuation factors})$$

$$\alpha_3 = 300 \times 10^{-6} \text{ Np/m}$$

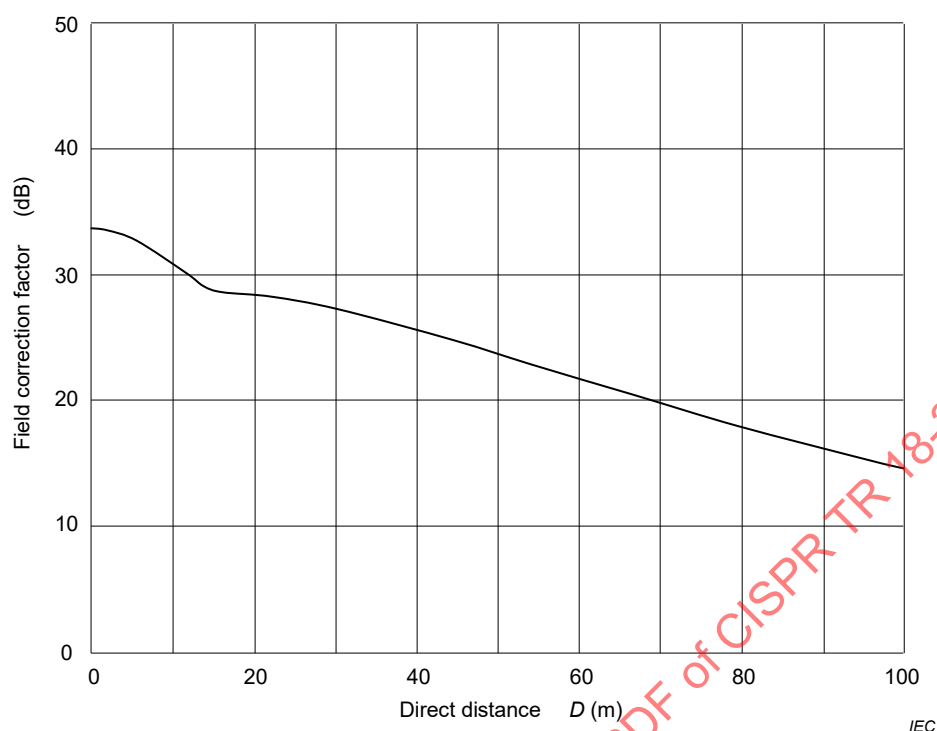


Figure 4 – Line with conductors in a triangular configuration

Correction to be applied to the excitation function calculated for the central phase to obtain the radio noise field strength in dB(μ V/m) as a function of the direct distance D from the axis of a line having the following characteristics and consequent modal matrix and attenuation factors:

$h = 33$ m (minimum height above the ground of the lateral phases)

$h = 20$ m (minimum height above the ground of the central phase)

$S = 15$ m (distance between phases)

$d = 3$ cm (sub-conductor diameter)

$n = 8$ (number of sub-conductors in a bundle)

$s = 450$ mm (bundle spacing)

$\rho = 100 \Omega \cdot \text{m}$ (ground resistivity)

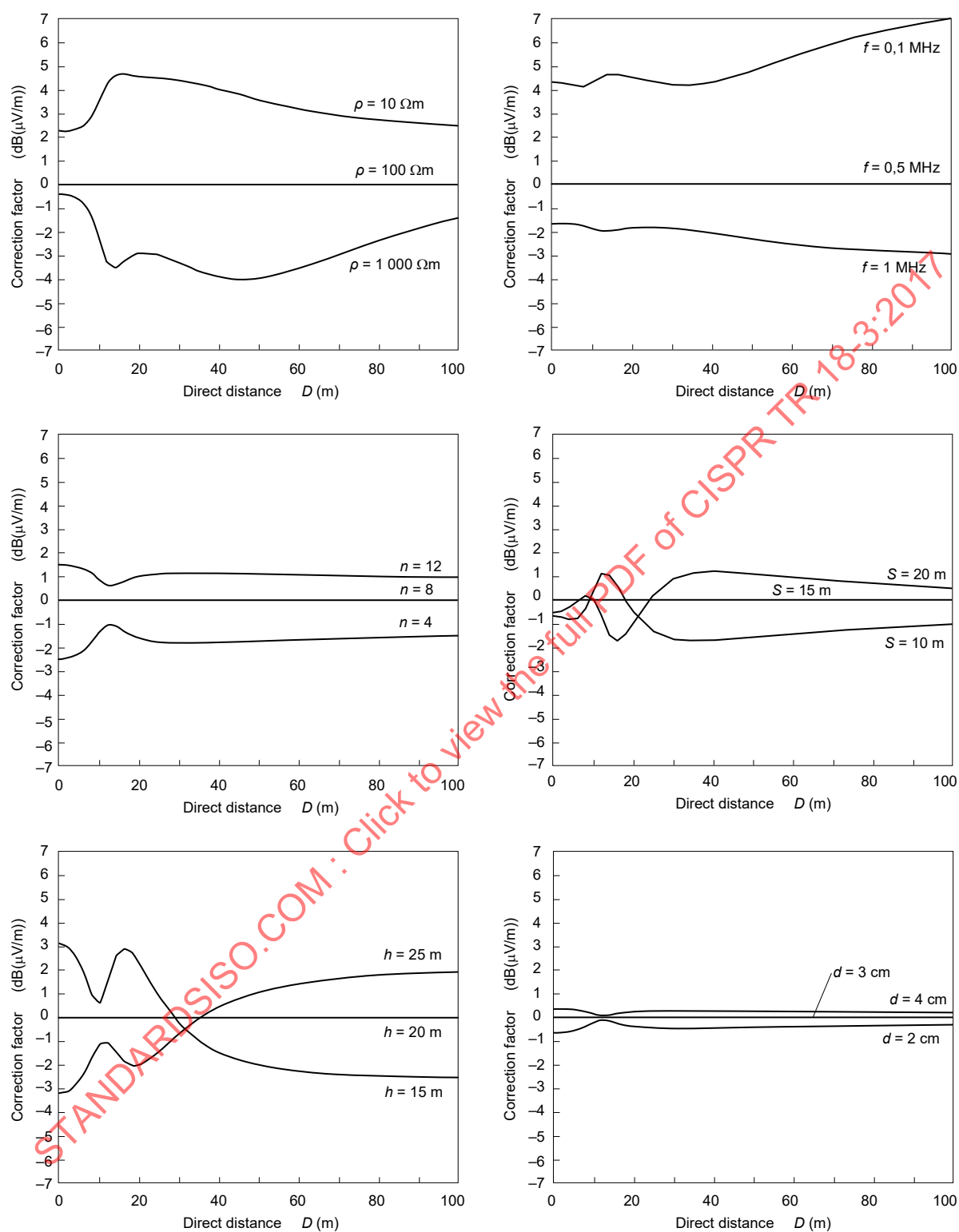
$f = 0,5$ MHz (frequency)

