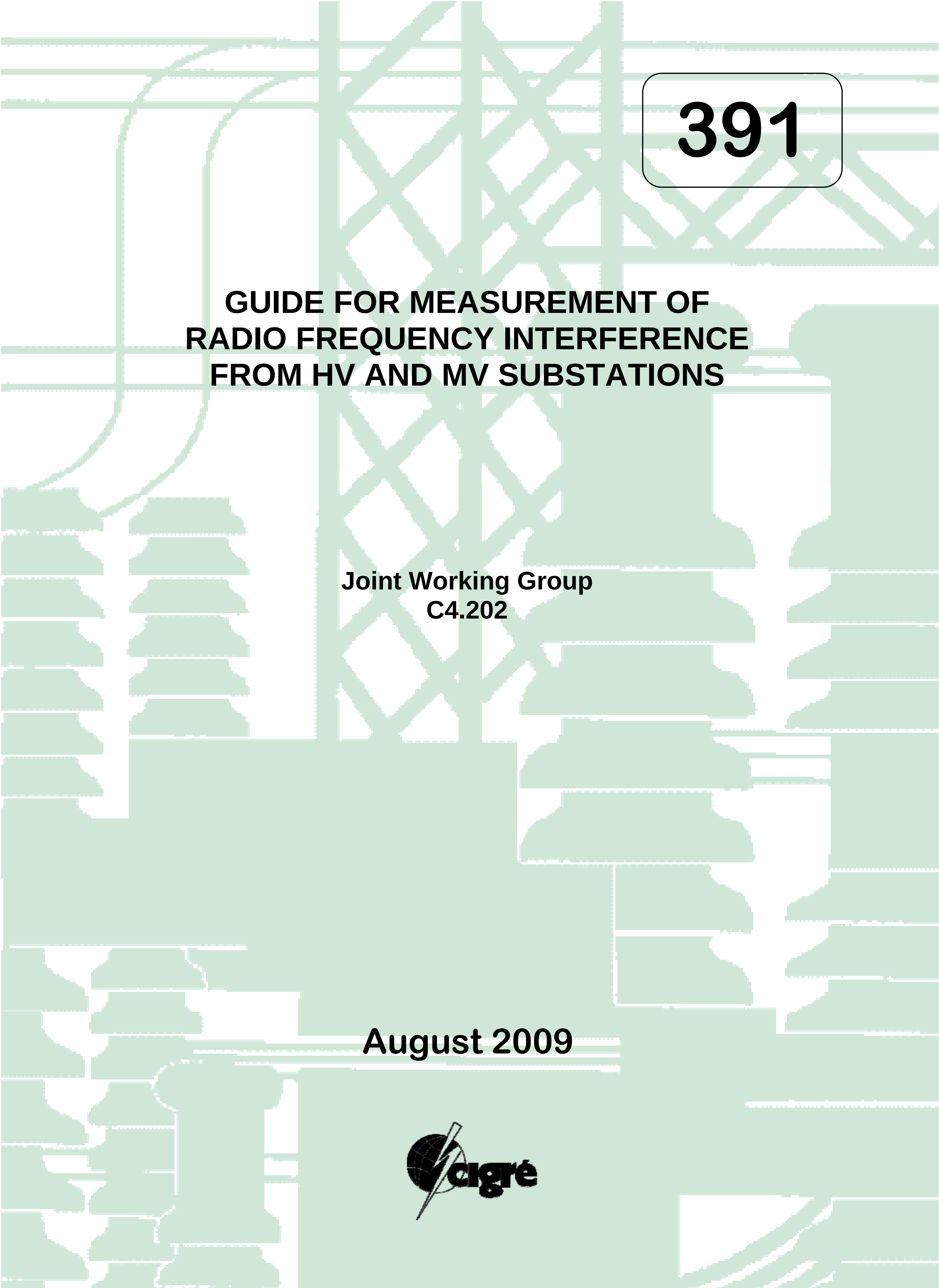

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GUIDE FOR MEASUREMENT OF RADIO FREQUENCY INTERFERENCE FROM HV AND MV SUBSTATIONS

Joint Working Group
C4.202

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GUIDE FOR MEASUREMENT OF RADIO FREQUENCY INTERFERENCE FROM HV AND MV SUBSTATIONS

DISTURBANCE PROPAGATION, CHARACTERISTICS OF DISTURBANCE SOURCES, MEASUREMENT TECHNIQUES, CONVERSION METHODOLOGIES AND LIMITS

Joint Working Group
CIGRE/CIRED C4.202

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0. Executive summary

0.1. Introduction

Historically Radio Frequency Interference (RFI) from high voltage electric power installations has been related to interference with AM broadcast distribution due to high voltage ac line corona. Consequently, this aspect is covered well in the literature and in relevant standards, i.e. the CISPR 18 series [8]. Measurement of electric and magnetic fields inside substations is also covered in the literature. Very little has been documented regarding radio frequency interference from HV and MV substation and the purpose of this guide is to fill this gap. However, recent Cigré papers provide valuable background information [32], [37].

Besides, two important innovations call for a review of both measurement technique and criteria. The first is the ongoing replacement of analogue radio transmission with digital radio transmission, utilizing much broader bandwidth than the analogue AM radio transmission. The other is the extensive use of power electronics for all power levels and modern semiconductors often imply fast switching and consequential higher frequencies. Thus, with regard to RFI from electric power substations and their connecting power lines, both the frequency characteristics of the emitting source and the characteristic of the radio receivers have changed. Consequently, modified measurement procedures are proposed in the guide. The most significant change is that regarding RFI from other than corona sources when the complete frequency range of interest has to be scanned [37]. It is not sufficient to measure at a single frequency such as 0.5 MHz (the reference frequency for corona). Figure 1 shows measurement set-up for RFI measurement in the frequency range 9 kHz to 30 MHz.

Figure 1: RFI measurement in the frequency range 9 kHz to 30 MHz.

There are also other important factors to be considered for measurement of RFI from HV and MV substations. The physical size of the substation impacts on the measuring distance as it should be at least in the same order as the size of the installation to be representative of the RFI in the environment. Another consequence of the size is that all measurements must be performed as an in situ measurement that implies the presence of significant background noise in all measurements. Guidance is given on how to handle these factors and also other practical aspects such as selection of measurement points and considerations for operation modes and loading.

Conversion of measurement results in relation to measurement methods and measurement distances is one important subject of the guide. Especially how attenuation versus distance depends on frequency and other parameters is a complex but very important aspect. As part of the work, JWG C4.202 has recalculated the requirement in some available standards to a common measurement point. For frequencies below 30 MHz, the discrepancy between the standards in the allowed RFI level is very significant, in the order of 60 dB which means a factor of 1000 in the emitted electromagnetic field. The results presented in the guide indicate a lack of basic background information such as from measurements and knowledge about attenuation versus distance, which is very significant.

One other part of the work was to establish the reference RFI level requirement for a given radio receiver location. This is deduced from various relevant standards. The guide concludes with proposed RFI limits for substations in relation to voltage level and power rating based on the levels in IEC 62236-2. The proposed measuring procedure is supported by theoretical and practical background information.

0.2. Scope of the guide

The scope of the guide is limited to RFI from substations, including installations such as FACTS and HVDC. Also guided radiations by connecting lines of RFI origination in the substations is dealt with. The guide does not deal with RFI due to HV power line corona or broad band PLC in the power lines.

Single transients, such as those resulting from occasional operation of switches and circuit breakers, are not considered as RFI. However, radiations due to repetitive transients such as valve commutations in power electronic equipment, is considered as RFI.

The purpose of the guide is to advise suitable measurement procedures, which are as simple as possible, but still sufficiently accurate for determination of the worst case RFI from an installation. As there are a number of measurement positions and the complete frequency range has to be scanned, the RFI measurement procedure is quite time consuming.

The RFI requirement must always be expressed as a combination of measurement distance and field level, normally expressed as µV/m or dBµV/m. The reason is that the attenuation is significant. To be relevant to the RFI on a radio receiver in the surroundings, the combination of field level and measurement distance must be selected with care. The different ways of specifying the RFI requirements are clarified in the guide. Measurement procedures and RFI limits for HV and MV substation are proposed.

0.3. Characteristics of the disturbances

The general characteristics of the RFI from substations are repetitive transients. Figure 2 shows as an example of the disturbing current from power electronic equipment. Other sources give different pulse repetition patterns. In general there is pattern of fundamental frequency variation superimposed with transients of higher pulse repetition frequency. The frequency content of each single pulse can be anything in the order of 100 kHz to 100 MHz. This is further evaluated in the guide where also the different RFI sources are described.

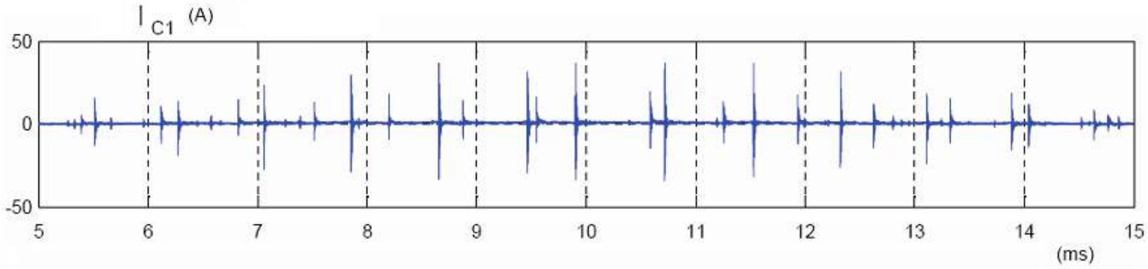

Figure 2: Example of disturbing current in ms scale.

One important characteristics of corona is the variation with weather. The bad weather corona is 20 dB or 10 times higher than the good weather corona. It is the bad weather corona that is decisive for the acceptable interference with surrounding radio receivers while most verification procedures for corona refer to good weather corona. This is a very confusing circumstance when discussing RFI limits for substations. The RFI from other sources do not have the same variation with weather at all. Instead sparking, or gap discharge, is worst in dry weather condition. A variation of 15 dB has been reported [37].

Besides, the description of the different sources for substation RFI emission, the guide gives a description of the state of the art and discusses available mitigation techniques.

0.4. Theoretical background

The scope of the guide covers a frequency range from 9 kHz up to a few GHz. The physical size of the installations varies from a few meters to several hundreds of meters. Some standards specifies a measuring distance in the order of ten meters while the radio receivers exposed to interference may be located at a distance of several kilometres. Consequently, the theoretical part of the guide covers all aspects from extreme near field up to far field. Besides, at high frequencies and/or long distances, the attenuation due to interaction with soil will be very significant. Thus, the guide documents the theory for propagation of radiated field up to a distance in order of ten kilometres.

Simplified models are used for demonstrating the characteristics of the RFI from substations, both the direct radiation and the guided radiation via connecting ac power lines. These models are very useful for understanding how the field is attenuated when radiating to the surroundings. The theoretical models are supported by comparison with published measurement results.

Figure 3 demonstrates the field variation due to attenuation for frequencies from 10 kHz to 1 GHz which shows significant attenuation across the range. Close to the source, the attenuation due to near field attenuation is very significant. At larger distances and at high frequencies the soil attenuation gives a significant attenuation contribution.

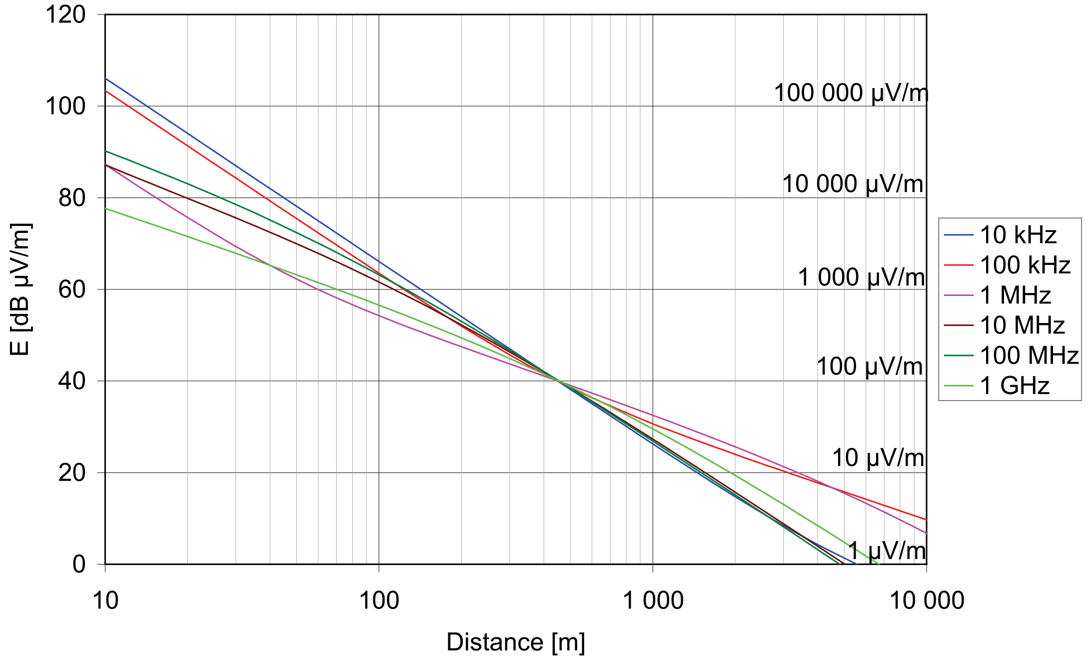

Figure 3: Attenuation versus distance for some frequencies. Base level: 100 µV/m at 450 m

Methods are also given for how to correlate the field measured using CISPR 16 narrow band detector with the broad band limit applicable for RFI in digital radio communication. This is provided that both limits and measurement are related to rms detectors.

0.5. Establishment of RFI limits for substations

The situation today regarding emission from substations is a bit confusing. Often the RFI level is discussed without referring to the location and distance from the source. Sometimes the acceptable noise level at the receiver's antenna is compared with the emission level measured close to a switchyard. That is hardly relevant as a sensitive receiver will not be located so close. Even so, limits for very different equipment are compared without any consideration of the typical distance to a radio receiver, or the impact zone. Low voltage equipment is located much closer to or inside domestic areas, while high voltage substations generally are remotely located. Lines are crisscrossing the landscape and pass much closer to domestic areas than the substation. Thus, it is reasonable that the RFI requirement for different items reflect the difference in impact. Stricter limits for lines than for substations; stricter limits for low voltage equipment than for high voltage equipment; stricter limits for mass products than for single installations in few locations.

One other difficulty is that there are very few standards stating acceptable limits for direct emission for frequencies below about 30 MHz. The reason is that for low voltage equipment, the standards do not call for measurement of the direct radiation in the lower frequency range but for limitation of electrical noise in the power supply cord for controlling the disturbances propagating into the low voltage network. However, for high voltage equipment, this is not possible, and the disturbances are verified by measuring the radiation from the connecting lines. However, there are few reference values to compare with. Figure 4 gives the level that is considered as the limit at the location of the radio receivers, deduced from relevant standards/recommendations available.

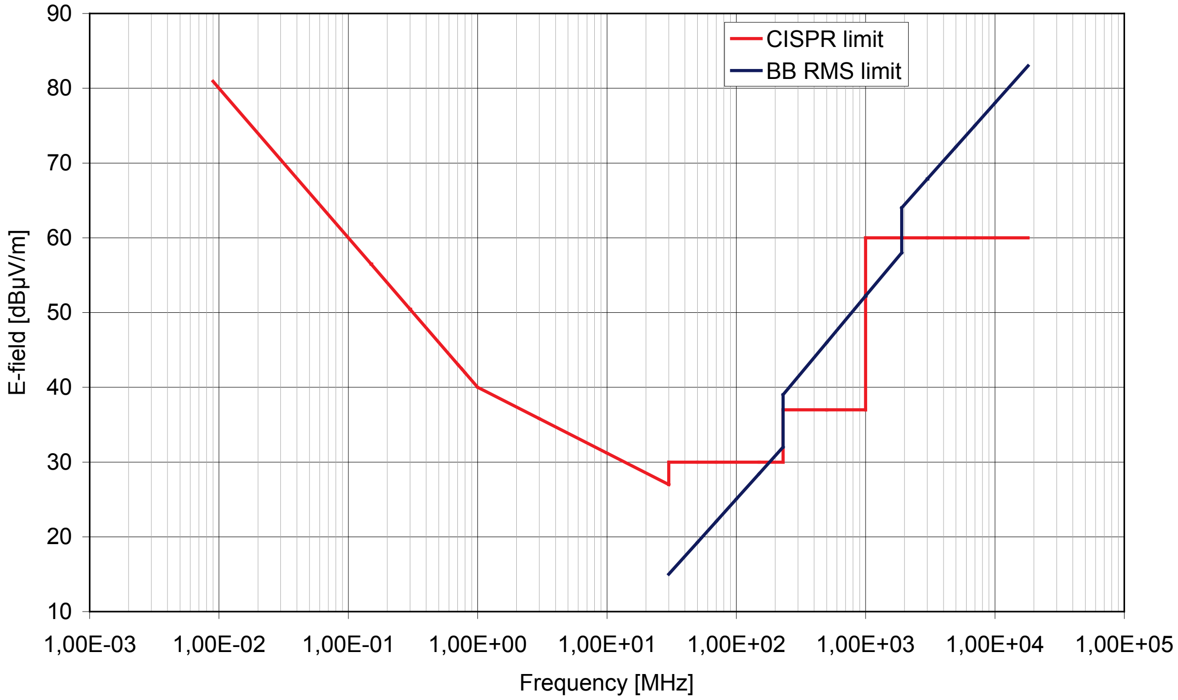

Figure 4: Reference level for RFI limits at the location of the radio receivers.

Table 1: Proposed measurement distances and limits for substations and equipment

Voltage level	**Rating of PE[1] equipment**	**Measurement distance**	**Limit curve**		**REMARK**
			9 kHz to 30 MHz	**> 30 MHz[3]**	
LV Domestic	Domestic: ≤1 kVA	10 m	(Limit 1)[2]	Limit 1	IEC 61000-6-3 applies
LV Industrial	Industrial: ≤100 kVA	30 m	(Limit 1)[2]	Limit 1	IEC 61000-6-4, CISPR 11 apply
2 – 30 kV	0,11 - 1 MVA	30 m	Limit 1 + 10 dB	Limit 1	
31 – 100 kV	1,0 - 7 MVA	30 m	Limit 2 - 5 dB	Limit 1	
101 – 170 kV	8 - 40 MVA	50 m	Limit 2	Limit 2	
171 – 250 kV	41-200 MVA	100 m	Limit 2	Limit 2	
251 – 420 kV	201 - 1000 MVA	200 m	Limit 2	Limit 2	
421 – 620 kV	1.1-5 GVA	200 m	Limit 2	Limit 2	
621 – 800kV	6-25 GVA	200 m	Limit 3	Limit 2	
801 – 1000 kV	26-100 GVA	200 m	Limit 3	Limit 2	
1001 – 1200 kV	> 100 GVA	200 m	Limit 3	Limit 2	

Notes:
1) Power Electronic equipment including HVDC and FACTS
2) Tentative proposal which may be applied.
3) For f > 30 MHz also the broadband rms limit "BB Limit" applies

The limits are defined in Figure 5. For BB limit rms value applies, for the others peak values apply.

The bandwidths for the "CISPR limit" are according to CISPR 16. However, the levels refer to peak value, except in the frequency range 30 MHz to 1 GHz where the quasi peak values apply. The "BB RMS limit" curve applies to protection of digital communication and are related to rms values. The bandwidths are broad band 1 MHz, 5 MHz and 20 MHz for the three parts of the lines. All details and references are given in the guide.

Table 1 shows the limits and measuring distances proposed in the guide for substations. A corresponding table for connecting lines is provided in the guide. The measuring distance is defined in Figure 6. The difference in requirement is considered to reflect the difference in impact.

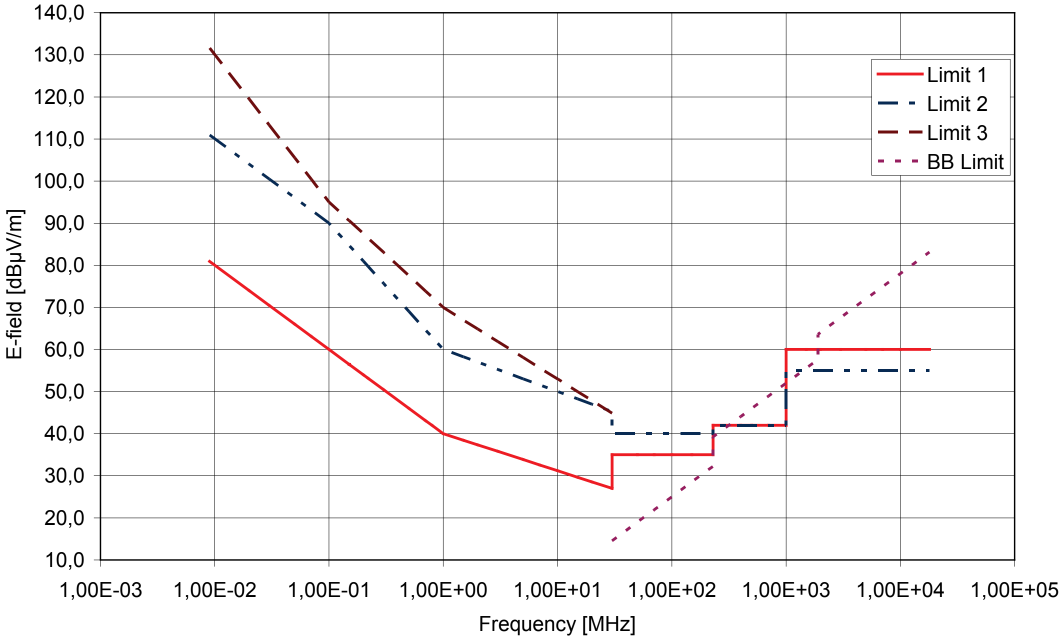

Figure 5: Definition of the limits in Table 1.

0.6. Measurement procedure and measurement uncertainties

The guide proposes suitable measuring procedures and relevant numbers of measuring points. Why the measurement distance must not be too short for being relevant is also addressed. Guidance is also given how to treat the practical limitations and obstructions at in situ measurement. The advices are based on practical experience within the JWG C4.202. Figure6 illustrates the contour for the limits and the most relevant measuring points. The distance *d1* is defined in Table 1.

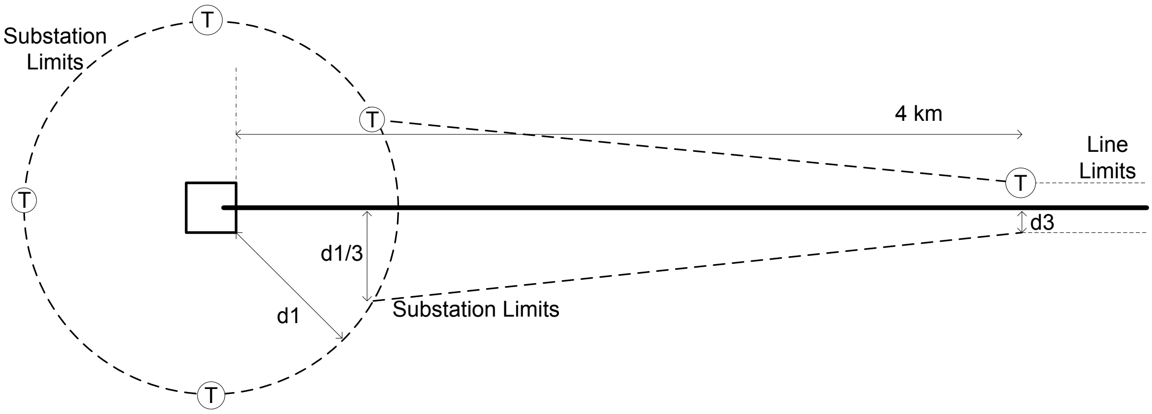

Figure 6: Contour line along which the often-specified limits applies. Circled T:s indicate measurement positions of interest.

The physical set up for RFI measurements are illustrated by Figure 1 and Figure 7. The guide also gives guidance regarding the practical arrangements.

One section in the guide deals with the measurement uncertainties. In addition to the measurement uncertainties that occur in an EMC laboratory, there are other uncertainties to be considered, such as the influence of voltage level and weather conditions. In the case of installations with power electronic equipment the operation modes and loading may also contribute to the uncertainties. Guidance is given on how to estimate those uncertainties. At operation reasonably close to the worst continuous case, those uncertainties are minor.

Figure 7: RFI measurement in the frequency range 30 MHz to 1 GHz.

0.7. Conclusions

The guide fills an important gap regarding RFI from HV and MV substations. It also treats the important considerations needed when measuring RFI from an installation with high power electronics such as FACTS and HVDC. A conclusion drawn from the few responses on a questionnaire regarding RFI from power lines and substations is that it is not common to measure RFI from a substation, probable as there is no realised interference. Recent measurements show that the substation RFI is much more complex than expected [37]. One important factor is the fast attenuation close to a substation due to the near field characteristics. Thus, the field close to the fence is not representative for the field in the surroundings where the radio receivers are located.

The proposed measurement procedure will give a reliable verification of the RFI level from the substations with a reasonable effort. Guidance is given how to avoid measurement uncertainties and how to check, if there is any doubt. For reliable measurements, the measurement distance should be at least as long as the physical size of the installation and related to the active part of the installation. This aspect is considered in the proposal in the guide. To use the fence as a reference point for the measurement distance may result in an unexpected high field in the surroundings. The RFI due to corona in the high voltage bus structures of a substation needs a separate verification procedure.

1. Introduction

1.1. Scope

The scope of the Radio Frequency Interference (RFI) measurement guide is measurement of RFI originating from HV and MV substations. The RFI may radiate directly from the installation or from connected HV or MV lines due to injected high frequency currents. Especially, the RFI due to installations of electronic power equipment such as HVDC FACTS or converters is treated. The guide also covers RFI due to corona at the substation HV equipment.

Electromagnetic interference due to a single isolated transient is not considered as RFI. Such a single transient may be caused by lightning events, power line earth fault, operation of circuit breakers, and other switching events in a high voltage substation. However, transients due to cyclic switching or the commutation process in power electronic circuits are treated as RFI. An example of repeated transients is shown in Section 4.2.5.5.

1.2. Background

From a compatibility point of view one might think that the emission and immunity requirements are coordinated in such a way that there is a margin for ensuring that a piece of equipment is not disturbed by other equipment in the surroundings. However, in the radio frequency band the margin is in the order of 100 dB (100 000 times in amplitude). The reason is that there must be space for all type of radio communication between the immunity requirement and the emission requirement. That means:

- The strongest radio transmitter in the surroundings shall not disturb a single piece of equipment. That is the criterion for the immunity requirement. Mobile radio transmitters and cellular telephones may be a specific problem.
- Emission from a piece of equipment must not disturb radio receivers in their surroundings, even for radio traffic from weak distant transmitters. That is the criterion for the emission requirement. The expected distance between the disturbing equipment and the radio receiver is an important parameter.

The requirements and verification procedures for low voltage equipment, such as vacuum cleaners and computers, are well established and specified in various standards, [4][20][21][22][23]. The verifications of both emission and immunity are performed in well-screened test rooms under very well controlled conditions.

Although, the electromagnetic environment is worse in a high voltage substation than in most other places, the immunity aspect of equipment used in the power industry can be dealt with as for low voltage equipment IEC 61000-6-5 [24]. However, the conditions for emission and emission verification differ completely between power systems and low voltage equipment. The most important aspects are:

- All metallic equipment energised to high voltage radiate due to corona and may even be sparking.
- The physical size of the installation can be very significant.
- The level of RFI due to corona and sparking vary significantly with the weather conditions, a factor of ten or 20 dB, see Section 4.2. The interference requirement is valid regardless of the weather conditions.
- At HVDC and FACTS installations not only the valves but also all connecting bus-work are radiating. Thus, the source of the EM emission is not single components but the complete installation.
- Even if individual equipment to some extent can be verified in a test laboratory, in situ measurement is the only way to verify the total emission.

Another important aspect is that low voltage equipment used inside domestic buildings may be very close to sensitive radio receivers, while the “respect distance” between high voltage equipment and a radio receiver is normally very significant, depending on voltage level and other conditions. This is a very important factor as the attenuation with distance is very significant close to a source.

1.3. Purpose of this guide

Electromagnetic (EM) emission from high voltage power lines due to corona is very well covered by the CISPR 18 series. The intention of this guide is to complement CISPR 18 regarding the aspects related to the use of very powerful power electronics. The emission pattern of power electronics can differ very significantly from the corona emission pattern. Furthermore, the use of electric power lines for communication via superimposed high frequency modulation adds an additional factor to the EM emission pattern.

Even if corona from HV power lines is well covered by the CISPR 18 series, corona from substation equipment is less well known and the concentration of possible corona sources in a substation may be significant. Besides, when measuring RFI from a substation, all sources of RFI within the substation must be considered.

The main purpose of this document is to be a guideline for planning and execution of the measurements for verification that the EM emission from a power installation is acceptable. The guide points out the different aspects to be considered for obtaining a measurement procedure that both is feasible from a practical point of view and relevant for determination of the risk that the installation causes unintended disturbances in practice.

Some important factors for both risk evaluation and determination of the measurement procedure are:

- How the EM emissions propagate from the installation to the surrounding radio receivers.
- The relevance of near field and far field phenomena.
- Impact of weather conditions.
- Attenuation of the EM emissions with the distance from the installation.
- Relevant reference points/boarder lines in definition of measuring distance.
- How measurement results are related to the principle of the used detector and bandwidth used.
- Characteristics of the radio receivers, which might be disturbed.

1.4. Description of the phenomena

Corona discharge and sparks emit EM fields due to the discharge activity. This is relevant for all equipment energised to high voltage, both lines and substation equipment. The activity may be more pronounced in substations with a high concentration of equipment. Disconnectors are critical items. The EM propagation is mostly via direct radiation. However, emission from strong local sources may also propagate via high frequency currents in connecting lines. It can be mentioned that the expected corona level increases with the voltage level.

The commutation process in power electronic equipment causes high frequency current to circulate in connecting bus work and ground system. These high frequency current loops act in the same way as magnetic dipole antennae with corresponding fields. The loop current multiplied with the loop area, i.e. the antenna area, determines the strength of the source. Even if only a small amount of the current is distributed further out in the substation and in connecting lines, the radiation can be significant due to the large antenna area.

If high frequency current is injected in a connecting line, the line acts as an antenna where the radiation is determined by the frequency, the current amplitude and the distance between the line used and the return path (i.e. the antenna area). This antenna is much smaller if a conductor in the same line works as the return path rather than when a zero sequence current is injected so that the ground works as the return path.

Direct radiation from a “point source” such as a substation only affects the very close surroundings. The disturbance propagating via lines can reach a much larger area. People may also live close to the lines. The lower the voltage is, the higher is the likelihood that the lines will pass close to sensitive equipment. Consequently, the limits for a distribution line should be more stringent than the limit from a point source such as a substation. The limit should be expressed as the allowed level as a function of distance. Furthermore, the limits for lower voltage lines and equipment should be more stringent than the limit for high voltage equipment, especially when considering that low voltage systems distribute electrical power within domestic buildings.

1.5. The state of the art

The situation today regarding emissions from substations is a bit confusing. Often the EM level as such is discussed without referring to the location and distance from the source. Sometimes the acceptable noise level at the receiver’s antenna is compared with the emission level measured close to a switchyard. That is hardly relevant as a sensitive receiver will not be located so close.

One other difficulty is that there are very few standards stating acceptable limits for direct emission at frequencies below about 30 MHz. The reason is that for low voltage equipment, the standards do not call for measurement of the direct radiation in the lower frequency range but for the limitation of electrical noise in the power supply cord for controlling the disturbances propagating into the low voltage network. However, for high voltage equipment this is not possible, and the disturbances are verified by measuring the radiation from the connecting lines. But, there are few reference values to compare with.

For corona, the CISPR 18 series gives good guidance. The frequency spectrum from corona is very well defined and 0.5 MHz is used as a reference. Therefore, the corona level is often checked by measuring the corona level at 0.5 MHz, and sometimes at a few other single frequencies. Procedures applied for measuring a single frequency may not be practical when dealing with broadband disturbance without a defined frequency pattern and the complete frequency range has to be checked.

An industrial praxis for a power substation with a connecting line has been to define a contour line around the substation and the connecting line, as shown in Figure 1.1. A normally used value has been 100 µV/m, or 40 dB(µV/m), in the frequency range 500 kHz to 500 MHz.

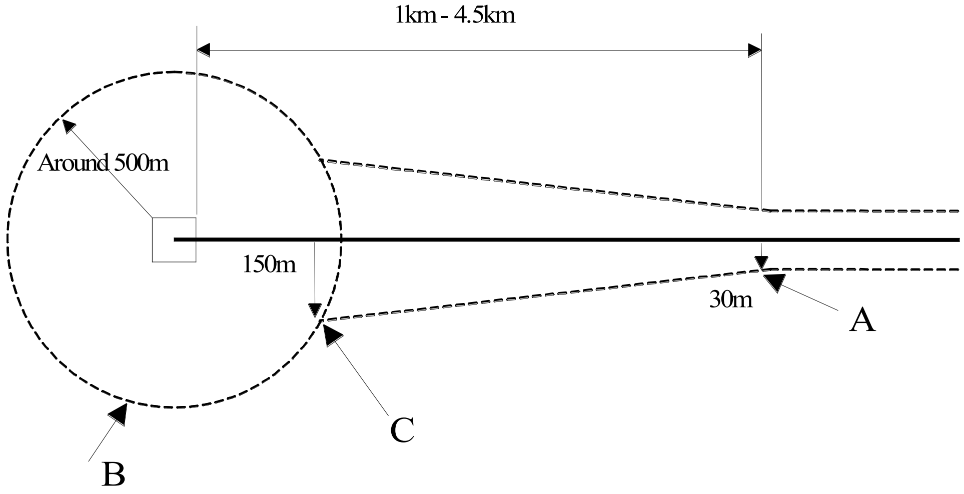

Figure 1.1: Contour line along which the often-specified limit of 100 µV/m (40 dBµV/m) applies. **Positions A, B and C indicate positions of interest.**

In recent years, some standards related to emission from a substation have been issued worldwide. Even if it is not explicitly stated, the standards concentrate on controlling the corona. Sometimes the limits for a substation are much more stringent than the limits for a corresponding line of the same voltage.

There is one standard developed for power electronics of high power rating, EN 50121-5, regarding frequency converters for a railway power supply. This standard calls for measurement in the complete frequency range from 9 kHz to 1 GHz. In the year 1996 issue there was a specific limit for the fixed station, lower than for the train. However, in the year 2000 issue the same values are allowed for the fixed installation as for the train, which may be a bit too generous, as the disturbance from the train is a temporary disturbance. One other question mark with the standard is that it specifies the disturbance to be measured 3 m outside the fence. To move the fence some meters may fix a formal problem, but not a disturbance issue.

Even if the levels are specified in µV/m, the practical procedure is to measure the electrical field at 30 MHz and above while the magnetic field is measured with a loop antenna for lower frequency and converted to µV/m by using the free-space impedance 377 ohm.

The corona level of equipment in a switchyard is normally controlled by the RIV test in the high voltage laboratory in accordance with IEC 60694 [19] and IEC 62271-1 [26]. This standard specifies that for a certain voltage level, related to the rated voltage, the amplitude of the transient voltage peaks (the RIV voltage) due to corona discharge must not exceed 2500 µV. This procedure disqualifies equipment with electrode configurations that are too sharp. However, there is no conversion function established between the test parameters expressed as test voltage level combined with measured RIV voltage and the level of RFI emission due to corona, expressed as µV/m at a certain distance. The relevant question is: When you know the requirement on the installation, expressed as µV/m at a certain distance, how to translate that requirement to a relevant RIV test to be specified for the equipment in the switchyard?

1.6. Design and verification procedures

The corona design of lines and bus work is guided by CISPR 18. Much of the design is based on experience supported by calculation of the maximum electrical field [31]. For equipment and clamps, the procedure is often such that the corona rings are added and the design is modified, based on experience, until the equipment pass the RIV type test.

The design for limiting the emission from FACTS and HVDC is also based on experience. Often the direct emission from the valves is reduced by a feasible shielding arrangement. Emission from external current loops is estimated by calculation of the high frequency current in the loop, combined with the loop area. If needed, the loop emission is reduced by RFI filters, series reactors and/or shunt capacitors.

The verification is performed by measurement guided by the CISPR 16 series, especially CISPR 16-1-1 [5]. The measuring points and the acceptable limit are agreed between the supplier and the user based on the concrete situation, with guidance of the available and applicable standards. In the EU/EES area also the requirements in the EU EMC Directive [9] has to be followed as applicable.

In the beginning of 2006 a questionnaire regarding RFI experience was sent out to the SC C4 members. The few responses are summarised and reported in Appendix I.

2. Background noise

The background noise sets a sensitivity limit for receivers, and it needs to be considered in the planning and evaluation of in situ measurements. Figure 2.1 shows a frequency scan obtained using an EMC test receiver in peak detection mode and with typical EMC measuring antennae [32]. The frequency scan was performed in a suburban recreation area in the United States, far from power electronic installations. Radio interference measurement methods are as specified in CISPR 16-1-1 [5].

The spectrum in Figure 2.1 is divided into three bands: 9 - 150 kHz, 150 kHz - 30 MHz, 30 MHz - 1 GHz with different measurement bandwidths, thereby giving the step changes at the band limits. From about 2 MHz to 30 MHz the lower level is limited by the receiver system noise. A typical EMC measurement system is not sensitive enough to measure the true background level in this frequency range. Also from about 300 MHz and up to 1 GHz the lower level is limited by the receiver system noise. Levels of atmospheric noise and man-made noise from the recommendation ITU-R P.372-8 [27] are also shown, converted to the CISPR bandwidths. Up to a few MHz the atmospheric noise is dominating. At higher frequencies, man-made noise is the main limiting factor. Man-made noise in this respect concerns the background level where an individual source cannot be identified. Incidental noise from local sources may be higher and largely varying depending on time and place.

The frequencies below 150 kHz are typically used for long distance communication. An important use has previously been emergency communication and navigation at sea. This is now being taken over by satellite services. It is a general tendency that this frequency range has become less important for communication due to the relatively low data rate achievable at these frequencies.

The narrow peaks seen in Figure 2.1 are radio transmitters, for example in the AM-band from 0.54 MHz to 1.6 MHz, in the FM-band around 100 MHz and around 900 MHz some of which are likely to be cellular phone frequencies.

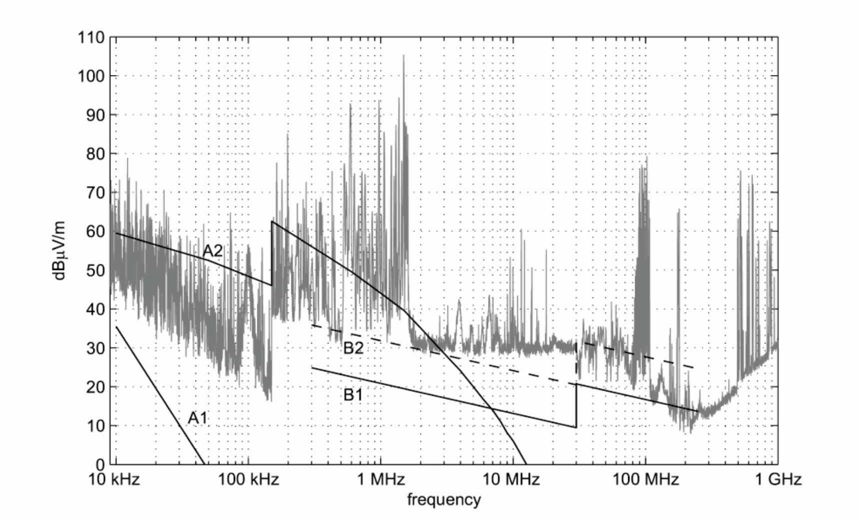

Figure 2.1: The figure shows the result of a frequency scan with an EMC measurement system, including radio noise curves from Rec. ITU-R P.372-8:
A: atmospheric noise, value exceeded 99.5% of the time (A1), exceeded 0.5% of the time (A2)
B: business area man-made noise, exceeded 50% of time (B1), exceeded 10% of the time (B2)

3. Characteristics of the radio receivers

3.1. General

The purpose of this chapter is to increase the understanding between the radio communication society and the power engineering society. It is easier to avoid disturbances when the impact of different measures is known. It will also help when it is necessary to perform a risk assessment regarding possible RFI.

