

Radio interference characteristics of overhead power lines and high-voltage equipment —

Part 1: Description of phenomena

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the General Electrotechnical Standards Policy Committee (GEL/-) to Technical Committee GEL/110, upon which the following bodies were represented:

- Association of Control Manufacturers (TACMA) (BEAMA Ltd.)
- Association of Manufacturers of Domestic Electrical Appliances
- BEAMA Interactive and Mains Systems Association (BIMSA)
- BEAMA Ltd.
- British Industrial Truck Association
- British Lighting Association for the Preparation of Standards (Britlaps)
- British Telecommunications plc
- Department of Health
- Department of Trade and Industry
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- Association of Manufacturers Allied to the Electrical and Electronic Industry (BEAMA Ltd.)
- British Industrial Ceramic Manufacturers' Association
- Bus and Coach Council
- Department of Trade and Industry Electricity Division
- Electrical and Electronic Insulation Association (BEAMA Ltd.)
- Railway Industry Association of Great Britain

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National foreword

This Part of BS 5049 has been prepared under the direction of the General Electrotechnical Standards Policy Committee. It is identical with CISPR 18-1:1982 *Radio interference characteristics of overhead power lines and high-voltage equipment — Part 1 Description of phenomena*, published by the International Electrotechnical Commission (IEC) on behalf of the International Special Committee on Radio Interference (CISPR).

The purpose of this Part of BS 5049 is to discuss the physical phenomena involved in the generation of electromagnetic noise fields; it also includes the main properties of such fields and their numerical values.

The technical data given in Part 1 will 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 which are included in Parts 2 and 3 of this standard.

This Part of BS 5049, together with Part 3, supersedes BS 5602:1978 which is withdrawn.

Cross-references

International standard	Corresponding British Standard
	BS 5049 <i>Radio interference characteristics of overhead power lines and high-voltage equipment</i>
CISPR 18-2:1986	Part 2:1994 <i>Methods of measurement and procedure for determining limits</i> (Identical)
CISPR 18-3:1986	Part 3:1994 <i>Code of practice for minimizing the generation of radio noise</i> (Identical)

The Technical Committee has reviewed the provisions of CISPR 16, to which normative reference is made in the text, and has decided that they are acceptable for use in conjunction with this standard.

References to page numbers in the text are to page numbers in CISPR 18-1 (1982) and should be ignored for the purposes of this British Standard.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 54, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

1 Scope

This publication 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 300 MHz.

2 Object

This publication has been prepared in order to provide information on the many factors involved in protecting the reception of radio and television broadcasting from interference due to high voltage overhead power lines and associated equipment. The information given should be of assistance when means of avoiding or abating radio noise are being considered. The publication does not deal with interference due to the fields produced by power line carrier signals.

Information is mainly given on the generation and characteristics of radio noise from a.c. power lines and equipment operating at 1 kV and above, in the frequency ranges 0.15 MHz to 30 MHz (a.m. sound broadcasting) and 30 MHz to 300 MHz (f.m. sound broadcasting and television). The special aspect of spark discharges due to bad contacts is taken into account. Some information is also given on interference due to d.c. overhead lines for which corona and interference conditions are different from those of a.c. power lines. Interference due to the current collecting equipment of overhead railway traction systems is not included.

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

The clause on limits concentrates on the low frequency and medium frequency bands as it is only in these that ample evidence, based on established practice, is available. No examples of limits to protect reception in the frequency band 30 MHz to 300 MHz have been 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 at frequencies higher than 300 MHz are so low that interference is unlikely to be caused to television reception.

The values of limits given as examples are calculated to provide a reasonable degree of protection to the reception of 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 standards 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 to minimize interference and it is hoped that this publication will aid other radio services in the consideration of the problems of interference.

3 Introduction

3.1 Radio noise from high voltage, that 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 and fittings;
- b) discharges and sparking at highly stressed areas of insulators;
- c) sparking at loose or imperfect contacts.

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 fittings 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.

3.2 If the field strength of the radio noise at the aerials used for receiving broadcast sound and television services is too high, it can cause degradation of the sound output and, in the case of television, the picture also.

3.3 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 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 fine 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.

3.4 For the interference-free reception of radio and television 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.

3.5 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 be propagated along the line over a considerable distance.

3.6 The scope of this publication 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 broadcast services.

4 Radio noise from power lines

4.1 Physical aspects of radio noise

4.1.1 *Mechanism of formation of a noise field*

Corona discharges on conductors, insulators or line fittings 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 propagates 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 change-over is not abrupt and the phenomena 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 aerial 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.

4.1.1.1 *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 of a current wave $I(t)$.

