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TECHNICAL REPORT

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INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE

Radio interference characteristics of overhead power lines and high-voltage equipment –
Part 1: Description of phenomena

CISPR TR 18-1:2017-10(en)

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Radio interference characteristics of overhead power lines and high-voltage equipment –
Part 1: Description of phenomena

INTERNATIONAL
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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 1: Description of phenomena

FOREWORD

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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

CISPR 18-1, 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.

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

a) updated description of the RF characteristics of spark discharges which might contain spectral radio noise components up to the GHz frequency range;

b) addition of state of the art in HVDC converter technology

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

DTR	Report on voting
CIS/B/653/DTR	CIS/B/674/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 web site 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 at a later date.

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INTRODUCTION

This Technical Report is the first of a three-part series dealing with radio noise generated by electrical power transmission and distribution facilities (overhead lines and substations). It contains information in relation of the physical phenomena involved in the generation of electromagnetic noise fields. It also includes a description of the main properties of such fields and their numerical values. Its content was adjusted such as to allow for use of the lateral distance *y* for the establishment of standard profiles for the lateral radio noise field emanating from HV overhead power lines.

The technical data given in this Part 1 of the CISPR 18 series are intended to be a useful aid to overhead line designers and also to anyone concerned with checking the radio noise performance of a line to ensure satisfactory protection of wanted radio signals. The data should facilitate the use of the recommendations given in its Parts 2 and 3 dealing with

– methods of measurement and procedures for determining limits, and a
– code of practice for minimizing the generation of radio noise.

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

This document has been prepared in order to provide information on the many factors involved in protecting the reception of radio, especially (but not limited to) analogue television, and digital terrestrial television broadcasting, hereafter denominated as digital television broadcasting, from interference due to background noise generated by AC and DC high voltage overhead power lines, distribution lines, and associated equipment. The information given should be of assistance when means of avoiding or abating radio noise are being considered.

Information is mainly given on the generation and characteristics of radio noise from AC power lines and equipment operating at 1 kV and above, in the frequency ranges 0,15 MHz to 30 MHz (a.m. sound broadcasting), 30 MHz to 300 MHz (f.m. sound broadcasting, analogue television broadcasting) and in the range 470 MHz to 950 MHz (digital television broadcasting). The special aspect of spark discharges due to bad contacts or defects is taken into account. Information is also given on interference due to DC overhead power lines for which corona and interference conditions are different from those of AC power lines. The radio broadcast services mentioned above are examples only and the information in this document relates, in a technology-neutral way, to protection of radio reception in general, for the given frequency ranges.

The general procedure for establishing the limits of the radio noise from overhead power lines and associated equipment is given, together with typical values as examples, and methods of measurement.

The clause on limits for conductor corona, which may occur in normal operation of power lines, concentrates on the low frequency and medium frequency bands as it is only in these bands where ample evidence, based on established practice, is available. Examples of limits to protect radio reception in the frequency band 30 MHz to 300 MHz are not given, as measuring methods and certain other aspects of the problems in this band have not yet been fully resolved. Site measurements and service experience have shown that levels of noise from power lines generated by conductor corona at frequencies higher than 300 MHz are so low that interference is unlikely to be caused to analogue television reception.

Presently, there are no limits for radio noise due to spark discharges, which may occur at bad contacts or on the surface of polluted insulators, to protect radio reception in the UHF band (around 470 MHz to 950 MHz) for digital television broadcasting. The characteristics of spark discharges in the UHF band are not fully understood yet. Furthermore, digital television systems employ error-correction functions, and the true effects of spark discharges to image quality are consequently not quite known.

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The values of limits given as examples are calculated to provide a reasonable degree of protection to the reception of e.g. radio broadcasting at the edges of the recognized service areas of the appropriate transmitters in the a.m. radio frequency bands, in the least favourable conditions likely to be generally encountered. These limits are intended to provide guidance at the planning stage of the line and national standards or other specifications against which the performance of the line may be checked after construction and during its useful life.

Recommendations are made on the design, routing, construction and maintenance of the lines and equipment forming part of the power distribution system to minimize interference and it is hoped that this document will aid other radio services in the consideration of the problems of interference.

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

Part 1: Description of phenomena

1 Scope

This part of CISPR 18, which is a Technical Report, applies to radio noise from overhead power lines, associated equipment, and high-voltage equipment which may cause interference to radio reception. The scope of this document includes the causes, measurement and effects of radio interference, design aspects in relation to this interference, methods and examples for establishing limits and prediction of tolerable levels of interference from high voltage overhead power lines and associated equipment, to the reception of radio signals and services.

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

Radio frequency interference caused by the pantograph of overhead railway traction systems is not considered in this document.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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 16-1-1, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-1: Radio disturbance and immunity measuring apparatus – Measuring apparatus*

CISPR TR 18-2:__ [1], *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.

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

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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

4 Radio noise from HV AC overhead power lines

4.1 General

Radio noise from high voltage alternating current (HVAC), which is to say above 1 kV, overhead power lines may be generated over a wide band of frequencies by

a) corona discharges in the air at the surfaces of conductors, insulator assemblies and hardware;

b) discharges and sparking at highly stressed areas of insulators;

c) sparking at loose or imperfect contacts and at defects in hardware (cracks, rust).

The sources of a) and b) are usually distributed along the length of the line, but source c) is usually local. For lines operating above about 100 kV, the electric stress in the air at the surface of conductors and hardware can cause corona discharges. Sparking at bad contacts or broken or cracked insulators can give rise to local sources of radio noise. High voltage apparatus in substations may also generate radio noise which can be propagated along the overhead lines.