Historically, all measurement of RFI from power system equipment has been performed in accordance with CISPR 16 [5]. Thus, most experience is related to the CISPR 16 procedure, including the specified bandwidth. Besides, all work regarding RFI from power systems are based on the characteristics of line corona. However, there have been at least three parallel developing paths making it necessary to review the base for treating RFI in general, and especially RFI from substations:

- There have been rapid developments of high power electronic equipment such as HVDC and FACTS, which have much more complex RFI characteristics than that of corona.
- Digital broadband radio communications are in operation. The characteristics of the digital communication are much more complex than the AM communications used earlier.
- A frequency scattering technique has been developed, making it possible to spread the RFI in several CISPR 16 band [5], thereby providing a countermeasure for too high levels at measurements in accordance with current standards. However, the experienced disturbances of the more broadband digital radio communication are not reduced.

Thus, the RFI situation is now much more complicated than it used to be. Consequently, the procedures for RFI evaluation and verification need a review for ensuring applicability for the present day and future situation. Still, it is essential that the procedure is as simple as possible.

3.2. Equipment immunity

As discussed in Section 1.2, the emission limits are not determined by compatibility with the equipment immunity levels. The immunity levels are much higher than the emission limits, in order of 100 dB. However, the emission levels are not measured inside the equipment itself, but at a certain measurement distance from the radiating equipment. Due to attenuation versus distance, the EM field is significantly higher very close to the equipment than at the measuring point, especially when power electronic equipment is installed in a shielded building, as indicated in Figure 5.1.

Consequently, for equipment used inside high power electronic equipment installations, or otherwise located close to the conductors carrying the transient currents of the commutations, the EMI fields might be higher than the immunity requirements in applicable standards [24], [33].

3.3. Different detectors used

The different principles that are used for measuring the RFI level are: average, rms, peak and quasi-peak. How the readings from these detectors relates to each other depend on the characteristics of the signal. For a continuous sinusoidal signal all four detectors show the same level. For an intermittent disturbance, the readings differ significantly. The peak detector shows the maximum peak, the average detector shows the average value, which is much lower. The RMS (Root-Mean Square) and quasi-peak detectors show something in between. The difference between the response of peak, quasi-peak and RMS detectors decreases with increasing noise pulse repetition rate. If the noise pulse repetition rate is much higher than the measurement bandwidth, then the response of these three detectors should be approximately the same. This can be understood by recalling that all detectors give the same response to a sine wave. For instance, consider a repetitive pulsed signal *i(t)* as in Figure 3.1.

All detectors are envelope detectors. Thus, they sense the envelope of the signal after the input filters. I.e. an RMS detector senses the rms value of the envelope, not the rms value of the signal itself.

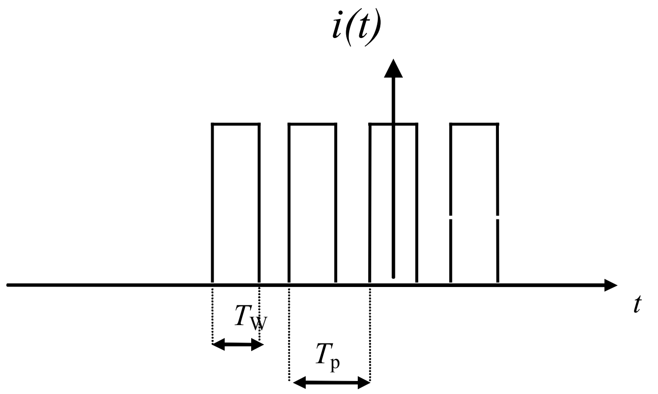

Figure 3.1: Periodic pulsed signal *i(t)*.

The disturbance signal *i(t)*, can be written as a Fourier series:

$$i(t) = \frac{1}{T_\mathrm{P}} \sum_{k=-\infty}^{\infty} c_k e^{j(2\pi f_k t + \varphi)} \tag{3.1}$$

The amplitude spectral components within the main lobe are schematically shown in Figure 3.2. The distance between each spectral component is $fp = 1/Tp$. Thus when the pulse repetition frequency is higher than the measurement bandwidth, only one sine-wave component will appear within the measurement bandwidth B. Thus all detectors will give the same response under these circumstances.

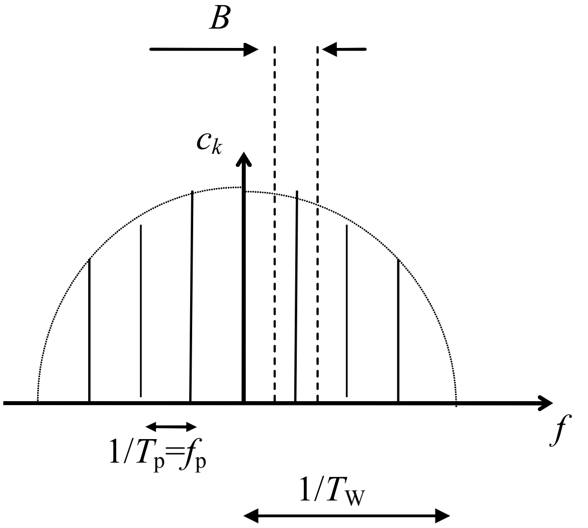

Figure 3.2: A schematic figure of the main lobe of the amplitude spectral components of *i(t)*. If the pulse repetition frequency f_p is higher than the measurement bandwidth *B* only one sine-wave component will enter the measurement detector.

The average reading is not considered to be representative of the experienced quality of a radio communication channel when related to signal to noise ratio. Neither is the peak reading. The RMS and the quasi-peak detectors are considered to better present the characteristics of the impact on the radio receiver (quasi-peak for analogue receivers and RMS for digital receivers).

The quasi-peak (QP) detector was originally developed to give a response that is proportional to the perceived disturbing effect on human beings when using an analogue service. This was done by the application of psychophysics (psychoacoustics for sound radio and psycho optics for TV). In particular it was necessary to weight impulsive noise from e.g. electric motors and spark-ignited engines. As the disturbance effect perceived by a human being is higher at high pulse repetition frequencies than at low pulse repetition frequencies, the detector response had to take this into account. This resulted in the definition of a detector that weighted repetitive impulsive emissions in accordance with the pulse repetition frequency - the quasi-peak detector. This behavior exists up to a certain limit in pulse repetition frequency (typically 10-20 kHz) beyond which a constant response is obtained. Thus, the quasi-peak detector simulates the human perception of EM disturbances on analogue radio receivers. However, this detector is not adequate for simulating the effect of EM disturbances on digital radio receivers.

Up to now, the RMS detector has not been used in EMI measurements even if the 2nd edition (1972) of CISPR 1[1] says that experience has shown that an RMS voltmeter might give a more accurate assessment of the interference effect on analogue radio than the QP detector. Measurement and simulation results have shown [34][35][36] that the RMS detector exhibits a response that can be correlated to the interference impact on digital communication systems.

As the peak detector always shows a higher value than the RMS detector and the quasi-peak detector, it is often used for scanning purpose, as it is much faster to use.

The frequency characteristic of the RFI from a disturbing source is seldom flat, especially when power electronic equipment is involved (corona is an exception). Therefore, the bandwidth of the detector is also an important parameter when estimating the impact on radio communication. If the detector has a too narrow a bandwidth, it underestimates the impact of the disturbance. If the bandwidth it too wide, the impact is overestimated. In addition, with a too wide a bandwidth it is difficult to identify the source of the disturbance when performing in situ measurement. Radio transmitters nearby in frequency may mask the RFI from a source under evaluation.[2]

3.4. Communication in the frequency band 9 kHz to 150 kHz

3.4.1. Background

There are several reasons for evaluating this frequency range further regarding impact on radio communication:

- There are very few standards calling for an emission limit in this frequency range, see Section 10.2.2
- The wavelength is long, thus the attenuation of the radiated field versus distance is higher than for higher frequencies see Figure 9.1. For more information regarding attenuation, see Section 9.1 and Equation (9.2).
- High power electronic equipment has a natural significant RFI emission in this frequency range and it is not too easy to reduce the emission in this frequency range, especially regarding broadband reduction.

Consequently, emission limits measured 100-200 m from a substation could in general be somewhat generous without leading to experienced RFI.

3.4.2. Services using this frequency range

This frequency range is typically used for long distance communication and especially where the long-range ground wave coverage of low frequencies is important, such as for radio navigation. Reception of the ground wave is possible up to about 1000 km from the transmitter. By ionospheric reflection, the communication distance can be further extended. The performance of radio receivers in this frequency range is limited by background noise consisting of atmospheric and man-made noise.

Some examples of frequencies in use:

- Various stations use frequencies 40 kHz, 60 kHz, 66.66 kHz, 75 kHz and 77.5 kHz for time signals.
- The frequency range 90-110 kHz is used for the LORAN-C radio navigation system.
- There are some stations for long range broadcasting operation from 68 kHz to 150 kHz.
- The frequency range 135.7-137.8 kHz is used for amateur radio in Europe.

More information regarding services using this frequency range can be found in Appendix E.

There is a tendency that this frequency range is becoming less important for communications due to the relatively low data rate achievable at these frequencies. An important use of these frequencies has previously been communication and navigation at sea. This is now being taken over by satellite services, and telegraphy is not used for emergency communication at sea any more.

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[1] CISPR 1: *Specification for CISPR Radio Interference Measuring Apparatus for the Frequency Range 0.15 Megacycle per Second (Mc/s) to 30 Mc/s* was withdrawn 1977 and replaced by CISPR 16.

[2] As an example: consider how to evaluate RFI from a source disturbing the AM broadcasting in the frequency range 0.54-1.6 MHz with the background noise in Figure 2.1.

3.4.3. Detector principle

Each communication channel uses a narrow band and it is considered that the CISPR 16 quasi-peak detector gives a good indication on how the communication channel is impacted by an external noise [5]. Amateur radio is further discussed in Section 3.8.

3.5. AM broadcasting

The AM broadcasting works with narrow band amplitude modulated radio signals. The bandwidth for each channel is 9-10 kHz. The characteristic of disturbances is correlated to how the human ear is affected by the noise. The quasi-peak detector defined in CISPR 16 is developed for being representative for how a broadcast listener is affected by the RFI noise. Thus, the measurement in accordance with CISPR 16 represents very well the sensitivity characteristics of the AM broadcast receivers.

The frequency range used for AM broadcasting is from 150 kHz to 1700 KHz for LW and MW. The short wave services use the frequency range up to around 15 MHz. The tendency is that AM broadcasting is replaced by FM broadcast and other services using higher frequencies.

3.6. FM broadcasting and TV

FM broadcasting and analogue TV transmission uses a frequency range around 50-300 MHz. Each channel uses a fairly narrow band and the useful signal is directly presented for the human listener and/or viewer. Thus, the CISPR 16 quasi-peak measurement method represents the experienced disturbances reasonably well, as long as the measurement bandwidth is about the same as the used bandwidth

3.7. Digital communication

In digital communications, the received information is processed before presenting it to the end receiver. In the transmitted telegram for digital communication there are a certain number of check bits so distorted information can be identified. Minor distortion can often be corrected. In digital communication, the signal to noise ratio can be expressed as a bit failure rate.

If the noise pulse repetition rate is low compared to the telegram repetition rate, the disturbed telegrams can be disregarded without affecting the quality of information received by the end receiver. The bandwidth of the communication channel can be used at a high repetition rate of quite short telegrams or for a longer telegram with more check bits with a corresponding lower repetition rate.

In digital communications it is also possible to filter out certain frequencies impacted by noise, only utilising the non-disturbed part of the used frequency range, at a cost of a lower telegram repetition rate. As there is a menu of fault correction measures, the quality of the information received by the end receiver has a fairly high quality until all fault correction measures are used. Then the quality drops drastically. However, the bit failure rate increases as the amount of disturbances increases.

Suitable detectors for disturbances of digital radio communication are under development and evaluation. At present, an rms detector seems to fit best. However, the new and important thing is that the bandwidth of the detector must correspond to the bandwidth used by the telecommunication radio channels. This bandwidth is significantly broader than the one stated in CISPR 16 [5].

3.8. Amateur radio

Amateur radio works in fairly narrow bands on very faint signals. Several narrow frequency bands are reserved for amateur radio, from 1.8 MHz to 29.7 MHz, each band is about 200 kHz wide. Often the radio amateurs from time to time select frequency bands with minimum background noise. Consequently, those bands are sensitive to additional continuous disturbances. Radio amateurs probably avoid setting up their equipment too close to a high voltage substation. However, it may be more difficult to avoid the surroundings of power lines.

Probably the quasi-peak detector represents the experienced disturbance quite well. However, CISPR 16 bandwidth might be too broad for representing the characteristics of the RFI noises correctly.

3.9. Other radio services

3.9.1. General

There are several other services, which need to be taken into account in an RFI risk analysis. Below are the most common ones discussed.

3.9.2. Aviation radio and radar

Regarding RFI with aviation traffic, it is only applicable for substations that are not too far from an airport. The critical aspect is RFI with aeroplanes if they pass at a low altitude above the substation when approaching the airport for landing. The RFI noise must not be so high that it opens up an unused navigation feature, i.e. RFI higher than the level of the noise discriminator, as that might disturb the pilot. The level for interference with the instrumentation is significantly higher. In addition, the frequencies of radio beacons for radio navigations should be considered. Minor RFI with the voice communication is less critical.

3.9.3. Communication with mobile services

Police, fire brigades and taxis use radio communication for contact between the central station and their mobile units, and for contact between the mobile units. Most of the traffic is voice communication and the communication is narrow band communication.

Regarding sensitivity to disturbances, it is most important not to disturb the main station as the transmitters in the mobile units have lower power than the transmitter in the main station. Besides, the main station cannot move. It is less critical regarding disturbance of the receiver in the mobile units as it is not unusual that contact is lost due to geographical obstructions, and the link from the mobile unit to the central station is the weak link.

3.9.4. Cellular telephones

With the high frequency used by cellular telephones, it is unlikely that RFI from a substation will interfere with cellular telephones. The other way around may be the case. The highest risk that RFI from a substation impacts on the traffic capacity is if the base station is located very close to the substation as the signal from the mobile telephones might be faint.

3.9.5. Suitable detectors

It is considered that the CISPR 16 measurement procedure [5] is relevant regarding RFI with those services.

3.9.6. Conclusive summary

Regardless of the type of radio communication the receiver’s sensitivity is characterised by:

- All RFI noise within the bandwidth used by the receiver has impact.
- The disturbance is related to the maximum field level, not the average value.
- The longer the duration of the disturbance peak, the greater the experienced disturbance.
- The higher the disturbance pulse repetition frequency, the greater the experienced disturbance

When related to standards for allowed emission it is necessary as a rule to cover all types of radio communication in the applicable frequency band. There are two basic considerations regarding the verification procedure:

1. The detection principle for representing the impact on the receivers. Detectors normally discussed are rms and quasi-peak, but it might be something else.
2. The measurement bandwidth to be used. This may be the real tricky issue due to the large variety of bandwidths used. Besides, there must be methods for discriminating the background noise considering in situ verification.

It might be necessary for some type of combined criterion, still considering the practical aspect regarding time for a complete verification.

4. Characteristics of the disturbance sources

4.1. General

There are several sources for RFI noise from power systems, lines and equipment. RFI due to corona and sparking are caused by electrical discharge activities in air. The commutation process in power electronic equipment such as HVDC and FACTS initiates high frequency currents in the nearby circuits, which causes RFI noise. The frequency characteristics of RFI noise from different sources differs significantly, as illustrated by Figure 4.1. It must be noted that the curves in Figure 4.1 only show the relative strength for each source. The figure shows neither the absolute field strength nor the relative strength between different sources.

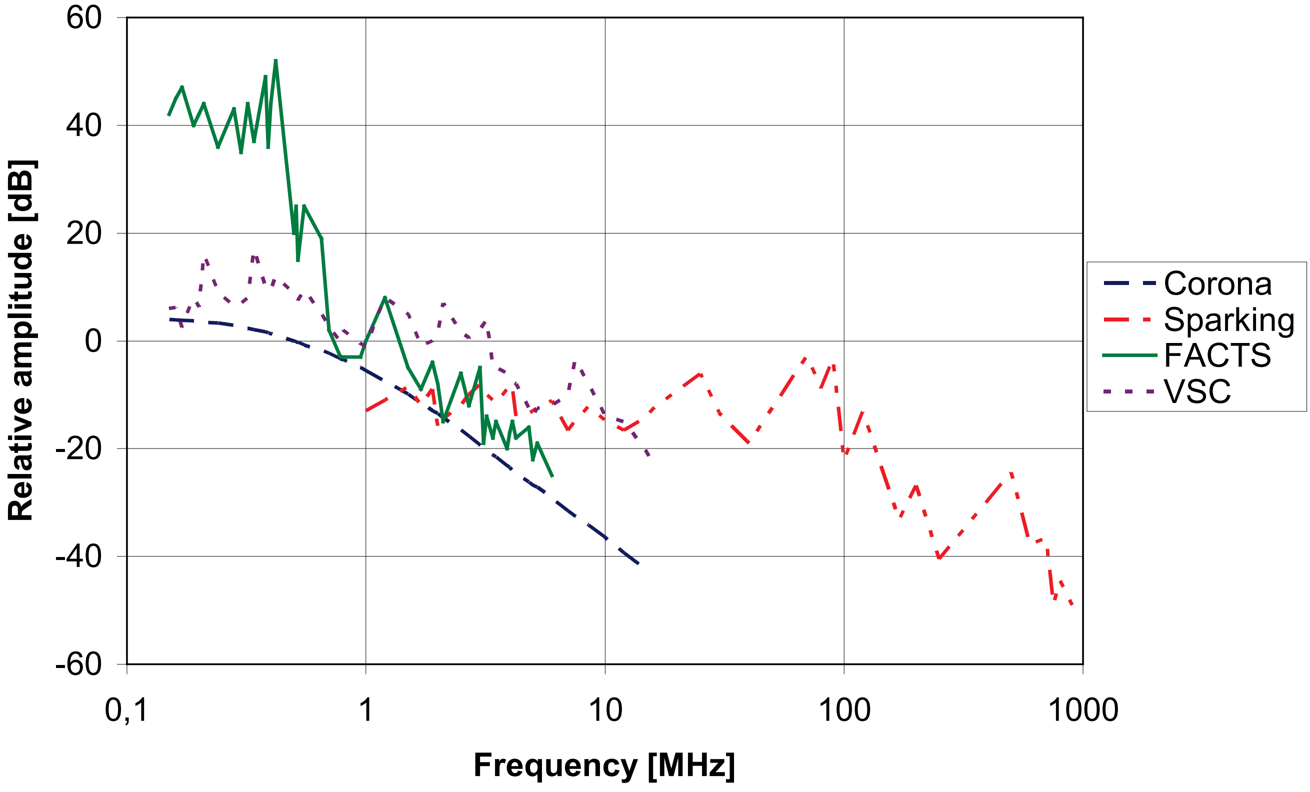


Figure 4.1: Typical relative frequency spectra for RFI fields from some sources in electric power systems.

Some comment to Figure 4.1:

- The curve for corona is taken from Figure B12 in CISPR 18.1 [8]. The measurement distance is 15 or 20 m from the nearest phase conductor of an ac power line.
- The typical curve for sparking is taken from Figure 11 of CISPR 18.1. The measurement distance is likely to be the same as for the corona curve.
- The curve for the frequency characteristic for the FACTS is deducted from Figure 3 in [32]. It is the field from a line commutated SVC measured 13 m from the building.
- The curve for the frequency characteristics of the VSC (Voltage Source Converter) is deducted from Figure 4 in the same document [32].The measurement distance is 8 m from the building.

It must be noted that the curves for FACTS and VSC do not represent typical curves. They are typical examples illustrating the difference in frequency characteristics of RFI from different sources.

Due to the different sources, the frequency characteristics of RFI from HV substations can be quite complex and very irregular [37]. This is valid also for substations without installations of either FACTS or HVDC.

The different sources are further discussed in Section 4.2.

4.2. Generation mechanism

4.2.1. General

There are three different types of discharge activities in air, which can result in RFI noise.

- Corona is a local electrical break down in the air close to a conductor or any other metallic object charged to high voltage. The reason for the local break down is that the local electrical field exceeds the withstand capability of the air.
- Sparking or gap discharge is often an electrical breakdown of the air between two metallic objects forming a small capacitor. The sparking is the discharge of the capacitor when the voltage withstand exceeds the withstand capability of the air. At least one of the metallic objects is electrically free floating. Sparking is often due to bad contacts.
- Arcing is when ionised air forms a part of the conductor for the current. Arcing may be to a broken conductor or due to a phase to earth fault. Arcing in an electric power system is only of short durations, as the protective system will see the consequences of the arcing and disconnect the faulty circuit. Consequently, arcing is not of concern regarding RFI from electric power systems.

Another important source of RFI is the transients introduced at the commutation process of power electronic equipment such as FACTS and HVDC.

A third source of RFI from electric power systems is when a power line is used as a telecommunication circuit by a superimposed high frequency current. The system is called PLC, Power Line Carrier. Some of the attenuation with distance is due to radiation losses. This means that a part of the signalling power is radiated from the power line as RFI noise.

One factor which increases the complexity of RFI verification from a substation is that the RFI level varies with weather conditions, operation voltage and operation modes while the requirements regarding limitation of interference is valid for normal operation conditions, even bad weather. Bad weather corona is in the order of ten times or 20 dB higher than the good weather corona [8][31]. The RFI due to sparking, or gap discharge, is higher at dry weather than at wet weather. A difference of 15 dB is reported [37]. The other variation is smaller, provided that the loading is not too low. Measurements uncertainties are further dealt with in Section 8.9.

4.2.2. HV corona

As corona not only creates RFI noise but also causes audible noise and lamination phenomena, it is of environmental concern. Consequently, the corona phenomenon is very well investigated. The publication CISPR 18.1 [8] gives a thorough description of the state of the art.

The basic physics behind corona is that the electrical field close to a conductor is higher than the electrical withstand capability of the air. Thus, there will be an electrical break down. However, as the electrical field is much lower at a greater distance from the conductor, the break down will not result in a flash over, only to a very local break down. That is called a partial discharge. As only the air and one conducting surface are involved, the discharge energy will be fairly low. Also the frequency bandwidth of the emitted RFI noise will be limited, see Figure 4.1. For more information, see Chapters 5 and 6 of CISPR 18 [8].

Not only the line conductors but also all fittings, insulators and equipment energised to high voltage may generate corona. This is valid for both a.c. and d.c. The d.c corona is somewhat different from the a.c. corona due to a space charge phenomenon, as described in Chapter 8 of CISPR 18.1.

Corona is a normal effect even with healthy equipment. However, the degree of corona depends both on design and on the weather.

4.2.3. Sparking

Unbounded conducting parts of a power line or substations, or even nearby metallic fences, when located in the strong electric field of high voltage power lines and associated equipment, can become electrically charged and the potential difference between adjacent conducting parts will increase, even if both parts are electrically floating, i.e. connected neither to a line conductor nor earth. If the distance separating the conducting parts is small, the increased field strength in the intervening space may reach the critical level and lead to a complete breakdown of the gap. Avalanche ionisation initiate the development of an arc, gap discharge occurs, the potential difference across the gap then falls to a low value and the arc extinguishes. The whole sequence of events can be repeated when the parts become re-charged, as the space is once again electrically stressed and the next gap discharge takes place.

As the discharge is between two metallic parts, the discharge energy is much higher than for a corona discharge. The significant factor in the shape of the discharge impulse at sparking is its steep rise time and, consequently, a broad band of high frequencies is produced and emitted, as illustrated by Figure 4.1.

Sparking often occurs if the contact between different metallic parts or details is bad, perhaps due to oxidation. Another common reason for sparking is a broken string insulator. Sparking might also occur in cavities inside insulating material. Thus, severe sparking may be due to inefficiency in design or erection of equipment or due to material defects. However, measurements reported in [37] show that sparking or gap discharge also may be the result of a normal ageing process of the metallic parts in the substation. The reported activity was significantly higher in dry weather than in wet weather.

More information about sparking can be found in chapter 7 of CISPR 18.1 [8].

The complex phenomena of insulator surface discharges are discussed in chapter 6 of CISPR 18.1. Both corona and sparking may play their roles.

4.2.4. Arcing

For sparking, at least one of the metallic parts is electrically floating. This is not the case for arcing. If a discharge for example occurs between a line conductor and earth, it will not result in a short spark, but a continuous arc until the current is interrupted. Typically, the current is interrupted by a circuit breaker, triggered by an earth fault protection. Another reason for arcing is if the main current conductor is broken, which may be due to overheating and melting of a bad contact. Such an arc may continue until the arc or the line conductor reaches earthed metallic equipment. The subsequent earth fault will be sensed by the system protections and the current will be interrupted by circuit breakers as in the case described above.

Consequently, arcing in power systems will only be very rare events of very short duration, in contrast to electrical arc welding. Thus, arcing is not considered as a source for RFI from electric power systems.

4.2.5. Commutations

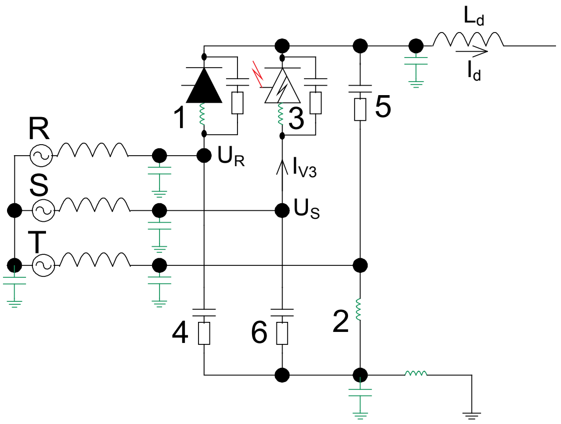
4.2.5.1. General

At commutations in power electronic equipments such as HVDC and FACTS, the current is commutated from one current path to another current path. Thus, the commutations can be seen as a current switching event. The duration of each commutation process depends on the converter configuration, as described below.

As a commutation involves switching events, it also enforces transients in voltage and current. The high frequency current components will be a source for RFI emission as it spreads out in the connecting circuits.

4.2.5.2. Line commutated converters

Figure 4.2 shows the circuit for a commutation process in a conventional line-commutated six-pulse bridge. The capacitors and reactances marked green are the parasitic circuit elements. Only the commutation valves 1 and 3 are indicated by thyristor symbols together with the snubber circuits. The conducting valves 1 and 2 are represented by their parasitic inductance while the non-conducting valves 4 to 6 are represented by their snubber circuits.



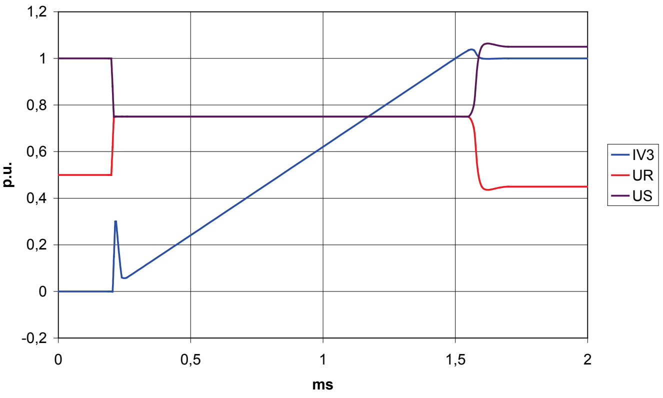


Figure 4.2: Commutation circuit for a line commutated converter.

Figure 4.3: Current and voltage at the commutation according to Figure 4.2.

When the commutation starts with firing of the thyristor valve 3, the voltage U_S of phase S is more positive than the R phase voltage U_R, see Figure 4.3. As valve 1 is conducting, firing of valve 3 introduces a short circuit between phase R and phase S. Due to the short circuit, the phase capacitances are discharged through valve 3, as indicated in the current I_{V3} in Figure 4.3. After the capacitive discharge, the current derivative is determined by the driving voltage and the circuit inductance . The total current I_d is kept constant at 1.0 p.u. by the smoothing reactor L_d. When the current in valve 1 tends to be reversed, the thyristor acts as a diode and the commutation process is finished.

The rise time of the capacitive discharge current is typically in the order of 2 to 10 µs and this current pulse is the main source for RFI from a line-commutated converter, HVDC or FACTS. In addition, the transients at valve firing may introduce ringing in the parasitic circuit elements that will cause RFI at the ringing frequencies.

4.2.5.3. Forced commutated converters

While in a line-commutated converter, the current commutation is driven by the network voltage, the power electronic components take a much more active part in a forced commutation converter, both at the turn-on and the turn-off process. For controlling the switching losses in the power electronic components, the current transition time must be much shorter in a forced commutation converter than in a line-commutated converter.

Figure 4.4 shows one phase of a two level voltage source converter as an example of a forced commutated converter. The dc side voltage is kept constant during the commutation process by large dc side capacitors. The a.c. side current is kept fairly constant during the commutation process by the converter reactor L_C. In this example, the a.c. side current is assumed to be 0.9 p.u.

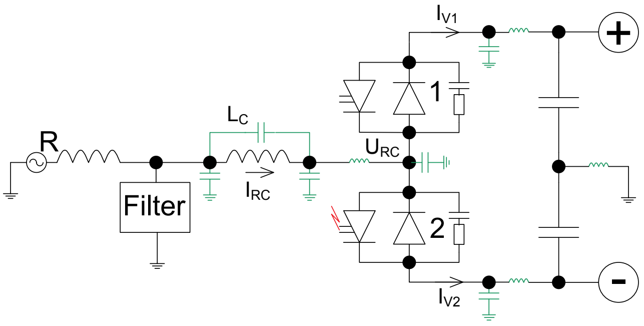


Figure 4.4: Commutation circuit for a forced commutated converter.

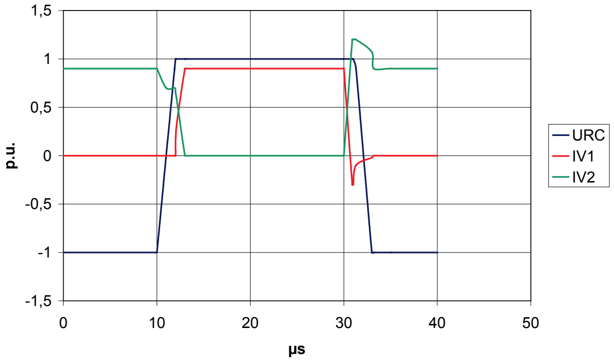


Figure 4.5: Current and voltage at the commutation according to Figure 4.4.

Figure 4.5 shows the currents in valve 1 and valve 2, together with the converter side phase voltage at two successive commutations. In Figure 4.4, only the components taking part in the commutation process are shown.

Prior to the first commutation at t=10 µs the IGBT in valve 2 is conducting and all the a.c. current flows through valve 2, I_{V2}. At t=10 µs the IGBT in valve 2 is ordered to extinguish the current and starts to take up forward blocking voltage. The current I_{V2} is somewhat reduced due to the capacitive recharge as the phase voltage rise from -1 p.u. to +1 p.u. When the phase voltage reaches + 1.0 p.u. the diode in valve 1 starts to conduct and the IGBT can complete the current extinction. Typically, the commutation process takes a few microseconds. (The IGBT in valve 1 is fired, but this has no effect as the current is driven through the diode in valve 1).

At commutation in the opposite direction, as indicated at t=30 µs, the IGBT in valve 2 is ordered to fire, i.e. take over the current. During this commutation the current is driven both by the converter reactor and the pole capacitors. The IGBT increases its current until the current in the diode in valve 1 is extinguished. However, the diode is a real diode with space charge in the semi-conducting layers. As a consequence, the diode current, shown as I_{V1} will be negative before the current is interrupted, as shown in Figure 4.5. The sharp diode current extinction may trigger more ringing in the parasitic circuit elements than the IGBT current extinction. Anyhow, due to the short commutation time the current derivatives are quite high with corresponding RFI emission.

4.2.5.4. Radiation mechanism

The commutation process in power electronic equipment causes high frequency current to circulate in the connecting bus work and ground system. These high frequency current loops act in the same way as magnetic dipole antennae with corresponding fields. The loop current multiplied with the loop area, i.e. the antenna area, determines the strength of the source. Even if only a small amount of the current is distributed further out in the substation and in the connecting lines, the radiation can be significant due to the large antenna area. As the generation is a function of local resonances, the frequency spectra can be quite irregular with several emission peaks at different frequencies. For line-commutated equipment, the general pattern is that the amplitude decreases with the frequency above 1-5 MHz, see Figure 4.1.

For schemes utilising forced commutation, such as voltage source converters, the fast commutations might cause resonance peaks for frequencies up to 10 MHz due to resonances with parasitic capacitances and inductances. In some cases, resonances at the semiconductor component level of some hundred MHz have been observed. The commutation frequency of the forced commutation is often in the range of 1- 2 kHz. Consequently, the harmonics of the commutation process have to be considered regarding their impact on RFI and PLC disturbances, as well as the transient oscillations caused by single commutation events.

4.2.5.5. Characteristics of the disturbances

In most cases, the disturbances from power electronic equipment do not have the characteristics of continuous signals. Instead the disturbing signals in most cases have the characteristic of repetitive transients. Figure 4.6 shows a typical example. Each transient is due to a commutation, or switching event, in the power electronic converter. In Figure 4.6, the amplitude of the transients differs between the different transient pulses. Even the ringing frequency and other properties of the transients may differ.

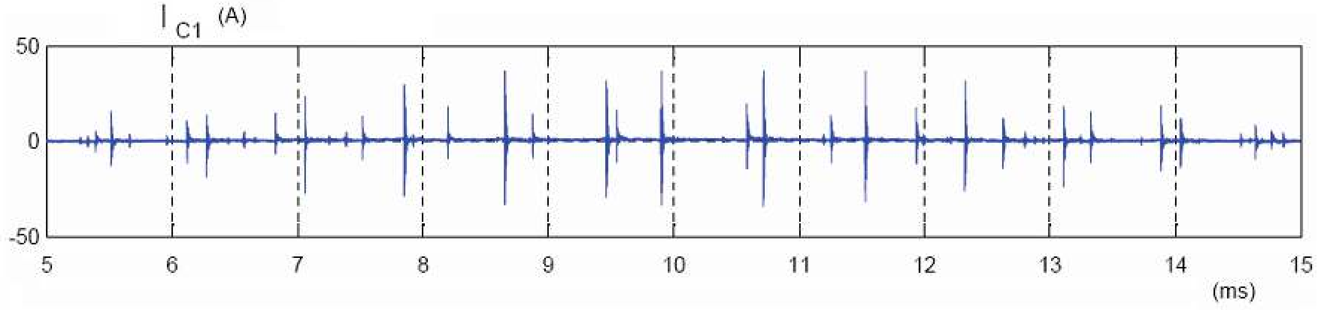


Figure 4.6: Example of disturbing current in ms scale.

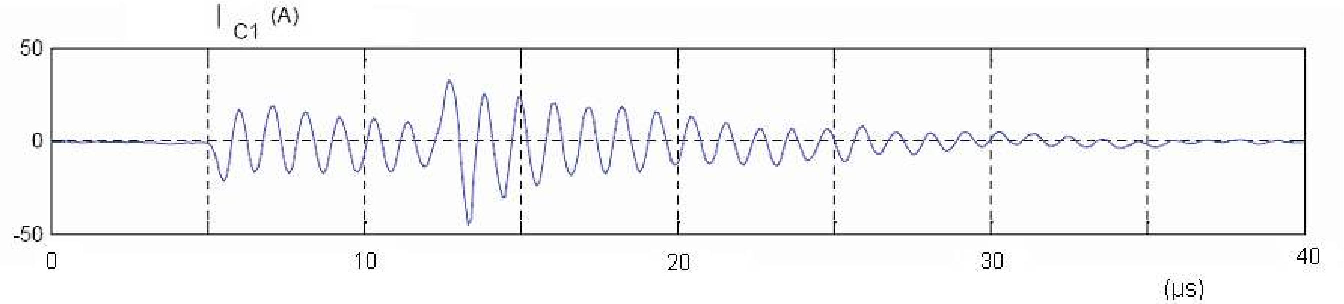


Figure 4.7: Enlargement of one transient in Figure 4.6 to a µs time scale.

Figure 4.7 shows an example of a transient in the µs scale. In this case the transient is a short ringing current around 900 kHz. The frequency spectrum of the signal is shown in Figure 4.8. As the spectrum analysis is performed by using the fast Fourier Transformation, FFT.

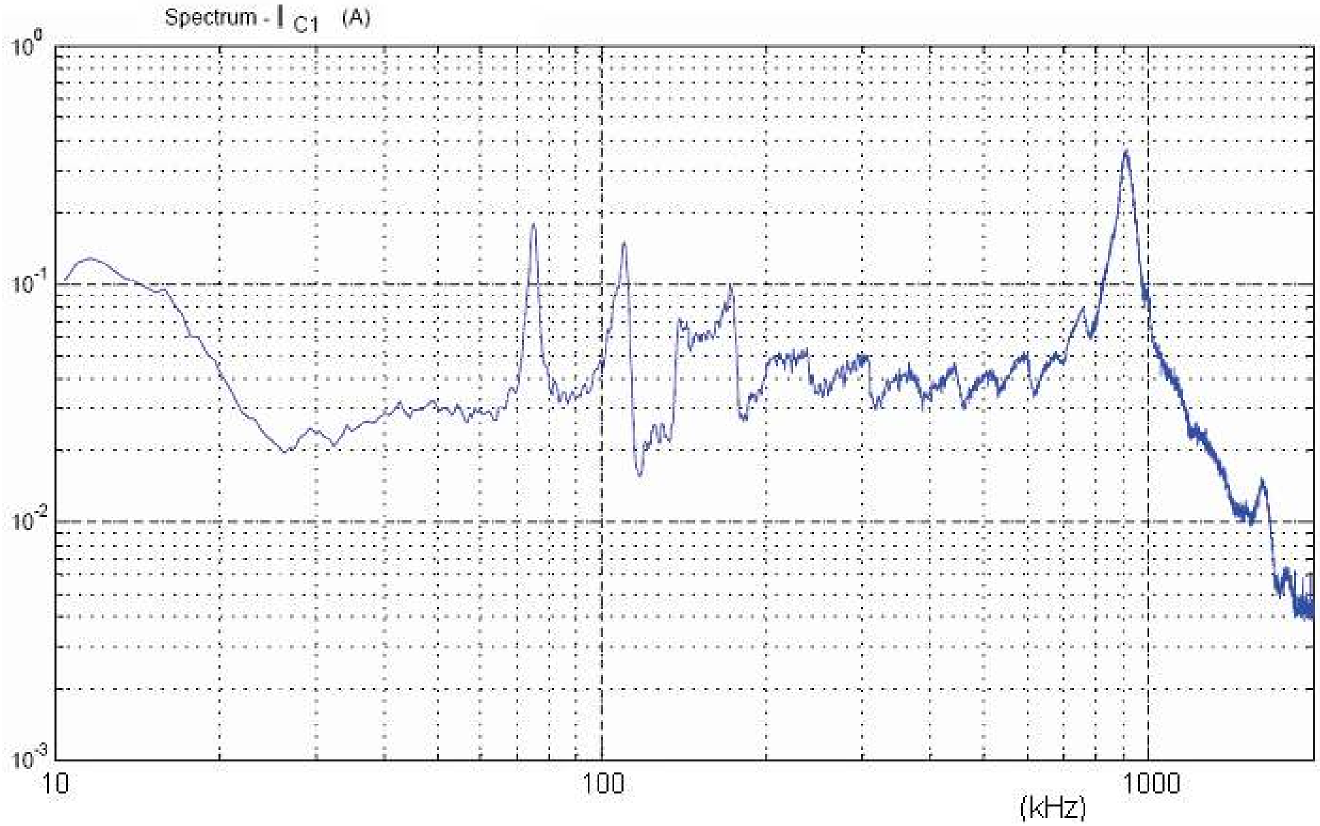


Figure 4.8: The frequency spectrum of the current in Figure 4.6.