For a given frequency the two quantities are related by the expression $U(\omega) = ZI(\omega)$ 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:

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

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

U_0 and I_0 are the amplitudes at the source and x is the distance of propagation along the line.

In the 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 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 publication. 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.

4.1.1.2 Electromagnetic field

The 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 fields 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:

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

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 fields differ from those for radiated fields in free space as they are largely determined by the geometrical arrangement 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 respectively.

The electric field $E(y)$ at ground level of a single conductor line, which is the vertical component of the total electric field, is given by the approximate formula based on simplified assumptions:

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

where I is the current, in amperes, propagating in the conductor h is the height, in metres, of the conductor and y is the lateral distance, also in metres, from a point directly under the conductor to the measuring point.

Furthermore, for an infinitely long single conductor line, the induction zone, or near field, has the same simple ratio of electric and magnetic fields 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 electric field is the vectorial sum of the individual fields associated with each phase conductor. A more comprehensive treatment, together with practical methods of assessing the electromagnetic field, is discussed in Clause 9 of C.I.S.P.R. Publication 18-2: Radio Interference Characteristics of Overhead Power Lines and High Voltage Equipment, Part 2: Methods of Measurement and Procedure for Determining Limits (under consideration). The formula given above is a simplified version accurate for $D = 20$ m and $f = 0.5$ MHz where D is the distance, in metres, between the measuring set aerial and the nearest conductor of the line and f is the measurement frequency. For a wider range of D and f it would be necessary to take into account all the parameters affecting the formula.

4.1.1.3 Aggregation effect

In the case of uniformly distributed noise sources, the field 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:

$$E^2(y) = 2 \int_0^\infty E_0^2(y) e^{-2ax} dx$$

or

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

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 the case of multi-phase lines, the calculation follows the same 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.

4.1.2 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 set is basically a tuneable selective and sensitive voltmeter with a specified pass-band. When connected to a suitable rod or loop aerial and properly calibrated, it can measure the electric or magnetic component of the noise field.

Depending on the design of the measuring apparatus, the noise level can be measured in terms of r.m.s., peak or quasi-peak values. The r.m.s. 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 r.m.s. 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. This principle is adopted in the C.I.S.P.R. measuring instruments, details of which are given in C.I.S.P.R. Publication 16. The noise level is thus defined by the value measured by such an instrument expressed in microvolts or microvolts per metre. Using the ratio of the electric to magnetic fields, $E/H = 377$, the measured values can be expressed by convention in microvolts per metre even for instruments using a loop aerial responding to the magnetic field.

4.1.3 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 a.c. voltages, g_c is the peak value of the gradient, r is the radius of the conductor in

centimetres, $\delta = \frac{0.294\rho}{273+t}$ is the relative air density ($\delta = 1$ for $\rho = 1.013$ mbar and $t = 25^\circ\text{C}$).

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 and consequently to a lower corona inception voltage than is obtained from the above formula. 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 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 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 fine weather and disappears or decreases during rain or fog, it is due to bad contacts.

4.2 Main characteristics of the noise field resulting from conductor corona

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, the lateral 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.

4.2.1 Spectrum

The 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:

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 falls with frequency. In the range of broadcasting frequencies, where the positive discharges have a predominant effect, the spectrum is independent of the conductor diameter.

b) *Attenuation*

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 formula is a good representation of this spectrum:

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

where ΔE (dB) is the variation of the radio noise level from the reference frequency of 0.5 MHz and f is the frequency expressed in megahertz over the range 0.15 MHz to 4 MHz.

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

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

4.2.2 Profile

The variation of the noise fields as a function of distance from the line is characterized by a decrease depending on the frequency. Measurements are taken along a perpendicular to a midspan 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 must be avoided.

The profile is determined at a height of 2 m above the ground from a point immediately beneath an outside conductor over a distance not exceeding 200 m. Beyond this distance the noise level of the lines generally becomes negligible. The reference frequency for C.I.S.P.R. measurements is 0.5 MHz.

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 terminal 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.

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 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. The direct field decreases as the square of the distance, the radiation field decreases directly as the distance. Close to the line the direct field predominates, whereas at greater distances the radiation field predominates. Based on certain aerial concepts, the two fields may be expected to be equal at a distance of around $300/2\pi f$ metres where f is in megahertz. 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 Appendix C). Close to the line the lateral attenuation may be described by:

$$E = E_0 + 20k \lg D_0/D$$

where:

E = noise level, in decibels (1 μ V/m) at distance D

k = attenuation factor

E_0 = noise level, in decibels (1 μ V/m) at the reference distance D_0

Further from the line the attenuation factor gradually decreases until it reaches a value of unity. Some investigators consider that the two fields are equal at around $300/2\pi f$ metres as discussed above. The equation at the end of Sub-clause 10.3.13 of C.I.S.P.R. Publication 18-2, for example, shows the profile in the 0.4 MHz to 1.6 MHz band assuming that the distance is 100 m from the line.