$$|N| = \begin{vmatrix} 0,476 & 0,707 & 0,447 \\ -0,740 & 0,0 & 0,775 \\ 0,476 & -0,707 & 0,447 \end{vmatrix} \quad (\text{modal matrix})$$

$$\alpha_1 = 25 \times 10^{-6} \text{ Np/m}$$

$$\alpha_2 = 15 \times 10^{-6} \text{ Np/m} \quad (\text{modal attenuation factors})$$

$$\alpha_3 = 250 \times 10^{-6} \text{ Np/m}$$



IEC

Figure 5 – Line with conductors in a flat configuration

Corrections in dB to be applied to the reference radio noise electric field strength obtained from Figure 2, to account for ground resistivity ρ , frequency f , number of sub-conductors n , interphase spacing S , minimum height above the ground h and sub-conductor diameter d .

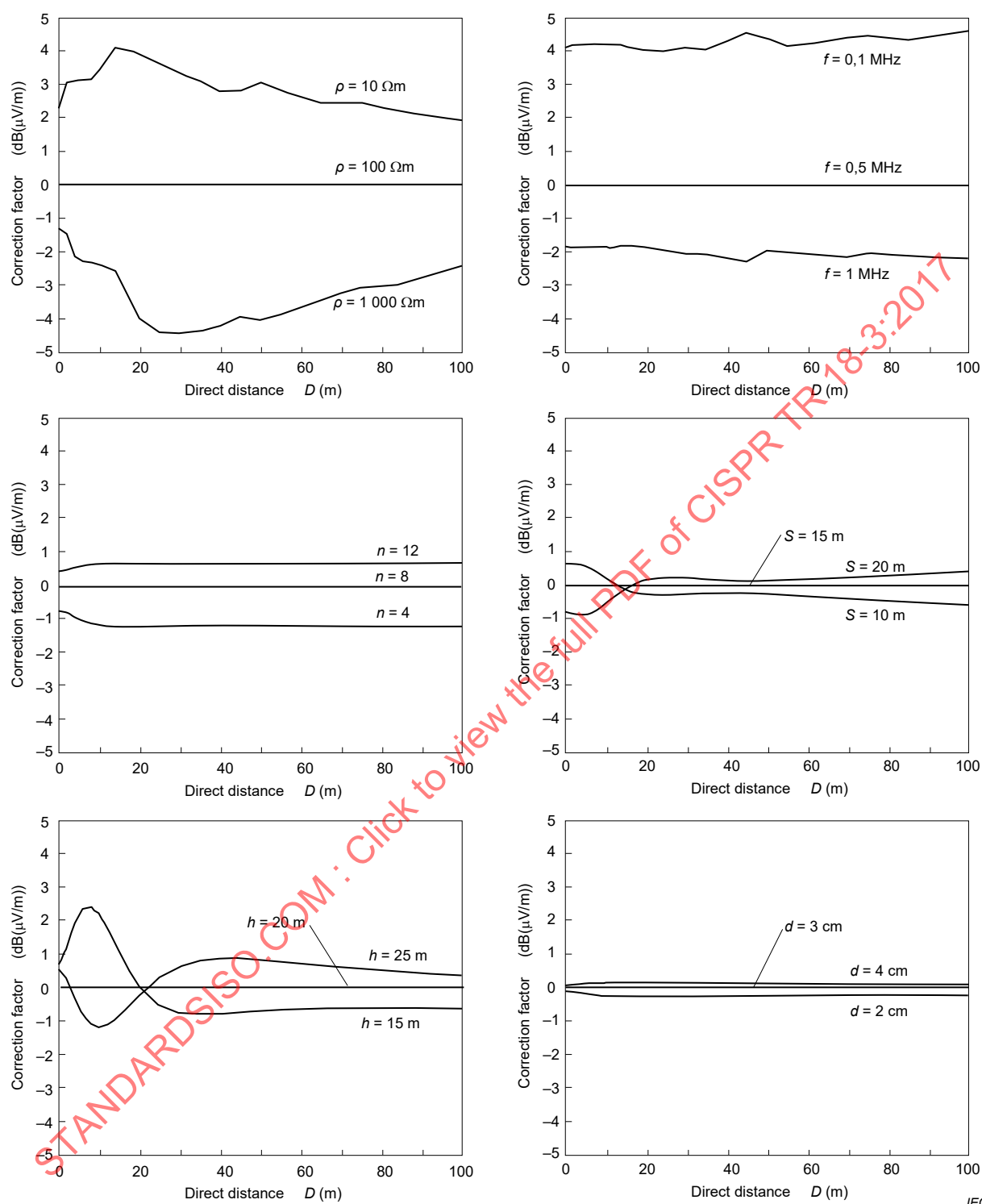


Figure 6 – Line with conductors in a delta configuration

Corrections in dB to be applied to the reference radio noise electric field strength obtained from Figure 3, to account for ground resistivity ρ , frequency f , number of sub-conductors n , interphase spacing S , minimum height above the ground h and sub-conductor diameter d .