It should be noted that Figure 4.8 shows the average value of each frequency component, as it is obtained by an FFT analysis. The peak values may be significantly higher. As an example, the average amplitude of the 900 kHz signal is about 0.35 A in Figure 4.8. In Figure 4.7 the peak value of the 900 kHz ringing is in the order of 35 A, thus a magnitude of two decades higher. The output from most of the RFI detectors described in Section 3.3 is better correlated to the peak value of the ringing than the average frequency content in the signal. This is especially true for the peak detector.

4.2.6. PLC

Power Line Carrier (PLC) is the concept to communicate via a modulated carrier signal superimposed on the power frequency voltage of the power line. The signal is connected to the power circuit via a small PLC capacitor. PLC reactors are used for blocking the carrier signal from entering circuits other than the intended power line. The concept has been used by the power industry for protection and communication purpose for quite a long time. Used for communication via high voltage lines it is a narrow band communication with a carrier frequency somewhere in the frequency band 30 to 500 kHz. The signal is normally induced as a balanced signal on two phase conductors. The RFI emission due to this will have the same characteristics as that of a broadcast radio station. However, due to the balanced currents, the amplitude of the RFI will be limited.

The PLC or BPL (Broadband Power Line communication) discussed for public access to data communication is a broadband signal induced in the low voltage or MV network [38], [39]. The induction will be unbalanced. The reasons for concern are:

- The broadband spectra used for the communication.
- The use of unbalanced circuits for signalling current.
- Mass usage.
- Use inside domestic buildings where most sensitive receivers are located.

For reliable PLC communication, the signal to noise ratio in the receiving end must be sufficient. Due to the attenuation of the lines, the signal level in the sending end must be even higher. Thus, the PLC current in the sending end must be at least two orders of magnitude larger than the high frequency currents due to corona and other noise. Thus, PLC may be a cause of RFI, if there is a frequency band conflict.

5. Disturbance propagation

5.1. General

Figure 5.1 gives an overview of RFI from a HV substation which can propagate to the surroundings. The figure shows an example when the substation includes an installation for HVDC, FACTS, or other high power electronic equipment.

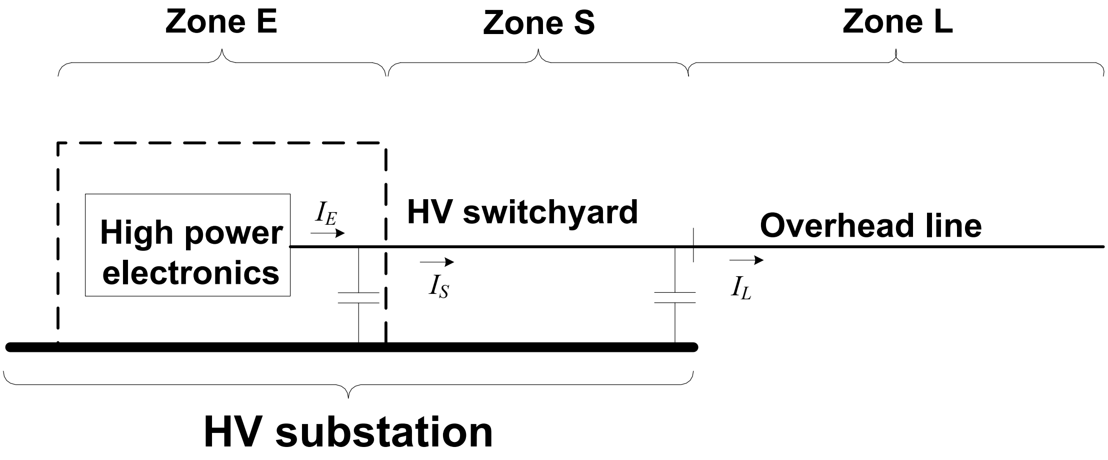


Figure 5.1: Overview of RFI from a substation with installation of FACTS or HVDC.

For the substation, the station earth grid is indicated. The capacitor at the border between the substation and the line is to indicate that the high frequency current I_L penetration via the line is in most cases much lower than the high frequency current I_S which is circulating within the substation. In the same way, the capacitor at the border between the power electronic installation and the substation is to indicate that the high frequency current I_S circulating within the bus bars of the substation is in most cases much lower than the high frequency current I_E which is circulating within the high power electronics.

One reason for distinguishing between different zones is that the measures for reducing the emission differ. For the zones S and L it is essential to limit the high frequency current in the outer circuits. For emission in zone E, the countermeasures must be directed to the equipment itself or to improved screening. For more information see Chapter 7.

5.2. Sources of RFI

5.2.1. Power electronic installations

At the commutation process of high power electronic equipment, i.e. HVDC and FACTS, high frequency currents circulate inside the power electronic equipment installation. Consequently, the power electronic equipment radiates RFI.

If the power electronic equipment is installed in a metallic building, or a building with metallic structures, the building will screen the radiation from the power electronic equipment by the induced compensating currents in the conducting metallic parts. The level of RFI is reduced. However, from the outside world, the building appears as the source for the emission of RFI to the surroundings. That part of the RFI reaches the surroundings as a direct radiating wave.

5.2.2. Corona from substation equipment

A high voltage substation is a concentration of different types of high voltage equipment, often quite compact. Consequently, corona is inevitable. Thus, the complete high voltage switchyard, with bus structures, disconnectors, breakers, instrument transformers etc, will act as a source of emission of RFI due to corona.

Sparking might also be a primary cause of RFI from the high voltage switchyard. Also the RFI due to corona and sparking will reach the surroundings mainly as a direct wave.

5.2.3. RFI emission due to spread out of high frequency currents

As indicated in Figure 5.1, a smaller or larger fraction of the high frequency current inside the high power electronic installation will be spread into the bus structures of the switch yard and even into the connected lines. These outer circuits consequently will act as antennae and emit RFI. This spreading of RFI due to the spread of high frequency current, is also defined as guided wave of RFI along the bus structures and the lines. Thus the RFI can be seen as a direct emission from the bus structures and lines due to the spreading of the high frequency current, or a distribution of guided RFI waves travelling along the bus structures or lines, guided waves originating from the power electronic installation or the corona.

High intensity of corona or sparking in a substation may also cause emission of high frequency current into the connecting lines, which will help to spread the RFI to a longer distance from the substation than the reach of the RFI from the primary source itself. Thus, also high local corona activity may result in emission of RFI distributes as guided waves along connected lines.

5.3. RFI in the three zones in Figure 5.1

5.3.1. Zone E

Zone E in Figure 5.1 indicates a zone where the direct wave RFI from the high power electronic installation as such dominates. Thus the RFI level depends on the internal design of the power electronic installation and the screening effect of the building, if any.

5.3.2. Zone S

A fraction of the high frequency current from the high power electronic equipment will penetrate into the bus structures of the high voltage switchyard via the high voltage connection to the power electronic equipment, current I_s in Figure 5.1. The current loop will be closed via the earth grid. Consequently, the combination of the high frequency current I_s and the high voltage bus structures will act as magnetic dipole antennae and as a source for RFI emission.

In Zone S there will also be RFI due to corona and may be sparking in the high voltage equipment. Thus in Zone S there is a mixture of RFI origination from different sources. In addition Zone S and Zone E are often overlapping

5.3.3. Zone L

Some fraction of the high frequency current in the high voltage switchyard will penetrate further out as guided waves in the connecting lines causing radiated RFI emission also from the lines, current $\mathrm{I_L}$ in Figure 5.1.

The reason for narrowing the measuring distance farther from the substation, as shown in Figure 1.1, is that a fraction of the current I_L is earth mode current, which is damped out fairly quickly. However, at measurement of a few kilometres from substation the conducted RFI emission from the line is felt to be representative of the RFI emission also farther from the substation.

Regarding RFI from the substation, RFI due to line corona or sparking is treated as background RFI noise.

5.4. Disturbance reach

RFI radiated directly from the substation are distributed from the substation to the surroundings as electromagnetic radiation. As a first approximation within a distance r of $\lambda/2\pi$ from a substation, the attenuation of the field strength decreases as $1/r^2$ [40]. For a larger distance, the attenuation for free field radiation is proportional to $1/r$ where r is the distance to the installation. However, at long distances in relation to the wave length, the interaction with the soil gives additional attenuation and consequently the field strength decreases as $1/r^2$, see Section 6.4 and Section 9.1 for more information. Besides, at distances smaller than the physical size of the installation, the field level may be very irregular with significant local variation [40].

RFI propagated via the connected ac lines may interfere with more remote radio receivers than the direct radiation. The reason is that attenuation is lower for line-bound currents than for the direct radiation, especially for transients induced as line-to-line currents. The attenuation is higher for zero sequence currents, and moreover, the attenuation increases with the frequency. When PLC is used for communication in the power system, the limits for PLC disturbances may be more significant than the RFI criteria regarding the acceptable amount of induced high frequency currents in the line. See also Appendix C.

6. Modelling and calculation

6.1. Introduction

Describing an electromagnetic complex environment like the one of an electric substation is very complicated not only for the model itself, but mainly for the difficulty in knowing, even with rough precision, all the sources of electromagnetic field contained inside the fence circumscribing the area relevant to the substation (see Section 5).

Thus, the purpose of this chapter is to present just some very simple models to be able to give some indications about the order of magnitude of the field produced at a certain distance from the substation area. Moreover, the use of these simple models should be an aid in understanding and pointing out the essential aspects of the generated electromagnetic field. There are some examples of calculation of radiated RFI from a substation in the literature [41], [42].

The first part of this chapter, Section 6.2 is devoted to the description of some common models of impulsive waveshapes that represent, with good approximation, real transient waveshapes.

The second part, Section 6.3, of this chapter deals with the theory for calculation of radiated electric and magnetic fields. Although the equations in a strict theoretical meaning are valid for electrical and magnetic dipoles, even a large substation can be divided into a large amount of dipoles. Therefore, well outside a substation, the characteristics for the simple dipoles is valid also for the field from a complex substation.

Section 6.4 describe and gives the formulae for considering the extra attenuation due to impact from the earth. Finally, Section 6.5 gives some conclusive remarks regarding the far field and the near field behaviour of the radiated field.

6.2. Analytical models of common wave shapes

6.2.1. General

This paragraph is devoted to present some simple models of wave shapes that can be considered as an idealization of the real wave shapes generated by sparks, switching and power electronics. Note that the presented models are relevant to single pulses while, in the reality, we generally have repetitive pulses. In spite of this, single pulses models are useful: in fact, the measurement receivers are envelope detectors. Therefore, the frequency characteristic of a single pulse is a primary parameter. A peak detector only senses the frequency content of a single pulse. For other detectors, the pulse repetition rate also impacts the reading, as a separate parameter. However, an rms detector senses the rms-value of the envelope, not the rms value of the signal itself. Consequently, the radiation and attenuation properties for a single pulse or transient are relevant also for repetitive transient.

The advantage in the use of these wave shapes is that their spectra can be represented by simple analytical expressions. Among the models presented, the ring-wave is considered to be representative for the transients caused by power electronic equipments, see Section 4.2.5 of this guide.

In the following, we present three different wave shapes:

- double exponential pulse;
- ring-wave;
- damped oscillatory wave.

6.2.2. The double exponential pulse

The double exponential pulse can represent a single pulse related to corona and micro gap discharges [43].

The formula of the current y=y(t) in the time domain is given by:

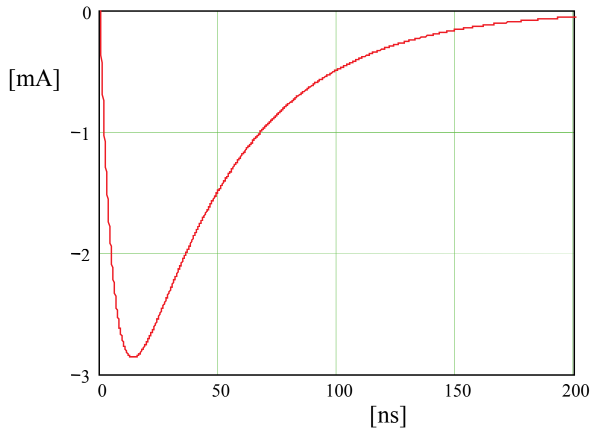
$$y(t)=\begin{cases} A\left(e^{-at}-e^{-bt}\right) & t\geq 0 \\ 0 & t<0 \end{cases} \tag{6.2.1}$$

By indicating with j the imaginary unit and *f* the frequency, the Fourier Transform Y(*f*), representing the spectrum, is:

$$Y(f)=\frac{A(b-a)}{ab-4\pi^2 f^2+j2\pi f(a+b)} \tag{6.2.2}$$

The parameter A is related to the amplitude of the curve (but it is not the peak value), while the parameters *a* and *b* are related to the shape.

In Figures 6.2.1a and 6.2.1b an example of the wave shape is given (negative and positive pulse), while, in Figure 6.2.2, the corresponding normalized[3] spectra are shown.



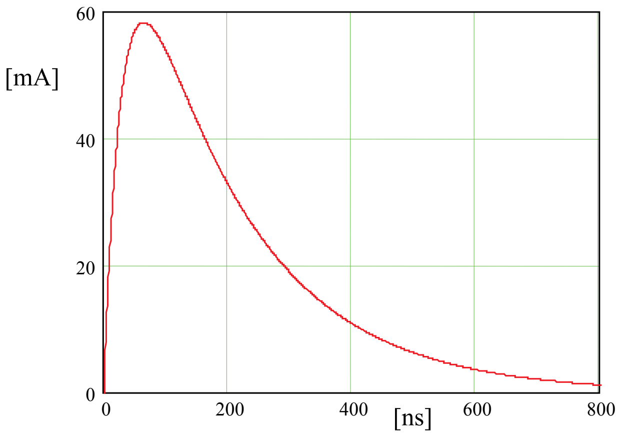


Figure 6.2.1a: Example of negative corona pulse

Figure 6.2.1b: Example of positive corona pulse

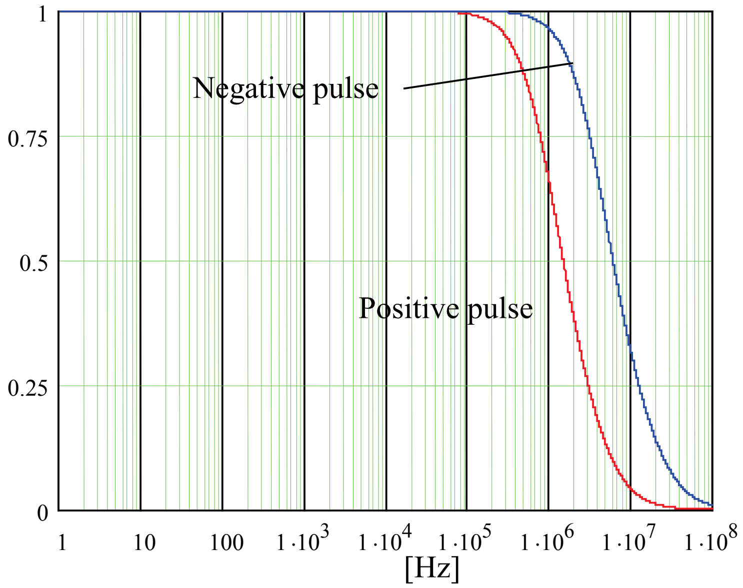


Figure 6.2.2: Normalized corona pulse spectra

6.2.3. The ring-wave

The ring-wave is the typical oscillatory transient travelling on lines and can be represented by the following equation:

$$y(t) = \begin{cases} A\left(e^{-at} - e^{-bt}\right)\sin(2\pi F\,t) & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{6.2.3}$$

while the relevant Fourier Transform is:

$$Y(f) = A\left[\frac{2\pi F}{a^2 + j4\pi af + 4\pi^2\left(F^2 - f^2\right)} - \frac{2\pi F}{b^2 + j4\pi bf + 4\pi^2\left(F^2 - f^2\right)}\right] \tag{6.2.4}$$

---

[3] i.e. the ratio between the spectrum at the generic frequency f and the spectrum evaluated at f=0

The ring-wave is characterized, in addition to parameters A, a, and b, by the oscillation frequency F. Figures. 6.2.3 and 6.2.4 show an example of the wave shape and of the corresponding normalized spectra. The ring-wave is considered to be representative for the transients caused by power electronic equipments, see Section 4.2.5.

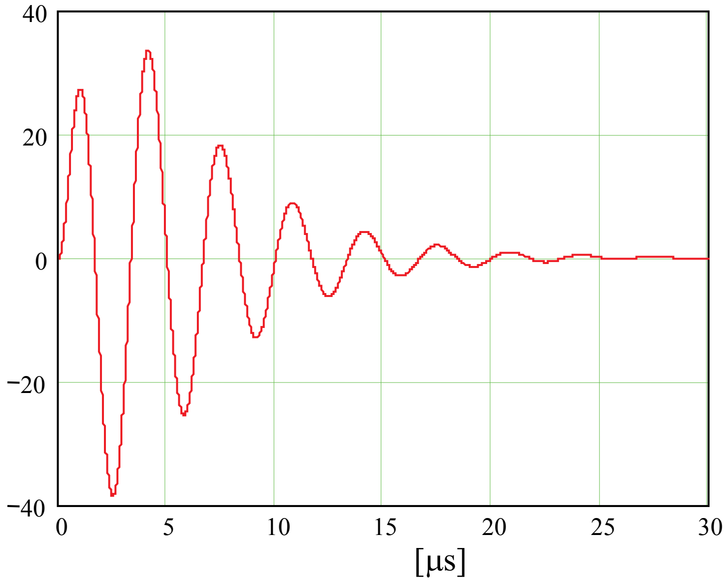


Figure 6.2.3: Example of ring-wave; F=300kHz

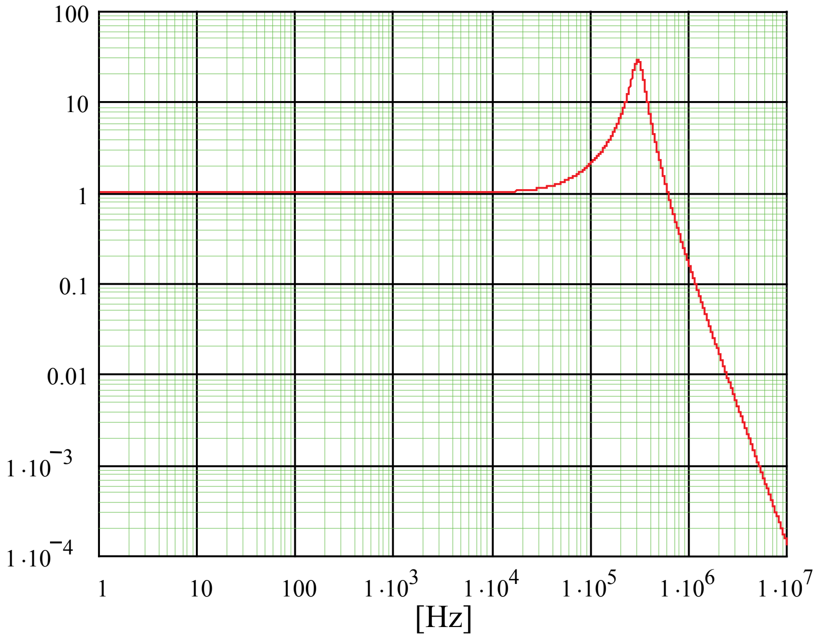


Figure 6.2.4: Normalized spectra of wave shape shown in Figure 6.2.3

6.2.4. The damped oscillatory wave

The damped oscillatory wave, typical of switching operations in substations, is represented by the following equation:

$$y(t) = \begin{cases} A\left(e^{-at}\right)\sin(2\pi F\, t) & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{6.2.5}$$

and its Fourier Transform is given by:

$$Y(f) = A\left[\frac{2\pi F}{a^2 + j4\pi a f + 4\pi^2\left(F^2 - f^2\right)}\right] \tag{6.2.6}$$

Figures 6.2.5 and 6.2.6 show an example of this kind of wave shape and of the corresponding normalized spectrum.

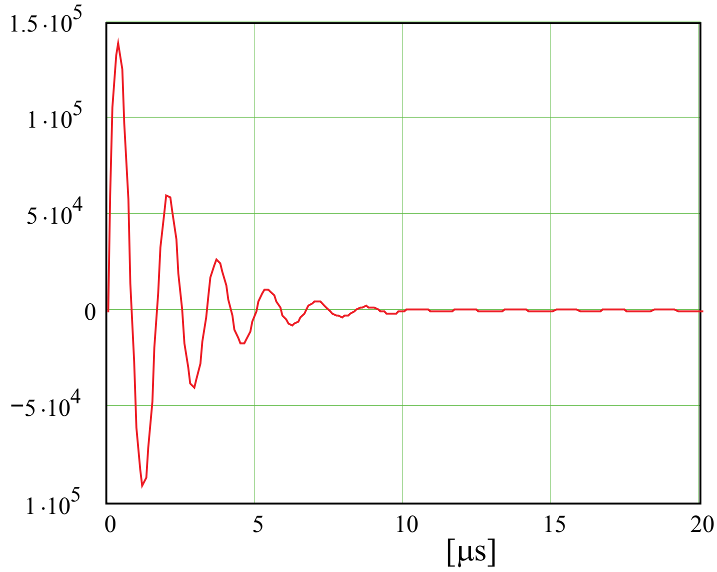


Figure 6.2.5: Example of damped oscillatory wave; F=600 kHz

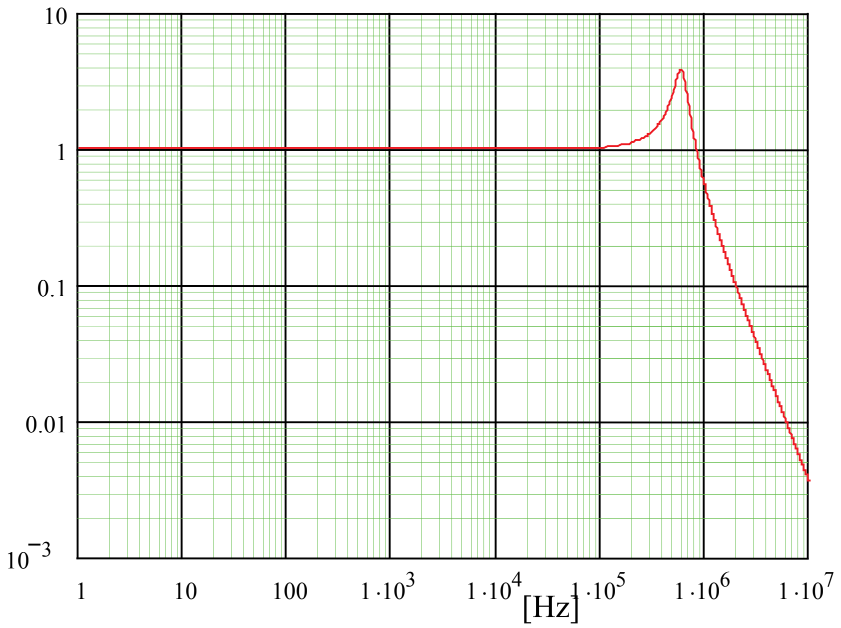


Figure 6.2.6: Normalized spectra of wave shape shown in Figure 6.2.5

6.2.5. Attenuation of RFI via a connected line

Attenuation curves for the electric field generated by a current pulse travelling along a line are shown in Appendix C. The scope of the appendix is to present a simple model able to predict the level of attenuation of the electric field radiated by a current pulse travelling along a line, some kilometres long, placed over a perfect earth. Thus, Appendix C describes the phenomenon related to the electromagnetic emission from a power line due to conducted impulsive wave shapes, travelling along the line itself, and arising from a substation area.

As specified in chapter 4 of the Guide, the source of these pulses can be sparking, arcing and commutation operations inside the substation area. However, Appendix C does not deal with the specific nature of the conducted disturbance. A common wave shape (e.g. ring-wave) is assumed and the appendix gives a prediction of the level of electromagnetic field radiated by the line for different frequencies, different lateral distances from the line and different distances from the origin of the conducted wave shape (i.e. the substation) seen in this model as a point.

6.3. Calculation of radiated fields

6.3.1. Introduction

Any current carrying element can radiate or is susceptible to electromagnetic radiation. Within a substation, typical intentional or unintentional radiating elements (antenna) and elements, which are susceptible to radiation, are: overhead lines, cables, bus structures and radio antenna. Broadly speaking the longer the conductor, or the bigger the conductor loop area, the better it is at transmitting or receiving electromagnetic radiation.

Magnetic dipoles and electric dipoles form the fundamental radiating unit. A radiating structure can be represented by a number of these current carrying elements and the total electromagnetic radiation from the radiating structure will be the sum of the contributions from each of the constituent dipoles. In free space an isolated oscillating current element of amplitude *I*, frequency *f*, length *dl* and directed along the *z* axis, as depicted in Figure 6.3.1, forms an electric dipole and the radiated electromagnetic fields (*E* and *H*) at a distance *r*>> *dl* can be given in polar form [44]:

$$H_r = H_\theta = 0\,; \quad H_\phi = \frac{Idl}{4\pi}\sin\theta\left(j\frac{\beta_0}{r}+\frac{1}{r^2}\right)e^{-j\beta_0 r} \tag{6.3.1}$$

$$E_r = \frac{Idl}{2\pi}\eta_0\cos\theta\left(\frac{1}{r^2}-j\frac{1}{\beta_0 r^3}\right)e^{-j\beta_0 r} \tag{6.3.2}$$

$$E_\theta = \frac{Idl}{4\pi}\eta_0\sin\theta\left(j\frac{\beta_0}{r}+\frac{1}{r^2}-j\frac{1}{\beta_0 r^3}\right)e^{-j\beta_0 r} \tag{6.3.3}$$

$$E_\phi = 0$$

where $\beta_0 = \frac{2\pi}{\lambda_0}$, λ_0 is the free space wavelength (c/f) and $\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$ is the impedance of free space.

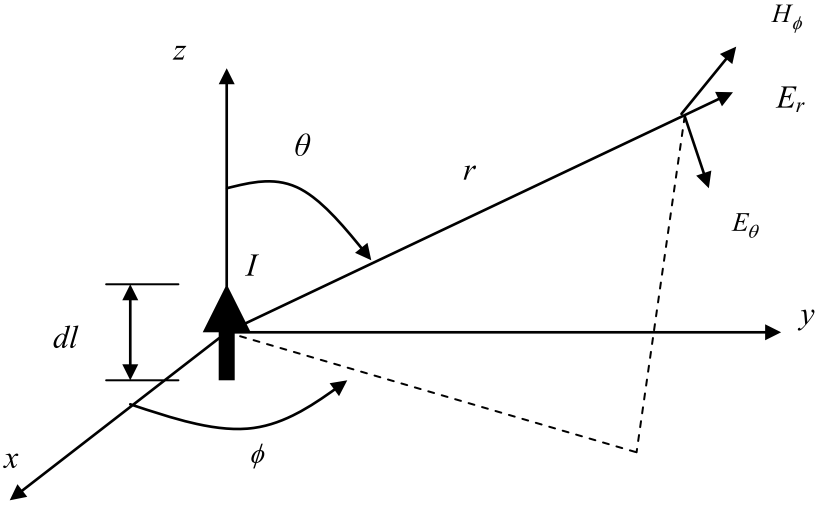


Figure 6.3.1: An elementary current element directed in the z-axis and the radiated electromagnetic fields generated by it

The variations in (6.3.1-6.3.3) is illustrated in Figure 6.3.2 that shows the maximum absolute amplitude of E_r, E_θ and $H_\Phi*\eta_0$ versus the distance in p.u. (i.e. the distance r divided by the wavelength λ_0).

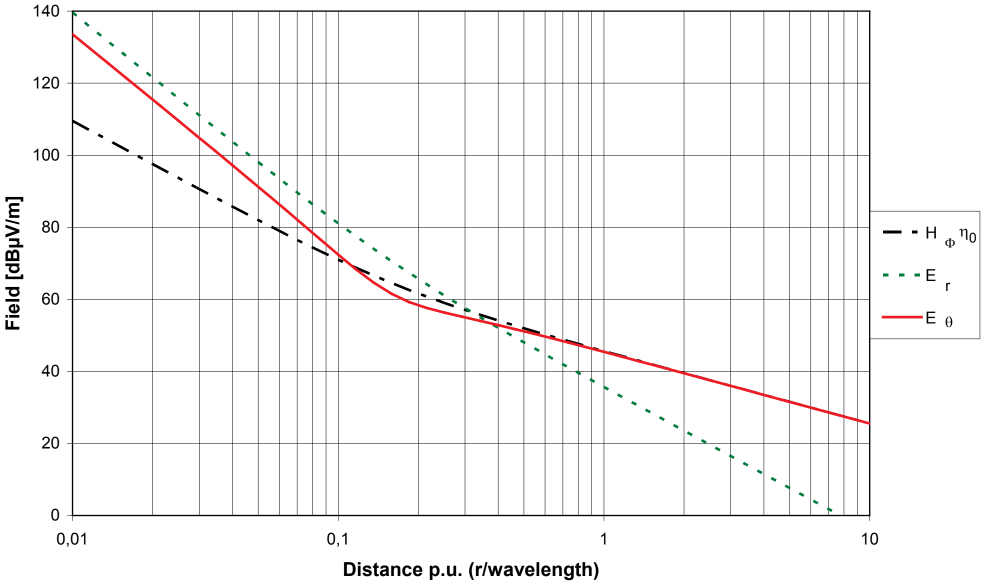


Figure 6.3.2: A graphical illustration of the variation in Equations (6.3.1-6.3.3). $I*dl/\lambda_0^2$ is set to 10^{-6}. Note that E_r varies as cos(θ) while H_Φ and E_θ vary as sin(θ).

In free space an isolated oscillating current element loop of amplitude *I,* radius *b* and in the *x-y* plane, as depicted in Figure 6.3.3, forms a magnetic dipole and the radiated electromagnetic fields (*E* and *H*) at a distance *r*>> *b* can be given in polar form [44]:

$$E_r = E_\theta = 0\,; \quad E_\phi = -j\frac{b^2 I\beta_0\eta_0}{4}\sin\theta\left(j\frac{\beta_0}{r}+\frac{1}{r^2}\right)e^{-j\beta_0 r} \tag{6.3.4}$$

$$H_r = \frac{b^2 I}{2}\beta_0\cos\theta\left(\frac{1}{r^2}-j\frac{1}{\beta_0 r^3}\right)e^{-j\beta_0 r} \tag{6.3.5}$$

$$H_\theta = \frac{b^2 I}{4}\beta_0\sin\theta\left(j\frac{\beta_0}{r}+\frac{1}{r^2}-j\frac{1}{\beta_0 r^3}\right)e^{-j\beta_0 r} \tag{6.3.6}$$

$$H_\phi = 0$$

where $\beta_0 = \frac{2\pi}{\lambda_0}$, λ_0 is the free space wavelength and $\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$ is the impedance of free space.

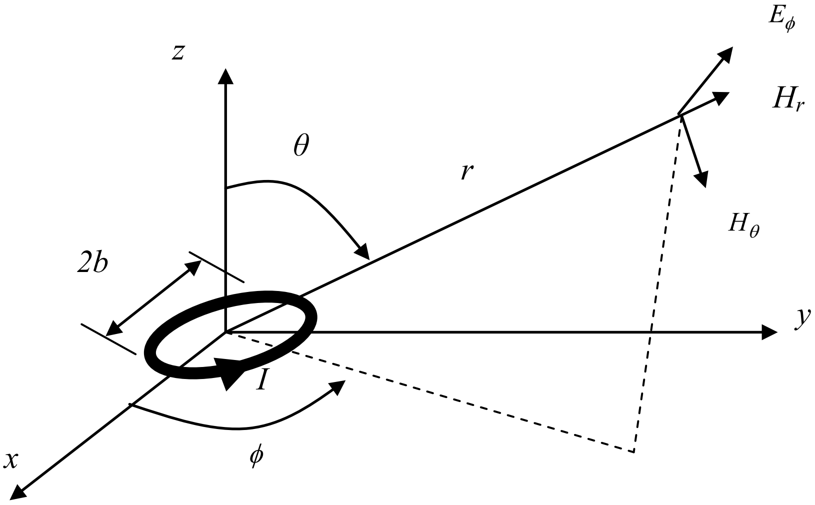


Figure 6.3.3: An elementary current element directed in the z-axis and the radiated electromagnetic fields generated by it.

The variations in (6.3.4-6.3.6) is illustrated in Figure 6.3.4 that shows the maximum absolute amplitude of $H_r\eta_0$ $H_\theta\eta_0$ and E_Φ versus the distance in p.u. (i.e. the distance *r* divided by the wavelength λ_0). The magnetic field is multiplied with the free space impedance η_0 for simplify the comparison with the electric field

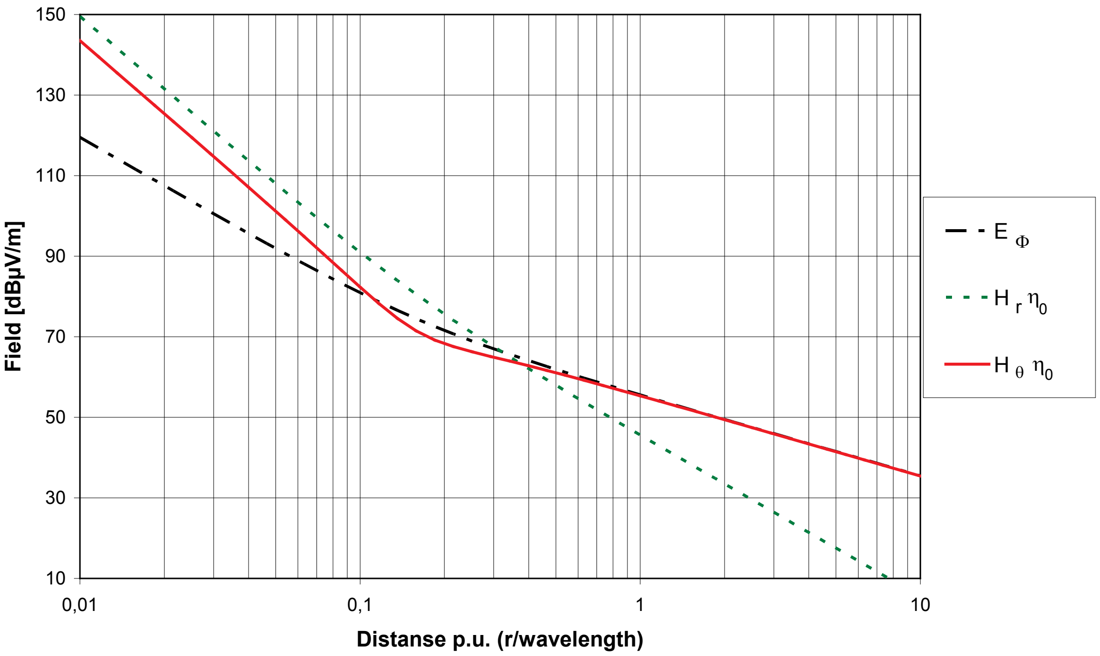


Figure 6.3.4: A graphical illustration of the variation in Equations (6.3.4-6.3.6). $2*\pi*b^2*I/\lambda_0^3$ is set to 10^{-6}. Note that H_r varies as cos(θ) while E_Φ and H_θ vary as sin(θ).

Most substation conducting structures have dimensions of many wavelengths and often the observation point is at a distance comparable to the size of the structures. Equations (6.3.1-6.3.6), therefore, can not be used directly but the total electromagnetic field radiating from a large current carrying structure is found by the addition of the fields produced by each suitably small segment which have lengths such that dl<<r, dl<<λ. Thus if the current distribution is known over the surface of the antenna then the total radiation can be calculated by integrating over the antenna surface. Often approximations have to be made or the solution found numerically because the surface current is not well defined or closed form solutions of the integrals can not be defined. A complete analytic solution is possible for a uniform horizontal transmission line [45] but the radiation from the supply and load bushings are significant and difficult to characterise analytically. For a good assessment of the field strengths within a substation it is probably best to use a suitable field solver such as NEC or equivalent.

From the expressions for the radiated fields and Figures 6.3.2 and 6.3.4 several observations can be made.

1. Electric dipoles produce only E_r, E_θ and H_ϕ electromagnetic field components
2. Magnetic dipoles (current loops) produce only H_r, H_θ and E_ϕ electromagnetic field components
3. For distances less than 0.5 wavelengths ($r<0.5\ \lambda_0$) there is a rapid variation in the radiated field strengths with distance and $E/H>\eta_0$ for an electric dipole source or $E/H<\eta_0$ for a magnetic dipole source. This is the *near field* region.
4. For distances greater than 0.5 wavelengths ($r>0.5\ \lambda_0$) the field strengths vary as $1/r$ and $E_\theta / H_\phi = \eta_0$, $E_r\approx 0$ for an electric dipole or E_ϕ / H_θ , $H_r\approx 0$ for a magnetic dipole. This is the *far field* region. At 0.5 λ_0 the deviation in amplitude is less than 10 percent from the ideal far field. The deviation in phase angle is less than 2 °.
5. The electromagnetic field strengths are proportional to the length *dl* for an electric dipole or proportional to the area b^2 for a magnetic dipole.

For small radiating structures the *far field* region can therefore be defined as $r>0.5\ \lambda_0$ within the substation. However, many structures have lengths of several wavelengths and an alternative definition for the far field region: $r> 2D^2/\lambda_0$ is more appropriate, where *D* is the maximum dimension of the structure. The criterion is that the deviation in phase angle of waves from the two ends of the antenna is less than π/8 radians. Thus within the substation it can be generally considered to be a *near field* environment and the ratio of *E/H* will theoretically depend on whether the source is primarily an electric dipole or a magnetic dipole.

6.3.2. An example system

To illustrate the problem of estimating the radiated emissions from a substation structure a radiating system of comparable dimensions is considered as shown in Figure 6.3.5. The example system represents an overhead transmission line 5 m above the ground plane and of length 10 m. At one end is a vertical current source and the other end is shorted to ground by a vertical transmission line. Such a geometry is typical of that found in an air insulated substation with the vertical line sections representing transformer or circuit breaker bushings. The transmission line is excited by a broadband current source which has an amplitude of about 44 Amps in the frequency range 0.1 MHz to 10 MHz. The observation point is taken to be 10 m away from the plane of the transmission lines centrally located and at a height of 1 m from the ground plane which is a typical EMC measurement location for loop antenna.

There are several ways in which the radiated electromagnetic fields could be estimated.

1. The first method is to assume only the horizontal transmission line and its image contributes to the radiated fields and that the current is uniform along the whole length. This would involve using Equations (6.3.1-6.3.3) applied to the horizontal line and its image.
2. The second method is to assume that the radiating system and its image represent a current loop of dimension 10m × 10 m and constant current around the perimeter. This would involve using Equations (6.3.4-6.3.6) and approximating $b^2\pi = 10\times10\ \text{m}^2$.
3. A third approach would be to recognise that the dimensions of the radiating loop is comparable to the distance of measurement (i.e. $r \approx D$) so that for instance a more exact version of Equations (6.3.1-6.3.6) is required, e.g. a more exact expression for the radial magnetic field component from a large current loop are [44]:

$$H_r = \frac{{r_D}^2 I}{2({r_D}^2 + r^2)^{3/2}} \cos\theta \left[1 + \frac{15 {r_D}^2 r^2 \sin^2\theta}{4({r_D}^2 + r^2)^2} + .. \right] e^{-j\beta_0 ({r_D}^2 + r^2)^{1/2}} \qquad (6.3.7)$$

$$H_\theta = \frac{-r_D^2 I}{4(r_D^2 + r^2)^{5/2}} \sin\theta \left[2r_D^2 - r^2 + \frac{15 r_D^2 r^2 \sin^2\theta}{8(r_D^2 + r^2)^2} (4r_D^2 - 3r^2) + .. \right] e^{-j\beta_0 (r_D^2 + r^2)^{1/2}} \qquad (6.3.8)$$

$$E_\phi = \frac{{r_D}^2 I r \beta_0 \eta_0}{4\ {r_D}^2 + r^2()^{3/2}} \sin\theta \left[1 + \frac{15 {r_D}^2 r^2 \sin^2\theta}{8({r_D}^2 + r^2)^2} + .. \right] e^{-j\beta_0 ({r_D}^2 + r^2)^{1/2}} \qquad (6.3.9)$$

   where $E_r = E_\theta = H_\phi = 0$, $r_D = \sqrt{D^2 / \pi}$ and $r\sin\theta$ is the height of the observation point above ground.