If the field strength of the radio noise at the antennas used for radio reception is too high, it can cause degradation of the quality and performance of the respective radio communication or broadcast service and application.

The generation of radio noise is affected by weather conditions, for example, conductor corona is more likely to occur in wet weather because of the water droplets which form on the conductors whereas, under these conditions, bad contacts can become bridged with water droplets and the generation of radio noise, by this process, ceases. Consequently, loose or imperfect contacts are more likely to spark in dry weather conditions. Dry, clean insulators may cause interference in fair weather, but prolonged sparking on the surfaces of insulators is more likely to occur when they are polluted, particularly during wet, foggy or icy conditions.

For interference-free reception of radio signals, it is important that a sufficiently high ratio is available at the input to the receiver between the level of the wanted signal and the level of the unwanted radio noise. Interference may therefore be experienced when the signal strength is low and the weather conditions are conducive to the generation of radio noise.

Unlike analogue radio reception, to realize interference-free reception of digital signals, it is important to keep the bit error rate (BER, BER used to evaluate digital communication quality) below a certain value, for example, below around 10^{-2} in the front of Viterbi decoder in case of a ISDB-T system. In this regard, a BER of around 10^{-2} in the front of Viterbi decoder assures a BER below 10^{-8} at the input of a display by error-correction function, which is commonly employed in modern digital communication systems.

When investigating radio noise it should be borne in mind that the local field may be caused by a distant source or sources as the noise may propagate along the line without substantial losses, over a considerable distance.

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4.2 Physical aspects of radio noise

4.2.1 Mechanism of formation of a noise field

4.2.1.1 General

Corona discharges on conductors, insulators or line hardware or sparking at bad contacts can be the source of radio noise as they inject current pulses into the line conductors. These propagate along the conductors in both directions from the injection point. The various components of the frequency spectrum of these pulses have different effects.

In the frequency range 0,15 MHz to a few megahertz, the noise is largely the result of the effect of propagation along the line. Direct electromagnetic radiation from the pulse sources themselves does not materially contribute to the noise level. In this case, the wavelength is long in comparison with the clearances of the conductors and thus the line is not an efficient radiator. However, associated with each spectral voltage and current component, an electric and a magnetic field propagate along the line. In view of the relatively low attenuation of this propagation, the noise field is determined by the aggregation of the effects of all the discharges spread over many kilometres along the line on either side of the reception point. It should be noted that close to the line the guided field predominates, whereas further from the line the radiated field predominates. The changeover is not abrupt and the phenomenon is not well known. This effect is not important at low frequencies but is apparent at medium frequencies.

However, for spectral components above 30 MHz where the wavelengths are close to or less than the clearance of the line conductors, the noise effects can be largely explained by antenna radiation theory applied to the source of noise, as there is no material propagation along the line.

It should be appreciated, however, that 30 MHz does not represent a clear dividing line between the two different mechanisms producing noise fields.

4.2.1.2 Longitudinal propagation

In the case of a single conductor line mounted above the ground, there is a simultaneous propagation of a voltage wave $U(t)$ and a current wave $I(t)$.

For a given frequency, the two quantities are related by the expression $U(\omega) = Z(\omega) \times I(\omega)$ where Z, also a function of ω, is the surge impedance of the line.

During propagation the waves are attenuated by a common coefficient α where:

$$U_x = U_0 e^{-\alpha x}$$

$$I_x = I_0 e^{-\alpha x}$$

where

U_0 and I_0 are the amplitudes at the source, and

x is the distance of propagation along the line.

In case of multi-phase lines, experience shows that any system of voltages or currents becomes distorted in propagation, that is to say, the attenuation varies with the distance propagated and it differs for each conductor. Theory of propagation and actual measurements on power lines have shown that noise voltages on the phase conductors can be considered as being made up of a number of "modes", each one having components on every conductor. One mode propagates between all conductors in parallel and earth. The others propagate

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between conductors. Each mode has its own different propagation attenuation. The complete theory of modal propagation is complex and involves matrix equations outside the scope of this document. Reference is made here to CIGRÉ and other published works. It is important to note that the attenuation of the conductor-to-earth mode propagation is fairly high, that is to say 2 dB/km to 4 dB/km, while the attenuation of the various conductor-to-conductor modes is a small fraction of 1 dB/km at a frequency of 0,5 MHz.

4.2.1.3 Electromagnetic field

The radio noise voltages and currents propagating along the line produce an associated propagating electromagnetic field near the line.

It should be noted here that in free space the electric and magnetic components of the field associated with radiated electromagnetic waves are at right angles both to each other and to the direction of propagation. The ratio of their amplitudes represents a constant value:

$$\frac{E_{(\mathrm{V/m})}}{H_{(\mathrm{A/m})}} = 377\,\Omega$$

and is called the intrinsic impedance or impedance of free space.

On the other hand, the fields near the line are related to the radio frequency voltages and currents propagating along the line and their ratio depends on the surge impedance of the line for the various modes. Furthermore, the directions of the electric and magnetic field components differ from those for radiated fields in free space as they are largely determined by the geometrical arrangements of the line conductors. The matter is further complicated by the fact that soil conditions affect differently the mirror image in the ground of the electric and magnetic field components, respectively.