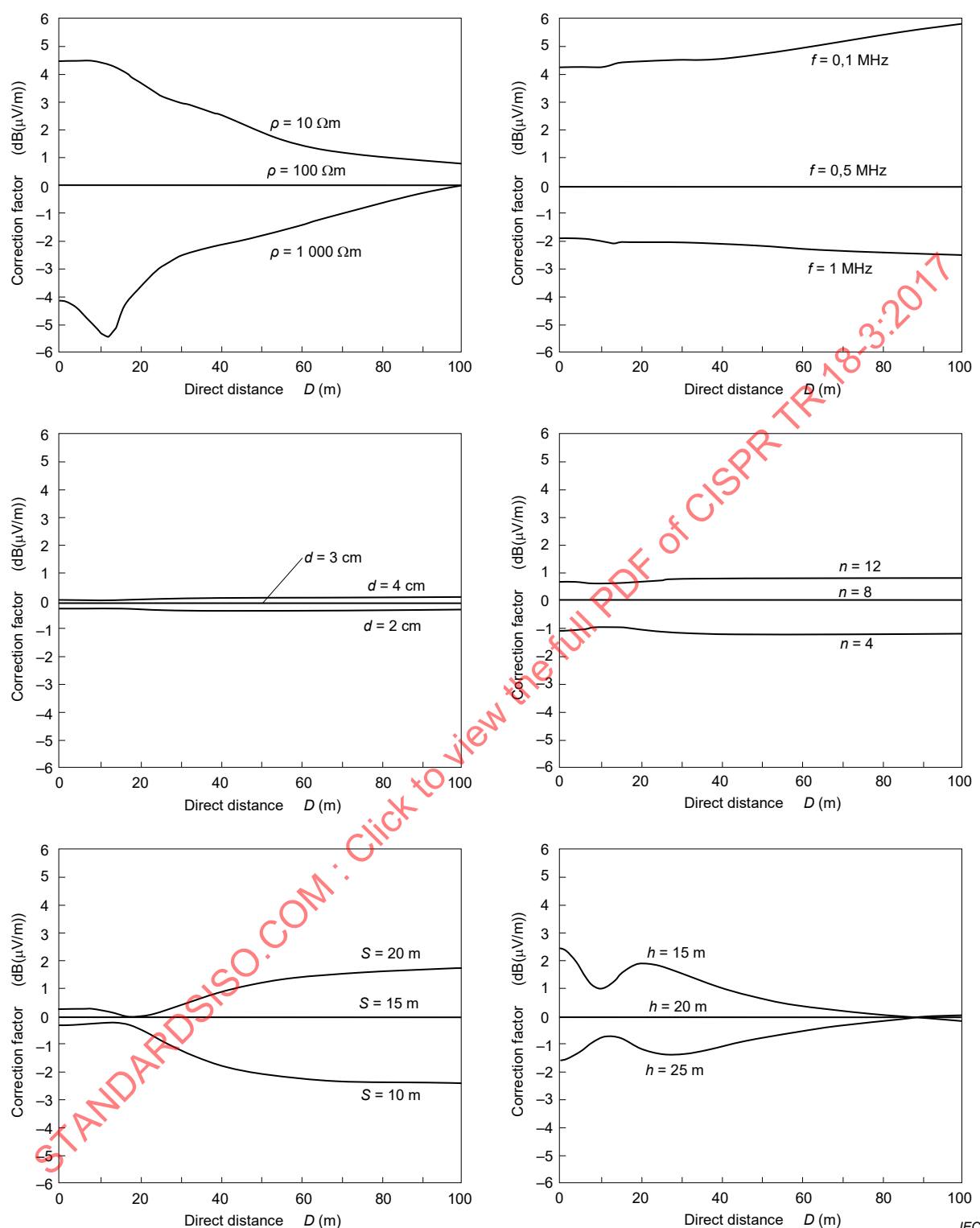


Figure 7 – Line with conductors in a triangular configuration

Corrections in dB to be applied to the reference radio noise electric field strength obtained from Figure 4, to account for ground resistivity ρ , frequency f , number of sub-conductors n , interphase spacing S , minimum height above the ground h and sub-conductor diameter d .

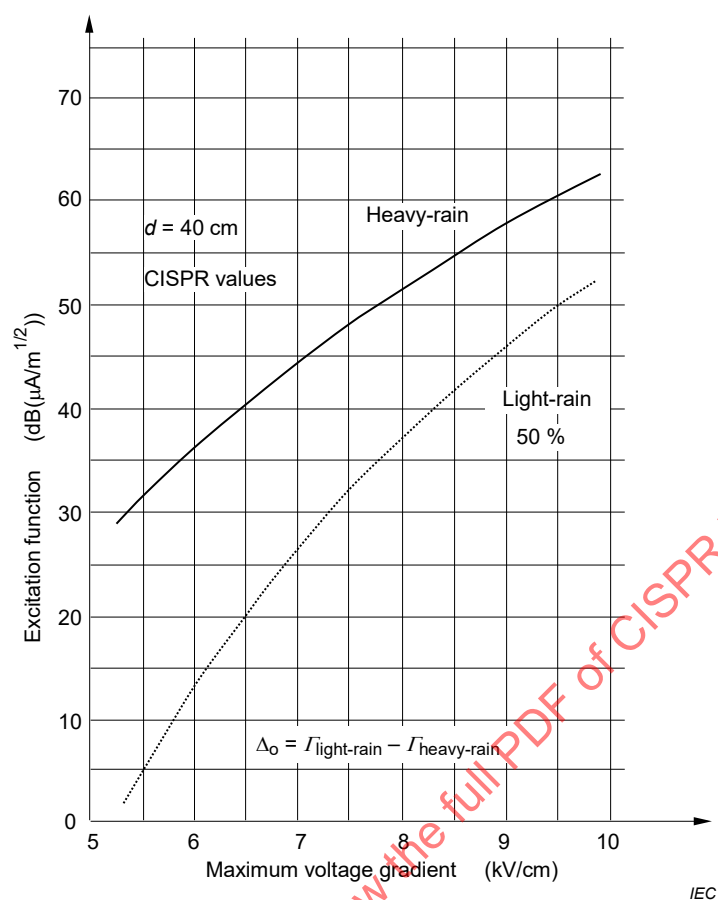


Figure 8 – Tubular conductors of 40 cm diameter

Correction factor in dB to be applied to the heavy rain excitation function to obtain that under light rain as a function of the maximum voltage gradient.

Annex A (informative)

Formulae for predicting the radio noise field strength from the conductors of an overhead line

A.1 CIGRÉ formula for general use

This simple formula will give the most probable radio noise field strength level and the summation of fields made by a CISPR measuring receiver at a frequency of 500 kHz and at a direct distance of 20 m from the nearest conductor with the antenna 2 m above ground.

The elementary formula for a single phase of an AC line is:

$$E = 3,5 g_{\max} + 12 r - 30, \quad \text{in dB}(\mu\text{V/m}) \quad (\text{A.1})$$

where

E is the level of the radio noise field strength, in dB($\mu\text{V/m}$);

$g_{\max}$ is the maximum gradient of the RMS value of the voltage at the conductor surface, in kV/cm;

r is the conductor radius, in cm.

Precise calculation of the maximum voltage gradient at the conductor surface is recommended because of its important effect on the radio noise level. A calculation method is suggested in Annex A of CISPR TR 18-1:___²⁴.