4. A forth approach is to recognise that at higher frequencies the transmission line lengths approach a wavelength so that the current can no longer be assumed to be constant along the length of the transmission line. In this case the exact formula given by [45] for the radiation from a long line can be used for each line Section and its image. The total field is then the sum of these fields.
5. The final approach considered here is to simply use a 3D numerical field solver. In this example the TLM time domain method was used at three frequencies (0.1, 1, 10 MHz).

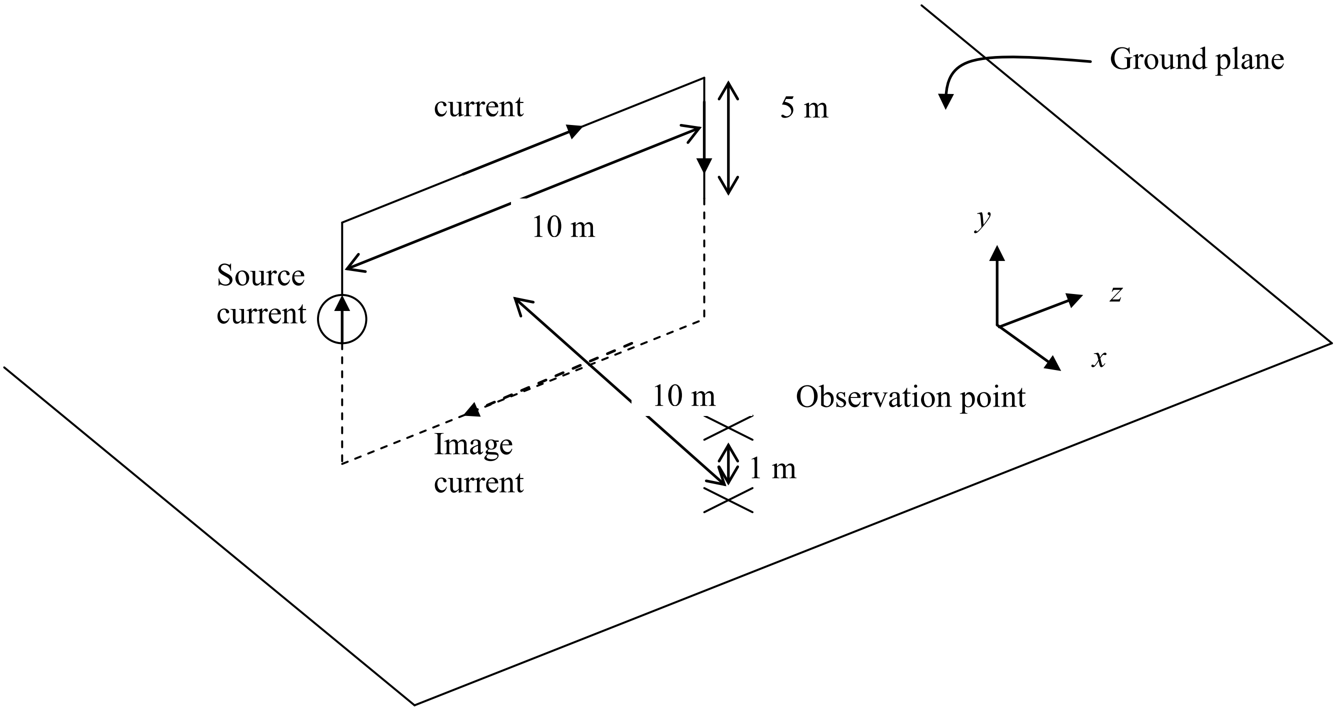


Figure 6.3.5: A 10m long overhead transmission line 5 m above the ground plane with a source represented by a vertical line section and terminated by a vertical line section and an observation point 10 m from the plane of the transmission line and 1m above ground.

6.3.3. Results

Figure 6 shows the estimated radial magnetic fields from the considered structure for the 5 methods discussed

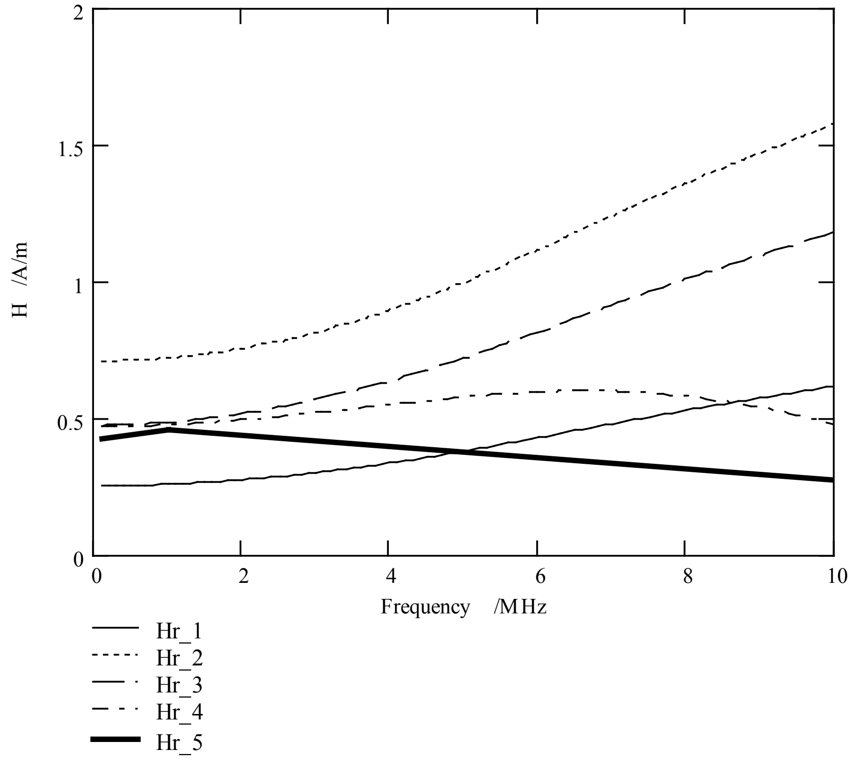


Figure6.3.6: The radial magnetic field deduced by the 5 different approaches. *H*r_1 method 1, *H*r_2 method 2, *H*r_3 method 3, *H*r_4 method 4 and *H*r_5 method 5

Figure 6.3.6 shows that method 1 initially under estimates the radial magnetic field because it does not full take into account the effect of the size of the radiating body. Method 2 always over estimates the magnetic field because it does not include the effect of the vertical line sections. Method 3 gives good agreement at low frequencies but at higher frequencies it does not include the effect of the current variation due to its finite wavelength. Method 4 shows reasonable agreement with the numerical model.

Figure 6.3.7 shows the estimated longitudinal electric fields *E*z from the considered structure for 4 of the methods discussed

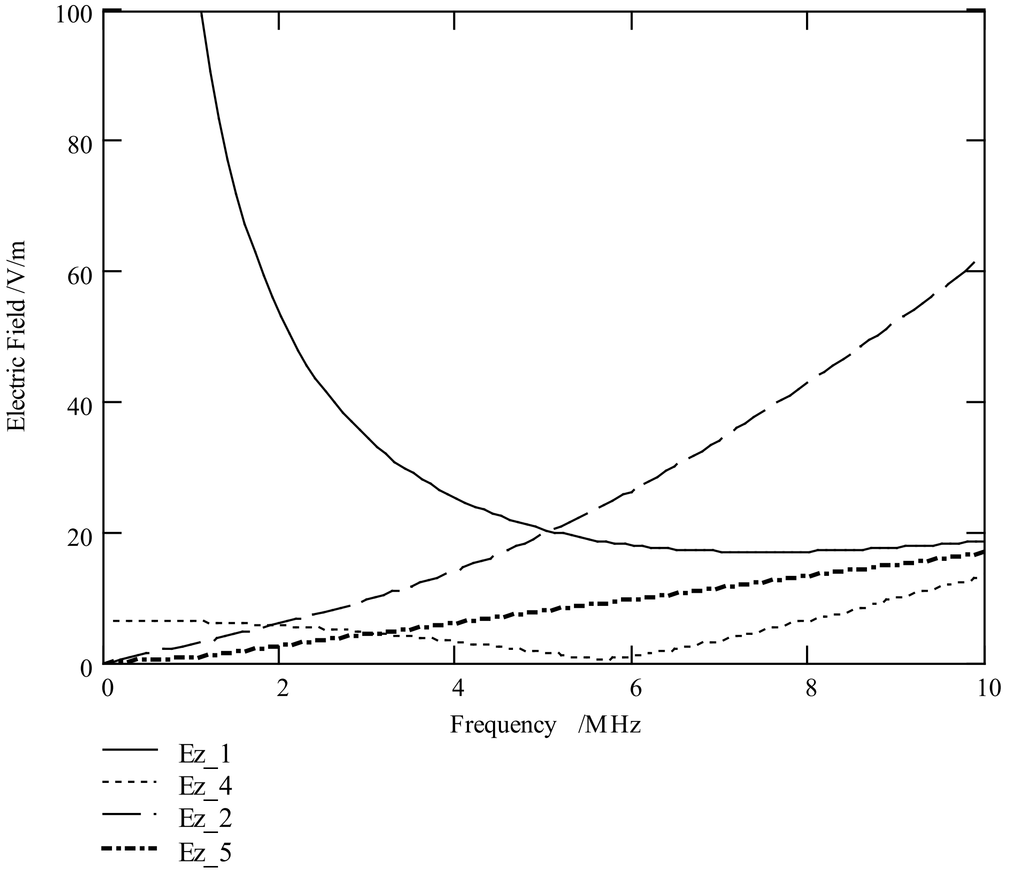


Figure 6.3.7 The longitudinal Electric field *Ez* deduced by 4 different approaches. *Ez*_1 method 1, Ez_2 method 2, Ez_4 method 4 and *Ez*_5 method 5

In Figure 6.3.7 it can be seen that method 1 overestimates the longitudinal electric fields at low frequencies and method 2 over estimates the longitudinal electric field at high frequencies. Method 4 also slightly over estimates the longitudinal electric fields at low frequencies and this is possibly due to representing the vertical sections as uniform transmission lines.

Figure 6.3.8 shows the estimated electric field components using methods 4 and 5.

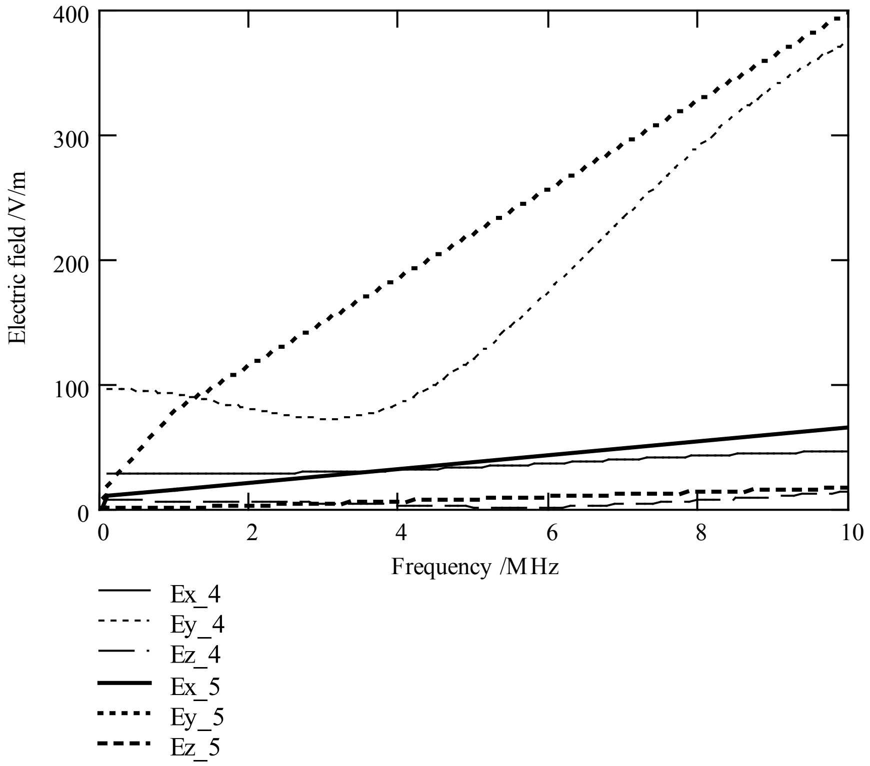


Figure 6.3.8: The Electric field components *Ex*, *E*y and *Ez* deduced by methods 4 and method 5 (_4 corresponds to method 4 and _5 corresponds to method 5).

6.4. Electric field propagation over "good earth"

6.4.1. Introduction

The attenuation of the electric-field over ground is an important question for the development of electromagnetic emission measurement methods at frequencies below 30 MHz. In this paper, results for this attenuation are summarized. Two different simple models are commonly used to predict this attenuation; the two-beam model and the short-dipole model. Both models have limitations in practical applications were the wavelength is larger than the electric size of the antenna and if interaction with ground is present at the same time. A useful model is created if the simple two-beam model is extended with an inductive source modelled as a short dipole. The resulting model gives results with good agreement with measurements.

6.4.2. Simple two-beam model

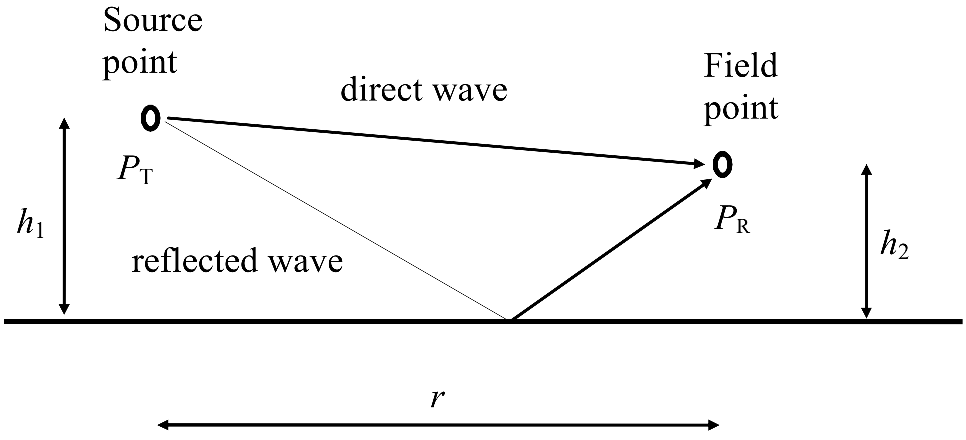


Figure 6.4.1: Geometry for the model.

If only a simple two-beam model is used, it can be shown that the received power P_R, see Figure 6.4.1, in the receiving antenna can be calculated as

$$P_R \approx \frac{P_T A_R}{\pi r^2}\left[\sin(\frac{2\pi h_1 h_2}{\lambda r})\right]^2, \tag{6.4.1}$$

where A_R is the effective antenna cross section of the receiving antenna and P_T is the transmitted power. If $\lambda r >> h_1 h_2$, then $\sin x \approx x$, which gives the characteristic $1/r^4$ decay of the received power (thus, a $1/r^2$ decay for the electric field strength). However, this simple model assumes far-field conditions and does not take inductive source fields into account.

6.4.3. Short dipole

For practical purposes, the free-space magnitude of the vertical component of the electric field from a short horizontal dipole can in general be modelled using (6.2.3)

This model catches the principal behaviour of the attenuation of the magnitude of the field. For $R<\lambda/2\pi$, the magnitude decreases with 60 dB per frequency decade. For $R>\lambda/2\pi$, the magnitude decreases with 20 dB per frequency decade, see Figure 2. However, since this model does not consider the interaction with the ground wave, the $1/r^2$ -decay from the two-beam model at larger distances is not reproduced.

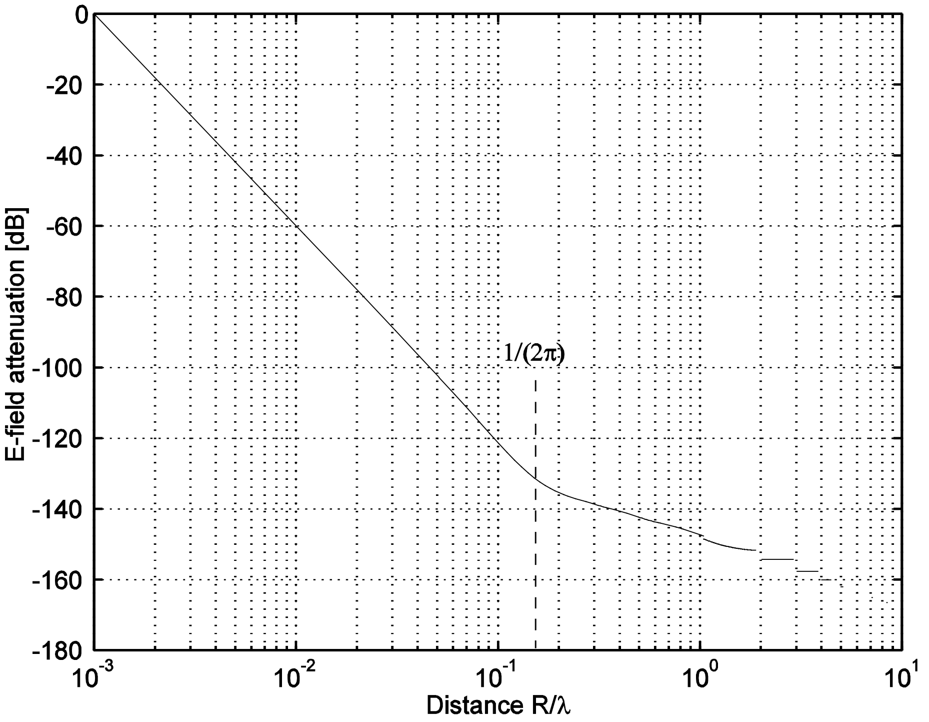


Figure 6.4.2: Attenuation of vertical E-field component for short dipole in free space.

6.4.4. Model with inductive source included in the two-beam model

In [46], a model for electric field propagation above plane earth in the region from 1 meter to 10 km from the source is developed by using classical ground-wave propagation theory extended to include induction fields from the source. The model covers the frequency range from DC to 1 GHz. The paper is extensive and covers a lot of details. Therefore, the model and results in [46] are summarized in this paper to extract the interesting part for the CIGRE measurement guide.

The model is valid as long as the criterion

$$\frac{2\pi h_1 h_2}{\lambda r} < 1 \qquad (6.4.3)$$

is fulfilled where h_1, h_2 and r are defined according to Figure 1 and λ is the wavelength of the radiated field. The propagation model is based on the formulation of Burrows and Gray [47] and gives the ground-wave field intensity over a plane earth as

$$E(r) = 2E_0^*(r)A(r)G(h_1)G(h_2) \qquad (6.4.4)$$

where

r	distance from source to point measured on the plane;
h_1	source height;
h_2	height of field point (receiving antenna);
$E(r)$	ground-wave field intensity at distance r and height h_2 above plane;
$E_0^*(r)$	free-space radiation (inverse distance) field at distance r from source;
$A(r)$	surface wave attenuation factor;
$G(h)$	height gain factor, independent of distance r.

$A(r)$ is dependent on ε_r (dielectric constant) and σ (conductivity) and λ. Values of $A(r)$ are numerically plotted in [47]. If the source dimensions are of order D, then the condition $D < \sqrt{r\lambda / 2}$ must be fulfilled. By using the equations above together with values on $A(r)$ from [47], the attenuation of the vertical electric field component can be calculated.

The results are summarized in Figure 6.4.3 for ε_r=15, σ=10^{-2} which are conditions denoted as “good earth”. The Figure shows the attenuation for the vertical E-field component just above the ground. As can bee seen in Figure 6.4.3, the distance dependence of the vertical E-field attenuation can be divided in three regions where $1/r$-, $1/r^2$- and $1/r^3$- attenuation patterns are dominating. Between these regions, quite distinct breakpoints can be observed. The $1/r^2$ dependence dominates as expected for conditions corresponding to the simple two-beam model, i.e. long distances and high frequencies. Short distances and low frequencies give the typical $1/r^3$ dependence. The results in [46] have also been compared with good agreement with measurements for frequencies < 10 MHz [48].

In Figure 6.4.4, the theoretical results from [46] are compared to measured results from [40] and [49]. The measurements have only been done for the distances 50 meters and 100 meters. For comparison, the attenuation related to the absolute value at 50 meters has been used since it is the slope of the attenuation curve that is interesting. For these measurement points the agreement with the model in [46] is good.

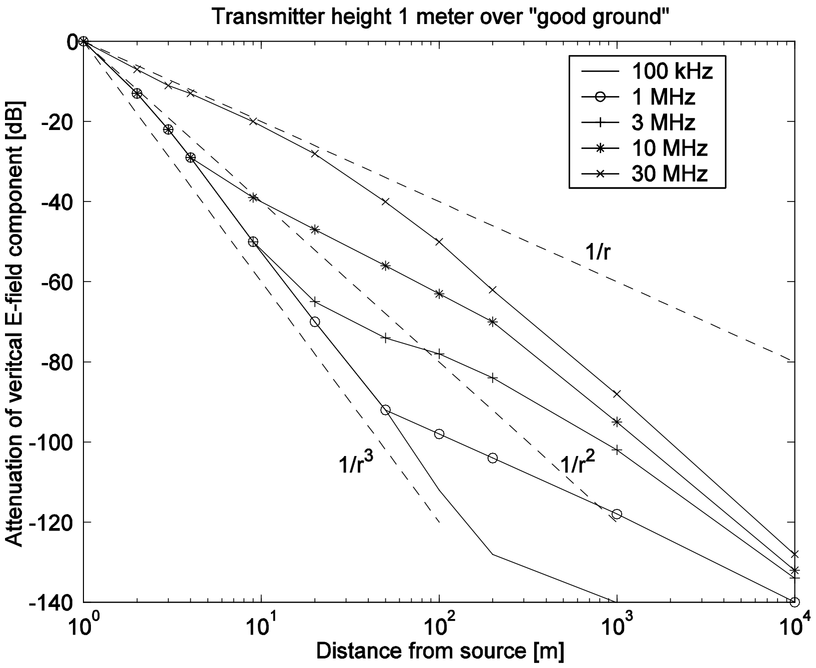


Figure 6.4.3: Attenuation of vertical E-field component (just above ground) for different frequencies and distances from source [46].

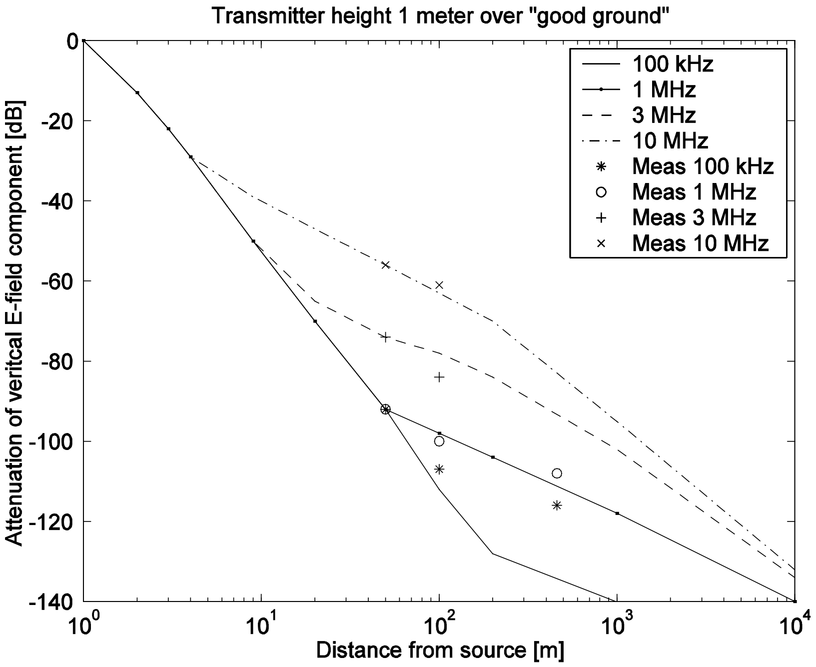


Figure 6.4.4: Comparison of attenuation of vertical E-field component from [46] with measured values from [40], [49].

6.5. Discussion regarding far field and near field

6.5.1. General

As demonstrated by Figures 6.3.2 and 6.3.4 there is no sharp border between the near field region and the far field region. As different criteria can be applied the border between near field and far field is often debated. Some aspects will be given here.

An important additional factor is that the Equations (6.3.1-6.3.6) are valid for dipoles in free space. As substations are quite large objects located on the earth, the response of the earth also impact the attenuation.

In addition, the reason for discussing the near field/far field issue in this guide is due to the following practical reasons:

- For controlling the measurement uncertainties
- For defining a suitable measurement distance
- For defining suitable measuring point
- To be able to estimate the attenuation versus distance

It can be concluded that, if possible, it is preferable to perform the measurements in the far field region.

6.5.2. Related to wave length

The breaking point in Figures 6.3.2 and 6.3.4 is $\lambda_0/2\pi$. This is why this distance is sometimes defined as the border between the near field region and the far field region. However, the border between far field and near field is fuzzy. For sure, the far field conditions prevail at the distance $r >> \lambda_0/2\pi$. Already at distances $r > 0.5\ \lambda_0$ the deviations from the far field conditions is small.

6.5.3. Related to antenna length

For controlling the phase shift of the wave from different locations of the antenna the criterion $r > 2D^2/\lambda_0$ is used where D is the physical size of the antenna. With the physical size of substation that criterion gives a very long distance at high frequencies. However, a complete substation is not excited in the same way as an ordinary antenna. Considering the construction of the substation and the sources within it, the complete substation is only excited for frequencies well below 1 MHz. For higher frequencies only a fraction of the substation is excited at a time. Besides, in case of power electronic installations, different part of the substation is excited at different commutations due to the location of the commutation valves.

6.5.4. Related to size of the installation

In the exact formula 6.3.7 there is an extra term r_D due to the physical size of the installation. This term must be considered unless the distance $r >> r_D$, $r_D = D/(\pi)^{1/2}$. This can also be seen as a near field condition.

6.5.5. Attenuation due to soil

Due to the reaction from soil, the wave travelling close above the soil will be attenuated, as evaluated in Section 6.4. If the height of the sending antenna is h_1 and the height of the receiving antenna is h_2 there is in accordance with Equation (6.4.3) a critical distance ds, $ds = 2\pi h_1 h_2/\lambda_0$.

At a distance $r > ds$, the amplitude of the field is attenuated per Equation (6.4.4). On the other hand if the distance $r << ds$, the field can be locally amplified by a factor 2 [50]. This can also be understood from Equation (6.4.1). The distance ds versus frequency for normal configurations is shown in Figures 6.5.9 and 6.5.10. The height of the receiving antenna is about 1.5 m and the height of a substation is in the order of 15-40 m.

Equation (6.5.1) defines the breaking point d(SA) for soil attenuation in accordance with [47], vertical polarisation.

$$d(SA) = MAX\left\{\frac{2\pi h_1 h_2}{\lambda}; \frac{\lambda}{2\pi}\frac{\varepsilon^2 + (60\sigma\lambda)^2}{\sqrt{(\varepsilon-1)^2 + (60\sigma\lambda)^2}}\right\} \qquad (6.5.1)$$

6.5.6. Practical examples

Figure 6.5.9 shows the border for the far field based on different criteria for a medium to small size substation. The physical dimension D=20 m and the height of the structures h_1=15 m. An important limit is the r_D limit implying that the measuring distance should be $r >> 11$ m. Considering the $\lambda/2\pi$ criterion it is hard to be in the far field region for frequencies below about 150 kHz. The 0.5λ criterion can be hard to reach for frequencies below about 1 MHz. The $2D^2/\lambda$ criterion hardly has any impact.

The critical distance *ds* for validity of Eq (6.4.4) is quite short for frequencies below 30 MHz. The amplification due to interaction is only a risk for frequencies above about 300 MHz, well outside the substation. For longer distances than *d(SA)* the soil attenuation as per Section 6.4.4 will give attenuation as $1/r^2$. For sand ε=10, σ=0.001 [S/m]. For good earth ε=15, σ=0.01 [S/m] [46].

It can be commented that the complete substation will be in the near field region.

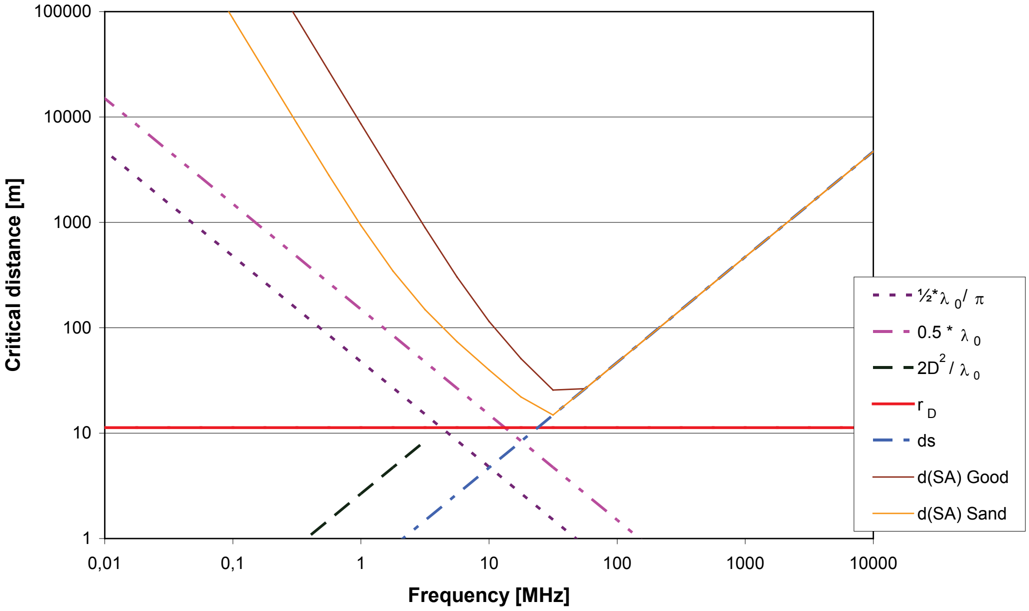


Figure 6.5.9: The critical distances for various far field criteria versus frequency. D=20 m. h_1=15 m and h_2=1.5 m.

Figure 6.5.10 shows the same curves for a larger substation with D=200 m and h_1=40 m The conclusions are the same as for Figure 6.5.9 except that for such a large substation the measurement distance should be r>>110 m.

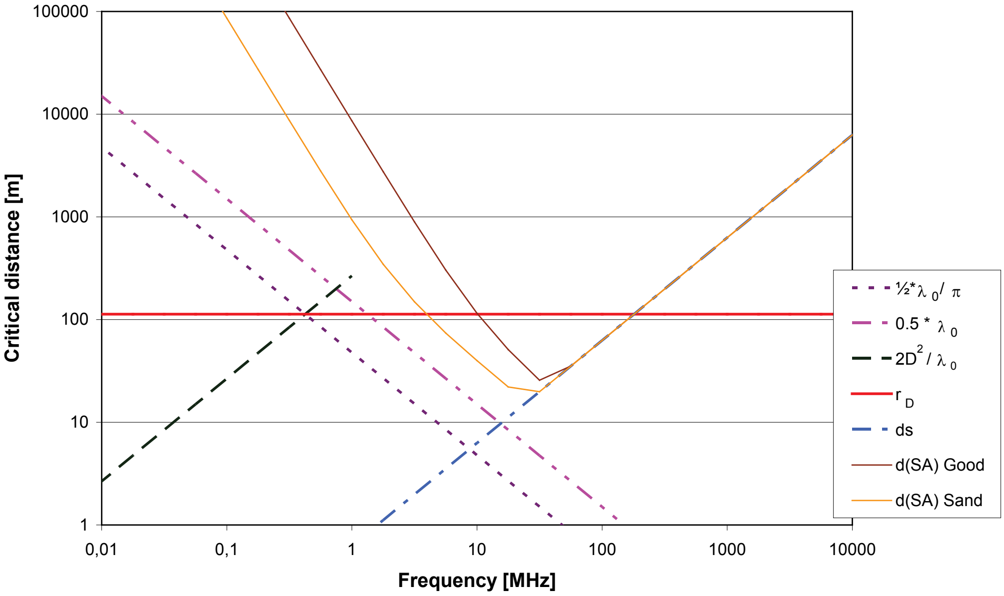


Figure 6.5.10: The critical distances for various far field criteria versus frequency. D=200 m. h_1=20 m and h_2=1.5 m.

6.5.7. Comparison with measurements

Comparison with measurements in [40] shows that a magnetic dipole representation gives a reasonable description of the radiation from a substation with power electronic equipment, screened by a metallic structure. However, there are some deviations:

- The relation between the electric field and the magnetic field is close to $E=H\eta_0$ even for distances much shorter than $\lambda_0/2\pi$ probably due to the size of the installation.
- As a first approximation the attenuation for both the magnetic field and the electric field was as $1/r$ for $r>\lambda/2\pi$ and as $1/r^2$ at shorter distances.
- At very short distances, less than the size D of the installation there were large local variations.
- A measurement at 300 m of a 290 MHz source shows a higher attenuation than the $1/r$ formula. That may confirm the increased attenuation due to interaction with the soil.

7. Mitigation techniques

7.1. General

Mitigation of RFI depends on both the source of RFI and the method of propagation of the disturbance as described in Chapter 5. Direct radiation must either be counteracted at the source, or the source has to be screened or moved further away. Disturbances due to the spreading of high frequency current can be counteracted at the source or reduced by filtering or layout measures.

7.2. RFI from HV equipment

7.2.1. General

Direct RFI from high voltage equipment is due to corona or may be even sparking. So far, this is as for HV lines. However, the variety of high voltage equipment in a substation is much larger than for a line. Besides, the concentration of high voltage equipment in a substation is quite dense. Consequently, corona from a substation may be more pronounced than corona from a HV line. In addition, the possibilities for sparking are more in a substation than on a line.

7.2.2. Corona

Countermeasures for corona are large diameters for conductors or several conductors in a bundle. Also, all pieces of metal energised to high voltage must have a smooth surface or be screened by an auxiliary smooth electrode, i.e. corona rings. Special care has to be paid to equipment with a moving contact, such as disconnectors.

One difficulty when trying to control the corona level from a substation is that the type test of high voltage equipment does not include the RFI-level expressed as an amount of EMI field, but is expressed as partial discharge at a certain voltage. Thus, the test prior to installation is not directly related to the experienced RFI level after energization. This is likely to work as long as requirement and design are as usual, but may lead to surprises if the conditions change.

7.2.3. Sparking

All sparking is a sign of either a deficiency in design or installation or damaged equipment. The cause for sparking has to be identified and remedied.

7.3. RFI from power electronics

7.3.1. General

Measures for limitation of the direct RFI from power electronic equipment is often deeply integrated with the internal design of the equipment. Thus, it is to a large extent a part of the design. Anyhow, the mitigation menu is given here.

7.3.2. Limitation of current derivatives

The primary source of RFI from power electronic equipment is high current derivatives. Consequently, if the current derivatives are smoothened then also the RFI is reduced. Also the form of the pulse and the amplitude of the higher derivatives have importance for the frequency content of the pulses. Thus, a smoothed pulse is better than one with sharp corners, even if the maximum current derivative is the same.

Curves A and B in Figure 7.1 have the same maximum derivative. However, curve A has a higher content of higher frequencies.

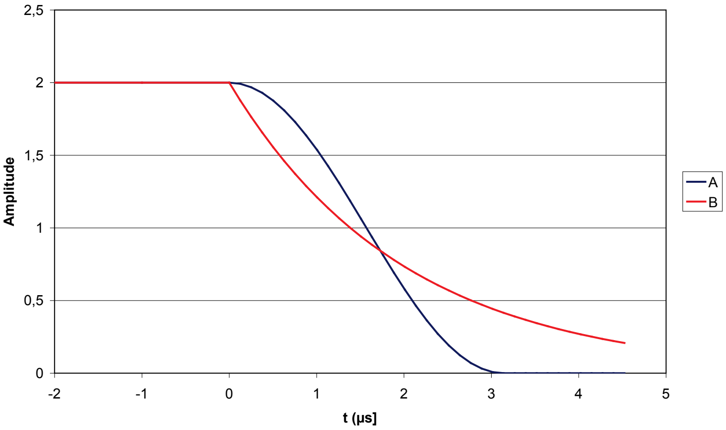


Figure 7.1: Transient with the same derivative but different hf content.

7.3.3. Damping

Damping of oscillations and ringings also reduces the total RFI, even if the peak amplitude is the same, shortening of the duration decreases the RFI.

7.3.4. Minimising area of current loops

One way to reduce direct RFI from power electronic equipment is to minimize the area of the loops with high frequency currents. This means, the area of the primary radiating antennae are reduced.

7.3.5. Screening of direct radiation

The direct radiation from power electronic equipment can also be reduced by installing the equipment in a screening building. Screening of high frequency requires a tight screen without electric openings. Screening low frequency magnetic fields requires good conducting capability of the screen, i.e. significant thickness of the screen.

7.3.6. Location

It is also possible to reduce the RFI, to some extent, by locating the strongest source as far away as possible from the measuring point, as those represent the impact on the surroundings. Other buildings may also have some screening effect. The technique is similar to the one for minimising the impact of audible noise disturbances.

7.4. RFI due to spread out of high frequency currents

7.4.1. General

Some of the measures for direct radiation also have a good effect on the conducted disturbances, i.e. reduction of the current derivatives, damping measures and minimizing the areas of loops with high frequency currents. The additional measures for reducing the conducted disturbance aim to prevent the high frequency current reaching the outside world. Thus, to counteract the RFI, the antenna effect is reduced through reduction of the high frequency currents in the antenna and/or reducing the antenna areas.

7.4.2. High frequency filters

The tools to control the high frequency currents are high frequency filters. Basically, capacitors are used for shunting the high frequency currents and reactors are used for blocking purposes. Depending of the frequency of concern, tuning circuits may be added.

For being effective for frequencies below 100-150 kHz, the cost of the filter increases significantly with decreasing frequency.

7.4.3. Minimising antenna loop areas

The location for filters shall be selected for best effect. The shunting capacitors shall be located as close as possible to the source and the blocking reactors shall be located for preventing that the high frequency currents reaching capacitors located further out. Also, the complete layout regarding equipment location and design of the bus structures should aim towards a reduced area for the loops with high frequency currents, i.e. minimizing the area of the radiating antennae.

The areas of the antenna loop made up of connecting lines cannot be reduced. Consequently, the hf current in connected lines must be controlled to acceptable values by the filters.

8. Considerations for measurement technique

8.1. Detector characteristics

The limits for RFI requirements below 1 GHz are up to now related to the use of a quasi-peak detector defined by CISPR 16-1-1 [5]. Other detectors are peak, RMS (Root-Mean-Square) and average. The detector to be used in combination with digital radio communication is under consideration. Measurement and simulation results have shown that the RMS detector exhibits a response that can be correlated to the interference impact on digital communication systems [34]. In [51] it is shown that if the impulsiveness ratio IR given by (8.1) is measured for pulsed interference, it is possible to estimate the impact on a digital radio receiver by using simple mathematical expressions from additive white Gaussian noise interference.

$$IR = 20\log_{10}\frac{E_{\mathrm{RMS}}}{E_{\mathrm{average}}} \tag{8.1}$$

where the parameters E_{RMS} and E_{average} are RMS and average measurements of the electric field strength.