The electric field strength $E(y)$ at ground level of a single conductor line, which is the vertical component of the total electric field strength, can be predicted by the following empirical equation that has, in a lot of cases, proven to give a good approximation:

$$E(y) = 120\ I \frac{h}{h^2 + y^2}$$

where

I is the radio noise current, in A, propagating in the conductor;

h is the height above ground, in m, of the conductor;

y is the lateral distance, in m, from a point at ground level directly under the conductor to the measuring point; and

E is the electric field strength, in V/m.

Furthermore, for an infinitely long single conductor line, the induction zone, or near field, has the same simple ratio of electric and magnetic field strength as the far field from a radio transmitter, that is to say 377 Ω, and this is approximately true for all values of ground conductivity.

In the case of a multi-phase line, the total electric field strength is the vector sum of the individual field strength components associated with each phase conductor. A more comprehensive treatment, together with practical methods of assessing the electromagnetic field, is discussed in 5.3 of CISPR TR 18-2:__[2]. The equation given above is a simplified version accurate for a distance of D = 20 m and f = 0,5 MHz where D is the direct distance, in

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

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m, between the measuring antenna and the nearest conductor of the line, and f is the measurement frequency. For conventional power transmission lines (i.e. with a conductor height above ground which is less than 15 m), this direct distance D approximately corresponds to a lateral distance y of 15 m. For a wider range of D and f, it would be necessary to take into account all the parameters affecting the equation.

4.2.1.4 Aggregation effect

In the case of uniformly distributed noise sources, the field strength generated by a unit length of a phase conductor can be expressed at any point along the line as a function of the longitudinal distance x and the lateral distance y, that is to say, $E(y,x)$. At a given lateral distance of y,

$$E(y,x) = E_0(y)e^{-\alpha x}$$

The random pulses on a long line with uniformly distributed noise sources combine together to form the total field. The manner in which they combine is not unanimously agreed upon. Some investigators consider that they combine quadratically:

$$E^2(y) = 2\int_0^{\infty} E_0^2(y)\mathrm{e}^{-2\alpha x}\mathrm{d}x$$

or

$$E(y) = \frac{E_0}{\sqrt{\alpha}}.$$

Other investigators believe that, if a quasi-peak detector is used to measure the field strength, the individual pulses do not add and others have obtained results between the two extremes. This disagreement is only important in analytical prediction methods, the results obtained by the different methods vary by only 1 dB or 2 dB.

In case of multi-phase lines, the calculation follows the sample principle but is complicated by the presence of several modes, each mode having a different attenuation coefficient. A more detailed discussion, with examples of calculation, is given in Clause 6.

4.2.2 Definition of noise

The instantaneous value of the noise varies continuously and in a random manner, but its average power level over a sufficiently long period, for example, 1 s, gives a stationary random quantity which can be measured. Another quantity suitable for measurement is the peak or some weighted peak value of the noise level.

A noise measuring instrument is basically a tuneable selective and sensitive voltmeter with a specified pass-band. When connecting to a suitable rod or loop antenna and properly calibrated, it can measure the electric or magnetic component of the noise field. For measurements of the magnetic component of the noise field in the frequency range up to 30 MHz, normally a loop antenna is used. For measurements of the electric component of the noise field in the frequency range above 30 MHz, use of a biconical antenna is recommended.

Depending on the design of the measuring receiver, the noise level can be measured in terms of RMS, peak or quasi-peak values. The RMS value defines the noise in terms of energy. Many types of noise from electrical equipment, as well as noise due to power-line corona, consist of a succession of short pulses with approximately stable repetition frequencies. In such cases, the nuisance effect of the noise can be realistically indicated by a quasi-peak type of voltmeter rather than by the RMS type. The quasi-peak value is obtained from a circuit which includes a diode and a capacitor with relatively short charge and long discharge time constants. The voltage on the capacitor floats at a value somewhat below the peak value and depends on the repetition rate, that is to say a weighting feature is included in the response

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This principle is adopted in the CISPR measuring receiver, details of which are given in CISPR 16-1-1. The noise level is thus defined by the value measured by such an instrument expressed in microvolts (μV) or microvolts per metre (μV/m). Using the ratio of the electric to magnetic field components, E/H = 377 Ω, the measured values can also be expressed by convention in μV/m even for instruments using a loop antenna responding to the magnetic field component.

4.2.3 Influence of external parameters

To determine the corona inception gradient g_c of a cylindrical conductor with smooth surface, Peek's formula is often used:

$$g_c \text{ (kV/cm)} = 31\delta\left(1+\frac{0{,}308}{\sqrt{\delta r}}\right)$$

For AC voltages, g_c is the peak value of the gradient, r is the radius of the conductor in centimetres, $\delta = \frac{0{,}294p}{273+T}$ is the relative air density (δ = 1 for p = 1 013 mbar and T = 25 °C).

However, practical conditions on overhead lines do not agree with these idealized assumptions. Stranding of the conductors, surface imperfections and irregularities lead to local enhancements of the electric field strength and consequently to a lower corona inception voltage than is obtained from the above equation. This often means that the critical gradient for initiating radio noise has, under foul weather conditions, about half the value given by Peek's formula.

Atmospheric conditions likewise play an important part in occurrence of corona and spark discharges. In conditions of rain, fog, snow or dew, drops of water form on the surface of the conductor, and at low temperatures ice can form. This further reduces the corona inception voltage and increases the noise level as shown in Clauses 5 and 6.

With regard to bad contacts and the production of small sparks, the effect of rain and humidity is to bridge the relevant gaps either by water droplets or by humid layers, thus reducing the level of this type of noise.