For single-circuit three-phase lines, the previous formula can be expanded to:

$$E_1 = 3,5 g_{\max 1} + 12 r_1 - 33 \log_{10} \frac{D_1}{20} - 30$$

$$E_2 = 3,5 g_{\max 2} + 12 r_2 - 33 \log_{10} \frac{D_2}{20} - 30$$

$$E_3 = 3,5 g_{\max 3} + 12 r_3 - 33 \log_{10} \frac{D_3}{20} - 30$$

where D_1 , D_2 and D_3 are the direct distances, in m, from the phase conductors to the antenna of the measuring instrumentation.

These formulae can also be used to determine the level of the radio noise field strength at measuring positions other than the 20 m reference distance.

The summation of these three field strength contributions is made in the following way: if one of the fields is at least 3 dB greater than each of the other two, they are both neglected, otherwise, we have.

$$E = \frac{E_a + E_b}{2} + 1,5, \quad \text{in dB}(\mu\text{V/m})$$

²⁴ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

where E_a and E_b are the two highest among the above three levels.

For a double circuit line, the radio noise field strength produced by each of the six conductors is calculated as above at the measuring position. The fields produced by the phases corresponding in time are then added quadratically and the three resulting fields are summated as above.

It should be noted that this method will give the most probable noise level of a line in fair weather at 500 kHz. To obtain the level at a frequency different from 500 kHz, the correction shown in Figure B.14 of Annex B of CISPR TR 18-1: ²⁵ should be used. If calculations have to be made for distance different from 20 m, then the formula in 5.3.6 of CISPR TR 18-2: ²⁶ should be used.

The radio noise level for weather conditions other than mean dry, fair weather can be estimated using Figure B.15 of Annex B of CISPR TR 18-1: ²⁷.

The effect of different altitudes of phase conductors above ground can be taken into account by using the following expression:

$$E_h = E_o + \frac{a - a_o}{300}, \quad \text{in dB}(\mu\text{V/m})$$

where E_o is the radio noise field strength level, in dB($\mu\text{V/m}$) at an altitude a_o of the respective phase conductor E_o actually belongs to, in m, and E_h is the radio noise field strength, in dB($\mu\text{V/m}$), at the observation point of E_o , caused by a phase conductor located at a different altitude a above ground, in m.

A.2 Collation of predetermination formulae used by several institutions around the world

Table A.1 contains an overview about the separate terms of in predetermination formulae for AC lines used by several institutions around the world. The information in Table A.1 was obtained from a literature research, for more information see [5], [14], [15].

Table A.2 presents the complete formulae comprising all relevant terms as in Table A.1 used for comparison purposes, i.e. for comparison of the radio noise level radiated from different designs of HV overhead power transmission lines.

Table A.3 eventually presents examples for calculations of absolute field strength levels together with the results of these calculations.

Table A.4, in contrast to above Table A.1 to Table A.3, presents empirical predetermination formulae, which were derived from long term test results using test lines, for DC lines in fair weather used in several institutions.

Table A.5 shows formulae for calculation of the excitation function, in dB($\mu\text{A}/\sqrt{m}$), in fair weather for DC lines.

²⁵ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

²⁶ Under preparation. Stage at the time of publication: CISPR/RPUB 18-2:2017.

²⁷ Under preparation. Stage at the time of publication: CISPR/RPUB 18-1:2017.

Table A.1 – Empirical methods, terms of the predetermination formulae developed by several institutions, survey

Formula	Reference value [dB(µV/m)]	Maximum gradient G [kV/cm]	Conductor diameter	Number of subconductor	Direct distance D [m]	Frequency f [MHz]	Weather
E	E_0	E_G	E_d	E_n	E_D	E_f	E_{wl}
CIGRE ^a	-30	3,5 G_m	6 d	–	$-30 \log\left(\frac{D_d}{20}\right)$	–	–
400 kV-FG ^b (Germany)	53,7 ± 5	$K_g(G_m - 16,95)$ $K_g = 3$ for 750 kV class $K_g = 3$ for other lines, Gradient limits: (15 - 19) kV/cm	$40 \log\left(\frac{d}{3,93}\right)$	$E_n = -4$, 1 circuit $E_n = 10 \log\left(\frac{n}{4}\right)$, $n > 1$	$20 K_D \log\left(\frac{20}{D}\right)$ $K_D = 16 \pm 0,1$ (0,5 to 1 MHz)	$20 \log\left(\frac{1 + 0,5^2}{1 + f^2}\right)$	0 for fair weather 17 ± 3 for rain
ENEL ^b (Italy)	47	3,8 ($G_a - 15,0$)	$40 \log\left(\frac{d}{5,0}\right)$	$10 \log(n)$	$30 \log\left(\frac{20}{D_d}\right)$	$20 \log\left(\frac{1 + 0,5^2}{1 + f^2}\right) + \frac{q}{300}$ (Foul L_{50})	14
CRIEPI ^b (Japan)	–	3,7 ($G_m - 12,2$) ± 3	$40 \log\left(\frac{d}{2,53}\right)$	–	$20 \log\left(\frac{10h}{D^2}\right)$ h : height difference between conductor and antenna	$E_f = 0$ for 1 MHz $-12 (\log f)^2 - 17 \log(f)$	Use of bottom surface gradient G_p
WESTINGHOUSE ^b (USA)	46	3,5 ($G_m - 17,5$)	$30 \log\left(\frac{d}{3,51}\right)$	–	$20 \log\left(\frac{30,7h}{D_d^2}\right)$	$10(1 - f)$	24 (Rainy L_5)
EGU ^b (Czech Republic)	11	4,5 G_m	–	–	$-34 \log(D_d)$	$-22 \log(f) - 15 \log^2(f)$	–