A new weighting detector has also been considered. In CISPR 16-1-1 [5], an RMS/Average weighting receiver has been proposed for international standardisation in order to more realistically measure the interference potential of emissions on digital radio communication systems.

The peak detector always gives higher reading than the other detectors, if the bandwidth is the same. Besides, the measuring time is significantly shorter than for the other detectors. Therefore, the peak detector can always be used for a first scanning. Only if the peak values are above the requirements, this part of the measurements has to be repeated with a proper detector according to CISPR 16-1-1. Normally only a fraction of the frequency range has to be scanned at that repetition.

In the frequency range 1 GHz to 18 GHz CISPR 16-1-1 [5] specify properties for Peak detectors, Average detectors and RMS detectors.

8.2. Bandwidth

The bandwidth to be used in accordance with CISPR 16-1-1 [5] is:

• 9 - 150 kHz	200 Hz
• 0.15 - 30 MHz	9 kHz
• 30 MHz - 1 GHz	120 kHz
• 1 - 18 GHz	1 MHz

These bandwidths (below 1 GHz) were once chosen to represent the bandwidths of the corresponding analogue radio services in each frequency band. The bandwidth for RFI with digital radio communication systems is under consideration. As a general rule, it is always convenient to use a measurement bandwidth with approximately the same size as the communication system of interest. If the difference between the measurement bandwidth and communication system bandwidth is too large, the correlation between the measured result and the corresponding interference impact on the system will be weak. If, for instance, the measurement bandwidth is considerably smaller than the system bandwidth and the bandwidth of the interference is larger than the measurement bandwidth, then the interference power perceived in the radio system will be much higher than is measured. This property is taken advantage of when spread-spectrum techniques are used on computer clocks. In that case the emission measurement limit can be passed but a nearby or co-located radio-communication system can perceive strong interference impact. Thus, the measurement bandwidths should be chosen by considering the communication systems that use the frequency region of interest.

8.3. Frequency profile

If power electronic equipment such as HVDC or FACTS is installed in a substation the complete frequency range should be scanned in each measuring point.

Even for an ordinary ac power substation, it should be verified by a frequency scan in the first measuring point that corona is the only RFI source. For the remaining measurement positions it is sufficient to verify the RFI level by measuring RFI around 0.5 MHz. Besides, it must be verified that the plant is free from sparking by measuring the RFI level around 60 MHz. If broad band sparking or gap discharge is the dominating source, as reported in [37], the complete frequency range should be covered by the measurement.

However, it must be noted that power electronic equipment may also be used in auxiliary systems such as variable speed motor drives.

8.4. Time variation

Both RFI from Equipment Under Test (EUT), which means the substation, and the background RFI noise varies with time. The fact that the background noise varies with time complicates the task of distinguishing the RFI caused by the substation from the background noise. This is further discussed in Section 8.5. However, it is important to be aware that the background noise also varies with time.

The variation of RFI from the EUT, i.e. the substation, depends on the load and mode of operation. Also, the corona from the HV switchyard varies with voltage and weather conditions.

For power electronic equipment, i.e. HVDC and FACT, the RFI level depends on the mode of operation and the loading. Thus the supplier and the user should agree on the operation conditions during the measurements. However, as the RFI levels are measured in dB, small variation has marginal impact on the result. If there is a doubt, some of the measurement might be repeated at some different operating conditions. Only continuous modes of operation should be considered.

As conclusions:

- It must be defined if the RFI limits are related to bad weather or good weather corona.
- If corona is a relevant source, the voltage should be on the higher part of the continuous voltage span.
- HVDC and FACTS should operate in a continuous mode of operation expected to be reasonably close to a worst case.

8.5. Background noise

The generated noise level has to be compared with the background noise level, which is significant in most locations. The background level is received when measuring with the installation closed down, or by performing the measurement at a greater distance to the installation than the propagation of the generated noise.

However, it might be harder to discriminate between background noise and plant RFI than anticipated. The reason is that the background noise is not constant but can vary significantly from time to time. One way to discriminate between different sources is to listen to the measured signal. Different types of sources give different, often characteristic modulation of the signal. Another way to identify RFI frequencies from the plant is to measure at a closer location where noise from the source has higher amplitude.

As conclusions:

- Measurements of background RFI noise may be done when the EUT is disconnected or turned OFF. As an alternative, measurement may be made at a large distance from the EUT installation.
- The antenna shall have the same orientations during measurement of background noise as for the verification measurements.
- There must be more than one measurement of the background noise as it varies over time.
- Frequencies in the RFI from the EUT can be identified by an extra measurement at a much shorter distance.
- To listen to the RFI noise is a way to identify the source.

8.6. Measurement distance

8.6.1. Substations

Some standards refer the measurement distance to the fence around the installation, with a given requirement limit. The hazard is then that the fence may be moved further away from the installation, denoting that the impact zone from the total RFI level is increased. The measurement distance related to the requirement limit should therefore instead be referred to the source (i.e. the closest building wall or the closest high voltage piece of equipment), not to the fence [40].

For the same requirement regarding RFI impact on the surroundings, the measurement distance and the specified level limit must be balanced against each other. A shorter measurement distance means a higher RFI level as the limit.

At a measurement too close to the active area of a substation, it may not be possible to see the impact of a stronger source in the centre of the switchyard, a source that might be dominating at a longer distance.

Measurements performed too close to the source will give local variations, and it will not be representative for the total RFI emission from the installation [40]. The measurement distance should therefore be greater than the physical dimension of the installation. Furthermore, neither should measurements be performed too far away from the source since it will then not be possible to distinguish the generated noise level from the background noise level.

The measurement distance for substations may be dependent on voltage level, as the size also is likely to depend on the voltage level. For substations for voltages of more that 245 kV, 200 m is considered as a suitable measurement distance.

8.6.2. Lines

For lines it is recommended to measure at a distance of 30 m from the closest phase conductor up to a voltage of 620 kV, see Appendix D, Section D.4. For higher voltages the recommended measuring distance is 50 m. The closest measurement point should be around 4 km from the active part of the substation, see Figure 12.1. This is somewhat longer than the recommended 15-20 m in CISPR 18-1 [8], for verification of line corona.

8.7. Location of the antenna

8.7.1. General

As a base, the location and types of antennae shall follow the recommendations in CISPR 16-1-1 [5].

In addition, some extra precautions are needed when considering RFI from substations:

- The antenna shall not be located too close to overhead lines or power cables.
- The antenna shall be located in such a way that it will not be shielded by fences or other large metallic structures. It should be noted that metallic structures gives a shielding effect both in the forward and backward directions as the shielding effect is caused by circulating currents.
- The antenna shall not be located too close to large metallic structures.
- There shall be free line of sight between the installation and the antenna
- If a rod antenna is used it should not be located so that it picks up the large fundamental electric field from overhead line or bus structures.

8.7.2. Direction of the antenna

8.7.2.1. General

For interference with the surrounding, the vertical electrical field is generally more important than the horizontal electric field, as the attenuation with distance is higher for the horizontal electric field. As the electric and the magnetic field in the RFI radiation is orthogonal, the horizontal H-field is the relevant one

8.7.2.2. Rod antenna

A rod antenna can only be installed in one way, and that is for measurement of the vertical electrical field.

8.7.2.3. Loop antenna

In some guides for RFI measurements it is stated that the antenna shall be orientated in the direction giving the highest field. This procedure is possible when measuring at a single frequencies with an instrument giving a direct reading of the field level. However, this method is not applicable when scanning the complete frequency range. The direction for maximum reading may not be the same for all frequencies. Instead, it is recommended that the antenna is directed in two orthogonal directions, as applicable. The maximum field level is estimated as the RMS sum of the field in the orthogonal directions.

The loop antenna should be located with the plane of the loop in a vertical plane. The antenna should be directed with the "face" directed against the EUT for measurement of the radial magnetic field and with the edge against the EUT for measuring the transverse magnetic field. So far, there is no indication of a need to measure also in the third direction, i.e. the vertical magnetic field by locating the plane of the loop in a horizontal plane.

8.7.2.4. BiLog antenna

BiLog or similar antennae for measurement of Electric field above 30 MHz should be directed towards the EUT. This means that the EUT should be located where the antenna has the highest gain. The dotted lines in Figure 8.2 gives a general indication of the direction of the antenna. See also the comment below Figure 8.2.

The antenna should be rotated for measurement of the vertical electric field. The horizontal electric field does not need to be measured.

8.7.3. Antenna height

For frequencies when the soil attenuation depends on the height of the antenna, i.e. when the expression $2\pi h_1 h_2/\lambda$ determines *d(SA)* in Equation (9.3), and the distance is longer than *d(SA)*, the signal from the antenna increases linearly with the height of the receiving antenna. For the preconditions in Figure 6.5.10 and a measuring distance of 200 m, this is the case for the frequency range 30-300 MHz approximately. This means that if the antenna height is increased from 1.5 to 2.0 m the reading increases by 2.5 dB. An increase of the height from 2.0 to 3.0 m will increase the reading with an additional 3.5 dB, and so on. This is a direct consequence of the mechanism described in Section 6.4. For other frequencies the antenna height has no impact, provided that there is free line of sight, electrically.

For RFI around HV and MV substations, the practical aspect is important as the terrain may be rough. Besides, the weather may be windy. It is much easier to handle antennae, which is a bit heavy, with a height of 1.5 m than antennae with higher height. The important thing regarding replicative measurement is to have a defined antenna height.

Despite the recommendation in Section 6.2.4 of CISPR 11 [4] an antenna height of 1.5 m is recommended for RFI measurement for substations and connecting lines.

8.7.4. Safety note

It must also be noted that the earthing grid of the substation might rise to a significant potential for a fault within the substation or in the system. This risk must be considered when using long cables for RFI measurement.

8.8. Directivity – number of measuring points

8.8.1. Directivity

Normally there are no pronounced directivity lobes in RFI from a substation. Anyhow, the strongest radiation source might be located on one side. Thus, as a consequence, it can not be assumed that the radiation is the same in all directions even if the general character of each source is omni-directional. Besides, it must be noted, that a large building can give a shielding effect.

Thus, it is not sufficient to measure in one direction only, but to measure at some locations around the installations. No measuring point should be beside large buildings.

8.8.2. Number of measuring points

In general terms, the measuring points indicated by circled T in Figure 8.1 give sufficient coverage of an ordinary substation. However, there are often obstructions of different kind around a substation. Therefore, the general idea in Figure 8.1 has to be adapted to the local conditions. For all measuring points, there should be an open line of sight to the radiating installation.

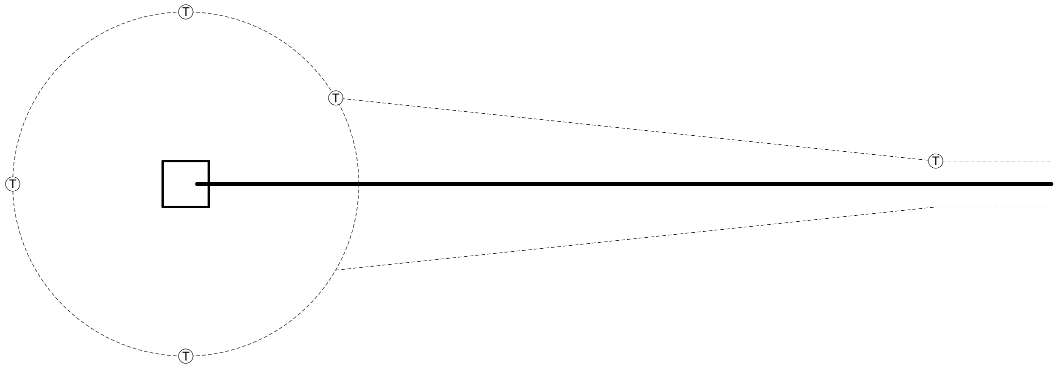


Figure 8.1: Typical location of measuring points around a substation.

8.8.3. Number of measurement points at a very large plant

As at each measuring position it takes time to perform the verifications, the number of measuring points should not be larger than necessary. However, the number of measuring points must be sufficient for covering the complete substations. This is a reason for not selecting too short a measurement distance. The number and location of measurement points depends on the local conditions and the size of the substation. For large plants more measuring points may be needed. Figure 8.2 gives some guidance.

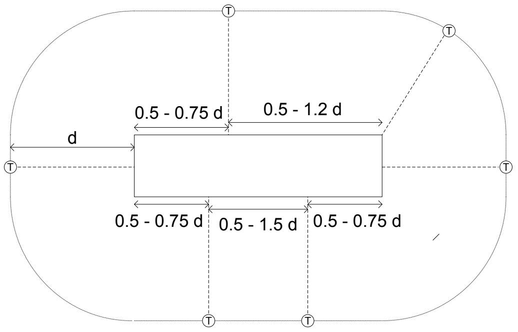


Figure 8.2: Typical location of measuring points around a large substation, measurement distance d.

Comment: For frequencies above 300 MHz it shall be assured that the radiation source is within the 6 dB border of the antenna directivity lobe. The antenna may be turned for pointing at different parts of the substation for defining a possible local source. The source in the substation may be assumed to be omni-directional. A pronounced local high frequency source may imply an additional measuring point. The reason for this concern is that the directivity of the antennae is more pronounced at higher frequencies.

If the physical size of the active part of the substation is not more than 1.5 times the measurement distance d it is sufficient to measure in the four orthogonal directions. If any direction is longer than 1.5 times d, some more measuring points should be added as indicated in Figure 8.2.

In many cases, the active part of a substation is not shaped as a rectangle, but has a much more irregular form. Besides, the locations of the connecting lines also have to be considered. Thus, Figure 8.1 can only give an indicative guidance.

There is also a need for a measuring point at each outgoing line a few kilometres from the substation, point A in Figure 1.1.

8.9. Measurement uncertainties

8.9.1. General

This section lists the various reasons for measurement uncertainties. Some causes can be completely eliminated or controlled to an insignificant level. Other causes have to be handled and estimated.

The basic methodology for handling measurement uncertainties is defined in CISPR 16-4-2 [7] and an example of an uncertainty budget is given in Annex C of CISPR 16-2-3 [6]. However, both of those standards mainly deal with lab measurements and radiated disturbances in the frequency range 30 MHz to 1 GHz. Therefore, complementary information is needed for in situ measurement of radiated disturbances from electric power substations in the frequency range 9 kHz to 1 GHz.

8.9.2. Measurement equipment

8.9.2.1. General

The uncertainties related to the measurement equipment are the same as for corresponding equipment in EMC laboratories. Two main differences is the possibility that strong sources may saturate the signal in the antenna and that the cable between the antenna and the receiver may be much longer.

8.9.2.2. Antenna

The antenna calibration certificate will give the antenna transducer factor, i.e. the antenna output signal versus the input field. The second step is that the antenna transducer factor is correctly programmed into the detector/receiver. See further information in Section 8.9.2.4.

One uncertainty is the direction for the field to be measured. This uncertainty is overcome by measurement in the two orthogonal directions of interest. The maximum field is obtained by the square root of the quadratic summation of the two amplitude readings. The maximum addition is 3 dB when the readings in both orthogonal directions are the same.

Another cause for measurement uncertainty is if the total signal is so high that it exceeds some equipment limits. That can be overvoltage protection devices or saturation of active antenna amplifiers. The high amplitude may be caused by a signal outside the measurement frequency range of interest. The saturation may show up in the measurement as sidebands to the signal causing the saturation. Therefore, antennae sensitive to E-field shall never be located underneath high voltage lines or bus structures, and antennae sensitive to H-field shall never be located close to bus structures with high current, especially currents of higher frequencies

8.9.2.3. Measurement cables and accessories

The attenuation of the measuring cables between the antenna and the detector, including accessories as dampers and external filters, has to be measured and included in the total transducer factor of the equipment. The contacts should be kept in good conditions to avoid variations during handling and measurement.

8.9.2.4. EMI test receivers

The accuracy of the EMI test receiver is given by the data sheet and should be certified by regular calibrations. That should also include the accuracy for the calibration of the antenna characteristic and the attenuation of cables and accessories.

If a peak detector is used it always gives higher levels than rms and quasi-peak detectors. If the level within the peak detector mode is higher than the limit for a certain frequency range, that range has to be investigated in rms or quasi-peak mode as appropriate.

8.9.2.5. External disturbances

The cable between the antenna and the detector may pick up disturbances if located close to a strong disturbance source. Also disturbances in the power supply may disturb the measurements. The disturbances from such external sources can be verified by replacing the antenna by a 50 ohm resistor. The noise level from such external sources must be well below the stipulated limit and preferable at a level not higher than the general broadband background noise. Consequently its contribution to the measurement uncertainties is negligible.

8.9.3. Background noise

The background noise may cause measurement uncertainties, too high a reading, as the background noise varies with time. Thus, fractions of the background noise may be interpreted as RFI from the EUT. Variation in the broadband general background noise level is quite easy to identify. More difficult to handle is noise from sources that are switched on and off. Even the ionosphere may act like such a switch, see also Section 8.5.

If both the background noise and the RFI emission from the EUT are close to the limit, the combined RFI level may be up to 6 dB too high with a peak detector and up to 3 dB too high for an RMS or quasi-peak detector.

Background noise may be a tricky issue at measurement of RFI from a new extension of an existing substation, especially as the RFI from the old equipment may be significantly higher than the RFI from the new equipment.

Background noise always results in too high a reading, if impacting. If necessary the uncertainties due to background noise has to be investigated case by case.

8.9.4. Variation in emission from the EUT

8.9.4.1. General

The measurement shall be representative for the worst normal operation conditions which can be defined as continuous operation. However, regarding corona from substation high voltage equipment, the limit is related to good weather corona. Thus bad weather conditions may result in too high measurement values.

8.9.4.2. Operation mode

For power electronic equipment the highest RFI emission is in the operation mode giving the highest voltages at the valve turn on. The manufacturer should advice about the worst operation mode. If there is any doubt, the RFI emission in most critical operation modes can be checked by measurement at a suitable measuring point, which can be quite close to the equipment.

Only modes for continuous operation shall be considered, not the transient operation modes during fault and disturbances.

It must be noted that the differences between different operation modes can be insignificant. The uncertainty due to a lower turn on voltage U_{turnon} can be estimated as $20 \log_{10} (U_{turnonMAX}/U_{turnon})$ [dB].

8.9.4.3. Loading

As a general rule, the emission is highest at the highest load in the worst operation mode. Therefore, the measurements shall be performed at high load. A conservative approach is that the uncertainty in emission due to a lower amplitude is $20 \log_{10}(S_{max}/S)$ [dB], where S is actual loading and S_{max} is max MVA loading in the worst operation mode (80 % loading corresponds to an uncertainty of 1.9 dB and 50 % loading to an uncertainty of 6.0 dB). For many applications the variation with loading is lower.

If any doubt, the variation with loading can be checked at a suitable measuring point.

8.9.4.4. Busbar voltage

For measurement related to corona the bus voltage should be as close to maximum continuous voltage as possible.

A conservative estimation can be based on the formula in Section 8.2 of CISPR 18.1 [8]. If the parameter $g_{\max}$ (maximum surface gradient of the line, in kilovolts per centimetres) is set to 25 kV per cm, which is the insulation strength of the air, the uncertainty can be calculated as $1.6 \times 25 \times (U_{\max} / U_{measurement} - 1)$ dB, where U_{max} is the maximum busbar voltage and $U_{measurement}$ is the voltage at the measurement.

As no other information is available, it is assumed that the voltage variation for gap discharge follows the same formula as the corona voltage variation.

8.9.4.5. Weather conditions

The most important parameter regarding corona is the weather conditions. Bad weather corona is about 20 dB higher than good weather corona [8]. In the opposite, RFI due to gap discharge is worst in dry weather. At measurements reported in [37] the difference was in the order of 15 dB in the frequency range 30 - 150 MHz.

8.9.5. Measurement distance

The significant uncertainty regarding the measurement distance is neither to identify the location of the measurement location nor to measure a distance accurately but to identify the outer border of the EUT, i.e. the substation. Table 8.1 shows the measurement uncertainty versus the uncertainty in measurement distance, in per cent.

Table 8.1: Measurement uncertainty due to uncertainty in measurement distance

Attenuation region	Uncertainty in measurement distance				
	1 %	2 %	5 %	10 %	20 %
Uncertainty at 1/*r* attenuation	0.09 dB	0.17 dB	0.42 dB	0.83 dB	1.58 dB
Uncertainty at $1/r^2$ attenuation	0.17 dB	0.34 dB	0.85 dB	1.66 dB	3.17 dB

As the uncertainty regarding the location of the EUT boarder is a certain distance in meters, the percentage will be less at a longer measurement distance. Thus, regarding measurement uncertainty due to uncertainty in measurement distance, the measurement distance should be as long as practically possible. This also lowers the frequency range with 1/*r* attenuation. Besides, it must be remembered that the substation is not a homogenous source. It may consist of several sub-sources located inside the EUT border. Also this uncertainty is covered with a long measurement distance.

Table 8.1 shows that for a small percentage uncertainty in measurement distance the contribution to the measurement uncertainty is negligible.

8.9.6. Local variations and directivity

8.9.6.1. Terrain obstructions

The general rule is that there shall be free line of sight between the EUT and the measurement antenna. The antenna shall not be located to close to large metallic objects such at fences. The distance between the antenna and a fence shall be at least five times the height of the fence both forward and backwards.

For high frequencies, i.e. the height of the fence is in the order of $\lambda/4$ it is important that the antenna is not screened by the fence. If in doubt, the measurement distance or the antenna height may be varied for verification that the fence does not impact upon the measurement result.

8.9.6.2. Local variations and directivity

Close to the substation there may be significant local field variations, see Sections 6.5 and 8.6. These variations should be avoided with the recommended measurement distances. However, outgoing lines and cables may act to guide RFI emission radiation. Measurement too close to cables or overhead lines may result in too high measurement results.

8.9.6.3. Directivity

The experience so far is that substations are omni-directional sources [40]. The measurement uncertainty due to source directivity may be in the order of 3-5 dB, when related to one general direction. If critical an additional measuring point can be added in a critical direction at the critical frequency. However, when coming to practice, the geographical conditions may limit the possible measuring points, especially considering the location of lines etc.

8.9.7. Acceptance criteria

For each measurement an uncertainty budget should be established. Annex C in CISPR 16-2-3 shows an example for measurement in a lab. Thus, it has to be modified based on the factors mentioned above. Then the expanded measurement uncertainty U_{measure} in analogue with U_{lab} in Section 4.1 of CISPR 16-4-2 [7] should be established.

In line with Section 4.1 of CISPR 16-4-2; Compliance or non-compliance with a disturbance limit should be determined in the following manner.

If U_{measure} is less or equal to U_{base} in Table 8.2, then:

- Compliance if no measured disturbance exceeds the disturbance limit.
- Non-compliance if any measured disturbance exceeds the disturbance limit.

If U_{measure} is greater than U_{base} in Table 8.2, then:

- Compliance if no measured disturbance, after it has been increased by (U_{measure} - U_{base}), exceeds the disturbance limit.
- Non-compliance if any measured disturbance, after it has been increased by (U_{measure} - U_{base}), exceeds the disturbance limit.

The figure for 30 MHz to 1GHz in Table 8.2 is the same as U_{cispr} in Table 1 of CISPR 16-4-2 [7]. Also the other values are based on the values in Table 1 of CISPR 16-4-2, interpreted as the values for radiated disturbance is considered to be 0.7 dB higher than the values for conducted disturbance.

Table 8.2: Values of U_{base}.

Measurement	U_{base}
Radiated disturbance 9 kHz to 150 kHz	4.7 dB
Radiated disturbance 150 kHz to 30 MHz	4.3 dB
Radiated disturbance 30 MHz to 1 GHz	5.2 dB

8.9.8. Conclusions

Proper calibration of the measurement equipment, including cables and accessories is one key point for good measurement accuracy. One key issue is planning of the measuring points for avoiding terrain obstructions and reasons for local variations such as cables and lines.

The uncertainties due to measurement distance are mainly controlled by selecting a reasonably long measurement distance.

Uncertainties due to variation in EUT emission can be practically eliminated, either by operating the scheme at high load in a worst operation mode, or to perform a correction based on reference measurement in one close measurement point.

A typical uncertainty budget for the frequency range 150 kHz to 30 MHz is shown in Appendix H.

9. Conversion

9.1. Between different measuring distances

As discussed in [40], as the first approximation the RFI level from a substation can be assumed to follow the formula for the E-field from a magnetic dipole, in accordance with Equation (9.1). See also Section 5.4.

$$E = -j\frac{f\mu_0 m\beta^2}{2}\left[\frac{-1}{j\beta r} + \frac{1}{(\beta r)^2}\right] \tag{9.1}$$

Where

m is the magnetic moment IA in [Am^2]
A is the area of the current loop [m]
I is the current in the loop [A]
r is the distance in [m]
f is the frequency in [Hz]
μ_0 is the permittivity of free space
β is defined by $\beta = \frac{\omega}{c} = \frac{2\pi f}{c} = \frac{2\pi}{\lambda}$ where c is the speed of light and λ is the wavelength

Manipulation of Equation (9.1) gives that the relation between the field levels E_1 in point 1 located at a distance of r_1 m and a corresponding measuring point 2 can be written as:

$$E_2 = E_1\frac{r_1}{r_2}\frac{\sqrt{1+\left(\frac{c}{2\pi f\ r_2}\right)^2}}{\sqrt{1+\left(\frac{c}{2\pi f\ r_1}\right)^2}} \tag{9.2}$$

In accordance with measurements reported in [40], Equation (9.2) is also valid for the H-field as a first approximation.

When the soil attenuation in accordance with Sections 6.4-6.5 is considered, Equation (9.2) is extended to (9.3).

$$E_2 = E_1 \frac{r_1}{r_2} \frac{\sqrt{1+\left(\frac{c}{2\pi f\ r_2}\right)^2}\left(1+\frac{r_1}{d(SA)}\right)}{\sqrt{1+\left(\frac{c}{2\pi f\ r_1}\right)^2}\left(1+\frac{r_2}{d(SA)}\right)} \tag{9.3}$$

The soil attenuation distance *d(SA)* is defined by Equation (6.5.1).

Note: Within a very short distance, < 30 m, the local variation may be significant [40].

Figure 9.1 demonstrates the effect of the frequency dependence on the attenuation versus distance. A flat limit of 100 µV/m (or 40 dBµV/m) at a distance of 450 m from the active source is an often used requirement. The figure shows the E-field level versus distance for the frequencies 10 kHz (and below), 100 kHz, 1 MHz and 10 MHz (and above). The breaking point between attenuation as $1/r$ and $1/r^2$ is 4800 m, 480 m, 48 m and 4.8 m for 10 kHz, 100 kHz, 1 MHz and 10 MHz respectively. At higher frequencies the attenuation due to soil, see Section 6.4, impacts the curve. The breaking distance *d(SA)* for $1/r^2$ attenuation at longer distances is 8.6 km, 115 m, 63 m and 630 m for 1MHz, 10 MHz, 100 MHz and 1 GHz, see Figure 6.5.10. Good earth and antenna heights of 20 m and 1.5 m are assumed. At both low and high frequency, the attenuation is very significant.

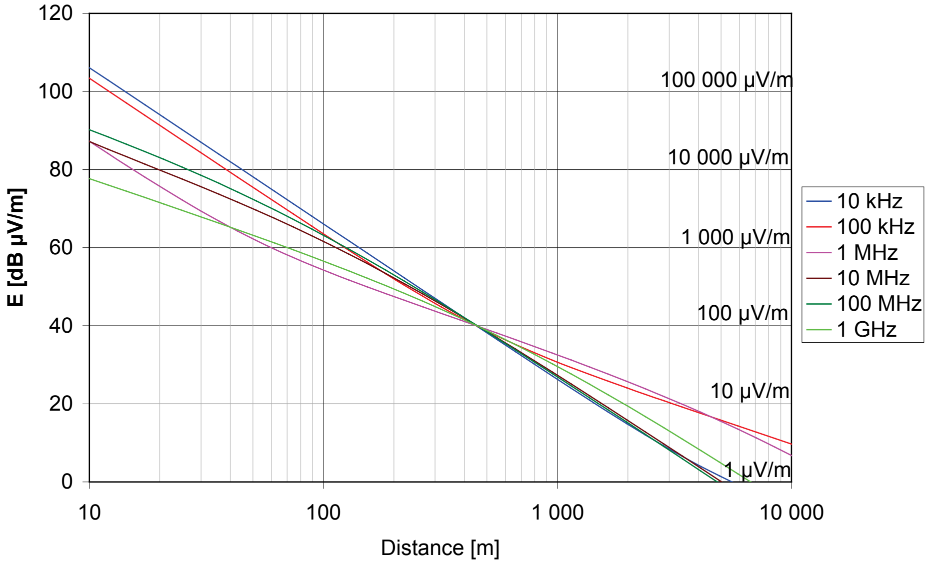


Figure 9.1: Attenuation versus distance for some frequencies. Base level: 100 µV/m at 450 m.

9.2. Different detectors

For practical applications, there is no general method to convert values between different detectors since the relation between different detector responses is highly dependent on the waveform of the interference signal. The peak detector always gives the highest reading and the average detector the lowest reading when the bandwidth is the same. See also Section 3.3. In Table 9.1, the different detector responses are shown for a few disturbance signals. This table is made from data in [5]. If, for instance, the measurement is done on a noise process, with a zero-mean Gaussian amplitude distribution, the quasi-peak value is 1.85 times the RMS-value. A commonly used rule of thumb says that the RMS value can be approximately estimated as the peak value divided by 4 for a zero-mean Gaussian noise process.

Table 9.1: Basic characteristics of the EMI detectors. I_{RMS} is the RMS value of the disturbance *i(t)*. *I(f)* is the Fourier transform of the disturbance signal at the frequency where the measurement is done.

Input wave form to the RF stage	Peak	Quasi-Peak	Average	RMS
Sine wave	I_{RMS}	I_{RMS}	I_{RMS}	I_{RMS}

Periodic pulse	$\sqrt{2}I(f)W_{\mathrm{M}}^{\mathrm{imp}}$	$\sqrt{2}I(f)W_{\mathrm{M}}^{\mathrm{imp}}P(x)$	$\sqrt{2}I(f)f_{\mathrm{p}}$	$\sqrt{2}I(f)\sqrt{W_{\mathrm{M}}^{\mathrm{imp}}f_{\mathrm{p}}}$
Gaussian amplitude distribution (0,σ$_n$)	$\sim\sqrt{W_{\mathrm{M}}^{\mathrm{rn}}}$	$1.85\sqrt{W_{\mathrm{M}}^{\mathrm{rn}}}\sigma_{\mathrm{n}}$	$0.88\sqrt{W_{\mathrm{M}}^{\mathrm{rn}}}\sigma_{\mathrm{n}}$	$\sqrt{W_{\mathrm{M}}^{\mathrm{rn}}}\sigma_{\mathrm{n}}$

W_M^{imp} is the impulse bandwidth of the measurement equipment. $W_{\mathrm{M}}^{\mathrm{rn}}$ is the noise bandwidth of the measurement equipment. *P(x)* is the ratio between quasi-peak and peak value. f_p is pulse repetition frequency. σ_{n} is the standard deviation of the Gaussian noise.

9.3. Different bandwidth

Conversion between different bandwidths is possible in two cases, i.e. at narrow band signals and at broad band signals

9.3.1. Conversion between different bandwidths: Narrow band signal

If the bandwidth of the signal is within the bandwidth of the most narrow measurement bandwidth, the reading will be the same even for a broader bandwidth.

9.3.2. Conversion between bandwidths: Broadband signal

If the bandwidth of the signal is wider than the widest of the measurement bandwidth the conversion is as follows:

E_1 is the reading in dB of the detector with bandwidth BW_1

E_2 is the reading in dB of the detector with bandwidth BW_2

For broadband Gaussian noise, the conversion between different measurement bandwidths is [28]

- All four detectors: $E_2 = E_1 + 10\log_{10}(BW_2 / BW_1)$

(This is valid for RMS detectors, Average detectors, Quasi-peak detectors, and Peak detectors)

For pulsed interference the dependence of measurement bandwidth is [28]

- RMS detector: $E_2 = E_1 + 10\log_{10}(BW_2 / BW_1)$
- Average detector: The response is not dependent of the measurement bandwidth (only on the pulse repetition frequency)
- Quasi-peak detector: $E_2 = E_1 + 20\log_{10}(BW_2 / BW_1)$
- Peak detector $E_2 = E_1 + 20\log_{10}(BW_2 / BW_1)$

9.3.3. Measurement with a smaller bandwidth

Due to background noise it may not be possible to perform the measurement with the specified bandwidth, but with a much smaller bandwidth. Appendix G shows how measurement with a smaller bandwidth can be evaluated against a requirement for a level measured with a broader bandwidth.

10. Overview and comparison of existing standards

10.1. General

Besides the engineering praxis described in Section 1.5 there are a few standards worldwide regarding acceptable level of RFI from HV substations. An overview is given in Section 10.2 below. One major difficulty when evaluating the requirements in the different standards is that they are based on very different conditions regarding the measurement procedure. Besides, in several cases the standards are based on an assumption that the frequency characteristics of all RFI are that of corona and sparking in accordance of Figure 11 and Figure B12 of CISPR 18.1 [8].

In order to compare the limits stipulated in various standards the limits have been recalculated for a common reference point 200 m from closest active part in a substation. The justification of this and the interpretation of the standards are further detailed below.

As RFI sources in a substation also may cause RFI from connecting lines, also RFI limits for lines have been recalculated for a common reference point at a distance 200 m from the line. As it is likely that people live closer to a line than to high voltage substations, also the levels at a reference point 50 m are calculated as a comparison.

10.2. Available standards

10.2.1. General

Long before the EU EMC Directive [9] was in force, the engineering praxis, described in Section 1.5, has been applied for HV substations and connecting lines. Regarding the EU EMC directive, the standard EN 50121-5 [13] for power supply systems for a railway system was the first relevant harmonized standard covering frequencies below 30 MHz. That standard is superseded by IEC 62236-2 [25]. However, there are also some other applicable standards worldwide. The standards used for comparisons are:

- ANSI Std 430-1986 [1] regarding procedures for measurement of radio noise from power lines and substations combined with the limits in ANSI C63.12-1999 [2].
- AS/NZS 2344:1997 [3] regarding limits of electromagnetic interference fro power lines and high voltage installations.
- The Canadian standard ICES-004: 2001 [15] regarding interference from high voltage power systems.
- CISPR 11 [4] regarding limits and methods of measurements of electromagnetic disturbances from industrial, scientific and medical radio-frequency equipment.

The frequency band for RFI covers the frequencies from 9 kHz up to 18 GHz. Very few standards stipulate limits from RFI in the frequency range 9 kHz to 150 kHz. Historically, the frequency band between 150 kHz and 30 MHz has been of concern for HV power systems as the RFI from corona is within this frequency range. Thus, this frequency range is better covered by standards. The frequency band between 30 MHz and 1 GHz is the band best covered by various standards as RFI from all low voltage equipment is regulated in this frequency band. Standards for frequencies above 1 GHz are under development. The complete frequency band from 9 kHz up to about 1 GHz may be of concern regarding emission from HV substations.

CISPR 11 [4] covers RFI from various equipment and may be used as a general reference for comparison. Group 1 class A equipment in CISPR 11 is applicable for high voltage substations. RFI limits for group 1 equipment is only given in the frequency range 30 MHz to 1 GHz. Limits for frequency bands 0.15-30 MHz, 1-18 GHz, and 18-400 GHz are under considerations. For group 2 equipment limits are given in the frequency range 0.15 MHz to 1 GHz.

10.2.2. 9 kHz to 150 kHz

10.2.2.1.General

There are very few applicable standards calling for an RFI limit in the frequency band 9 to 150 kHz. The present standards for railway systems and equipment IEC 62236-2 2003 [25] states limits also for RFI in the frequency band 9 kHz to 150 kHz. However, the same limits are applied for a fixed installation as for the moving train. Consequently, only the peak detection method is used. In the previous version of this standard package, lower limits were applied for fixed installations measured with quasi-peak detectors, see standard ENV 50121-5 (1996) [11].

ANSI C63.12-1999 [2] gives limits also for frequencies down to 9 kHz. The measurement procedure is defined in ANSI/IEEE Std 430-1986 [1]. It can be commented that the measurement procedure outlined in Std 430-1986 is quite ambitious, perhaps more suitable for an scientific analysis than for a routine RFI verification.

10.2.2.2.Interpretation for substations

For ANSI the interpretation for substations is that the measurement is performed 15 m outside the fence in accordance with Section 8.2 of IEEE Std 430-1986, and with the limits in Figure 3 of ANSI C63.12-1999 increased by 10 dB as substations are treated as an industrial environment.

For the previous railway application standards ENV 50121-5:1996 and EN 50121-5:2000,the measurement point is defined to be 3 m outside the fence, which is assumed to be 10 m outside the perimeter enclosing all active parts which can radiate RFI. This is in accordance with the second last paragraph of Section 6.1 in ENV 50121-5:1996. This means that for the purpose of comparison, the existence of the fence is disregarded[4]. The applied limits are the limits for 25 kV in Figure 1 of EN 50121-5:2000, that limit refers to a peak detector, and the limit in Section 6.1 of ENV50121-6:1996 refers to a quasi-peak detector. The limits that are given in µA/m are converted to µV/m by multiplication by the free-space impedance of 377 ohm. In the latest standard IEC 62236-3 the measuring distance is defined to 10 m outside the fence, which is assumed to be 17 m outside the perimeter of the active equipment.

10.2.2.3.Interpretation for lines

Although there is no statement about the RFI from the power feeder lines in the railway equipment standards, the limit is for comparison purpose applied 10 m outside the outer phase conductor for ENV 50121-5:1996 and EN 50121-5:2000. The limit for IEC 62236-2 is applied 17 m outside the outer phase. The same concept was used for the RFI conformance of the UK national Grid [52]. The same limits as for the substations are applied.

For ANSI a measurement distance of 15 m from the outer phase conductor is assumed based on Section 5.2.1.2 of ANSI/IEEE Std 430-1986. The same limits as for the substations are applied.

10.2.3. 150 kHz to 30 MHz

10.2.3.1.General

The frequency band 150 kHz to 30 MHz is much better covered by standards than the frequency range 9 kHz to 150 kHz. The reason is that the interference between power line corona and AM broadcasting is within this frequency band.

In addition to the standards mentioned in Section 10.2.2.1 there is an Australian/New Zealand standard AS/NZS 2344:1997 [3] and an Industry Canada Standard ICES-004 [15]. Besides, the engineering praxis described in Section 1.5 has been applied in this frequency band for the examples given in this section.

As a comparison the bad weather and good weather corona for 225 kV, 380 kV and 765 kV in accordance with CISPR 18-1 [8] are shown for lines in this section.

10.2.3.2.Interpretation for substations

The ANSI and the railway application standards are interpreted in accordance with Section 10.2.2.2 for substations.

AS/NZS 2344:1997 is interpreted so that the limits for Zone A of region 1 and region 3, in accordance with Table 1 in the standard are applied 20 m outside the fence, as specified in Section 7 (c) of the standard.

Interpretation of the Canadian standard ICES-004: The limits for 200 kV, 400 kV and 800 kV as per Schedule I with corrections in accordance with Schedule II is applied 15 m outside the fence (Section 4.3.2). Section 5.1.1 states that the limit applies for fair weather conditions.

The engineering praxis is interpreted as a limit of 40 dB applied 500 m outside the perimeter of the active, i.e. the high voltage, equipment.

10.2.3.3.Interpretations for lines

The ANSI and the railway application standards are interpreted in accordance with Section 10.2.2.3.

AS/NZS 2344:1997 is interpreted so that the limits for Zone A of region 1 and region 3, in accordance with Table 1 in the standard are applied at a distance defined in Table 2 of the standard. This means at a distance of 100 m from the outer phase conductor for a 200 kV line and at a distance of 300 m for a 400 kV line. Table 2 is interpreted in such a way that the standard is not applicable for 800 kV lines.