Rain and humidity thus affect the corona noise from conductors in a way opposite to that due to bad contacts. Hence when interference is observed during rain or fog, it can be concluded that it is caused by corona. On the other hand, when interference is observed during fair weather and disappears or decreases during rain or fog, it is due to bad contacts.

4.3 Main characteristics of the noise field resulting from conductor corona

4.3.1 General

To rationalize the measurement of radio noise from a transmission line and facilitate comparisons between different lines, it is desirable to standardize the conditions under which the measurement is to be carried out.

The main characteristics of the noise field are the frequency spectrum, its lateral field strength profile and the statistical variation of the noise with weather conditions. It is assumed as a first approximation that these characteristics are independent of each other.

4.3.2 Frequency spectrum

The frequency spectrum is the variation of the radio noise measured at a given point in the vicinity of a line, as a function of the measurement frequency. Two phenomena are involved:

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a) Current pulses

The current pulses generated in the conductors by the discharges show a particular spectrum dependent on the pulse shape. For this type of discharge, the measured noise level decreases with an increase of the measurement frequency. In the frequency range 150 kHz to 1,606 5 MHz, where the positive discharges have a predominant effect, the spectrum is independent of the conductor diameter.

b) Attenuation along the line

The attenuation of noise propagating along the line increases with frequency. This effect modifies the spectrum by reducing still further the noise level with increase in frequency.

The measured spectra are often fairly irregular because of the standing waves caused by discontinuities such as angle or terminal towers or abrupt ground level variations. In addition, the noise generation might vary whilst the measurements are being made.

To aid prediction calculations, "standard spectra" are used. Experience has shown that all spectra can be put into two families, one applying to horizontal conductor configurations, the other to double-circuit and triangular or vertical conductor configurations. The difference between these two families originates from the phenomenon mentioned in item b) above, the propagation differing slightly according to the type of line. However, as the difference is not material in relation to the accuracy of such calculations, only one standard spectrum is given in relative values, the reference point being taken at 0,5 MHz.

The following equation is a good representation of this spectrum:

$$\Delta E = 5\left[1 - 2\left(\lg 10 f\right)^2\right] \text{ in dB}$$

where

ΔE is the deviation of the radio noise level at a given frequency f which is different from the reference frequency of 0,5 MHz; and

f is the numerical value of the given frequency, taken in MHz, where the equation is valid over the range 0,15 MHz to 4 MHz.

It should be noted that other investigators have developed different equations which give similar results.

At higher frequencies the noise spectra are more difficult to predict.

4.3.3 Lateral profile

The variation of the noise fields as a function of increasing lateral distance from the line is characterized by a decrease depending on the frequency. Measurements are taken along a perpendicular to a mid-span which is as close as possible to an average span of the line under consideration. The proximity of substations or interconnections, sharp angles, neighbouring lines and great variations in level of terrain shall be avoided.

Lateral profiles of the radio noise field can be determined either using the direct distance D or the lateral distance y.

Conventions

(1) In order to allow for comparison of obtained profiles of the noise field, the profile is determined at a height of 2 m above the ground immediately beneath an outside conductor over a distance D or y not exceeding 200 m. Beyond this distance, the noise level of the lines generally becomes negligible. The reference frequency for CISPR measurements is 0,5 MHz.

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(2) For the profiles which relate to the direct distance D, this distance is to be taken from the nearest conductor of the line (reference point (x,y,z), i.e. x = place along the line at mid-span in between two towers where the measurements are made, y = 0 m and z = n m corresponding to the height above ground of the outmost sub-conductor) to the centre of the measuring antenna. For comparison purposes, it has been agreed that the reference distance through which the profiles eventually converge is the direct distance D_0 of 20 m also referred to later on as the *CISPR position*. Figure 2 shows an example.

(3) For the profiles which relate to the lateral distance y, this distance is to be taken laterally (at ground level) from the vertical projection to ground of the outmost sub-conductor of the transmission line (reference point (x,y,z), i.e. x = place along the line at mid-span in between two towers where the measurements are made, y = 0 m and z = 2 m corresponding to the vertical projection to ground of the outmost sub-conductor) to the centre of the measuring antenna. For comparison purposes, it has been agreed that the reference distance through which these profiles eventually converge is the lateral distance y_0 of 15 m.

The standard profiles shown in Annex B, Figures B.1 to B.13, refer to the lateral distance y. Care should be taken as to not confuse measurement results obtained from measurements at direct and/or lateral distances.

(4) Normalised and/or standard profiles (for the catalogue) are usually shown with a logarithmic scale of distance.

While the profiles obtained from measurements at direct distances correlate with the considerations on the prediction and predetermination equations, this is not necessarily the case for the profiles obtained from measurements at lateral distances. In the latter case, such correlation is only given for conventional transmission lines with a conductor height above ground of up to 15 m. As a rule, future profiles of the noise field will be presented as a function of the lateral distance y in relation to a reference distance y_0 = 15 m, see also Figure 1. Such a presentation is useful for predicting the width of the corridor along the pathway of the transmission line subject to interference. It can be used for any type of modern transmission line regardless of the height of the towers and the conductors above ground. It is quite obvious that in such conditions the classical prediction equations found elsewhere in this publication may become invalid. If needed, the validity of these equations should be checked.

The measured profiles are often irregular both because of the continual fluctuations of the radio noise during a series of measurements and because of irregularities such as angle or dead-end towers and terrain variations.

Numerous measurements carried out under some fifty different lines have provided a good experimental knowledge of these profiles, which has been confirmed by theoretical calculations [1, 35].