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 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.

4.2.3 Statistical distribution

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 is in existence fairly reliable data on the annual or seasonal variations in radio noise level. These results are often presented according to statistical analysis methods, that is 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 contribute 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 Figure 3 to Figure 6, pages 46 to 49, 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 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 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 is 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 must 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 Sub-clause 4.2.2, it should be remembered that beyond about 100 m to 200 m reliable measurements are not normally practicable.

The above generalized guide lines are illustrated in Figure 3 to Figure 6, pages 46 to 49, related to 400 kV to 750 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 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 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 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. For a more detailed discussion of the theoretical aspects of conductor corona [1, 2]¹⁾.

¹⁾ The figures in square brackets refer to “Bibliography and references”, pages 23 to 25.

5.1.2 Factors in corona generation

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.

5.1.2.1 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.

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

5.1.2.2 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 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.

5.1.2.3 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, snow flakes, etc., have a strong influence on the generation of 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.

5.1.2.4 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 collect 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

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

5.2.1 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:

$$I = \Gamma \frac{C}{2\pi\epsilon_0} \quad (1)$$

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 function is that it is a quantity independent of the conductor capacitance per unit length.

The radio noise current in a test cage is measured using measuring apparatus complying with Section 1 of C.I.S.P.R. Publication 16: C.I.S.P.R. Specification for Radio Interference Measuring Apparatus and Measuring Methods. The current at one end of the conductor or bundle is passed through a high-frequency coupling circuit similar to those described in Sub-clause 1.3 of C.I.S.P.R. Publication 18-2. 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 fair 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.

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

$$[I] = \frac{1}{2\pi\epsilon_0} \times [C] \times [\Gamma] \quad (2)$$

5.2.2 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 UHV lines. There is no standard length for test lines. Test lines, single and three-phase a.c. lines and bipolar d.c. 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 d.c. 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 $\mu\text{V/m}$ of the successive maxima and minima of the short line frequency spectrum. In terms of $\text{dB } \mu\text{V/m}$, 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 a.c. and d.c. lines [28, 32, 33].

5.3 Methods of predetermination

Because of the need for higher transmission voltages, a considerable amount of research has been conducted over the past 30 years, in various parts of the world, to understand the 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 a.c. test lines, on d.c. test lines, on operational lines, and in the laboratory, have resulted in several empirical and semi-empirical formulae for predicting radio noise. These formulae 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.

5.3.1 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 Sub-clause 5.4).

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

5.3.2 CIGRÉ method

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

The highest precision of predetermination, using any of these formulae, 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 formula, which is given in Sub-clause 11.2 of C.I.S.P.R. Publication 18-3: *Radio Interference Characteristics of Overhead Power Lines and High Voltage Equipment*, Part 3: (under consideration) [1].

5.4 Catalogue of standard profiles

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 Appendix 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.

Appendix B gives the estimated value of the radio noise field which it is possible to obtain under certain well-defined conditions. It also includes references which can be used for pre-determining the field that a new line may be expected to produce. It also includes, as examples, curves giving the field as a function of the distance from the line for certain types of line (see Figure B.1 to Figure B.11, pages 29 to 39).

The appearance of a given line in the catalogue in Appendix 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.

5.4.1 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 decibels higher.

Extensive statistical surveys have also indicated that there is 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.13, page 41).

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, fittings 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 r.m.s. per centimetre when referred to smooth conductors. However, for lines whose conductors are subjected to a surface stress less than, say, 12 kV r.m.s. per centimetre, it is the radio noise from the insulators and other fittings 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 fittings 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].

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 Appendix 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.12, page 40.

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.13, page 41).

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

The catalogue is summarized in Appendix C according to the conventions agreed in C.I.S.P.R.; that is to say the strengths of the radio noise fields are plotted as a function of distance, measured from the centre of the aerial loop to the nearest conductor of the line, using a logarithmic scale. From Figure C.1, page 43, it is seen that substantially straight lines are obtained and the field strengths at the reference distance of 20 m are obtained by interpolation.

The main radio noise levels, given in the catalogue, are listed in the table of Appendix 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 aerial and the nearest conductor of the line is greater than 20 m.

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

6.1 Physical aspects of radio noise sources

Insulators, fittings 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 fittings, surface discharges on insulators and sparks due to bad contacts. Commutation effects in a.c./d.c. converting equipment, which can also be a source of radio noise, are discussed in Clause 8.

This clause examines the phenomena of corona and surface discharges from the physical point of view; sparks due to bad contacts are dealt with in Clause 7.