Interpretation of the Canadian standard ICES-004: The limits for 200 kV, 400 kV and 800 kV as per Schedule I with corrections in accordance with Schedule II is applied 15 m from the outer phase conductor (Section 4.2.1). Section 5.1.1 of the standard states that the limit applies for fair weather conditions.

The engineering praxis is interpreted as a limit of 40 dB 30 m outside the outer phase conductor.

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[4] ANSI/IEEE Std 430-1986 is explicitly stated to be intended for substations, while the railway standards are intended for small converter equipment with the fence only a few meters from the building.

10.2.4. 30 MHz to 1 GHz

10.2.4.1. General

All the above mentioned standards except the Canadian ICES-004 specify limits also for the 30 MHz to 1 GHz frequency band. However, AS/NZS 2344:1997 only specify limits for lines. In addition the limits in CISPR 11 [4] were applied for comparison, as CISPR 11 is a quite general standard.

10.2.4.2. Interpretations for substations

For ANSI the interpretation is that the measurement is performed 15 m outside the fence in accordance with Section 9.2 of IEEE Std 430-1986, and with the limits in Figure 3 of ANSI C63.12-1999 increased by 10 dB as substations are treated as industrial environment.

Interpretation of the standards for railway equipment is as per Section 10.2.2.2. However, for frequencies above 30 MHz the limits are directly specified as dBμV/m for the E-field in the standards.

For the railway application standards the measurement point is assumed to be 10 m outside the perimeter enclosing all active parts which can radiate RFI in accordance with the second last paragraph of Section 6.1 in ENV 50121-5:1996. This means that for the purpose of comparison, the existence of the fence is disregarded. The applied limits are the limits for 25 kV in Figure 1 of EN 50121-5:2000, that limit refers to a peak detector, and the limit in Section 6.1 of ENV50121-6:1996 refers to a quasi-peak detector.

CISPR 11 [4] is interpreted in such a way that limits in Table 3 for in situ measurement for group 1, class A equipment is applied 30 m outside the perimeter of active equipment.

The engineering praxis is interpreted as a limit of 40 dB applied 500 m outside the perimeter of the active, i.e. the high voltage, equipment.

10.2.4.3. Interpretations for lines

For ANSI a measurement distance of 15 m from the outer phase conductor is assumed based on Section 5.2.1.2 of ANSI/IEEE Std 430-1986. The same limits as for the substations are applied.

Regarding the limits for railway application standards, the same limits as for substations are applied 10 m and 17 m outside the outer phase conductor for ENV 50121-5 and IEC 62236-2 respectively.

AS/NZS 2344:1997 states that the measurement shall be made for 60 MHz. However, the limit in Table B1 applies for the frequency range 0.03-1 GHz. The limit for 220 kV is 30 dBμV/m and the limit for 750 kV is 32 dBμV/m. The standard is interpreted in such a way that a limit of 31 dBμV/m is applied at the measurement distance of 20 m outside the outer phase conductor. The reason for measurement at only 60 MHz is that the emission from sparking is normally high at this frequency.

CISPR 11 [4] is interpreted in such a way that limits in Table 3 for in situ measurement for group 1, class A equipment is applied 30 m outside the outer phase conductor.

The engineering praxis is interpreted as a limit of 40 dB applied 30 m outside the outer phase conductor.

10.2.5. Above 1 GHz

In CISPR 11 [4] emission limits in the frequency ranges 1-18 GHz and 18-400 GHz are under consideration. So far, no standard applicable for HV substations specifies limits for frequencies above 1 GHz.

10.2.6. Difference between peak and quasi-peak

The difference in level between peak and quasi-peak detection depends on the pulse repetition frequency. For HVDC and FACTS, the difference is often in the order of 5-10 dB. For measurements reported in [37] the difference was generally about 10 dB

10.3. Base for the comparison

10.3.1. Limits for substations

One difficulty when comparing requirements of different standards is the location of the fence, as many standards refers to the fence or the property line. For the sake of this comparison it is assumed that the fence is located at the property line. Furthermore, it is assumed that the distance in meters between the fence and the active equipment is equal to the system voltage in kV divided by 10. Active equipment is a high voltage bus or equipment. The active equipment may also be a converter building for HVDC and FACTS. This means that for a 200 kV substation the distance between the fence and the radiating source is 20 m. For 400 kV and 800 kV substations the distance is 40 m and 80 m respectively. If the measuring point is 15 m outside the fence (property line) the distance between the source and the measuring point will be 35 m, 55 m and 95 m for 200 kV, 400 kV and 800 kV substations. This is important when recalculating the limit for another distance.

Based on information in [40], a sufficiently good estimation of attenuation versus distance of the RFI from a substations is to assume that the RFI field level is proportional to 1/r for longer distances than λ/2π and is proportional to 1/r^2 for shorter distances, where r is the distance between the radiation source and the measuring point. The formula according to Equation (10.1) has been applied. (Note: For longer distance the factors defined in Section 6.4 should be taken into account.)

$$E = \frac{K}{r}\sqrt{\frac{1}{r^2}+\left(\frac{2\pi}{\lambda}\right)^2} = \frac{K}{r}\sqrt{\frac{1}{r^2}+\left(\frac{2\pi f}{c}\right)^2}\ [\mu\text{V/m}] \qquad (10.1)$$

Where K is a proportional constant, r is the distance to the radiating source, f is the frequency in Hz, c is the speed of light and λ is the wavelength.

The constant K is defined by the level at the reference distance of the applied standard.

10.3.2. Limits for lines

For the lines the measurement distance refers to the distance to the closest phase conductor in all standards.

$$\frac{E_2}{E_1} = \left(\frac{r_1}{r_2}\right)^{1.65} \qquad (10.2)$$

Regarding attenuation, Section 8.2 of CISPR 18.1 [8] states that Equation (10.2) is valid at a distance of λ/2π Equation (10.2) only gives an exponent of 1.5 at that distance. Therefore, in the recalculation of the RFI levels for lines for another distance, the distance r in Equation (10.1) has been substituted by 0.732*d, where d is the distance to the closest phase conductor. The higher attenuation for the line RFI is somewhat surprising as the attenuation versus distance is expected to be higher when the source is a point source than when the source is a long line source.

10.4. Comparison of requirements

10.4.1. General

The limits in the standards have been recalculated for a reference limit at a common measurement distance, which is estimated to give the same limitations of the RFI from the radiating source as if the procedure in the standard has been applied. The correction factors given in various standards have not been used, but a common recalculation rule is used as per Section 10.3. As the attenuation versus distance is higher for lower frequencies, the limitation figures in the standards may have been deformed. The deformation is illustrated in Figure 10.1.

Even if the standard only has one limit for all voltage levels, the levels at 200 m from a substation will vary with voltage level as the distance between the active source and the fence is assumed to be dependent on the voltage level.

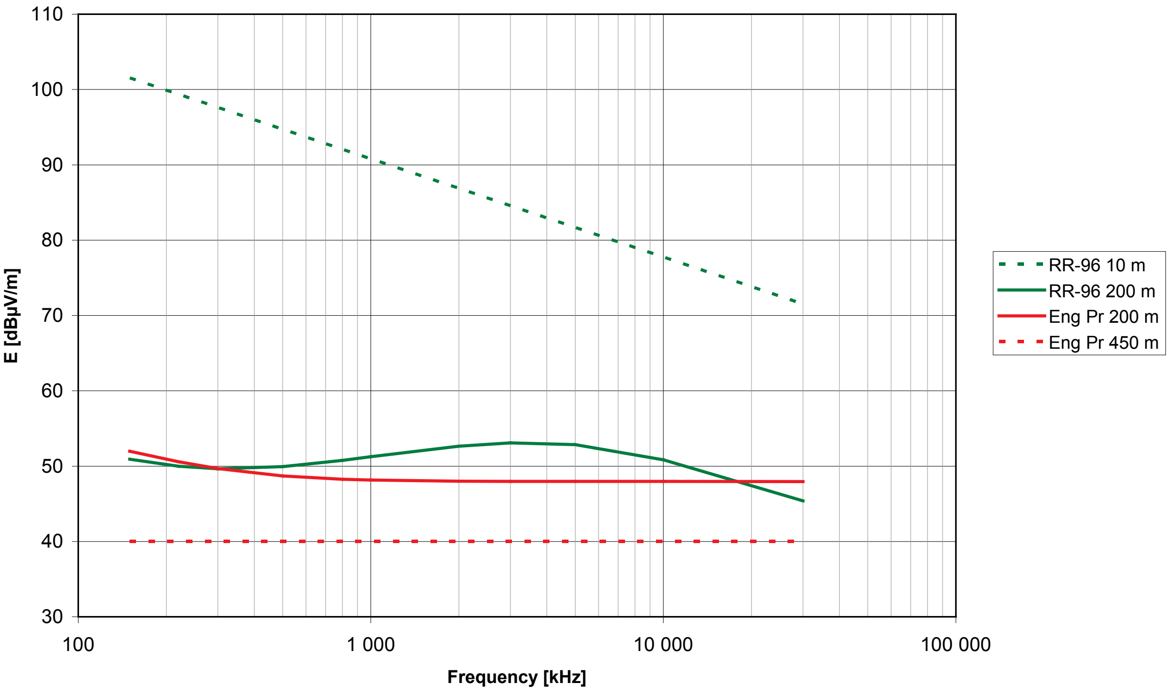

Figure 10.1: Deformation of limitation curves due to frequency dependent attenuation.

The limit in ENV 50121-5 [11] is defined as a straight line at a distance of 10 m, curve "RR-96 10 m". However, when this limit is recalculated for a distance of 200 m, curve "RR-96 200 m" it is not a straight line. The deformation is due to the frequency dependence of the attenuation versus distance. Figure 10.1 also shows how the straight line limit of 40 dBµV/m at a distance of 450 m is deformed when recalculated for a distance of 200 m, curve "Eng Pr 200 m".

10.4.2. 9 kHz to 150 kHz

The limits in applicable standards for the frequency range 9 kHz to 150 kHz have been recalculated for a common distance.

Definition of the curves in Figures 10.2.a - 10.2.c:

- IEC62236 – Limits in Figure 2 of IEC 62236-2:2003-04 have been applied
- RR 25 kV – Limits in EN 50121-2:2000 for 25 kV equipment have been applied.
- RR -96 – Limits in ENV 50121-5; 1996 have been applied.
- ANSI– Limits in ANSI Std 430-1986 combined with C63.12-1999 have been applied
- ANSI 200 – Limits in the ANSI standards are applied for a 200 kV substation.

Note: RR 25 kV is peak, the others are quasi-peak

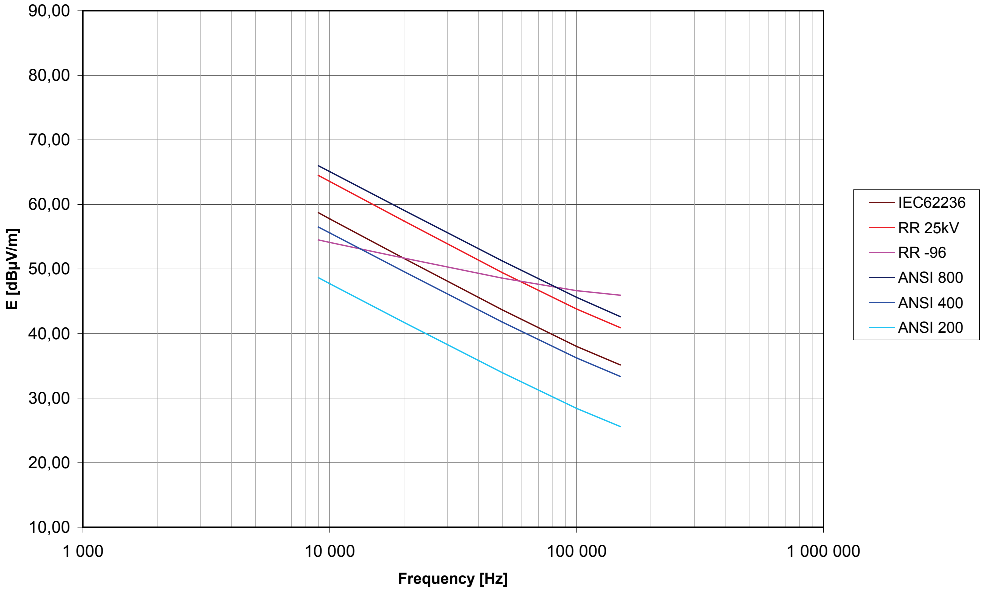

Figure 10.2a RFI limits applied 200 m from a HV substation

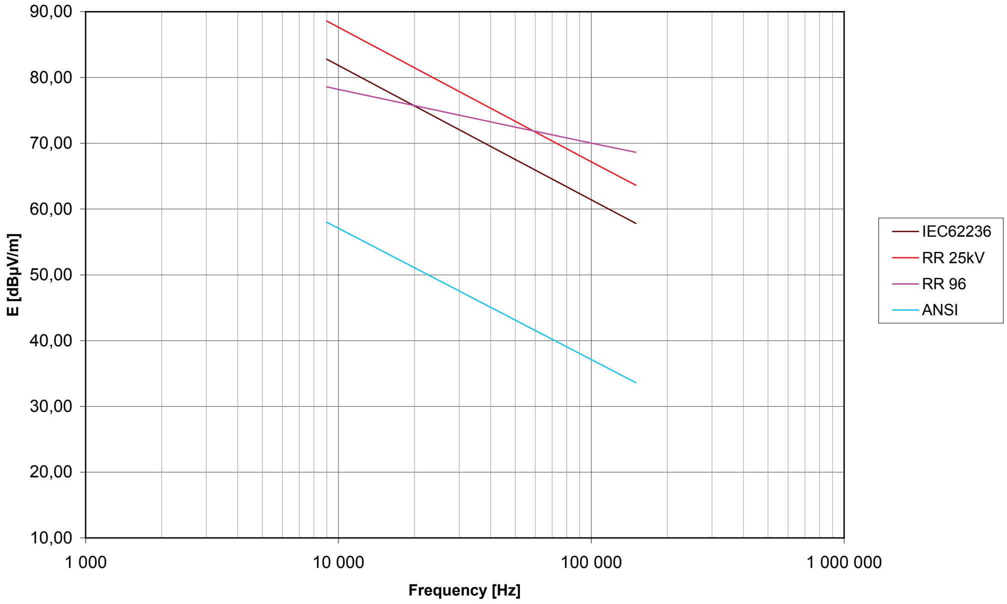

Figure 10.2b RFI limits applied 50 m from a HV power line

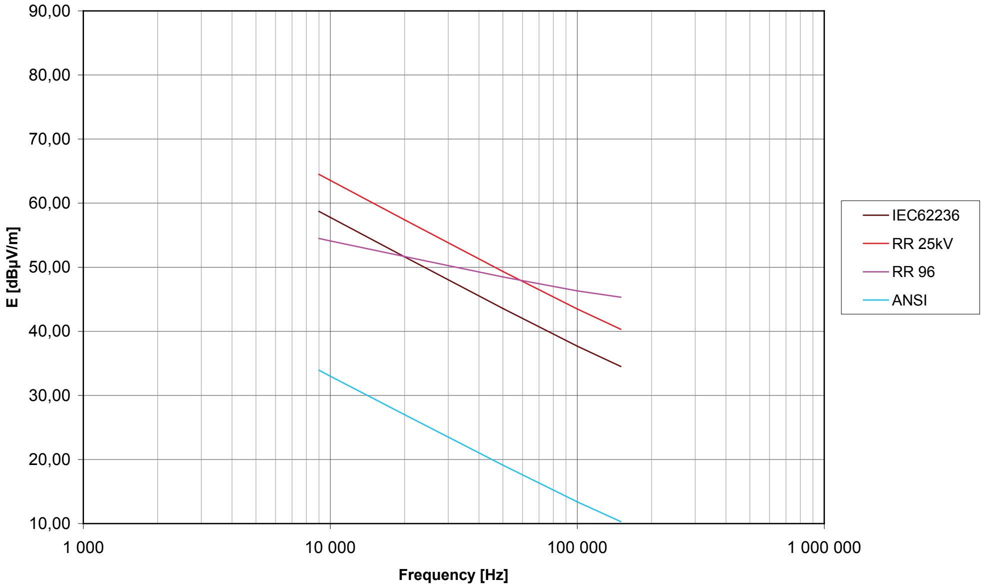

Figure 10.2c RFI limits applied 200 m from a HV power line

<u>Comments regarding the frequency range 9-150 kHz:</u>

The applied standards are fairly consistent regarding limits for the substation in the frequency range 9-150 kHz, seen at a distance of 200m, especially considering that EN 50121-2:2000 (RR 25 kV) stipulate the peak detector.

Considering the physical extension of the substation and the line, it seems that as the requirements may be more stringent for substations than for lines. The standards for railway applications EN 50121-2:2000 (RR 25 kV) and ENV 50121-5:1996 and IEC 62236-2 are hardly applicable for limits of RFI from ac power lines. The levels at 50 m from the lines are significantly higher than the background noise in Figure 2.1.

One observation is that for a substation, the level at 200 m varies with voltage, see Figure 10.2.a while the levels for lines do not vary with voltage, see Figures 10.2.b-c. The reason is the definition of measuring distance in ANSI Std. 430. For lines the measuring distance is the closest active part, i.e. the closest phase conductor and the limit does no vary with voltage. As a consequence the levels at other distances from the active part do not vary with voltage. For the substation the measuring distance in ANSI Std. 430 refers to the fence, and the distance between the H.V. equipment, i.e. the active part is considered to vary with voltage, see Section10.3.1. Thus, the ANSI limit does not vary with voltage, but the distance to the active part varies with voltage. As a consequence, the level at a fix distance of 200 m from the active part varies with the voltage.

NOTE. The note 1 in Section 4.2 of IEC 62236-2 [25] states: “There are very few external radio services operating in the range 9 kHz to 150 kHz with which the railway can interfere. Any exceedances of the relevant limit in Figure 2 (of IEC 62236-2) may be acceptable if it can be demonstrated that no compatibility problem exists.”

10.4.3. 150 kHz to 30 MHz

The limits in applicable standards for the frequency range 150 kHz to 30 MHz have been recalculated for a common distance.

Definition of the curves in Figures 10.3.a - 10.3.c: (The notifications GW and BW are explained below)

- Eng Pr – Limits in accordance with engineering praxis as per Section 1.5 have been applied.
- IEC62236 – Limits in IEC 62236-2; 2003-04, Figure 2 have been applied.
- RR -96 – Limits in ENV 50121-5; 1996 have been applied.
- ICES – Limits in Canadian standard ICES-004;2001, Schedule I and Schedule II have been applied
- ANSI – Limits in ANSI Std 430-1986 combined with C63.12-1999 have been applied
- AS/NZS – Limits in AS/NZ standard 2344:1997 have been applied

Note: All limits are quasi-peak.
The Figures 200, 400, and 800 show the voltage level in kV applied

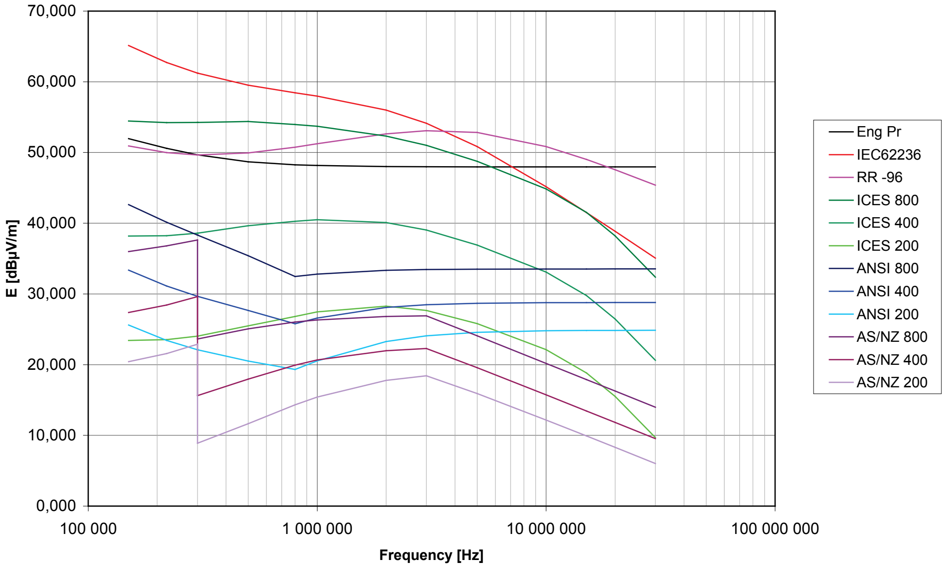

Figure 10.3a RFI limits applied 200 m from a HV substation

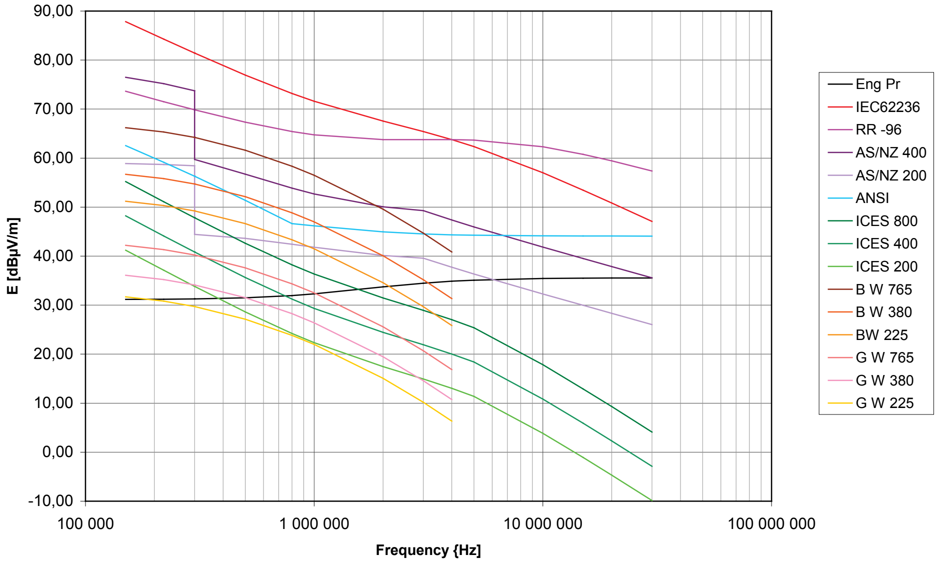

Figure 10.3b RFI limits applied 50 m from a HV power line, compared with corona levels

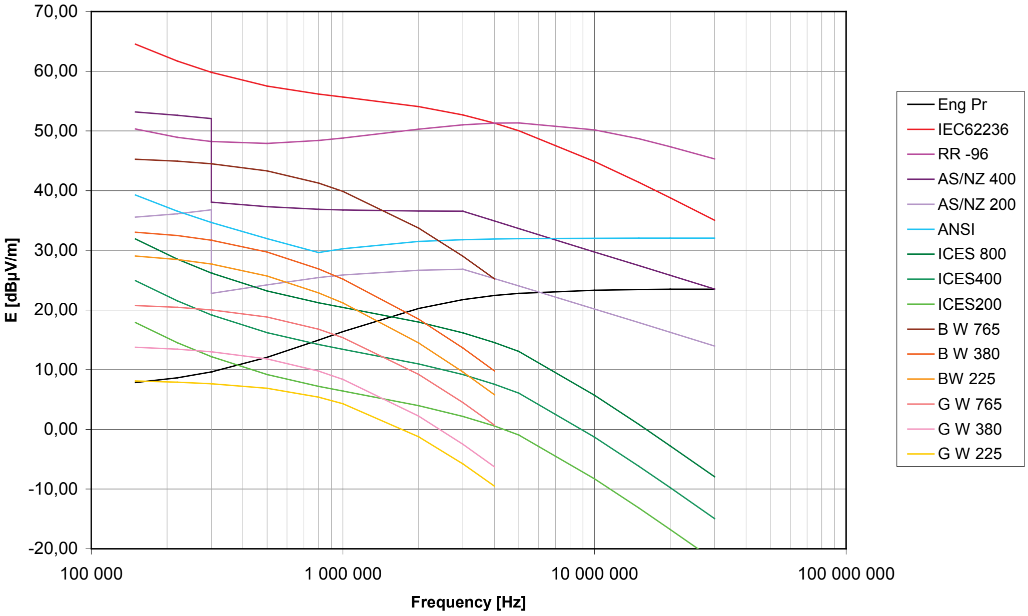

Figure 10.3c RFI limits applied 200 m from a HV power line, compared with corona levels

Note: BW means bad weather corona as per CISPR 18.1
GW means good weather corona as per CISPR 18.1.

The RFI levels for good weather and bad weather corona for 225 kV, 380 kV and 765 kV lines are taken from the Figures B3, B7 and B11 in CISPR 18.1 [8]. The frequency characteristics are in accordance with the equation on page 63 of CISPR 18.1.

Comments regarding frequency range 0.15-30 MHz:

The limits in ICES-004 fit well to the good weather corona. So does the engineering praxis for voltage up to 400 kV, especially when considering that RFI is often only verified at 0.5 MHz.

The ANSI standards and the AS/NZS 2344:1997 fit fairly well with the bad weather corona from lines. As for the frequency range 9-150 kHz the standards for railway application is felt to be a bit too generous if applied to RFI from lines.

The very large difference of 60-70 dB of allowed RFI at 200 m from a substation, depending on applied standard gives a clear indication that more work is needed in this area. One observation is that the engineering praxis and ENV 50121-05:1996 ends up with the same levels at 200 m even if the conditions regarding limits and measurement distances are very different in this two standards. The ANSI standards (C63.12-1999 combined with Std 430-1986) and AS/NZS 2344:1997 give much more stringent limitation for substation RFI than the other standards. Those standards allow significantly higher RFI for 50 m from the lines than 200 m from a substation. When applying ICES-004 the RFI levels at 200 m from a substation are fairly consistent with that at 50 m from a line.

The railway application standards and ANSI allow higher limits at lower frequency, which is consistent both with the background radiation, see Figure 2.1, and the RFI generation (corona in Figures 10.3b and 10.3c and generation from power electronics, see Figure 4.1).

10.4.4. 30 MHz to 1 GHz

The limits in applicable standards for the frequency range 30 MHz to 1 GHz have been recalculated for a common distance.

Definition of the curves in Figures 10.4.a - 10.4.c:

- Eng Pr – Limits in accordance with engineering praxis as per Section 1.5 have been applied.
- IEC62236 – Limits in IEC 62236-2; 2003-04, Figure 2 have been applied.
- RR -96 – Limits in ENV 50121-5; 1996 have been applied.
- CISPR11 – Limits in Standard CISPR 11; 2004 have been applied
- ANSI – Limits in ANSI Std 430-1986 combined with C63.12-1999 have been applied
- AS/NZS – Limits in AS/NZ standard 2344:1997 have been applied

Note: All limits are quasi-peak.
The Figures 200, 400, and 800 show the voltage level in kV applied

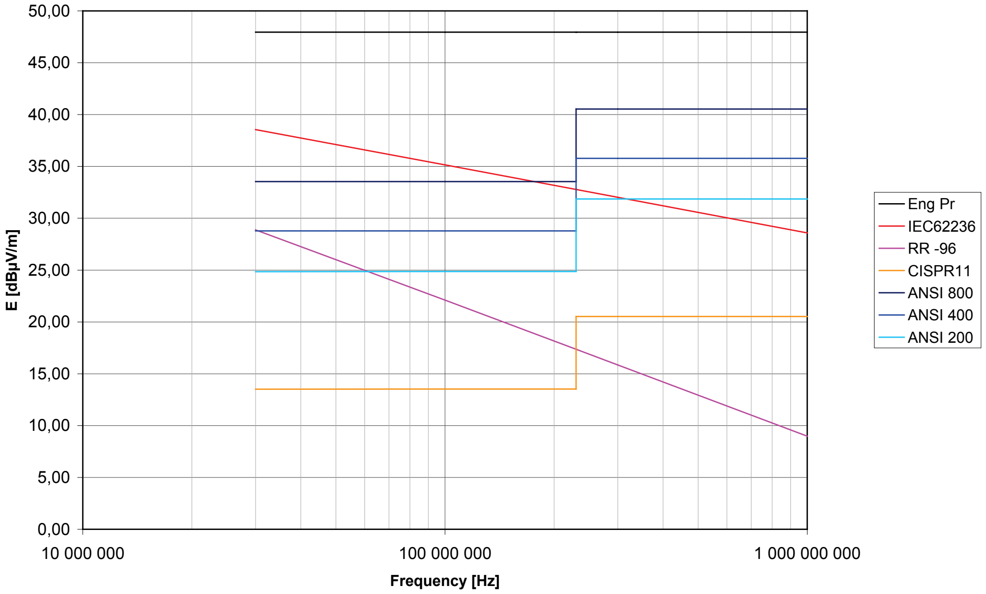

Figure 10.4a RFI limits 200 m from a HV substation

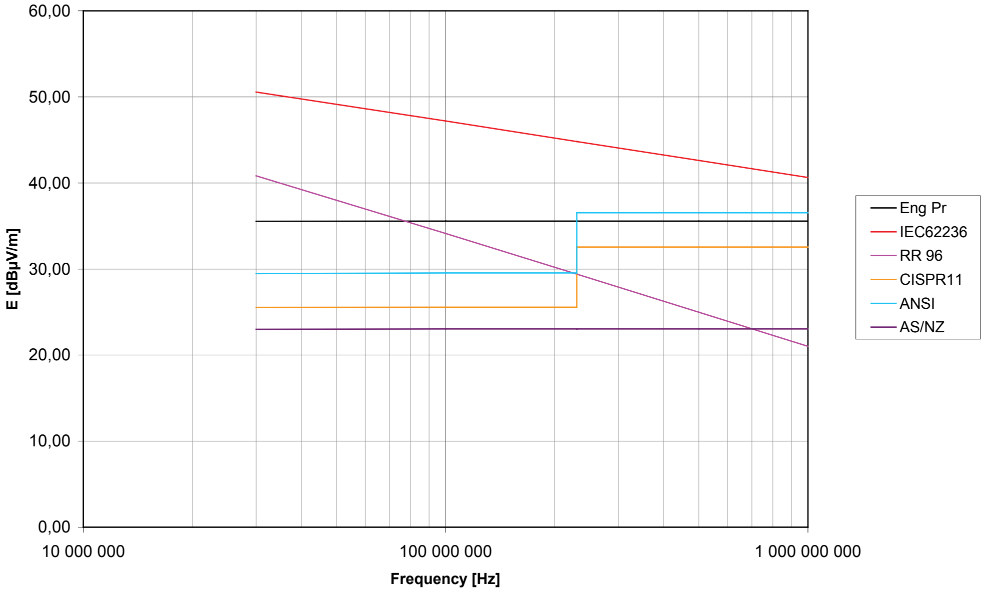

Figure 10.4b RFI limits 50 m from a HV power line

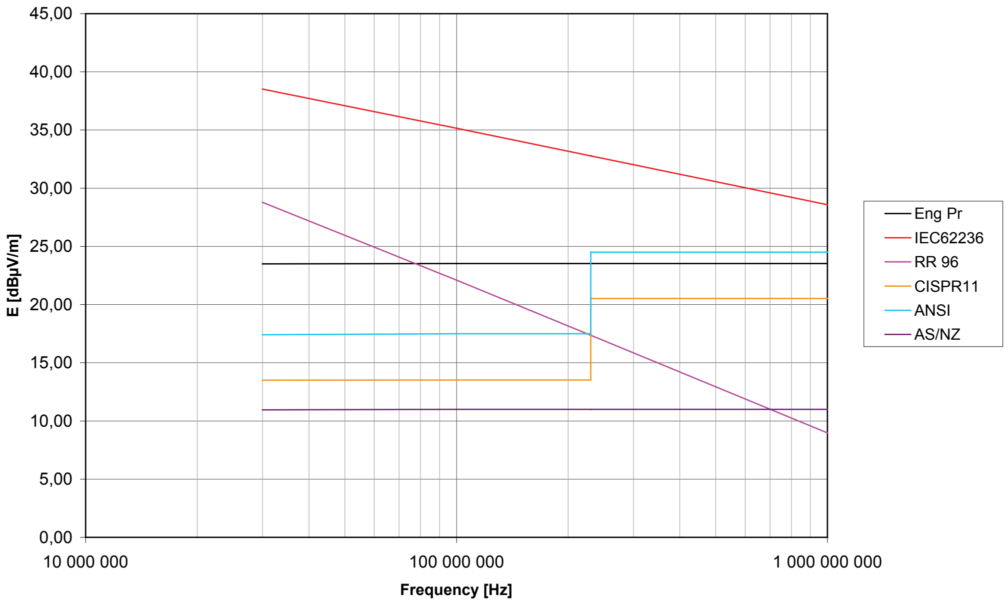

Figure 10.4c RFI limits 200 m from a HV power line

Comments regarding the frequency range 0.03-1 GHz:

The limits for RFI from lines seems to be very well established in this frequency range, especially if considering that AS/NZS 2344:1997 only requires verification at 60 MHz. EN 50121-2:2000 allows much higher values, probably because of the RFI due do arcing at the collector of an electrical engine.

When applying ANSI, the RFI levels at 200 m from a substation is fairly consistent with the RFI levels 50 m from a line. The engineering praxis allows 10-20 dB higher RFI and IEC 62236-2 is somewhat higher. ENV 50121-5:1996 is quite stringent regarding RFI from substation in this frequency range, which is likely to reflect the expected emission from railway power supply equipment.

It can be noted that the application of CISPR 11 results in 10-15 dB lower values at 200 m from a substation than when applying ANSI. The reason may be that CISPR 11 is intended for industrial, scientific, and medical (ISM) equipment of a much smaller physical size than a high voltage substation. Furthermore, ISM equipment is likely to be located closer to other equipment than a high voltage substation.

10.5. General comments

Some of the difference between the levels in the various standards can be due to different basic preconditions. This is especially valid for the frequency range 150 kHz to 30 MHz where the emission from corona is a major factor.

Radio communication shall work in all weather conditions, both in good weather conditions and in bad weather conditions such as rain, fog and hoarfrost. Therefore, standards and procedures primary intended as a quality check of the corona design in good weather, such as ICES-004 [15], must have a margin for avoiding interference to the surroundings in bad weather conditions. This margin varies marginally with the voltage level and is about 15 dB at 225 kV and 25 dB at 765 kV systems, see Figures 10.3.a-10.3.b.

On the other hand, if the standard is intended for verification of the corona level in bad weather conditions, such as AS/NZ standard 2344 [3] regarding lines, no such extra margin is needed, see Figures 10.3.b-10.3.c. (Even if the corona emission at bad weather is very relevant for the interference point of view, it might be questionable if verification of corona in bad weather conditions is the best procedure from a practical point of view.)

However, standards intended to verify emission due to power electronic equipment do not need to consider any variation due to weather conditions. There is no need for an extra margin in addition to the requirements for avoiding interference to the surroundings. The standards for railway applications [11][13][25] and the engineering praxis as per Section 1.5 belong to this group of standards.

The above complications due to weather conditions do not exist in the same way in the frequency ranges outside 150 kHz to 30 MHz. However, it can be commented that in [37] the worst conditions for broad band emission due to gap discharges was dry weather conditions.

Therefore, when comparing the limits in different standards, the preconditions for the limits should be taken into account.

11. Considerations for acceptable limits

11.1. General

Often, when acceptable RFI limits are discussed, the emission level is compared with the background noise level. However, regarding the risk for realised interference, it is not the field level at the source, but the field level at the location of the receiver that matters. Besides it is a worse situation if hundreds of receivers are disturbed than if one receiver, of the same dignity, is disturbed. A third parameter is the frequency band used by the receivers, which might be interfered. Some typical aspects: For what purposes is a certain frequency band used? How many receivers are there and where can they be located? At which disturbance level does the interference start?

The difference in stringency of the RFI requirement can be expressed as different levels for a given measurement distance, but is more often expressed as difference in measurement distance with the same requirement level. This can be expressed as a difference in respect distance between the source and a receiver that may be interfered.

11.2. Impact zone

The impact zone of an equipment, is defined as the amount of receivers that might be disturbed when its RFI level increases. It is reasonable that the larger the impact zone is, the stricter the RFI requirement should be. Thus, when comparing the levels for different types of equipment, the impact zone must also be considered. One very important, but often omitted, aspect is that all values regarding emission levels must be combined with the distance to the source. Otherwise, they are of no relevance.

Some general aspects for different equipment and installations regarding impact zone:

1. A 400 kV substation is often located in a remote area with few or no people living close to the substation. The total number of 400 kV substations is low.
2. The 400 kV lines run for long distances. They may pass quite close to populated areas. There are more 400 kV lines than 400 kV substations. Thus, the lines have a larger impact area than the substations.
3. There is a larger number of substations for the lower voltages 70-130 kV, and they may be located quite close to dense populated areas.
4. The 70-130 kV lines may crisscross dense populated areas.
5. There is a significant number of 10 kV substations and they may be located inside domestic buildings.
6. Low voltage and household equipment, such as vacuum cleaners and computers, are distributed in a very large number and used in domestic areas, and may be very close to sensitive radio receivers.
7. The 400/230 V low voltage distribution networks crisscross almost all walls of domestic buildings. When considering the amount of such lines and the closeness to used radio receivers the conclusion is that the impact zone of these distribution networks is much higher than the impact zone for 400 kV substations.

It is reasonable that the RFI requirement for different items reflect the difference in impact zone. Stricter limits for lines than for substations; stricter limits for low voltage equipment than for high voltage equipment; stricter limits for mass products than for single installations in a few location. This harmonizes well with the corona emission as per CISPR 18.1 [8].

It must also be noted that a line has a larger physical extension than a single point source. In ECC/REC/(05)04 [10] the typical distance between a LV line and a radio receiver is considered to be 3 m, to be compared with the 10 m for domestic equipment that can be regarded as a point source. The disturbed area around a point source is a circle around the source, while the disturbed area from a line, is a corridor following the complete extension of the line. This aspect is also valid when comparing substations (a point source) with the connecting HV and MV lines. This is demonstrated by Figure 11.1.

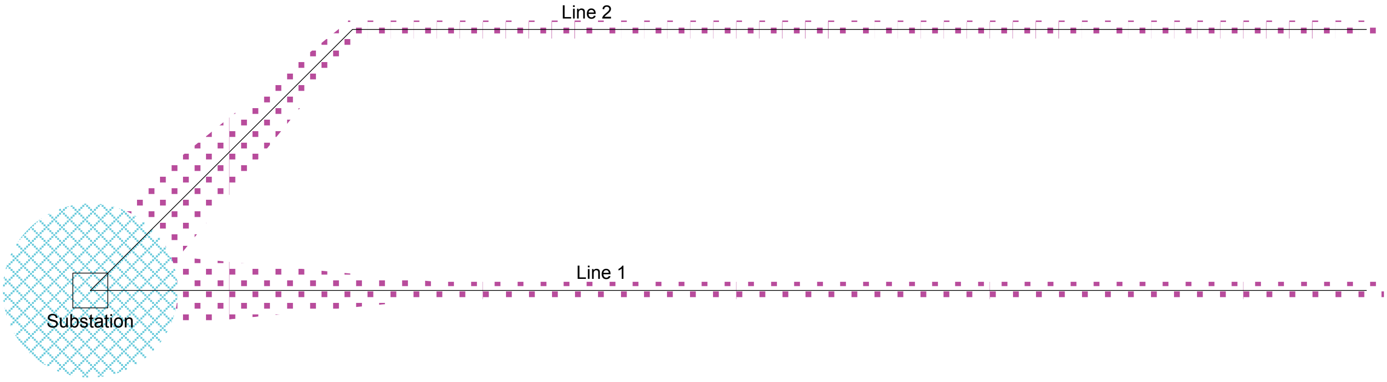

Figure 11.1: Comparison of impact zones of lines and substations

In Figure 11.1, the impact zone of the substation is indicated by blue shadow. This is the area where the RFI level is increased due to direct radiation from the substation. The impact zones of the lines are indicated by pink shadow. In those zones the RFI level is increased due to guided radiation via the lines. Even if the impact zone of the line is quite narrow, the covered area will be larger than the area covered by the impact of the substation due to the length of the lines. With the respect distances for 400 kV systems in Table D.4 and Table D.5 in Appendix D, a few tenths of km line length will cover the same impacted area as the direct radiation from the substation.