An accurate analysis has enabled profiles to be plotted as functions of classes of line voltage and configuration up to distances of about 100 m, beyond which the noise level is normally so low that reliable measurements are not practicable.

In the vicinity of a power line there are two types of noise fields, the direct or guided field and the radiation field. The latter is a result of irregularities in the line such as conductor sag and changes in line direction and imperfect ground conductivity. Both fields contribute to the resulting observed total field strength. The field strength component of the direct field decreases as the square of the increasing lateral distance from the line, while the field strength component of the radiation field decreases directly with the increase of this lateral distance. Close to the line the direct field predominates, whereas at greater distances the radiation field predominates. Based on certain antenna concepts, the magnitudes of the two field strength contributions may be expected to be equal at a distance of around $300/2\pi f$ m where f is to be taken as the numerical value of the frequency in MHz. In actual fact, the lateral attenuation close to the line falls off less rapidly than the square of the distance. The attenuation factor k for frequencies between 0,5 MHz and 1,6 MHz, for example, is 1,65 (see Annex C). Close to the line the lateral attenuation may be described by:

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$$E = f(D) = E_0 + 20k \lg D_0/D \quad \text{in dB}(\mu\text{V/m})$$

where

E is the level of the electric component of the noise field strength, in dB(μV/m), at a direct distance D;

k is the attenuation factor;

E_0 is the level of the electric component of the noise field strength, in dB(μV/m), at the reference distance D_0 = 20 m.

NOTE For conventional transmission lines, this direct distance D_0 corresponds to a lateral distance y_0 = 15 m.

Further from the line, the attenuation factor gradually decreases until it reaches a value of unity. Some investigators consider that the magnitudes of the two field contributions are equal at around 300/2πf m as discussed above.

Standard profiles are shown with a logarithmic scale of distance referring to a direct distance to the conductor of 20 m. This presentation shows the physical law of the noise field strength decreasing as a function of the distance from the nearest conductor. The profiles can also be presented as a function of the lateral distance. This presentation is useful for predicting the width of the corridor subject to interference.

4.3.4 Statistical distribution with varying seasons and weather conditions

The systematic study of fluctuations in the radio noise level of a line necessitates the continuous recording of the field strength under this line for at least a year at a fixed distance from the line and with a fixed measurement frequency. Numerous researchers, in many countries, have carried out such measurements with the result that there exists fairly reliable data on the annual or seasonal variations in radio noise level. These results are often presented according to statistical analysis methods, which are to say in the form of histograms or as cumulative distributions. The latter express the percentage of time during which the radio noise level was less than a given value.

The most important causes of fluctuations in recorded radio noise level are:

– the random nature of the phenomenon;
– variations of the meteorological conditions, both at the measuring point and along the few tens of kilometres of the line which contributes to the local interference;
– changes in the surface state of the conductors, which is affected not only by weather conditions such as rain and frost, but also by deposits of dust, insects and other particles.

These causes are very difficult to measure systematically. Even variations of the applied line voltage result in fluctuations in the radio noise level, but this cause is possible to measure.

The distribution of the noise levels likewise depends on the type of climate; a very humid climate, a rainy one, or one with abundant snow or frost will increase the percentage of high levels, whereas a very dry climate will reduce it.

The curves in Figures 3 to 6 in a temperate climate show examples of an all-weather distribution survey, together with a dry weather distribution and an average heavy-rain distribution. It can be seen that the overall curve is more or less a combination of two or three Gaussian distributions.

On such an all weather distribution, it is customary to define several characteristic radio noise levels:

– The *99 % level* is practically the highest possible level of the line, at a given point.
– The *average heavy-rain level* is the most stable and reproducible and the rainfall is considered to be heavy when it reaches 0,6 mm or more per hour. For this reason, the

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average heavy-rain level is often chosen as the reference level for the calculation of radio noise. Practically, the average heavy-rain level is a 95 % level and is about 5 dB lower than the 99 % level.

– The *average fair weather level*, corresponding to dry conductor conditions. This is important for practical purposes, but, due to the larger dispersion, a greater number of measurements throughout the year are necessary to obtain reliable results. Fortunately, measurements are more easily made in average fair weather than in average heavy rain.

– The *50 % level*, read on the all-weather cumulative curve. This 50 % level shall not be confused with the above defined average fair weather level, since it arises not only from dry weather conditions, but also from the whole range of climatic conditions prevailing during the long term recordings. Both the average fair weather and 50 % levels are furthermore strongly dependent on the surface state of the conductors; these levels can vary over a range of more than 10 dB according to whether or not the conductors are polluted, greasy, etc. Some experts consider that the 50 % level will not vary by more than 10 dB over a relatively long period, say a month or a year, even though individual readings may vary by more than 10 dB.

– The *80 % level*, read on the all-weather distribution curve, is chosen as the characteristic value, to be used as the basis for limits. This 80 % level, intermediate between the fair weather level and the average heavy-rain level, is probably less subject to uncertainties than the 50 % level and for this reason is preferred as the "characteristic level". A survey of numerous cumulative curves shows that the difference between the 95 % and 80 % levels lies between 5 dB and 12 dB. As mentioned in 4.3.3, it should be remembered that beyond about 100 m to 200 m, reliable measurements are normally not practicable.

The above generalized guidelines are illustrated in Figures 3 to 6, related to 400 kV to 765 kV lines, and are valid for lines where the predominant noise source is conductor corona.