Formula	Reference value [dB(μV/m)]	Maximum gradient G [kV/cm]	Conductor diameter	Number of subconductor	Direct distance D [m]	Frequency f [MHz]	Weather
Ontario Hydro ^b (Canada)	R	$A \log \left(\frac{G_m}{18,8} \right)$	$40 \log \left(\frac{d}{2,54} \right)$	–	$B \log \left(\frac{30,5}{D_d} \right)$	$20 \log \left(\frac{C+1}{C+f^2} \right)$	–
	$R = 34 \text{ dB} \pm 6$ (50 % value, fair weather) horizontal lines $R = 37 \text{ dB} \pm 6$ (50 % value, fair weather) vertical lines $R = 63 \text{ dB}$ (max. foul weather) horizontal lines $R = 66 \text{ dB}$ (max. foul weather) vertical lines			$A = 146$ for fair weather $A = 120$ for foul weather	$B = 40$ for horizontal lines $B = 32$ for vertical lines	$C = 1$ for $f \geq 1$ MHz $C = 0,5$ for $f < 1$ MHz	
KEPCO ^c (Korea)	–105,81 –81,98	$117,42 \log(G_a)$ $119,56 \log(G_a)$	$40,38 \log(d)$ $43,57 \log(d)$	$1,54 \log(n)$ $3,97 \log(n)$	$10,22 \log(D_d)$ $-19,05 \log(D_d)$	$-27,10 \log(f)$ $-25,07 \log(f)$	Fair Foul
BPA ^d (USA)	46	$120 \log \left(\frac{G_a}{17,56} \right)$	$40 \log \left(\frac{d}{3,51} \right)$	–	$\frac{q}{300} - C1 + C2$	$10 \left(1 - (\log(10f))^2 \right)$	17 (Rainy L_{50}) 24 (Rainy L_5)

^a CIGRÉ WG36.01, *Interferences produced by corona effect of electric systems – Description of phenomena practical guide for calculation*, 1974 (see also reference [14]).

^b IEEE Radio Noise Subcommittee Report, *Comparison of Radio Noise Prediction Methods With CIGRE/IEEE Survey Results*, IEEE Transactions On Power Apparatus And Systems, Vol. Pas-92, No. 3, May/June 1973 (see also reference [5]).

^c Munro Ju, Kwangho Yang, Sungho Myung, Kooyong Shin, Dongil Lee, *Development of New Formulas for Predicting Corona Noise from HVAC Transmission Lines*, ICEE 2002, pp. 2147-2150, 2002 (see also reference [15]).

^d CIGRÉ WG36.01, *Interferences produced by corona effect of electric systems – Description of phenomena practical guide for calculation*, December 1996 (see also reference [16]).

Table A.2 – Empirical methods, complete predetermination formulae developed by several institutions, survey (1 of 2)

No.	Method	Formulae for comparison purposes Relation $E - E_0$, in dB	Three phase number coefficients Limits of validity, as far as available
1	400 kV FG (DE)	$E - E_0 \text{ [dB]} = K_g \cdot \log_{10} \left(\frac{g_m}{g_{m0}} \right) + 40 \log_{10} \left(\frac{d}{d_0} \right) + 10 \log_{10} \left(\frac{n}{n_0} \right) + K_D \cdot \log_{10} \left(\frac{D_0}{D} \right) + 20 \log_{10} \left(\frac{1 + f_0^2}{1 + f^2} \right)$	$K_g = 3$ for $U = 765$ kV, and $K_g = 3,5$ for $U \leq 700$ kV, valid in the range $15 \text{ kV/cm} < g_m < 19 \text{ kV/cm}$. $K_D = 32 \pm 2$, valid in the range $0,5 \text{ MHz} < f < 1 \text{ MHz}$. $E_t = E_1$ for $E_t - E_2 < 3 \text{ dB}$, and $E_t = \frac{E_1 + E_2}{2}$ for $E_t - E_2 \geq 3 \text{ dB}$.
2	ENEL (IT)	$E - E_0 \text{ [dB]} = 3,8 \log_{10} \left(\frac{g_a}{g_{a0}} \right) + 40 \log_{10} \left(\frac{d}{d_0} \right) + 10 \log_{10} \left(\frac{n}{n_0} \right) + 30 \log_{10} \left(\frac{D_0}{D} \right) + 20 \log_{10} \left(\frac{1 + f_0^2}{1 + f^2} \right) + \frac{q - q_0}{300}$	$E_t = E_1$, the values of the components of E_1 from conductors of the same phase to be added quadratically
3	Shiobara (JP)	$E - E_0 \text{ [dB]} = F(g_m) - F(g_0) + 40 \log_{10} \left(\frac{d}{d_0} \right) + 20 \log_{10} \left(\frac{f}{f_0} \right) - 12 \left(\log_{10} \left(\frac{f}{f_0} \right) \right)^2 - 17 \log_{10} \left(\frac{10h}{D^2} \right) - 10 \log_{10} \left(\frac{n}{n_0} \right) + 30 \log_{10} \left(\frac{D_0}{D} \right) + 20 \log_{10} \left(\frac{1 + f_0^2}{1 + f^2} \right) + \frac{q - q_0}{300}$ As g_m , use of bottom-surface gradient G_P .	Fair weather (50 % values): $F(g_m) - F(g_0) = (3,7 g_m - 12,2) \pm 3$. Foul weather (in heavy rain): $F(g_m) - F(g_0) = 10,5 g_m - \left(\frac{g_m}{2} \right)^2 - 31$, $g_m \leq 17 \text{ kV/cm}$. $F(g_m) - F(g_0) = 4,375 g_m - \left(\frac{g_m}{4} \right)^2 + 19,5 g_m > 17 \text{ kV/cm}$
4	WESTING- HOUSE (USA)	$E - E_0 \text{ [dB]} = 3,5 \log_{10} \left(\frac{g_m}{g_{m0}} \right) + 30 \log_{10} \left(\frac{d}{d_0} \right) + 20 \log_{10} \left(\frac{h}{h_0} \cdot \left(\frac{D_0}{D} \right)^x \right) + 10 \log_{10} \left(\frac{f_0}{f} \right) + 40 \log_{10} \left(1 - \frac{\delta}{\delta_0} \right)$	$x = 2$ for $D < 60 \text{ m}$, and $x = 1$ for $D > 60 \text{ m}$, valid in the range $0,2 \text{ MHz} < f < 1,6 \text{ MHz}$.
5	EGU (CZ)	$E - E_0 \text{ [dB]} = 4,5 \log_{10} \left(\frac{g_m}{g_{m0}} \right) + 34 \log_{10} \left(\frac{D_0}{D} \right) + 22 \log_{10} \left(\frac{f_0}{f} \right) + 15 \log_{10} \left(\frac{f_0}{f} \right)^2$	
6	ONTARIO HYDRE (CA)	$E - E_0 \text{ [dB]} = K_g \cdot \log_{10} \left(\frac{g_m}{g_{m0}} \right) + 40 \log_{10} \left(\frac{d}{d_0} \right) + K_D \cdot \log_{10} \left(\frac{D_0}{D} \right) + 20 \log_{10} \left(\frac{c + f_0^2}{c + f^2} \right)$	