11.3. Impacted radio communication

The limits should also reflect the radio communication that can be disturbed. Which type of radio communication, if any, is used in the frequency range of interest, and how close is the closest radio receiver likely to be located. Also the background noise level and a realistic signal level have to be considered.

It is reasonable that standards for substations only consider quite normal situations. For each substation it is then realistic to make a risk assessment if there are nearby radio receivers requiring special precautions. Such specific risk assessment is hardly practical for lines, which needs to be considered when defining the levels in a standard.

11.4. Reference point for measurement

11.4.1. General

The ideal reference point for the verification measurement is the closest part of the dominating source. In such a case, the used measurement distance was not so important as long as the required level was determined considering the attenuation properly. However, the dominating source is normally not identified in advance and it may have a different location for different frequencies.

For practical purpose, the reference point must be a point that can easily be identified in advance. It is recommended to use the closest active part as the reference point. The active part is the wall of a converter building or the high voltage bus structures. For a line, a point straight below the closest conductor is the reference point.

As explained in Section 11.4.2, the fence is not a suitable reference point for RFI measurements

11.4.2. Compliance by moving the fence

To use the fence as reference for the measurement distance is a bit risky. The risk is demonstrated by Figure 11.2. The background is that standard ENV 50121-5 [11] states the limit at 0.5 MHz to be 94.7 dB [µV/m] at 500 kHz, 3 m outside the fence. This limit is marked Li in Figure 11.2. The 40 dB line is a reasonable level when AM broadcasting starts to be disturbed. The parameter *dF* is the distance between the active source and the fence.

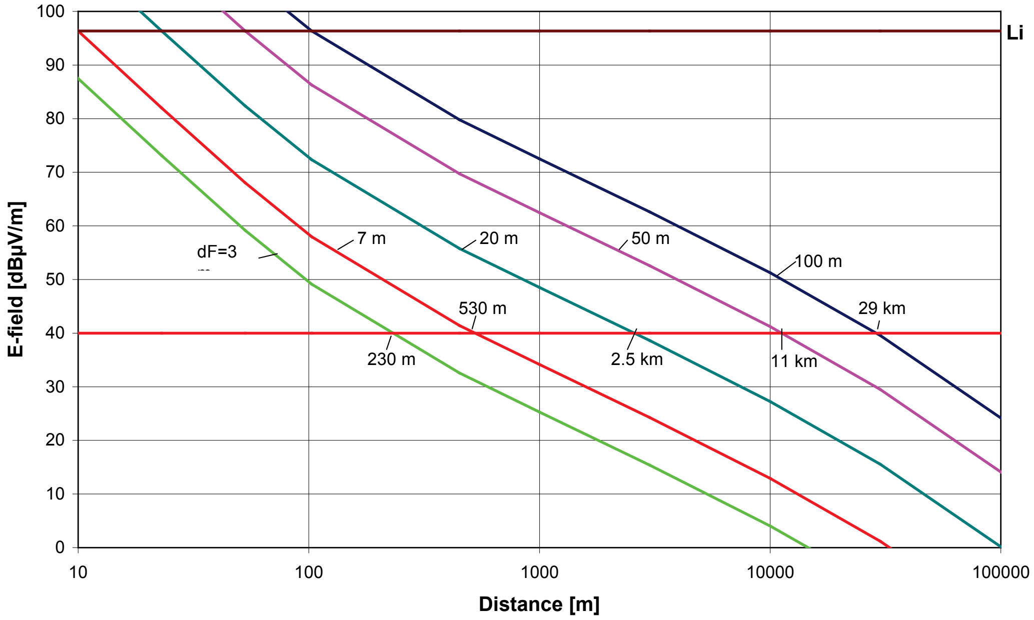

Figure 11.2: The consequential field levels versus distance if compliance is obtained by moving the fence.

The case with the fence 7 m outside the wall can be seen as a reference case, as the standard defines the measurement location to be 10 m outside the wall if there is no fence. In Figure 11.2 the attenuation is in accordance with Section 9.1. The Figure shows that for the reference case, if the level 94.7 dB [µV/m] is fulfilled 3 m outside the fence, i.e. 10 m outside the wall, the field level is reduced to 40 dB at a distance of 530 m. This is reasonably close to the normal engineering praxis to limit the field to 40 dB [µV/m] about 500 m outside the switchyard HV equipment.

If the fence is located 3 m outside the wall the disturbing source must be reduced to fulfil the 96.3 dB limit 3 m outside the fence. Then the 40 dB level is reached at 230 m outside the building.

However, if the fence is moved to 20, 50 or even 100 m outside the walls, which is not unrealistic for a large HV station, much stronger sources are allowed without jeopardizing the stipulated limit of 96.3 dB [µV/m] 3 m outside the fence. As a consequence, the border for the 40 dB [µV/m] level will be at a distance of 2.7 km, 17 km, and 43 km respectively. Such strong RI noise emitters are hardly acceptable.

Consequently, the fence is not a suitable reference for measurement distance.

11.4.3. Measurement distance

11.4.3.1. Lines

The proposal is to follow CISPR 18 and use a measurement distance of 30 m for the lines, up to a voltage level of 600 kV. For higher voltage level a measuring distance of 50 m is proposed.

If the measurement distance is longer than the respect distance it is hard to verify the conformance as the background noise level will be higher than the RFI of interest. At too short a measurement distance, the measured values may not be representative for the RFI level at a larger distance. Besides, the shorter the measurement distance, the more critical is the definition of the location of the measurement point.

11.4.3.2.Substations, frequency range 9 kHz to 30 MHz

The physical size of the substations needs to be considered. The size of the substation is assumed to be related to the voltage and power rating. The proposed measurement distances for substations, in relation to the closest active part is defined in Table 11.1:

Table 11.1: Proposed distances for substation RFI measurements

Substations without PE installation		**Substations with PE installations**	
Voltage rating	**Measurement distance**	**Power rating**	**Measurement distance**
$U \leq 100$ kV	30 m	$S \leq 7$ MVA	30 m
100 kV < $U \leq 170$ kV	50 m	7 MVA < $S \leq 40$ MVA	50 m
170 kV < $U \leq 250$ kV	100 m	40 MVA < $S \leq 200$ MVA	100 m
250 kV < U	200 m	200 MVA < S	200 m

Note: PE – Power electronic Equipments such as FACTS and HVDC.

At a conflict the longest measurement distance apply.

For more detailed information, see Table D.3 in Appendix D.

11.4.3.3.Comments

The proposed measuring distances are compromises of covering most equipment with a few measuring points, covering strong sources in the middle of the plant and to have a required level above the background noise. Measurement too close to an installation may give large local variations not relevant for a longer distance. Furthermore, at a short measurement distance, the definition of the reference point for the measurement distance is very critical.

11.5. Recommended procedure for defining the limit

11.5.1. General

As the disturbing receivers are the same, the same criteria should apply regardless to the type of equipment, considering the applicable conditions. The impact zone is the most important parameter.

11.5.2. Limit of RFI at the receivers

The acceptable level of RFI at a typical disturbed receiver should be the same regardless of the disturbing equipment. The level is well defined for frequencies above 30 MHz, see CISPR 11 [4] and IEC 61000-6-3 [22]. Table 1 of AS/NZS 2344 defines this limit in the frequency range 150 kHz to 30 MHz. Figure 3 of ANSI 63.12-1999 covers the complete frequency range from 9 kHz to 10 GHz. ECC/REC/(05)04 [10] is considered as the most up to date information regarding frequencies below 30 MHz. For more information, see Appendix B, which also has a tentative proposal regarding limits at the location of digital radio receivers.

The RFI limits at the receivers are a universal EMC issue and related to all sources of RFI. Figures B.2 and B.3 together with Tables B.1 and B.2 in Appendix B concludes the findings regarding that basic limit or reference curve.

11.5.3. Respect distance

The respect distance is the distance from a RFI source defining the border for an increased level of RFI. Thus, outside the respect distance the RFI from the source is down to a normal background level. The RFI from the source is not nil, but down to a reference level. See also Appendix B for more information.

The respect distance depends on type of equipment. When comparing IEC 61000-6-3 [22] and IEC 61000-6-4 [23], which are the generic emission standards for domestic equipment and industrial equipment, the levels are the same, but the measurement distance is 10 m for domestic equipment and 30 m for industrial equipment. This is used as a starting point for the tentatively proposed table in Appendix D. ECC/REC/(05)04 defines a respect distance of 3 m to domestic low voltage lines, including telecommunication lines.

Regarding high voltage systems, AS/NZ 2344 [3] defines the respect distances for lines of different voltages directly, while ICES-004 [15] defines the respect distances indirectly by defining different RFI levels for different voltage levels of substations and lines. Also IEC 62236-2 [25] defines the respect distances indirectly by defining a level and a measuring distance, provided that the reference level at the location of the radio receivers is known.

Primarily based on IEC 62236-2 [25] and ICES-004 [15] the respect distances have been analysed in Appendix D and limits are proposed for different voltage levels and power rating of power electronic equipment. Table D.4 shows the consequential respect distances for substations and high voltage power electronic equipment while Table D.3 shows the respect distance for the connecting power lines. It should be noted that the limits for lines are primarily for controlling the guided RFI emission from the substations.

11.5.4. Proposed requirements

The recommended measurement distances and limits are defined in Table D.2 and Table D.3 in Appendix D. For practical reason it is recommended to apply the limits for peak detectors in accordance with Table F.3 in Appendix F. It is recommended to also verify the RFI with digital radio systems by applying the limits in Table F.2. It should be noted that Tables D.2 and D.3 also have defined reductions or additions to the limits defined in Appendix F.

For frequencies above 1 GHz it may be sufficient with a simple check that there is no notable RFI from the substation.

11.6. Special considerations

At all new installations there should be a risk assessment performed if special considerations are needed regarding RFI. Some typical examples where special considerations are needed:

- Nearby location of an airport. A frequency range that is important regarding RFI with aviation traffic is 255-526 kHz for the non-directional radio beacon.
- Communication centres for emergency services such as fire brigades etc.

In all cases for special considerations, the frequency ranges for possible interference shall be identified.

The requirement at the location of the critical services has to be identified regarding level and bandwidth. Then the requirement has to be recalculated for the measuring distance in accordance with Chapter 9 in the guide.

It must be noted, that the soil attenuation at high frequencies is much less for aviation traffic due to the height of the receiving antenna. Reference is made to Equations (9.3) and (6.5.1).

12. Recommendations

12.1. Consistency between standards

Radio frequency interference is a global phenomenon. Therefore, there should be consistency between standards, regarding frequency characteristics of the specified limit and the overall impact. When standards regarding specified limits and measurement methods are adapted to the characteristic of a specific source, such as corona, a very uncertain situation will arise when new equipment such as power electronics is introduced. In some aspects the requirement may be too rigid, but missing other aspects, leading to both unnecessary cost and risk of RFI when in actual operation.

Instead the requirement in the standards should relate to the characteristics of impacted radio receivers. This is something that should be treated equally for all types of equipment.

The difference between standards for different equipment should be related to how close to the emitting equipment radio receivers are likely to be located and how the verifying measurements should be performed. In that aspect there is a significant difference between a vacuum cleaner fed by 220 V and a 10 GVA HVDC installation fed by EHV a.c. lines.

12.2. Measurement procedure

The recommended procedure follows Figure 1.1 with a few modifications. Reference is made to Figure 12.1.

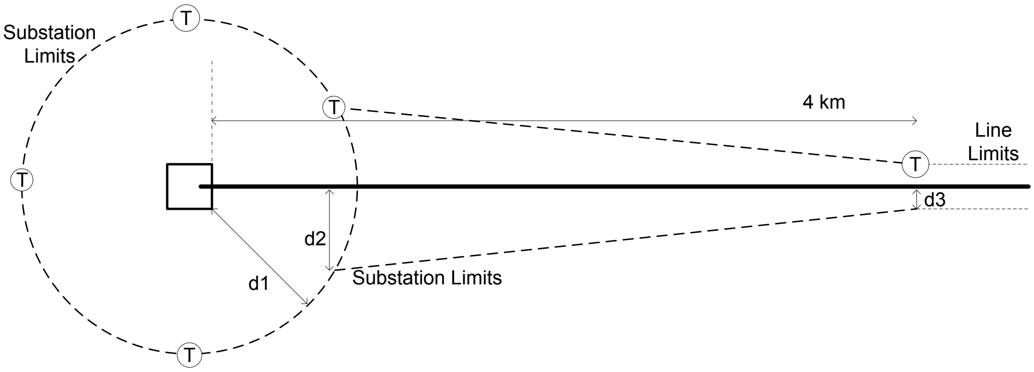

Figure 12.1: Recommended measurement procedure with definition of measuring point.

Comments:

- d_1 is the measuring distance for substations in accordance with Table D.2:
- d_3 is the measuring distance for lines in accordance with Table D.3, 30 m up to 600 kV a.c. and 50 m for higher voltages.
- d_2 is one third of d_1.

The circled Ts indicate the most relevant positions for measurement.

The limits for substations in accordance with Table D.2 is applicable both for the contour around the active parts of substations and the closest part of the contour along the line. After a distance of four km, the limits for the line in accordance with Table D.3 apply.

12.3. Weather conditions

It is recommended that the RFI measurements be performed in fairly good weather where possible. The reasons are:

- Practical reason, the measuring equipment is sensitive electronic equipment, in generally not designed for outdoor use in bad weather.
- The gap discharge activity, which is not easily controlled by other means is worst in dry conditions [37].

The RFI due to a.c. corona is much higher in bad weather conditions. Thus, it is not easy to combine verification of worst case corona with measurement of RFI due to other sources. Therefore it is recommended that the substation RFI due to corona is controlled by calculation, with the geometry as input, which is the normal procedure today. The RFI due to corona in high voltage equipment is controlled by the RIV test in equipment standards [19].

12.4. Use of new detectors

With the introduction of digital radio it is necessary to introduce a requirement for limitation in a broader frequency band than defined by the common CISPR 16 [5], see Section 3.7. Therefore, Appendixes B, D and F cover a proposal for a new procedure with broadband rms measurement of RFI as an adequate way for defining the degree of interference with new digital wireless communication systems. Appendix G shows that it is feasible to evaluate the compliance with a broad band limit by measurement with a much narrower band. The reason for measurement with the narrowband in situ verification may be the presence of radio transmitters.

12.5. Frequencies below 150 kHz

The limits for frequencies below 150 kHz, especially in the lower range down to 9 kHz need further evaluation. There are three aspects of importance: It is appropriate to refer to note 1 in Section 4.2 of IEC 62236-2 [25], which states: “There are very few external radio services operating in the range 9 kHz to 150 kHz with which the railway can interfere. Any exceedances of the relevant limit may be acceptable if it can be demonstrated that no compatibility problem exists.” The reasons for such a note are:

This frequency band is rarely used for radio communication, see Appendix E.

Countermeasures such as filtering and screening have much higher cost for the lower frequency range, and the natural emission for power electronic equipment increases with lower frequency.

The near field phenomenon is of relevance up to a quite large distance due to the long wave length.

The RFI level in this frequency range should be measured. However, if the emission is higher than the design criteria, a risk evaluation may show that there is no risk of RFI disturbances in real life.

12.6. Further work

Although not identified as a problem today, it is noted that there is no translation procedure for how to adapt the RIV voltage test requirement on equipment specified in the equipment standards [19] to the specified RFI requirement in dBµV/m. Thus, there is a need to develop the correlation between the parameters in the RIV test and the consequential RFI level in the field, both for good and bad weather conditions.

13. References

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Appendix A

Glossary

This appendix covers some of the most important terms in this guide. For more information see [16][17][18].

AM: Amplitude Modulation – the radio signal is added by modulating the amplitude of the radio frequency carrier wave. Cf. FM.

Arcing: The results of an electric current flowing through an air gap. The arc constitutes a conductor through the air gap.

Average detector: A detector that produces the average value of the envelope of a measured signal

Background noise: The RFI noise or electromagnetic field from other sources other than the EUT. This includes emission from broadcast stations and other radio transmitters. The background noise may mask the RFI emission from the EUT.

BPL: Broadband Power Line communication is when a broad band signal is superimposed on the electric voltage in power lines for data communication.

Commutation: When the current is switched (commutated) between different paths, especially in power electronic equipment. Often the commutation process is repeated cyclically.

Corona: Localised breakdown of the air surrounding a metallic conductor or object that has been charged to a high voltage. Locally the electric field would be higher than the withstand capability of air.

Corona ring: An electrode with a smooth surface, often in the form of a toroid, that is placed at or around a sharp electrode. The purpose is to reduce the electrical field to such an extent that corona is avoided. Corona rings are only used in high voltage conditions.

Digital radio communication: Useful information in the radio link is transmitted as digital information. (This is contrary to the analogue signal in a conventional AM or FM radio link.)

Directivity: Describes the performance of an antenna or a transmitter where the EM field is stronger in one direction than in another. i.e. the source is not omnidirectional. The directivity or antenna gain is expressed as the relation between the strongest field and the field from an omnidirectional source with the same total radiated power.For a receiving antenna, the directivity is the variation in sensitivity in different directions.

Direct wave: A radio wave propagating along a direct-ray path.

Electronic power conversion: The change of one or more electric parameters of an electric power system (essentially without appreciable loss of power) by means of electronic valve devices.
NOTE – Parameters are, for example, voltage, number of phases and frequencies including zero frequency.

EMI: ElectroMagnetic Interference is interference caused by electric and/or magnetic fields.

Envelope detector: A detector for tracking the envelope of the amplitude of a signal. For a signal $G(t)*e^{j\omega t}$ the function $G(t)$ represents the envelope.

EUT: Equipment Under Test.

FACTS: Flexible AC Transmission System is an acronym used to describe power electronic equipment for improving the operation or stability of a.c. power transmission systems. Some examples are: Static Var Compensators (SVC), Thyristor Controlled Reactors (TCR), and Thyristor controlled Series Capacitors (TCSC).

FM: Frequency Modulation – the radio signal is added by modulating the frequency of the radio frequency carrier wave. Cf. AM.

Free-space impedance: (or impedance in vacuum) is the quotient between the electric E-field and the magnetic H-field of a far field radio wave in vacuum. The numerical value is 377 ohm, corresponding to 51.5 dB difference in amplitude between the E-field and the H-field.

Guided wave (in a transmission line): An electromagnetic wave that propagates along or within physical boundaries or structures. These structures or boundaries may be bus bars or transmission lines. A guided wave in an open structure, such as a transmission line, is leaky and there is radiation loss. This leakage is manifested as an emitted direct wave from the transmission lines. (An alternative view is to consider the guided wave as a direct wave from the transmission line due to the high frequency current travelling along the line.)

High Frequency: Throughout the guide the term high frequency refers to all frequencies substantially above the power frequency, i.e. 9 kHz and above.

HVDC: High Voltage Direct Current. **IGBT:** Insulated Gate Bipolar Transistor. A high speed electronic component where the current is controlled by the gate voltage. Thus it acts as an electronic switch. The current rating is in the order of kA and voltage rating is up to a few kV.

Impact zone: The impact zone of a certain equipment represents the total increase of EMI if the radiation from this equipment is increased for the whole community. See also Section 11.2 of the guide.

Measurement distance: The distance between the receiving antenna of the measurement equipment and a defined boundary of the EUT.

Peak detector: A detector sensing the peak amplitude of the envelope of the measured signal.

PLC: Power Line Carrier. A narrow band signal superimposed on the a.c. voltage of high voltage lines for transmitting information between substations, often for power system protection purpose. Frequency is between 30 kHz and 500 kHz, the longer the line, the lower the frequency used. Two conductors are used for balanced transmission, eliminating the earth return mode. C.f. BPL. for broad band PLC.

Power electronic equipment (PE): Electronic equipment which deals with the conversion or switching of electric power with or without control of that power. Cf. Electronic power conversion. Some examples of power electronic equipment are: HVDC, FACTS, motor drives, rectifiers, auxiliary power supply, etc.

Quasi-peak detector: A peak detector provided with an input filter with a certain time constant. The detected amplitude will thus be lower than the reading of a peak detector, depending on the waveform of the pulse. The detector is an envelope detector. See also Section 3.3 of the guide.

Radio Frequency: The frequency range covered by the ITU radio regulations [29]. The present frequency range is from 9 kHz to 400 GHz.

Respect distance: The distance when the emitted RFI from a piece of equipment or an installation is attenuated to such a level that no interference is expected outside the respect distance. The field level is not down to zero, but to a reference level. For more information see Appendix B.

RFI: Radio Frequency Interference (also referred to as RI (Radio Interference)) is electro magnetic interference in the radio frequency range.

RI: the same as RFI.

RIV voltage: The amplitude of the high frequency ringing superimposed on the fundamental frequency voltage due to sparking, corona and partial discharge. This voltage is measured under the RIV test defined in IEC 60694 [19] and IEC 62271-1 [26] and is used to verify that the high voltage equipment is “free” from corona at normal voltage.

RMS detector: A detector sensing the RMS value of the envelope of the measured signal**.**

Sparking: A discharge through an air gap of a capacitance charged to the breakdown voltage. The time duration is short but the sparking may be repetitive. The front time is very short and this is the reason sparks emit broadband RFI of high frequency

RFI limits at the location of the receivers

B.1. Existing limits

In principle, the requirement at the location of a typical receiver should be the same regardless of the source of the radio frequency interference. These limits should apply at the boundary of the respect distance or the respect corridor. Figure B.1 shows the limits from some relevant standards. The measurement bandwidths are in accordance with Table 16 of CISPR 16-1-1 [5]: 200 Hz in the frequency range 9 kHz to 150 kHz, 9 kHz in the frequency range 150 kHz to 30 MHz, 120 kHz in the frequency range 30 MHz to 1 GHz, and 1 MHz above 1 GHz. All levels up to 1 GHz are based on quasi-peak detection, see Table 1 of IEC 61000-6-3 [22]. The limits given above 1 GHz are based on peak detection, see Table 6 of CISPR 11 [4]

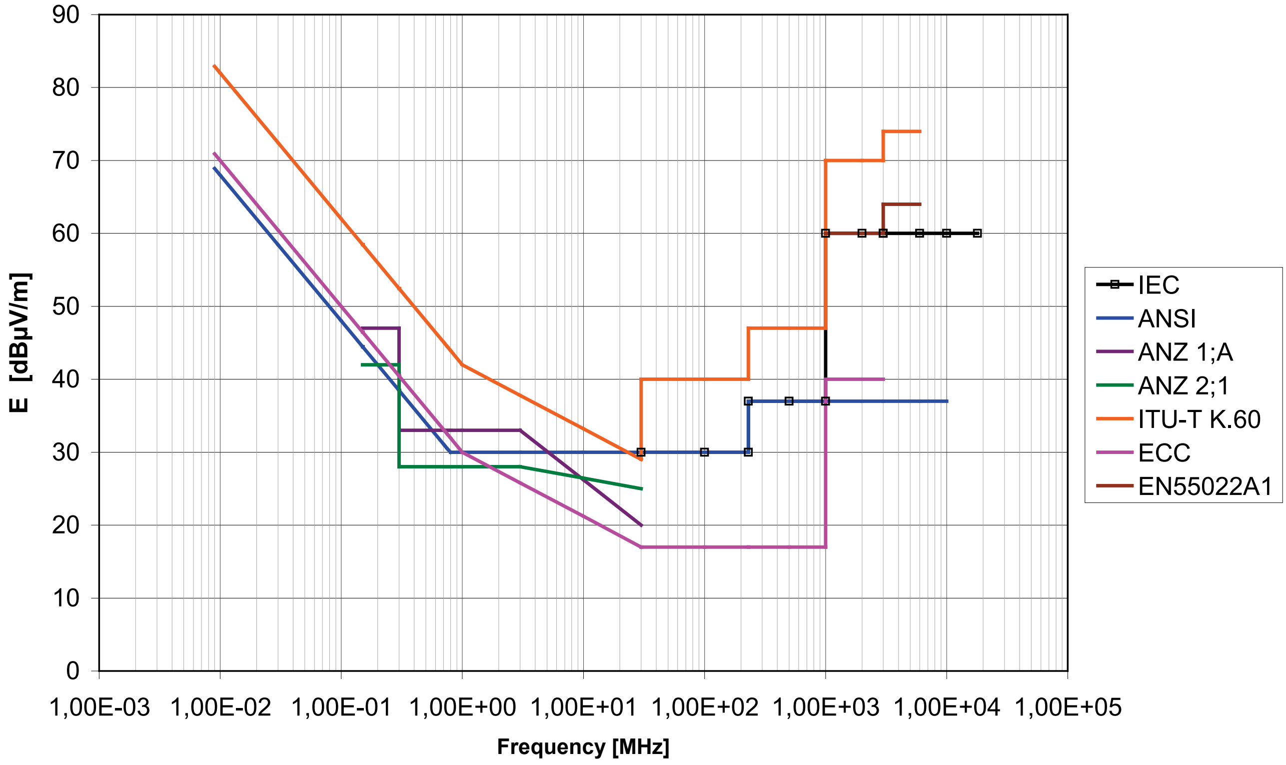

Figure B.1: Limit at the boundary of the respect distance in some standards.

In the frequency range 30 MHz to 1 GHz there is generally good agreement in the specified limits. The same limits are stipulated by several standards, see Table 1 of IEC 61000-6-3 [22], Table 1 of IEC 61000-6-4[23] (measurements at 30 m), Table 3 of CISPR 11 [4], Table 6 of EN 55022 [14] and Table 1 of ANSI C63.12 [2]. The reason for this good agreement is probably a result of all Standards requiring the radiated emission to be measured in this frequency range for almost all products. However, there are exceptions. Section 1 of Annex 2 of ECC/REC/(05)04 [10] stipulates lower limits. It should be noted that the limits in ECC/REC/(05)04 refer to peak detection. Therefore, the value in Figure B.1 is reduced by 10 dB to make it comparable with quasi-peak values (based on results in Figure 1 of [37]). Table 1/K.60 of ITU-T [28] stipulates a 10 dB higher limit than the IEC and CISPR standards.

The limits for the frequency range 150 kHz to 30 MHz is not so well established. However, Table 1 in Standard AS/NZS 2344:1997 [3] gives some guidance. Curve ANZ 1;A shows the limit for Region 1 Zone A, which applies for Europe. Curve ANZ 2;1 shows the limits for Region2 Zone1. Region 2 is the American continents. The ANSI curve shows the limits according to Table 1 of ANSI C63.12 [2], which should be compared with the curve ANZ 2;1. Comparison is also made with the limits according to Annex 2 of ECC/REC/(05)04, which defines the acceptable RFI limits in relation to radio communication. Also in this frequency range, the limit in ECC/REC/(05)04 is reduced by 10 dB to compensate for the difference between the peak and quasi-peak values. The limits in ITU-T K.60 are taken from Table 1/k.60 in the proposed revision of ITU-T Recommendation K.60 [28]. As for ECC, it is explicitly stated that the bandwidth between 9 kHz and 150 kHz is 200 Hz. As the levels in ITU-T Rec. K.60 refers to peak values in the frequency range 150 kHz to 30 MHz, the values in ITU-T K.60 are reduced by 10 dB to allow compatibility with the other Standards. As shown by Figure B.1, the values are fairly consistent in this frequency range. However, ITU-T Recommendation K.60 proposes a somewhat higher limit.

For the frequency range 9 kHz to 150 kHz, Table 1 of ANSI C63.12 and Annex 2 of ECC/REC/(05)04 gives some guidance. In Annex 2 of ECC/REC/(05)04 [10] it is explicitly stated that the limit is a straight line from 9 kHz to 1 MHz while the measuring bandwidth is 200 Hz in the frequency range 9-150 kHz and 9 kHz in the frequency range 150 kHz to 30 MHz. This seems consistent with the rare use of the frequency band below 150 kHz. The limits in ITU-T K.60 are taken from Table 1/k.60 in the proposed revision of ITU-T Recommendation K.60 [28]. As for ECC it is explicitly stated that the bandwidth between 9 kHz and 150 kHz is 200 Hz. As the levels in ITU-T Rec. K.60 refer to peak values in the frequency range 9 kHz to 30 MHz, the values in ITU-T K.60 are reduced by 10 dB to allow compatibility with the other Standards.

For frequencies above 1 GHz, the limits are not very well defined yet. Table 1 of ANSI C63.12 [2] defines the limit for 1-10 GHz as 37 dBµV/m, peak. In Annex 2 of ECC/REC/(05)04 [10] the limit for 1-3 GHz is set to 40 dBµV/m. CISPR 11 [4] has no limits for Class 1 equipment yet. However, Table 6 defines the limits for Class 2 equipment as 70 dBµV/m peak at a distance of 3 m, corresponding to 60 dBµV/m at the normal distance of 10 m. Table 9 in Amendment A1 of EN 55022 [14] states a limit of 60 dBµV/m in the frequency range 1-3 GHz and 64 dBµV/m in the frequency range 3-6 GHz. (The limits are reduced by 10 dB for assessment at a measurement distance of 10 m.). Table 1/K.60 in ITU-T Recommendation K.60 [28] proposes a limit of 70 dBµV/m in the frequency range 1-3 GHz and 74 GHz In the frequency range 3-6 GHz. As ITU-T recommendations is related to a low voltage line and not to a point source, the measurement distance of 3 m is the same as the respect distance and thus no reduction is justified.[5]

It should be noted that the above defined limits are applicable for both domestic and industrial equipment. The normal relaxation of 10 dB for industrial equipment is achieved by the larger respect distance between the disturbing equipment and the receiver, which may be disturbed.

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[5] The impact from a line is much larger than the impact from a point source with the same emission levels close to the source. This is due to the much larger extension of the line than the extension on a point source. The respect distance, i.e a typical distance between the RFI source and the typical radio receiver is considered to be 3 m for a low voltage line and 10 m for domestic equipment. See also Section 12.3 of the guide and Appendix D for more information.

Based on the above, Figure B.2 proposes the reference limit for the European zone at the location of the radio receivers. In the frequency range 9 kHz to 30 MHz it follows Annex 2 of ECC/REC/(05)04 [10], reduced by 10 dB for the estimated difference between peak and quasi-peak levels. In the frequency range from 30 MHz to 1 GHz the more established limits of 30/37 dBµV/m are applied.

Above 1 GHz, the limits in Table 6 of CISPR 11, recalculated for 10 m distance, are used.

The limits from Figure B.1 are also shown in Figure B.2 for comparison.

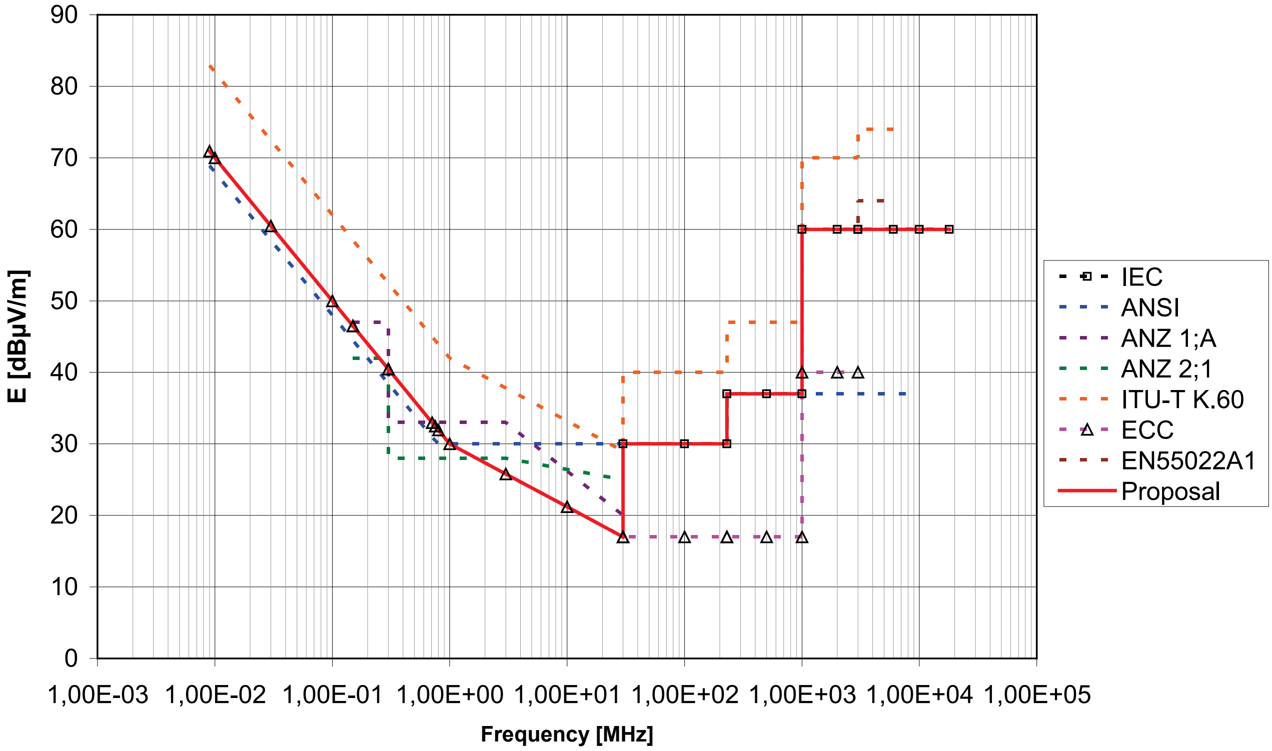

Figure B.2: Proposed limits at the location of the receivers

The proposed limits are also defined in Table B1.

Table B.1: Proposed limits at the location of a radio receiver

Frequency band [MHz]	Limit at the receiver [dBµV/m]	Bandwidth [kHz]	Detector	Remark
0.009 -- 0.15	30 – 20*log(*f*)	0.2	Quasi-peak	Frequency *f* in [MHz]
0.15 -- 1.0	30 – 20*log(*f*)	9.0	Quasi-peak	Frequency *f* in [MHz]
1.0 -- 30	30 – 8.8*log(*f*)	9.0	Quasi-peak	Frequency *f* in [MHz]
30 -- 230	30	120	Quasi-peak	
230 -- 1 000	37	120	Quasi-peak	
1 000 -- 18 000	60	1 000	Peak	

B.2. Limits related to digital radio systems

Limits for preventing interference with digital radio communication systems are proposed in [53]. All limits related to digital radio communication relates to an RMS detector, as motivated in [34][35][36]. Some alternative bandwidths are proposed in accordance with Table B.2. The bandwidths in accordance with CISPR 11-1-1 facilitate comparison with existing limits.

Table B.2: Bandwidths for proposed limits related to digital radio systems

Frequency range	Bandwidth CB as per CISPR 16-1-1	Bandwidth NB Narrow Band	Bandwidth BB Broad Band
30 MHz to 230 MHz	120 kHz	200 kHz	1 MHz
230 MHz to 1.9 GHz	120 kHz	200 kHz	5 MHz
1.9 GHz to 18 GHz	1MHz	1 MHz	20 MHz

The proposed limits in accordance with [53] are shown in Figure B.3. The proposed limits in accordance with Section B.1 and Figure B.2 are shown for comparison.

As the narrow band emission will be verified in relation to the narrow band limits in accordance with Section B.1 and Figure B.2, it is proposed that the complementary verification related to digital radio communication systems is based on the broad band proposal Bandwidth BB.

Thus, too high narrow band emission will be identified with the narrow band verification based on Section B.1 and the broad band emission will be identified with the verification based on the RMS BB limits in Figure B.3. One important point for this recommendation is to limit the time needed for the measurements.

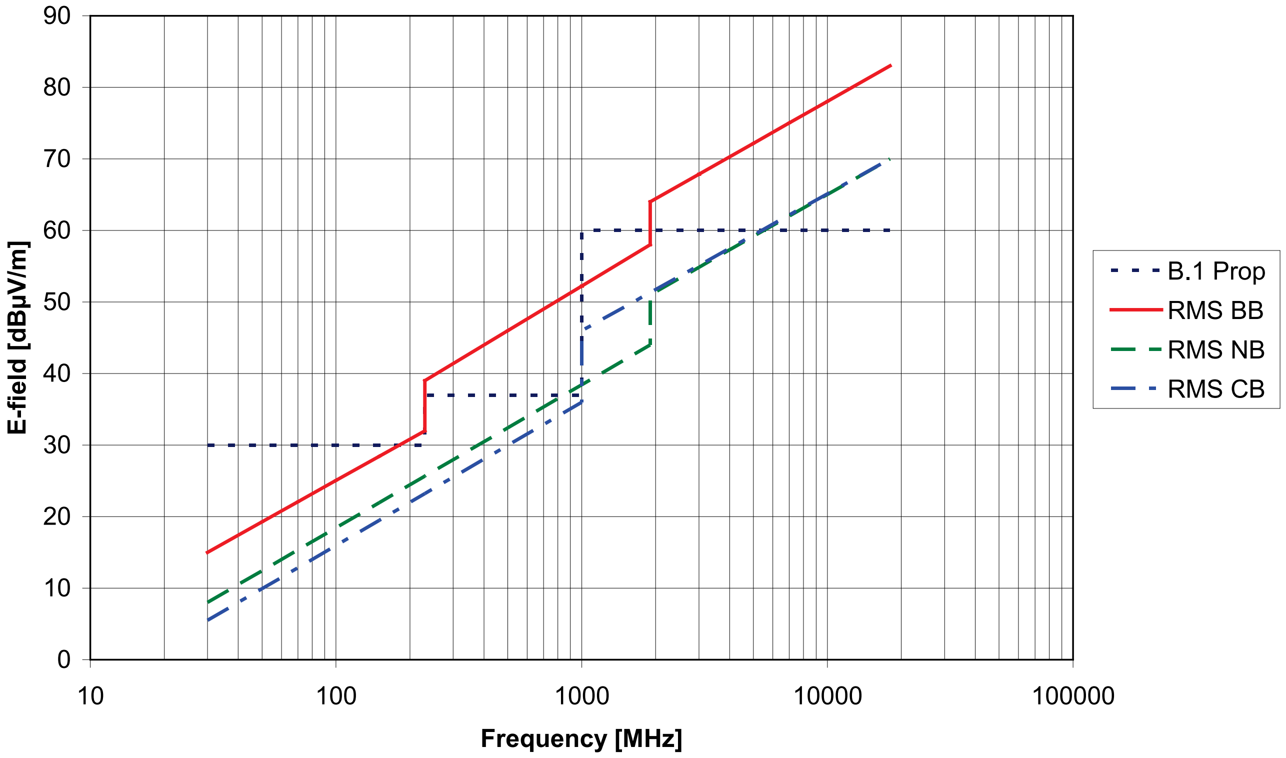

Figure B.3: Proposed RMS limits at the location of digital radio receivers

Attenuation curves for the electric field generated by a current pulse travelling along a line

C.1. Introduction

The scope of this document is to present a simple model for predicting the level of attenuation of an electric field radiated by a single current pulse travelling along a line, some kilometres long, above a perfect earth plane.

The main objective is to describe the phenomenon related to the electromagnetic emission from a power line due to a transient-current, travelling along the line, and arising from a substation area.

As described in Chapter 4, the source of these pulses could be due to sparking, arcing and commutation operations inside the substation area.

The specific nature of the conducted disturbance is of no direct interest in this document but a common waveshape (e.g. ring-wave) is assumed. The goal is to produce a family of curves showing the variation of the predicted level of electromagnetic field radiated by the line, with different frequencies; with different lateral distances from the line; and with different distances from the origin of the conducted waveshape (i.e. the substation, which is seen in this model as a point). The calculation was performed in the frequency domain through Fourier transformation.

C.2. Short description of the model and main assumptions

Figure C.1 shows a sketch of the main layout and elements considered in the model for the calculations.