5 Effects of corona from conductors

5.1 Physical aspects of corona from conductors

5.1.1 General

The generation of radio noise by conductor corona is by means of the electrical discharge, usually called corona, occurring at or near the conductor surface. Corona is defined as "a discharge with slight luminosity produced in the neighbourhood of a conductor and limited to the region surrounding the conductor in which the electric field strength exceeds a certain value". Many aspects of corona discharge on lines are unknown and undefined; however, the basic physical process is that of electron multiplication or avalanche formation. The electric gradient in the vicinity of the line conductor is the highest gradient and, if this gradient or electric stress is sufficiently high, any free electrons in the air around the conductor will ionize the gas molecules and electrons produced by this ionization will cause an avalanche. If an additional electron is formed in this gradient by some process from the original electron avalanche, a new avalanche is formed by this secondary process and the corona discharge is developed.

In the case of the transmission line conductor, it is believed that the important secondary process is the ejection of electrons from gas molecules by high energy ultra-violet light (photoionization) generated by the original avalanche. It has been found by several investigators that the radio noise level generated when the conductor is positive is significantly greater than it is when the conductor is negative. In the case of a positive overhead line conductor, the cathode is so far away that cathode emission is of no consequence and the secondary process existing in this case is photoionization of the gas.

When streamer corona forms at a point on the conductor, two types of pulse fields will exist. Near the streamer a localized field is formed and along the line the direct field is developed due to the pulses travelling down the line. For the design of extra high voltage lines, only the direct field is considered significant, and the most useful measurements are made at some distance from the streamer locations on the line conductor.

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For a more detailed discussion of the theoretical aspects of conductor corona, see [1, 2] [3].

5.1.2 Factors in corona generation

5.1.2.1 General

The possibility of a corona discharge taking place at the surface of a conductor is dependent upon several factors, these include:

a) theoretical conductor surface voltage gradient which depends on:
   1) system voltage;
   2) conductor diameter;
   3) spacing of the conductor from earth and other phase conductors;
   4) number of conductors per phase or in the bundle;
b) conductor diameter;
c) conductor surface conditions;
d) atmospheric and weather conditions.

Each of these factors will be considered separately.

5.1.2.2 Conductor surface voltage gradient

One of the most important quantities in determining the radio noise level of a line, especially when conductor corona is dominant, is the strength of the electric field in the air at the surface of the conductor or surface voltage gradient.

Because of the close dependence of conductor corona on the value of this voltage gradient, it is necessary to use a method of calculation which gives the gradient with a precision of about 1 %.

Since conductors are usually stranded, the surface voltage gradient varies about a mean value around the circumference of the conductor. However, it is customary to calculate the surface gradient for a smooth conductor with the same overall diameter, even if an experimental stranding factor has to be introduced.

Equations for the calculation of the voltage gradient at the surface of a conductor are given in Annex A for the simple case of a single-phase line with earth return or a monopolar DC line to the more complex three-phase multi-circuit and bipolar DC lines. Usually the calculations need a matrix equation and computer programs are used for both single and multi-circuit three-phase lines and the more complex high-voltage DC lines.

5.1.2.3 Conductor diameter

The radio noise level increases with increasing conductor diameter even if the conductor surface gradient remains the same. This phenomenon is due to the fact that the decay of the electric field strength from the surface of a conductor decreases with increasing conductor diameter. Therefore, the electric field surrounding a large conductor can support longer corona streamers than the electric field around small conductors.

5.1.2.4 Conductor surface conditions

The type of conductor, for example circular or segmental stranding, and the condition of its surface, that is to say the degree of smoothness or roughness, the presence or absence of pollution, water droplets, snowflakes, etc., have a strong influence on the generation of

[3] The figures in square brackets refer to the Bibliography.

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corona. A transmission line conductor when first strung will usually have higher corona activity due to surface irregularities such as aluminium burrs, bird droppings, dust, soil, mud or any other deposits causing corona even in fair weather. However, after a line is energized the corona losses and radio noise will decrease with time.

There are usually two time periods involved; the first period is the first few minutes after the conductor is energized and the corona activity is burning off the dust and other particles that have collected on the conductor before it was energized. The longer time period is needed to blacken completely a conductor which makes it look weathered and also destroys the surface grease on new conductors.

There is also evidence that as the conductor ages the radio noise level, even during rain, will decrease. The surface of a new conductor is hydrophobic, due to the oil that is present on the surface from the manufacturing processes, and water beads form on this oily surface. As the conductor ages, its surface becomes hydrophilic whereby the surface of the conductor draws up the water drops into the strands.

5.1.2.5 Atmospheric and weather conditions

A reduction in the barometric pressure or an increase in the ambient temperature, or both, can reduce the air density which reduces the breakdown strength of air and thereby increases the likelihood of a corona discharge taking place on a conductor. The barometric pressure is usually important only at altitudes above approximately 1 000 m. In areas that have sufficient rain, fog, frost or falling temperatures which can lead to the formation of ice or water droplets on the conductor, corona discharges are more likely to take place due to these conditions. Rain and snow are the cause of the highest corona activity at the surface of a conductor and can cause the radio noise level to increase by more than 20 dB compared with the noise from the same line under dry conditions. The water droplets or snow which collects on the conductor surface during a storm modify the electric field significantly, creating a large number of corona sources. Discharges may also occur when a snowflake or raindrop passes the conductor and initiates a discharge from the conductor to the particle.

5.2 Methods of investigation of corona by cages and test lines

5.2.1 General

Two basic methods have been used to investigate the corona phenomena from transmission lines. These are test cages and test lines [9, 21, 31].