Table A.2 (2 of 2)

No.	Method	Formulae for comparison purposes Relation $E - E_0$ in dB	Three phase number coefficients Limits of validity
7	AEP test line method (USA)	$E - E_0 \text{ [dB]} = 3,5 \log_{10} \left(\frac{g_m}{g_{m_0}} \right)$	Only for 500 kV and 750 kV lines with the same configuration as the test lines, $f_n = 1 \text{ MHz}$. Test line Configuration A: 500 kV ... Configuration B: 750 kV ... Configuration C: 750 kV ...
8	GE Project EHV, Base Case (USA)	This method gives the average RF disturbance level in fair weather. A series of graphs allow for correction for several parameters, see reference book Edison Electric Institutes – 1968 Chapter V, pp. 173-214 [1].	
9	CIGRE	$E - E_0 \text{ [dB]} = 3,5g + 12r - 30$	
10	KEPCO (KR)	Fair weather: $E - E_0 \text{ [dB]} = 117,41 \log_{10} \left(\frac{g_a}{g_{a_0}} \right) + 40,38 \log_{10} \left(\frac{d}{d_0} \right) + 1,54 \log_{10} \left(\frac{n}{n_0} \right) - 10,22 \log_{10} \left(\frac{D}{D_0} \right) - 27,10 \log_{10} \left(\frac{f}{f_0} \right)$ Foul weather: $E - E_0 \text{ [dB]} = 119,56 \log_{10} \left(\frac{g_a}{g_{a_0}} \right) + 43,57 \log_{10} \left(\frac{d}{d_0} \right) + 3,97 \log_{10} \left(\frac{n}{n_0} \right) - 19,05 \log_{10} \left(\frac{D}{D_0} \right) - 25,07 \log_{10} \left(\frac{f}{f_0} \right)$	
11	BPA (USA)	$E - E_0 \text{ [dB]} = 120 \log_{10} \left(\frac{g_a}{g_{a_0}} \right) + 40 \log_{10} \left(\frac{d}{d_0} \right) + 20 \log_{10} \left(\frac{1 + f_0^2}{1 + f^2} \right) + \frac{q - q_0}{300} - C_1 + C_2$	

Table A.3 – Predetermination formulae, examples for calculation of the absolute field strength levels (1 of 2)

No.	Method	Calculation of the absolute field strength level E in dB(μ V/m)	Collation of absolute field strength levels [dB(μ V/m)]		
			Fair weather	Average foul weather	Average heavy rain
1	400 kV FG (DE)	$E \text{ [dB } (\mu\text{V/m)}] = E_0 + K_g \cdot \log_{10} \left(\frac{g_m}{16,95} \right) + 40 \log_{10} \left(\frac{d}{3,93} \right) + 10 \log_{10} \left(\frac{n}{4} \right) + K_D \cdot \log_{10} \left(\frac{20}{D} \right) + 20 \log_{10} \left(\frac{1+0,5^2}{1+f^2} \right), f_0 = 0,5 \text{ MHz}$	56 ±5	–	73,7 ±3
2	ENEL (IT)	$E \text{ [dB } (\mu\text{V/m)}] = E_0 + 3,8 \log_{10} \left(\frac{g_a}{15} \right) + 40 \log_{10} \left(\frac{d}{5,0} \right) + 10 \log_{10} \left(\frac{n}{1} \right) + 30 \log_{10} \left(\frac{20}{D} \right) + 20 \log_{10} \left(\frac{2}{1+f^2} \right), f_0 = 1 \text{ MHz}$	55	64	68
3	Shiobara (JP)	$E \text{ [dB } (\mu\text{V/m)}] = E_0 + F(g_m) - F(g_0) + 40 \log_{10} \left(\frac{d}{2,33} \right) + 20 \log_{10} \left(\frac{10h}{D^2} \right) - 17 \log_{10} \left(\frac{1}{f_0} \right) - 12 \left(\log_{10} \left(\frac{1}{f_0} \right) \right)^2, f_0 = 1 \text{ MHz}$	–	–	–
4	WESTING- HOUSE (USA)	$E \text{ [dB } (\mu\text{V/m)}] = 3,5 \log_{10} \left(\frac{g_m}{17,5} \right) + 30 \log_{10} \left(\frac{d}{3,51} \right) + 20 \log_{10} \left(\frac{h}{13} \cdot \left(\frac{20}{D} \right)^x \right) + 10 \log_{10} \left(\frac{1}{f} \right) + 40 \log_{10} \left(1 - \frac{\delta}{1} \right), f_0 = 1 \text{ MHz}$	48	–	70
5	EGU (CZ)	$E \text{ [dB } (\mu\text{V/m)}] = 4,5 \log_{10} \left(\frac{g_m}{15} \right) + 34 \log_{10} \left(\frac{20}{D} \right) + 22 \log_{10} \left(\frac{1}{f} \right) + 15 \log_{10} \left(\frac{1}{f} \right)^2, f_0 = 1 \text{ MHz}$	37	47	–
6	ONTARIO HYDRE (CA)	$E \text{ [dB } (\mu\text{V/m)}] = K_g \cdot \log_{10} \left(\frac{g_m}{18,8} \right) + 40 \log_{10} \left(\frac{d}{2,54} \right) + K_D \cdot \log_{10} \left(\frac{30,5}{D} \right) + 20 \log_{10} \left(\frac{c+1}{c+f^2} \right), f_0 = 1 \text{ MHz}$	32 (horizontal lines) 36 (vertical lines)	–	61 (worst foul weather, horizontal lines) 36 (worst foul weather, vertical lines)
7	AEP test line method (USA)	$E \text{ [dB } (\mu\text{V/m)}] = 3,5 \log_{10} \left(\frac{g_m}{g_{m0}} \right)$	Configuration A	38,7	55,7
			Configuration B	45,5	62,5
			Configuration C	50,5	67,5

Table A.3 (2 of 2)