6.1.1 Radio noise due to corona discharges at fittings

Corona discharges are caused by high potential gradients at certain surfaces of fittings such as suspension clamps, guard-rings or guard-horns, spacers and joints. Assuming that the voltage applied to the fittings is progressively increased, numerous different discharge processes occur. Only some of these are able to generate radio noise, but all are luminous to some extent and contribute to corona losses. The phenomena are similar to those described in Sub-clause 5.1 in respect of conductors. Similarly, in this case, various corona modes occur, depending on the voltage applied and in the following sequence: onset streamer, glow and pre-breakdown streamer for positive corona; Trichel or negative pulses, glow, and pre-breakdown streamer for negative corona. A glow discharge does not produce radio noise but onset streamers do. Trichel pulses produce low levels of radio noise but pre-breakdown streamers produce very high levels at very high voltages.

The highest noise levels occur with modes corresponding to the pre-breakdown streamer, both positive and negative; however, these phenomena take place at much higher gradients than those corresponding to normal voltages and are therefore of little practical interest.

As in the case of conductors, radio noise from fittings tends to increase in high humidity or rain, as a result of the increase in local gradients due to the presence of drops of water on the surface of the fittings.

6.1.2 *Radio noise due to insulators*

Insulator noise may be due to various reasons, most of which are associated with phenomena occurring at their surfaces, for example, small discharges due to enhanced local gradients, corona discharges due to unevenness created by dry deposits or drops of water, or sparks across dry bands caused by leakage currents on polluted insulators. Only in special cases, for example defective insulators, is the noise due to phenomena occurring inside the insulator, that is to say sparking in internal voids or punctures. However, radio noise can result from discharges between the cement and porcelain or glass and may occur if small air gaps are present at this margin.

When the surface of an insulator is clean and dry, the current pulses at the origin of the radio noise are caused by discharges in areas of high potential gradient, depending on the geometry and material of the insulator and on the type of bonding to the cap and to the pin. Figure 7, page 50, shows, by way of an example, the equipotential lines, expressed as a fraction of the applied voltage, in a cross-section of a clean and dry insulator unit.

It should be noted that these lines are much more concentrated and, therefore, the gradients are higher, near the cap and pin, where the discharges that cause the noise actually occur. The values of local potential gradients in an insulator unit, and therefore the noise levels, depend on the value of the voltage applied to the unit and, in the case of insulators consisting of several units, they also depend on the voltage distribution along the insulator string. This distribution tends to be less uniform as the number of units increases and, consequently, for the longer insulator strings or post insulators, it is necessary to have devices, such as metal rings, to improve the voltage distribution.

The current pulses producing the radio noise on a clean and dry insulator do not differ substantially between positive and negative polarity and, generally, the pulses occur between the zero and peak values of the applied power frequency voltage. The shape of these pulses and, consequently, the cut-off frequency of their spectrum, depends on the self-capacitance of the insulator and the surge impedance of the line to which the insulator is connected. For normal values of these parameters, the cut-off frequency is about 1 MHz. The noise produced by a clean and dry insulator is therefore limited to frequencies up to about 30 MHz and, generally, for insulators with average characteristics, fairly low levels are produced. Bad design and unsuitable bonding can, however, cause higher levels extending to higher frequencies. As is also the case with corona discharges at fittings, television reception is not usually affected by this type of radio noise.

If the insulator is lightly polluted and reasonably dry, for example in fair weather, the phenomenon described above is accompanied by corona discharges at surface irregularities caused by pollutants on the insulator. Generally this second phenomenon produces less serious effects than the first so that the noise levels, except in the case of certain types of pollution, for example near chemical works, are not significantly different from, or only slightly greater than, those occurring with a dry and clean insulator.

If the surface of the insulator is clean, but damp or wet, the existence of drops of water produces pronounced corona discharges which, generally, produce higher levels of radio noise than are produced by discharges from points of surface pollution. This latter phenomenon, in damp conditions, may become less important due to a better voltage distribution. The noise level is generally greater than with dry insulators but, again, it is limited to frequencies up to a few megahertz.

When the surface of the insulator is heavily polluted and wet, the phenomenon is completely different, since radio noise is produced by current pulses which flow when sparking occurs across the dry bands that are created by heating due to the passage of leakage currents on the surface of the insulator. The amplitude and number of these pulses depend on the voltage stress across the insulating dry bands, on the insulator shape and dimensions, on the surface conductivity of the pollutant layer and on the characteristics of the material at the surface of the insulator. The cut-off frequency of the spectra relating to these impulses may reach a few tens of megahertz and therefore the radio noise may also affect television frequencies. With wet and polluted glass or porcelain insulators, the radio noise at the normal voltage stresses, that are imposed by dielectric withstand requirements, may reach much higher levels than in other conditions previously described.