5.2.2 Test cages

Test cages have been used by many experimenters to determine rapidly the excitation function of a conductor or a bundle of conductors [4 to 6]. The excitation function is related to the current in the bundle by the following:

$$I = \Gamma \frac{C}{2\pi\varepsilon_0} \tag{1}$$

where

I is the high frequency current injected into the conductor or bundle of conductors in A/m$^{1/2}$,

C is the capacitance in F/m;

Γ is the excitation function in A/m$^{1/2}$, and

ε_0 is the absolute permittivity of the air.

The main advantage of the concept of the excitation functions is that it is a quantity independent of the conductor capacitance per unit length.

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The radio noise current in a test cage is measured using measuring instruments complying with CISPR 16-1-1. The current at one end of the conductor or bundle is passed through a high-frequency coupling circuit similar to those described in 4.5 of CISPR TR 18-2:__[4]. The equivalent impedance of the resistors and of the measuring instrument used in these circuits is usually made equal to the characteristic impedance of the conductor or bundle to avoid the occurrence of successive reflections.

Test cages have been found to give reproducible radio noise data under heavy rain but, under foul weather conditions, they have proved inadequate because of the relatively small number of sources per unit length of conductor under normal stress. The length of conductor in a cage is generally too short to give a representation of an actual long line. Additionally, the surface condition of the conductor and meteorological conditions surrounding a short line near to the ground are not necessarily the same as the conditions on an operational line.

Application of the excitation function to multi-phase lines requires the use of Equation (1) in matrix form [7 to 9].

$$[I] = \frac{1}{2\pi\varepsilon_0} \times [C] \times [\Gamma] \qquad (2)$$

5.2.3 Test lines

Whilst test cages are built for reasons of economy and ease of testing, full-scale test lines are still being built, primarily to study corona phenomena on future ultra high voltage (UHV) lines. There is no standard length for test lines. Test lines, single and three-phase AC lines and bipolar DC lines, as long as 8 km and as short as 300 m have been built [10 to 30].

There have been some attempts to measure the excitation function on short test lines and with some success, especially on short DC test lines [28, 29].

For long transmission lines, the radio noise frequency spectrum exhibits a characteristic of a steadily decreasing level with increasing frequency. However, for short test lines this situation does not exist. Due to reflections of the radio noise voltages and currents at the line terminations, a standing-wave pattern in the frequency spectrum is created. This spectrum is characterized by sharp peaks and broad valleys, the exact form being dependent on the length of the line, the type of terminations, and the longitudinal location of the measuring point.

The approach that has been used by most investigators to correct the short-line frequency spectrum to the long-line spectrum is the "Geometric mean method" [12, 14 to 16, 18, 26, 29]. This correction is made by taking the geometric mean in terms of μV/m of the successive maxima and minima of the short line frequency spectrum. In terms of dB(μV/m), the arithmetic mean is used.

This approach, strictly speaking, is only valid for the idealized case of a perfectly horizontal single phase line with terminations that appear as pure open circuits for radio frequencies. However, experimental studies show that, for all practical purposes, this approach is valid for AC and DC lines [28, 32, 33].

5.3 Methods of predetermination

5.3.1 General

Because of the need for higher transmission voltages, a considerable amount of research has been conducted over the past 50 years, in various parts of the world, to understand the

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corona process. One of the primary purposes of this research was to develop methods to predetermine radio noise.

Radio noise measurements that have been conducted on short full-scale single and three-phase AC test lines, on DC test lines, on operational lines, and in the laboratory, have resulted in several empirical and semi-empirical equations for predicting radio noise. These equations can be used to predict the radio noise performance of different high-voltage lines, as long as the voltage and the design parameters are known. All the methods rely on experimental data either from test lines, operational lines or test cages. Two basic methods have evolved over the years, the first one being analytical or semi-empirical and the second being empirical or comparative.

5.3.2 Analytical methods

No purely analytical method of predicting transmission line radio noise exists. Two semi-empirical methods have been developed by Electricité de France (EDF) [8] and Project Ultra High Voltage (UHV) [7] in the United States of America. Both of these analytical methods rely on radio noise data from test cages and on highly complex analysis, and they are adequately described in the literature.

The calculation of radio noise from transmission lines using these analytical methods is a two-stage process. The excitation function is obtained from cage tests, the system of line capacitances is established and the injected noise currents per unit conductor length are calculated using Equation (2). The theory of modal propagation is applied to obtain the modal currents flowing in a given cross-section of the line. The attenuations of propagation of these modal currents are calculated and these currents are recombined into real high-frequency currents taking into account the quadratic summation over the whole line length to obtain the total noise currents.

The next step is to calculate the noise field near the line, which is based on the total noise currents through the cross-section of the line, or the noise voltages on the phases. The lateral noise profile can then be obtained (see examples in 5.4).

Computer programs are usually used to perform these complex calculations and such programs have been written at EDF and Project UHV.

5.3.3 CIGRÉ method

The comparative equations are generally quite simple and easy to use. Some of the best known equations for AC lines are described in a CIGRÉ Publication [1] and the technical literature [34, 35]. There are also several comparative equations for DC lines and these are described in Clause 8.

The highest precision of predetermination, using any of these equations, is obtained by choosing long-term data from an operational reference line which uses conductors or bundles close to those being studied [36, 37, 38].

CIGRÉ has made a more complete analysis of the different predetermination methods using the data collected by the CIGRÉ/IEEE Survey [6, 34, 35]. From this analysis they developed a new method that can be considered optimal. This method is expressed by a fairly simple equation, which is given in 5.3 of CISPR TR 18-3:__[5] [59].