No.	Method	Formulae for calculation of the absolute field strength level E in dB(μ V/m)	Reference field strength value E_0 [dB(μ V/m)]		
			Fair weather	Average foul weather	Average heavy rain
8	GE Project EHV, Base Case (USA)	This method gives the average RF disturbance level in fair weather. A series of graphs allow for correction for several parameters, see Reference book Edison Electric Institutes – 1968 Chapter V, pp. 173-214 [1].	–	–	–
9	CIGRE	E [dB(μ V/m)] = $3,5g + 12r - 30$, $f_0 = 1$ MHz	–30	–	–
10	KEPCO (KR)	E [dB(μ V/m)] = $117,41 \log_{10} \left(\frac{g_a}{1} \right) + 40,38 \log_{10} \left(\frac{d}{1} \right) + 15,4 \log_{10} \left(\frac{n}{1} \right) - 10,22 \log_{10} \left(\frac{D}{1} \right) - 27,10 \log_{10} \left(\frac{f}{1} \right)$, $f_0 = 1$ MHz E [dB(μ V/m)] = $119,56 \log_{10} \left(\frac{g_a}{1} \right) + 43,57 \log_{10} \left(\frac{d}{1} \right) + 3,97 \log_{10} \left(\frac{n}{1} \right) - 19,05 \log_{10} \left(\frac{D}{1} \right) - 25,07 \log_{10} \left(\frac{f}{1} \right)$, $f_0 = 1$ MHz	–105,8	–81,98	–
11	BPA (USA)	E [dB(μ V/m)] = $120 \log_{10} \left(\frac{g_a}{17,56} \right) + 40 \log_{10} \left(\frac{d}{3,51} \right) + 10 \left((1 - \log_{10} 10 f)^2 \right) + \frac{q}{300} - C_1 + C_2$	46	63	70

Table A.4 – Empirical methods, complete predetermination formulae for DC lines developed by several institutions, survey (1 of 2)

No.	Method	Formulae for comparison purposes in dB	Remark
1	BPA ^a (USA)	$R/I = 51,7 + 86 \log \left(\frac{g}{25,6} \right) + 40 \log \left(\frac{d}{4,62} \right) + 10 \left[1 - (\log(10f))^2 \right] + 40 \log \left(\frac{19,9}{D} \right) + \left(\frac{q}{300} \right)$	This formula has been changed to reflect new and better data collected from ±500 kV line (CISPR QP detector)
2	Anneberg ^b (SW)	$R/I = 25 + 10 \log n + 20 \log r + 1,5(g - g_0) - 40 \log \frac{D}{30}$	$g_0 = 22 \cdot \delta$ in kV/m where δ is the relative air density
^{a, b} CIGRÉ WG36.01, <i>Interferences produced by corona effect of electric systems – Description of phenomena practical guide for calculation</i> , December 1996 (see also reference [16]).			

Table A.4 (2 of 2)

No.	Method	Formulae for comparison purposes in dB	Remark																								
3	CRIEPI (JP)	For single circuit bipolar lines ^c $E = N_0 + 18(g_m - 25) + 40 \log_{10} \left(\frac{d}{2,53} \right) + 20 \log_{10} \left(\frac{10h}{D^2} \right) + K_w(W) - 17 \log_{10} \left(\frac{f}{f_0} \right) - 12 \left(\log_{10} \left(\frac{f}{f_0} \right) \right)^2$	Fair weather (50 % values) $f_0 = 1 \text{ MHz}$ $\begin{cases} 64,5, n = 1 \\ 58,5, n = 2 \\ 62, n = 3, 4 \end{cases}$ N_0 : height difference between a conductor and an antenna h : height difference between a conductor and an antenna K_w : correction for horizontal pole to pole distance, W , $K_w = 24,5/\sqrt{W} - 8,5$																								
		For double circuit bipolar lines ^d $E = N_0 + K_g(g_m - 20) + 20 \log_{10} \left(\frac{10h}{D^2} \right) + K_w(W) + K_h(H) + K_c(C) - 17 \log_{10} \left(\frac{f}{f_0} \right) - 12 \left(\log_{10} \left(\frac{f}{f_0} \right) \right)^2$ <table><tr><th>Pole arrangement</th><th>N_0</th><th>K_g</th><th>K_h</th><th>K_c</th><th>K_w</th></tr><tr><td>$\oplus -$</td><td rowspan="2">53</td><td rowspan="2">1,9</td><td rowspan="2"></td><td rowspan="2">$-0,5(C-16)$</td><td rowspan="2">$0,3(W-22)$</td></tr><tr><td>$- \oplus$</td></tr><tr><td>$\oplus \oplus$</td><td rowspan="2">54</td><td rowspan="2">2,3</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">$0,2(W-22)$</td></tr><tr><td>$- -$</td></tr><tr><td>$\oplus \oplus$</td><td>44,5</td><td></td><td>$0,3(H-22)$</td><td></td><td></td></tr></table>	Pole arrangement	N_0	K_g	K_h	K_c	K_w	$\oplus -$	53	1,9		$-0,5(C-16)$	$0,3(W-22)$	$- \oplus$	$\oplus \oplus$	54	2,3			$0,2(W-22)$	$- -$	$\oplus \oplus$	44,5		$0,3(H-22)$	
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^d T. Tsuzura, T. Sasano: <i>Studies on corona and field effects of Shiobara HVDC Test Line part 4 – Radio interference of 4 x 3.84 cm in bipolar double circuit configuration</i> , CRIEPI, No. 185018, Dec. 1985 [21].																											

^c UHV Transmission Committee, *Fundamental Study of bulk power transmission*, CRIEPI, No. 107, Oct. 1981 [20].^d T. Tsuzura, T. Sasano: *Studies on corona and field effects of Shiobara HVDC Test Line part 4 – Radio interference of 4 x 3.84 cm in bipolar double circuit configuration*, CRIEPI, No. 1850 18, Dec. 1985 [21].

Table A.5 – Formulae for calculation of the excitation function in fair weather for DC lines developed by several institutions, survey

No.	Method	Formulae for comparison purposes in dB	Limits of validity, as far as available Remarks																																																			
1	IREQ ^a (CA)	$\Gamma = \Gamma_0 + K_1 \times (g - 25) + 40 \log_{10} \left(\frac{d}{4,064} \right) + K_3 \log_{10} \left(\frac{n}{6} \right)$	The excitation function is expressed in terms of dB above $1 \mu A/\sqrt{m}$. The empirical constants Γ_0, K_1, and K_3 are given for different seasons and for different weather conditions in the table below. <table><tr><th>Season of year</th><th>Weather conditions</th><th>Γ_0</th><th>K_1</th><th>K_3</th><th>Maximum error (dB)</th></tr><tr><td rowspan="2">Summer</td><td>Fair</td><td>27,01</td><td>1,83</td><td>45,8</td><td>7,0</td></tr><tr><td>Foul</td><td>20,35</td><td>1,39</td><td>48,0</td><td>-3,2</td></tr><tr><td rowspan="2">Fall/Spring</td><td>Fair</td><td>23,44</td><td>1,68</td><td>29,9</td><td>3,9</td></tr><tr><td>Foul</td><td>19,84</td><td>1,68</td><td>63,5</td><td>4,9</td></tr><tr><td rowspan="2">Winter</td><td>Fair</td><td>18,74</td><td>1,63</td><td>19,65</td><td>4,9</td></tr><tr><td>Foul</td><td>19,52</td><td>1,47</td><td>10,0</td><td>-6,4</td></tr><tr><td colspan="2">Overall fair weather</td><td>22,94</td><td>1,71</td><td>30,8</td><td>-12,0</td></tr><tr><td colspan="2">Overall foul weather</td><td>19,77</td><td>1,50</td><td>33,9</td><td>-10,4</td></tr></table>	Season of year	Weather conditions	Γ_0	K_1	K_3	Maximum error (dB)	Summer	Fair	27,01	1,83	45,8	7,0	Foul	20,35	1,39	48,0	-3,2	Fall/Spring	Fair	23,44	1,68	29,9	3,9	Foul	19,84	1,68	63,5	4,9	Winter	Fair	18,74	1,63	19,65	4,9	Foul	19,52	1,47	10,0	-6,4	Overall fair weather		22,94	1,71	30,8	-12,0	Overall foul weather		19,77	1,50	33,9	-10,4
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2	CRIEPI (JP)	$\Gamma = \Gamma_0 + 2,3 F_m + 40 \log_{10} \left(\frac{d}{3,84} \right) + C_{STN}^b$	50 % value of QP in fair weather at frequency of 0,455 MHz, former JRTC F_m: maximum conductor surface gradient considering space charge near the line this formula can apply to conductor systems having $n = 1$ to 6 and $d = 2,24$ cm to 5 cm $\Gamma_0 = \begin{cases} -7,8 & \text{for } n = 1 \\ -13,8 & \text{for } n \geq 2 \end{cases}$ To calculate RI level based on CISPR standard at frequency of f MHz, add field factor at 0,455 MHz: $C_f = 0,455 \text{ MHz} + C_f$, and C_{STN}, where $C_f = 0,455 \text{ MHz} = -4,41$, $C_f = -\{12(\log f)^2 + 17 \log f\}$, and $C_{STN} = -3$																																																			

- ^a P.S. Maruvada, N.G. Trinh, R.D. Dallaire, N. Rivest, *Corona studies for bipolar HVDC transmission at voltages between ± 600 kV and 1200 kV – Part 1: long-term bipolar line studies*, IEEE Transactions on Power Apparatus and Systems, Vol. 100, No. 3, March 1981. [22]
- ^b Y. Sunaga, Y. Nakano, *Prediction method of radio noise and audible noise from HVDC transmission lines*, CRIEPI report, No. T92018, February 1993. [23]
- ^c The value of C_{STN} , which is the conversion factor from the former JRTC to CISPR standard, is derived from the following paper: T. Sasano, V. Chartier, *Audible noise and radio noise from UHV A.C. transmission lines (VI) Radio noise and audible noise from 8 x Chukar conductor at Lyons test facility*, CRIEPI, 177059, June 1978. [24]

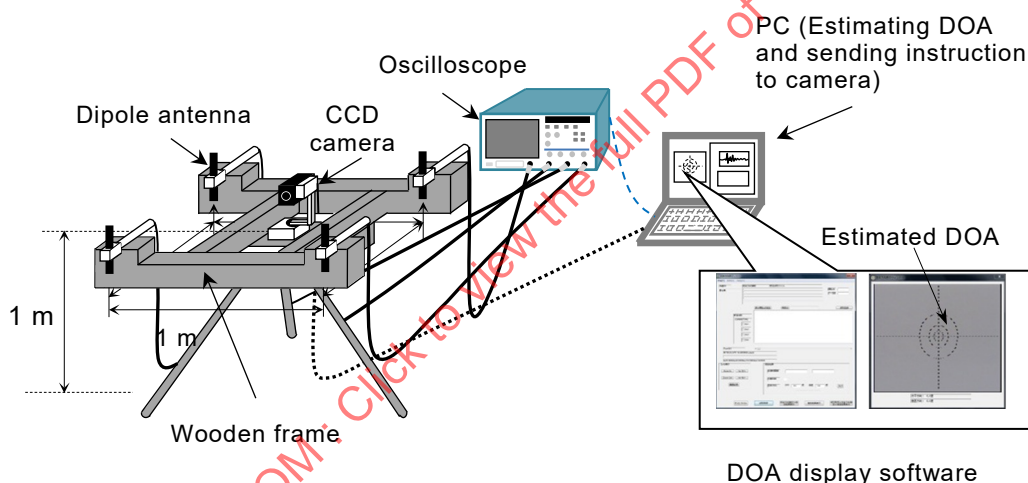
Annex B (informative)

Configuration of an RF-based spark discharge detector and Direction Of Arrival (DOA) estimation method

B.1 Configuration of RF-based spark discharge detector

Figure B.1 illustrates the configuration of the spark discharge detector. The detector consists of an antenna array, which has e.g. four vertical dipole antennas arranged in square with 1 m antennas spacing, coaxial cables, a high-speed digital oscilloscope, a personal computer (PC), and a CCD camera.

The antennas should be fixed to a wooden frame. The radio wave noise is received by the antennas and recorded by a digital oscilloscope (e.g. frequency band: DC ~ 12 GHz, sampling rate: 50 GS/s). The antennas and oscilloscope are connected by coaxial cables. A PC is applied to estimate the DOA. It is convenient to make camera to aim automatically at the estimated DOA by computer instruction.



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Figure B.1 – Configuration of RF-based spark discharge detector [17]

B.2 Direction of Arrival (DOA) estimation method based on Time Difference of Arrival (TDOA) [17]

When, referring to Figure B.2, the distance between a given radio noise source due to bad contact and the antenna array is sufficiently large compared with the spacing S between the individual antennas in that array, then the radio waves can be treated as plane waves, and the incident angle θ (azimuth angle in Direction of Arrival (DOA)) of the radio noise wave to the antenna array can be estimated, in general, from Time Difference of Arrival (TDOA) by the following expression,

$$\theta = \cos^{-1} \left(\frac{CT}{S} \right), \quad (\text{B.1})$$