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

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5.4 Catalogue of standard profiles

5.4.1 General

A large number of measurements on operational lines, together with calculations supported by measurements on cage and test lines, have been carried out and examples of the results for a variety of line designs are given in Annex B. The given values are valid only for lines constructed and maintained according to normal practice and not heavily polluted, as otherwise these conditions can give rise to higher radio noise levels than those due to conductor corona.

Annex B gives the estimated value of the radio noise field which is possible to obtain under certain well-defined conditions. It also includes references which can be used for predetermining the field that a new line may be expected to produce. It also includes, as examples, curves giving the field strength as a function of the lateral distance *y* from the line for certain types of line (see Figures B.1 to B.13).

NOTE The appearance of a given line in the catalogue in Annex B does not mean that this line generates an acceptable radio noise level; it gives only an indication of the order of magnitude to be expected for the given line design.

5.4.2 Principle of catalogue presentation

Radio noise measurements taken both on operational lines and on test lines have indicated that the stability and reproducibility of the field due to conductor corona is most accurate under conditions of heavy and continuous rain. It should be noted that this heavy rain value may not be the maximum foul-weather value, which can be a few dB higher.

Extensive statistical surveys have also indicated that there is a reasonable correlation between the heavy rain radio noise level and the 50 % fair-weather level, though the dispersion under fair-weather conditions is larger. For practical purposes, the 50 % fair-weather level is usually of greater importance, this value being derived from the heavy continuous-rain level by a reduction of between 17 dB and 25 dB, depending upon conductor surface conditions.

It is therefore possible to establish a catalogue of radio noise fields for certain transmission lines. For the practical use of this catalogue, three noise levels are considered, namely the 50 % fair-weather level and, depending on the origin of the profiles, either the heavy-rain level (20 dB higher) or the maximum foul-weather level (24 dB higher). From these reference levels, it is possible to estimate the radio noise levels for other types of weather, if the yearly statistical distribution of levels is known for the geographical area under consideration (see, for example, Figure B.15).

These principles are valid only for radio noise generated by conductor corona. The radio noise currents generated by other components of the line, insulator strings, hardware and so on, are not taken into consideration. These conditions are satisfied when the conductors of the line are subjected to a relatively high surface stress, in excess of, say, 14 kV RMS/cm when referred to smooth conductors. However, for lines whose conductors are subjected to a surface stress less than, say 12 kV RMS/cm, it is the radio noise from the insulators and other hardware which may, under certain conditions, predominate. Under these conditions, it is not possible to use this catalogue to predict the noise level since a good quality of insulators and hardware has been assumed.

The radio noise profiles for the 225 kV, 380 kV and 750 kV lines included in this catalogue were calculated by the Analig method [8].

The profiles for the 362 kV, 525 kV and 765 kV lines were determined from the results of the CIGRÉ/IEEE survey [35, 39].

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The radio noise profiles for the 345 kV and 765 kV HV transmission lines included in this catalogue were calculated by the comparative method [56].

The surface gradients have been calculated using the general method of potential coefficients. This method gives, with great accuracy, the electric surface gradient of each conductor of a line. A survey of methods for calculating transmission line surface voltage gradients is given in [40].

The shape of the lateral profiles of the radio noise field is essentially dependent on the conductor configuration. The distance between phases and their height above the ground have a major influence. The type of conductor or the bundle only slightly affects the shape of the profile owing to the structure of the capacitance matrix. When changing from one type of conductor to another with the same geometry, so long as the two matrices are proportional to each other, the profile will not be significantly changed. This assumption is sufficiently true to be applied in practice.

In Annex B, profiles have been assembled for certain types of overhead power line. The influence of the number and arrangements of conductors per phase, their diameter and their voltage gradient, were taken into account merely by applying the appropriate correction to a reference profile. Thus each figure in the catalogue gives such a reference profile and a table of values and corrections applicable to other lines using other conductors and bundles.

The profiles are given for a measurement frequency of 0,5 MHz and the radio noise levels for other frequencies, 0,15 MHz to 4 MHz, can be obtained from Figure B.14.

The variations of the radio noise level, due either to climatic conditions or surface state of the conductors, can also be taken into consideration by estimated corrections to the levels of the basic profiles (see Figure B.15).

Examples of measurements and calculations can be found in [8, 35, 39].

The catalogue is summarized in Annex C according to the conventions agreed so far in CISPR; that is to say the strengths of the radio noise fields are plotted as a function of the direct distance, measured from the centre of the loop antenna to the nearest conductor of the line, using a logarithmic scale. From Figure C.1, it is seen that substantially straight lines are obtained, and the field strengths at the reference distance of both, D_0 = 20 m (direct distance) and simultaneously y_0 = 15 m (lateral distance) are obtained by interpolation.

The main radio noise levels, given in the catalogue, are listed in the table of Annex C; from this table it is possible to compare the levels of the various lines given in the catalogue and to predict, with sufficient accuracy for practical purposes, the field strength to be expected from a proposed line of similar design, provided the distance between a receiving antenna and the nearest conductor of the line is greater than 20 m.

6 Radio noise levels due to insulators, hardware and substation equipment (excluding bad contacts)

6.1 Physical aspects of radio noise sources

6.1.1 General

Insulators, hardware and substation equipment may be the source of radio noise which may lead to radio and, in some cases, to television interference also. This may be due to various phenomena such as corona discharges in the air at insulators and hardware, surface discharges on insulators and sparks due to bad contacts. Commutation effects in AC/DC converting equipment, which can also be a source of radio noise, are discussed in Clause 8.

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