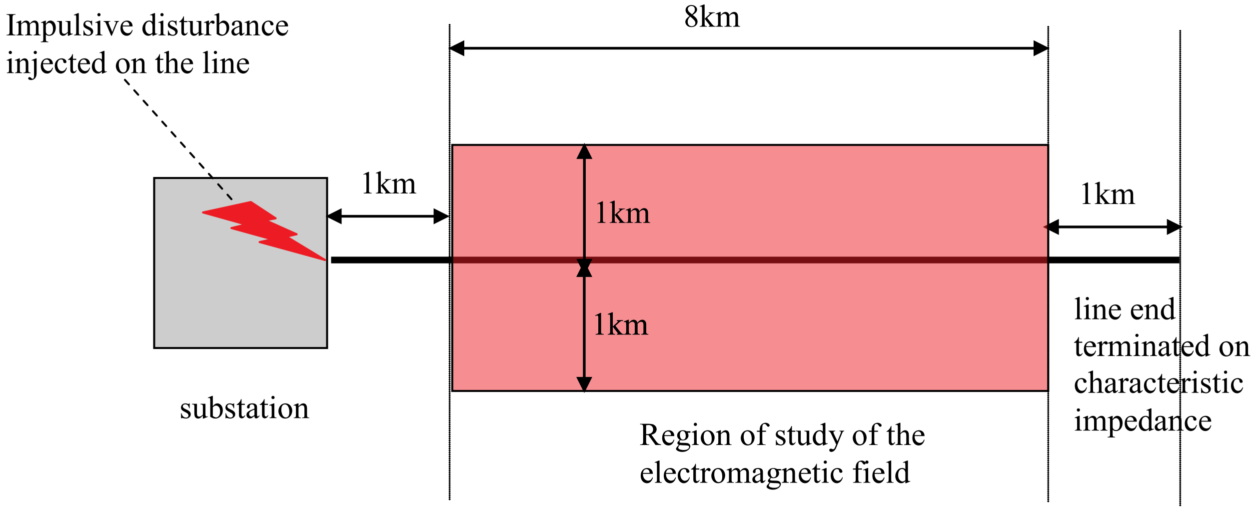

Figure C.1: Sketch of the layout (not in scale)

With reference to Figure C.1, the following points should be noted:

- The origin of the disturbance is inside the substation area, but the study-region begins 1km from it so that the contribution to the radiated field *directly from the substation* is negligible with respect to the contribution from the line;
- The line is assumed to be perfectly matched in order to have no reflection from the end of the line. This assumption is quite reasonable because most of the spectrum components, in particular the ones at higher frequencies, are generally sufficiently attenuated at a distance of 10km from the injection point so that the actual line termination has practically no influence on the phenomenon;
- The other boundary of the study-region is at 1km before the end of the line in order to neglect end effects.

The waveshape injected on the line is a ring-wave of the type described in Section 6.2; a mono-phase line is considered (for simplicity) where, at one end, is placed an ideal current generator injecting the disturbance, while, as already mentioned, the other end is terminated in its characteristic impedance Z_C, as shown in Figure C.2

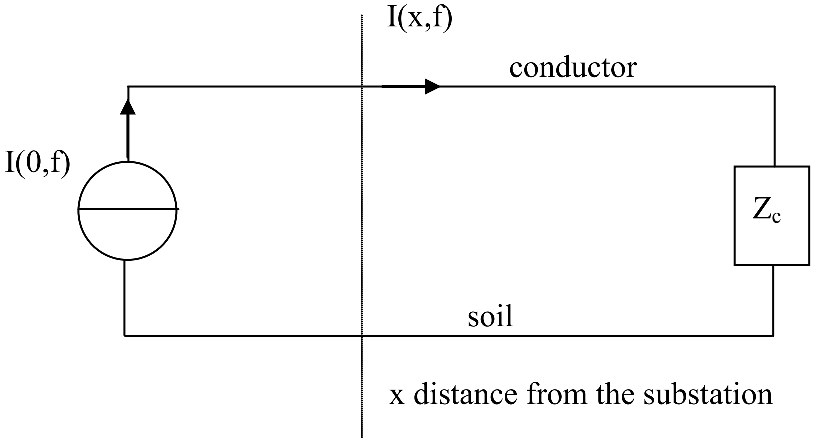

Figure C.2: Transmission line model of the monophase line

According to the model shown in Figure C.2, it is possible to analytically determine the value of each spectrum component of the current pulse travelling along the line by means of the formula:

$$I(x,f)=I(0,f)e^{-\gamma(f)x} \tag{C.1}$$

where γ(f) is the propagation constant of the line and $I(0,f)$ the value of the spectrum current evaluated at the origin of the line. In the case of the ring-wave, it is given for example by formula (6.4) of the guide.

The propagation constant is related to the per unit length impedance *z(f)* and admittance *y(f)* of the line through the relationship:

$$\gamma(f)=\sqrt{z(f)y(f)} \tag{C.2}$$

It should be noted that the per unit length impedances and admittances are related to geometrical and physical characteristics of the line.

Once the current propagating along the line is determined, the line itself can be considered as a very large radiating antenna. Thus the line could be considered to be composed of a large number of electric dipoles horizontally disposed with respect to the soil.

For our purposes, in order to simplify the model and the computations, the presence of the soil may be considered as a perfect conductor; thus, to calculate the field in the air-region ($z>0$) produced by an overhead line at height h, it is possible to consider the effect of the ground by means of a line image carrying an opposite current and located at $z=-h$. (Figure C.3).

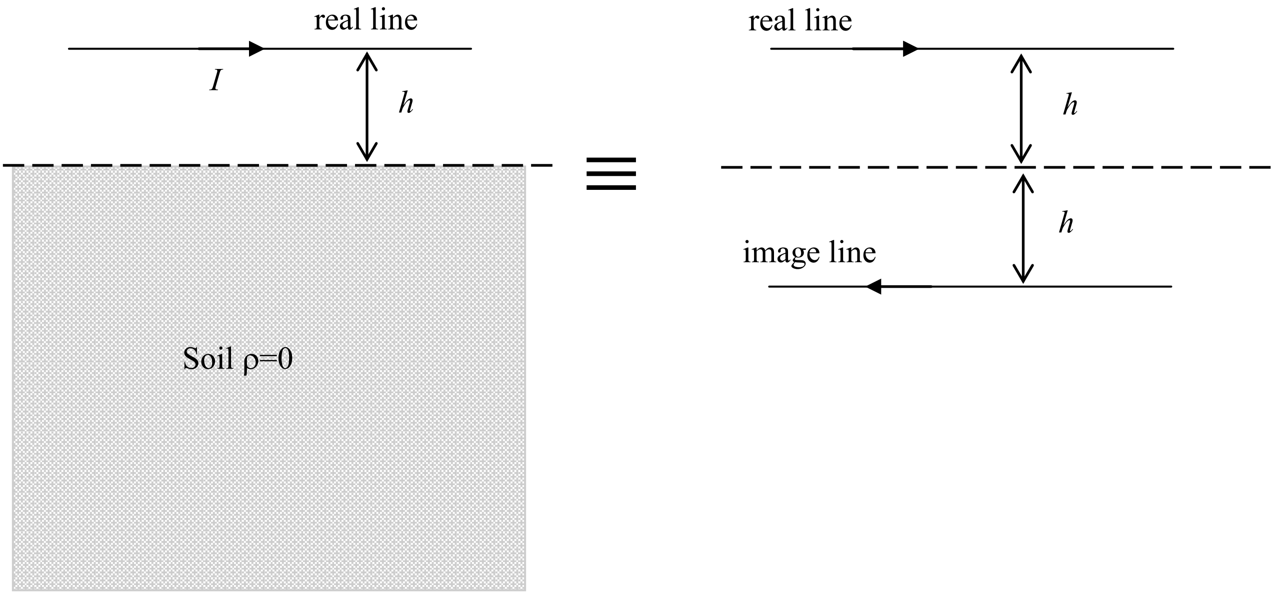

Figure C.3: Equivalent configuration of a line over a perfect ground.

Therefore, by means of the image method, the problem is reduced to calculating the radiated field by two very large antennae located in free space.

Each antenna can be discretized by means of a suitable number of electric dipoles having length l_{dip} satisfying the following conditions:

$$\left|\gamma(f) l_{dip}\right| << 1 \qquad l_{dip} << d_{min} \tag{C.3}$$

where d_{min} is the minimum distance from the line where the field is evaluated. The conditions given in (C.3) ensure that the portion of line, assimilated to a dipole, carries a constant current and is ''seen'' from the evaluation point as an infinitesimal dipole.

Under these hypotheses, one can apply the formulae for the field radiated by an electric infinitesimal dipole and these are found in many textbooks or papers.

Finally, in order to calculate the total electric field, one has to add all the contributions due to the total number N of dipoles forming the line and its image.

C.3. Relative attenuation curves

In this section, some results obtained by applying the model previously sketched are presented.

A line of height h=20m having the following per unit length parameters was considered:

- capacitance $c=6.93\cdot10^{-12}$F/m
- conductance to soil $g=50\cdot10^{-12}$S/m (average value taken from technical literature)
- impedance per unit length (function of frequency) of the circuit with earth return is shown Figures.3a and 3b (resistance and inductance); these parameters were evaluated (using formulae found in technical literature) by assuming a finite soil resistivity of 1000Ωm.

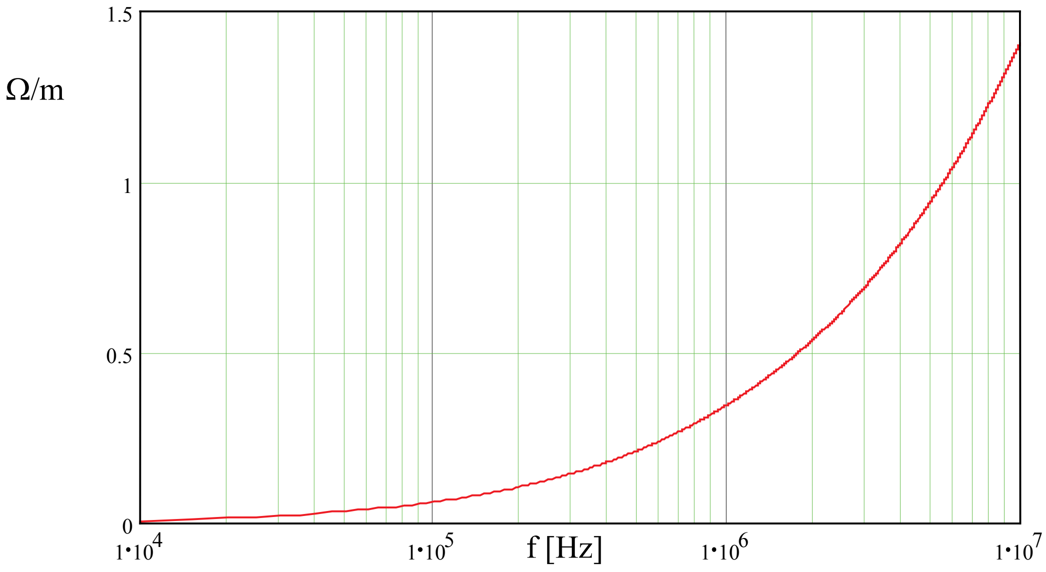

Figure C.3.a: Resistance per unit length of the line with earth return versus frequency

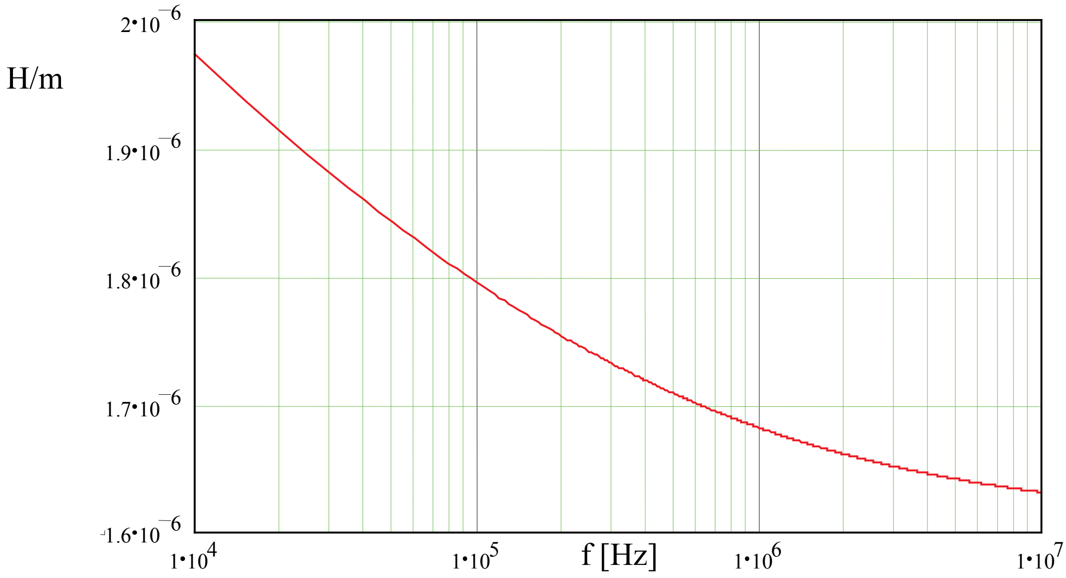

Figure C.3.b: Inductance per unit length of the line with earth return versus frequency

The relative attenuation in dB of the current spectrum versus frequency evaluated at different points along the line is shown in Figure C.4; the reference level is the current at the injection point that is at x=0.

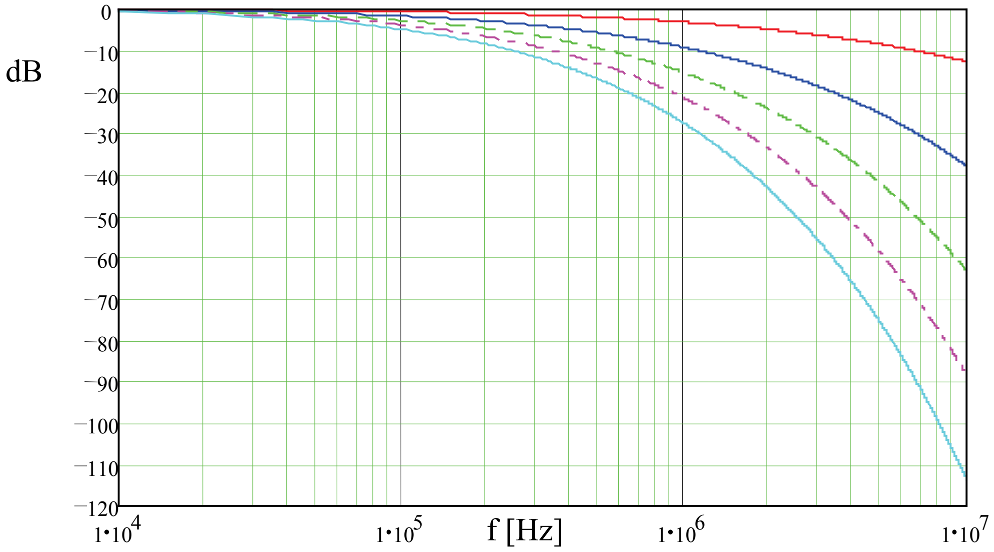

Figure C.4: Relative attenuation of the current spectrum versus frequency evaluated at different points along the line; from top to bottom, *x*=1000m, 3000m, 5000m, 7000m, 9000m.

As expected, lower frequency components can propagate along the line for longer distances from the origin due to the lower attenuation constant.

Figure C.5 shows the relative attenuation curves, in dB, of the electric field (in modulus) versus lateral distance from the line (in the range 10m to 1000m) and evaluated at different points along the line itself at a height of 1m from the soil surface. The results shown in each figure were evaluated at a fixed frequency. As a common reference point for all the curves at each frequency considered, the point located at x=1000m, y=10m and z=1m was chosen.

The relative attenuation A_E of the electric field was evaluated using:

$$A_E(x,y,z,f) = 20\log\left(\frac{|E(x,y,z,f)|}{|E(1000,10,1,f)|}\right) \tag{C.4}$$

The choice of the reference point is to take into account two attenuation phenomena:

- the attenuation of the current along the line (as shown in Figure C.4)
- the attenuation of the field with increasing lateral distance from the line

Therefore, by considering the study-region shown in Figure C.1, this point is the nearest point to the substation and to the line and the point where, at a given frequency, the field is at its maximum.

It should be noted that the field level shown in Figure C.5 is the summation of the contribution from all dipoles along the line. Thus, there is a possibility for destructive interference, which is the reason for the dips, as shown in Figures C.5.c and C.5.d.

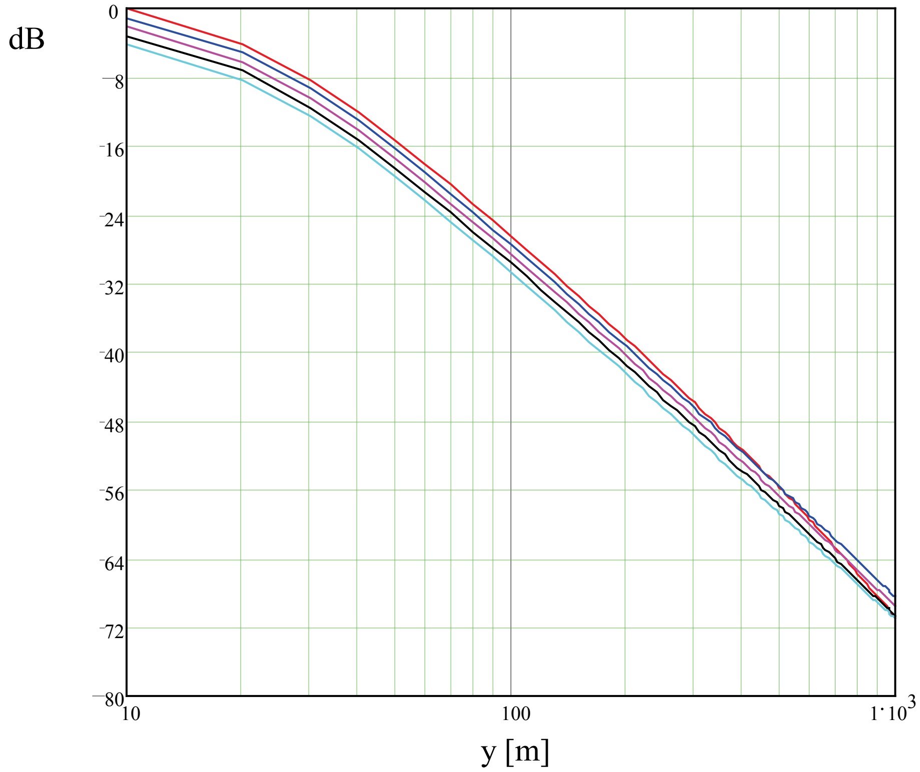

Figure C.5.a: Curves of relative attenuation of the electric field versus lateral distance evaluated at different points along the line; from top to bottom, *x*=1000m, 3000m, 5000m, 7000m, 9000m; *f*=100kHz

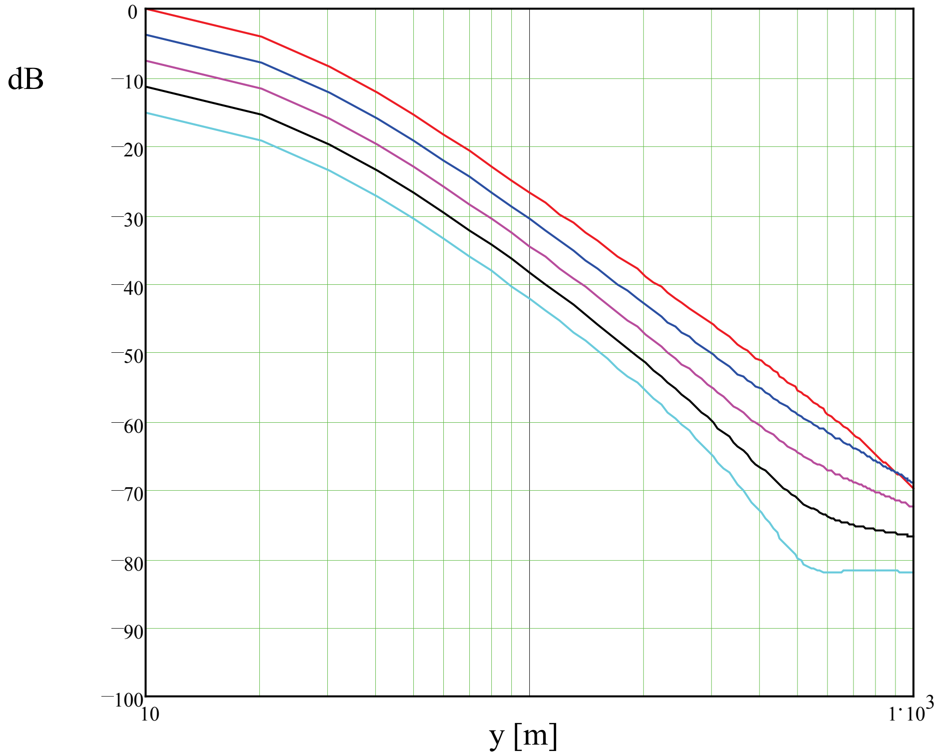

Figure C.5.b: Curves of relative attenuation of the electric field versus lateral distance evaluated at different points along the line; from top to bottom, *x*=1000m, 3000m, 5000m, 7000m, 9000m; *f*=500kHz

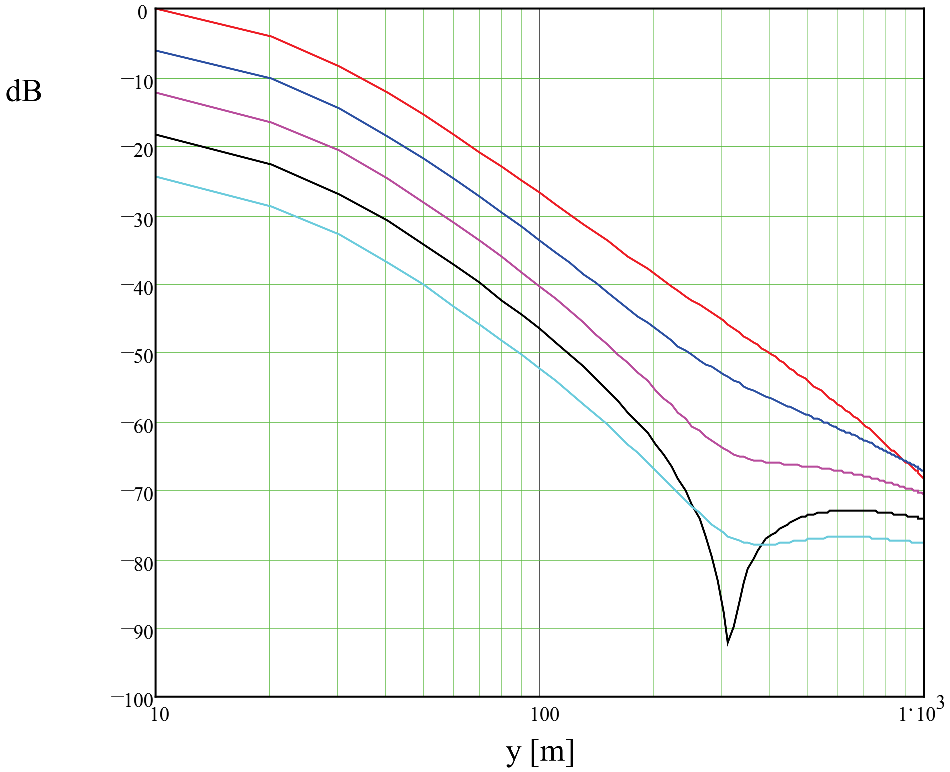

Figure C.5.c: Curves of relative attenuation of the electric field versus lateral distance evaluated at different points along the line; from top to bottom, *x*=1000m, 3000m, 5000m, 7000m, 9000m; *f*=1MHz

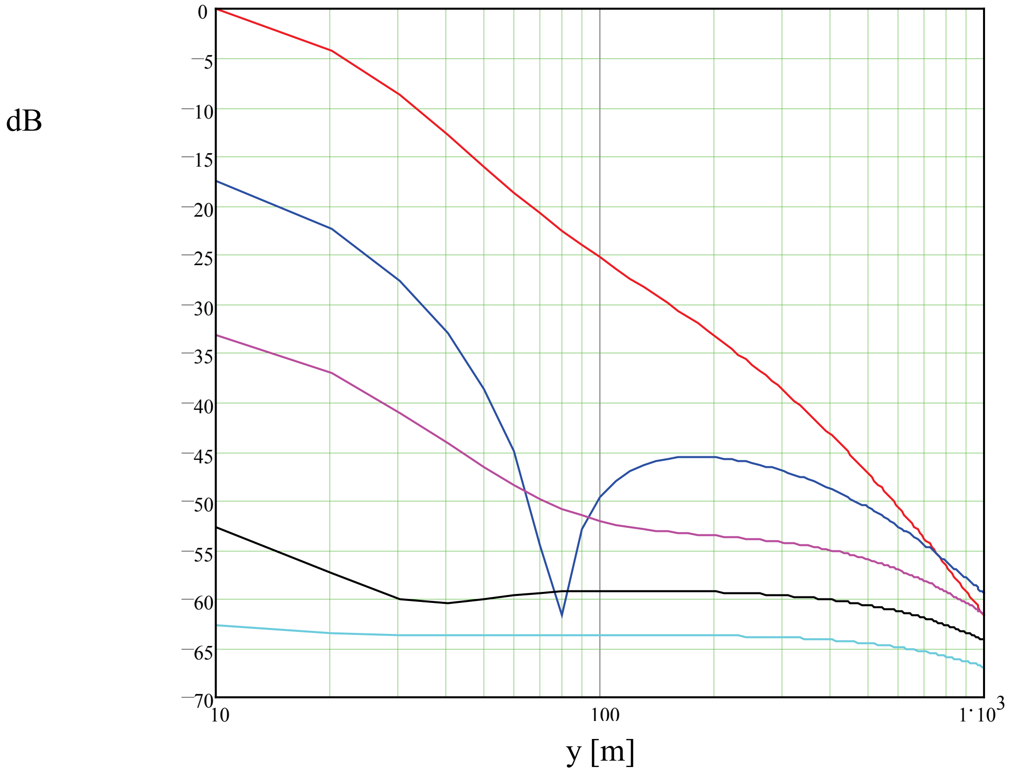

Figure C.5.d: Curves of relative attenuation of the electric field versus lateral distance evaluated at different points along the line; from top to bottom, *x*=1000m, 3000m, 5000m, 7000m, 9000m; *f*=5MHz

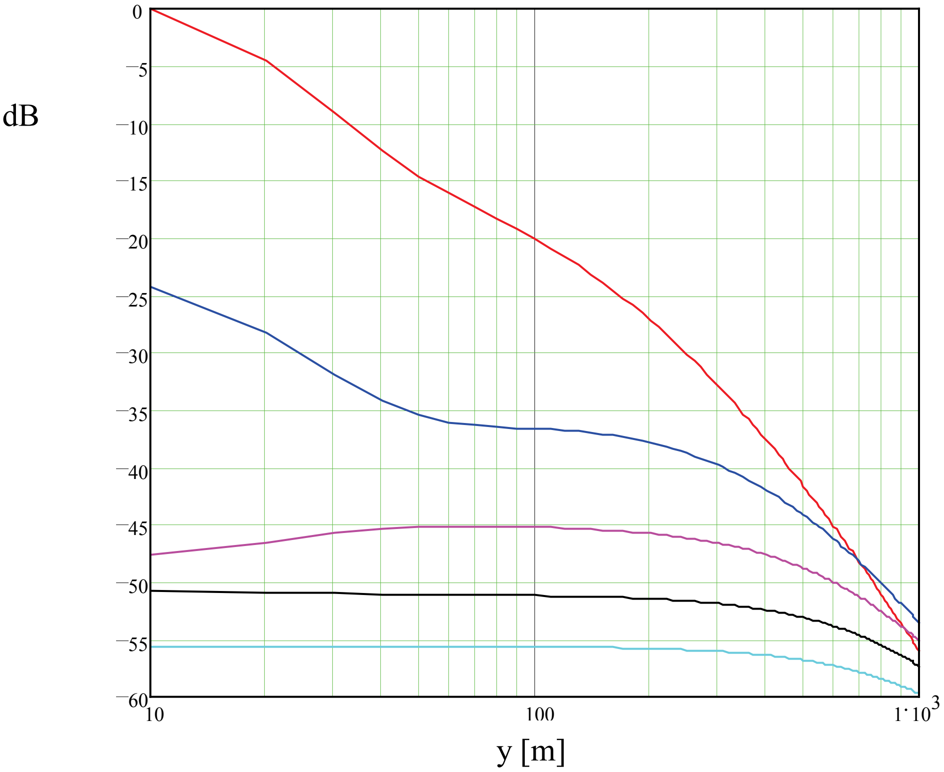

Figure C.5.e: Curves of relative attenuation of the electric field versus lateral distance evaluated at different points along the line; from top to bottom, *x*=1000m, 3000m, 5000m, 7000m, 9000m; *f*=10MHz

C.4. Ring-wave propagation along the line

In order to facilitate the understanding of the phenomena, Figure C.6 illustrates in the time domain how a ring-wave travels along the line. The result is obtained by applying the Inverse Fast Fourier Transform on the results from equation (C.1).

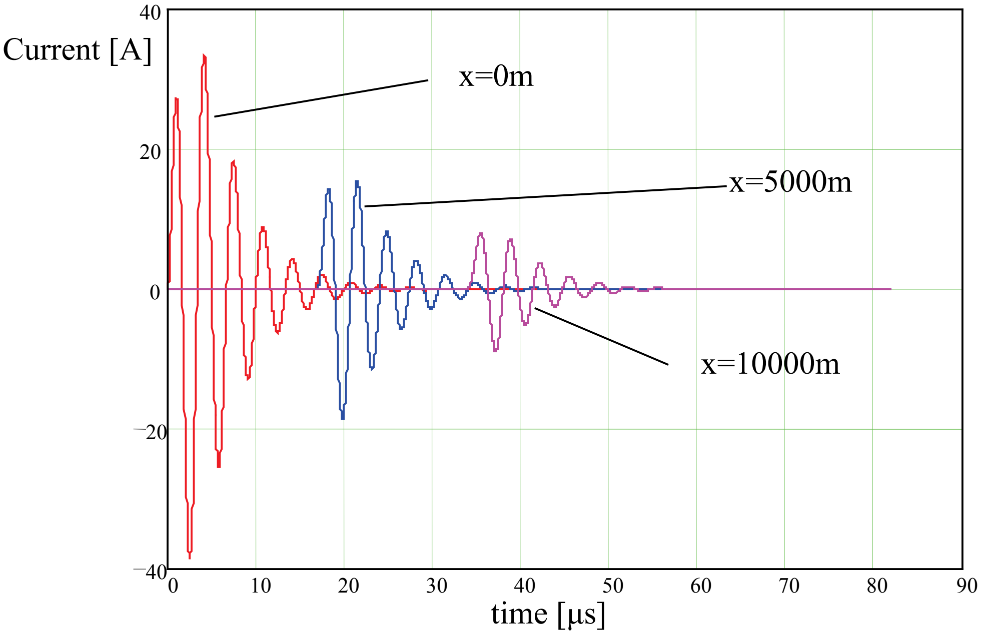

Figure C.6: Ring-wave versus time evaluated at three different points along the line

As expected, whilst the wave is propagating along the line, it is attenuated (due to the losses; see also Figure C.4) and distorted (because the single frequency components travel at different velocities and the attenuation varies with the frequency).

It can be noted that at the time of 55μs the waveshape has practically diminished at the observation point of 10km.

All this is valid for a single pulse. Nevertheless, in the case of periodic pulses, if the typical period between two successive pulses is much greater than the duration of a single pulse, the simplified model of a single pulse is still acceptable. See also comments in section C.6.

C.5. Attenuation of the guided and the direct waves

In Figures C.5.b-e, it can be seen that the attenuation is irregular at higher frequencies and larger distances. As explained in Section C.3, this is due to interference between fields originating from different parts of the line. The reason the interference is more pronounced at high frequencies and long distances is that the attenuation of the direct radiation does not follow the same formula as the attenuation of the ring-wave travelling along the line. The attenuation of the ring-wave along the line (or the guided wave) is a certain dB per km, which can be deducted from Figure C.4[6] and Equation (C.2). In contrast, the attenuation for the direct wave is as 1/r or $1/r^2$, see Section 6.3.

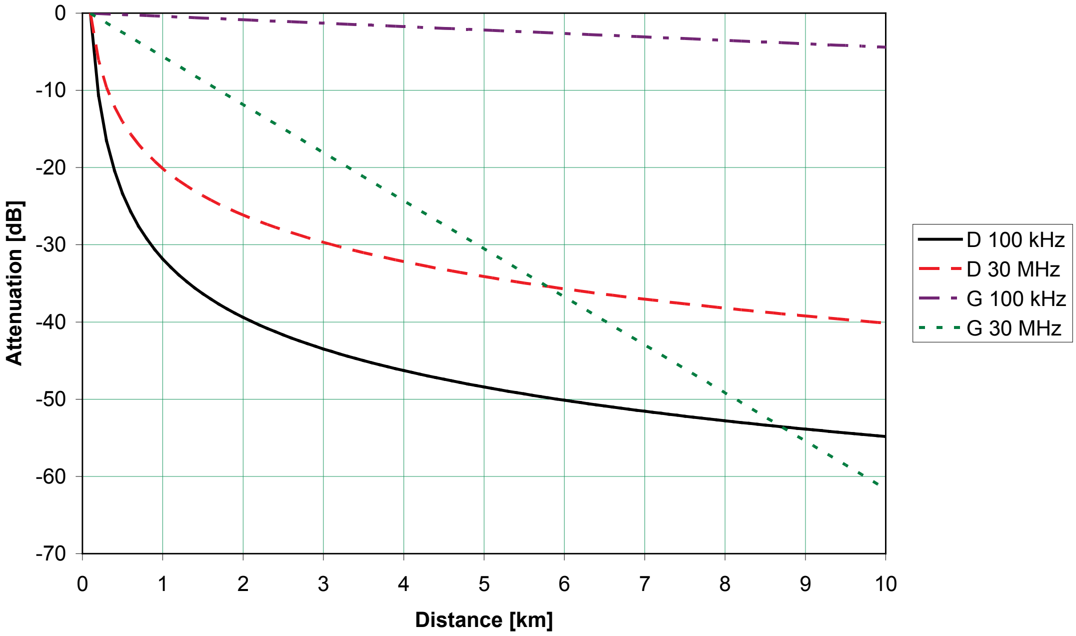

Figure C.7.a: Attenuation of direct wave and guided wave versus distance (linear scale).

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[6] In accordance with Figure C.4 the attenuation for about 6.8 MHz is at 1000m – 10 dB, at 3000 m – 30 dB, at 5000 m – 50 dB, at 7000 m – 70 dB and at 9000 m – 90 dB. Thus, the attenuation for this frequency is 10 dB/km. The attenuation increases with the frequency. In any case, from formula (C.2), attenuation and phase variation for any frequency f can be deduced.

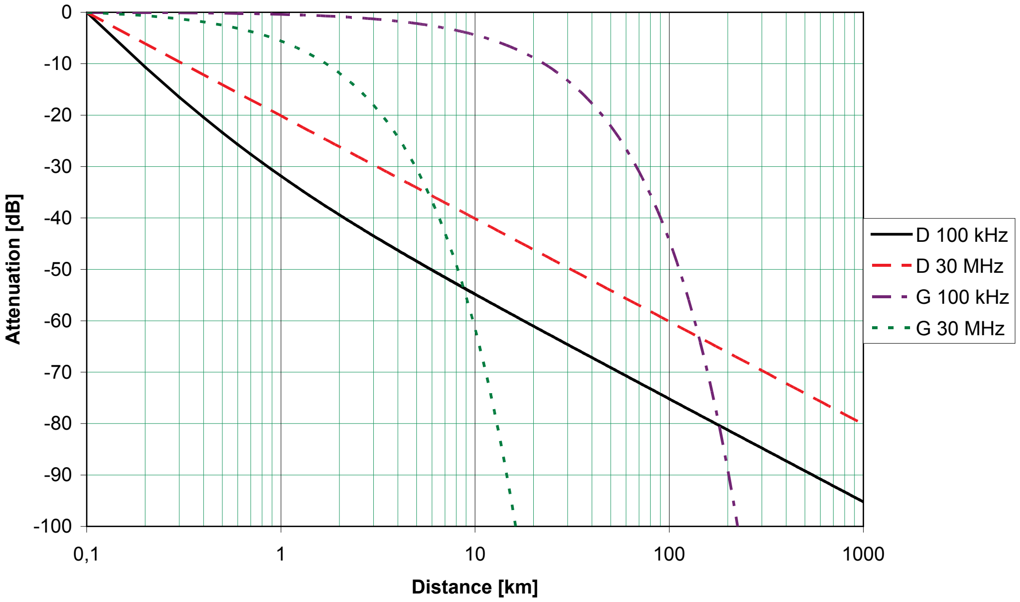

Figure C.7.b: Attenuation of direct wave and guided wave versus distance (logarithmic scale).

Figure C.7a and b show the attenuation for the direct wave and the guided wave for frequencies of 100 kHz and 30 MHz versus distance with a reference point at 100 m.

After about 5.8 km the attenuation of the wave travelling along the line is higher, than the attenuation of the direct wave travelling in the air. For the frequency of 100 kHz, the attenuation of the ring-wave in the line is much smaller than that of the direct wave. However, after about 180 km, the attenuation of the ring-wave along the line exceeds the attenuation of the direct wave. As long as the attenuation of the direct wave in the air is much larger than that of the ring-wave travelling along the line, no interaction can be seen, see Figure C.5.a. For longer distances or higher frequencies there are interactions.

C.6. Comments to the results

Figures.C.5 clearly show that, at lower frequencies, small differences in lateral attenuation exist by moving the observation point along the line; this occurs because the current propagating along is practically constant.

By increasing the frequencies, the gap between the curves increases because the current assumes quite different values along the line; consequently the fields evaluated at different points along the line are also quite different.

Although the general trend of all the curves is an increase of the attenuation with the lateral distance from the line, some curves, at higher frequencies, presents points of minima or maxima; this phenomenon can be explained as destructive or constructive interferences of the fields generated by the series of dipoles forming the line and are more evident for particular frequencies and distances. For example, in Figure C.5.d, at the frequency of 5MHz and at coordinates x=3000m, y=80m, z=1m the electric field resulting from the sum of many dipoles had undergone destructive interference. Conversely, in Figure C.5.e, at the frequency of 10MHz, and at coordinates x=5000m, y=80m, z=1m one can observe the result of a constructive interference.

Implication of repetitive pulses: The measurement receivers are envelope detectors. Therefore, the frequency characteristic of a single pulse is a primary parameter. A peak detector only senses the frequency content of a single pulse. For other detectors, the pulse repetition rate also impacts the reading, as a separate parameter. However, an rms detector senses the rms-value of the envelope, not the rms value of the signal itself. Consequently, the radiation and attenuation properties for a single pulse or transient are relevant also for repetitive transients.

C.7. Conclusion

The model described in this section is designed to be a help in estimating the level of attenuation of the electromagnetic field radiated by a monophase line when an impulsive disturbance is injected at one end of the line.

Assessment of respect distances and limits for power installations

D.1. Introduction

In theory, it is quite simple to define the limit when the limit at the location of the radio receivers, i.e. the reference level, is defined. It is just to define a suitable measuring distance and to establish the respect distance, i.e. the typical distance between the source of RFI emission and the radio receivers. Subsequently, it is just a recalculation of the reference level at the respect distance for a limit at the measurement distance.

The established respect distance from domestic equipment to radio receivers is 10 m, see Appendix B. For industrial equipment it is 30 m. The respect distance from low voltage lines and telecommunication lines inside buildings to radio receivers is considered to be 3 m [10]. However, there are no established respect distances for HV substations. Therefore, the respect distance will be estimated based on the limits stipulated in existing standards, i.e. IEC 62236-2 [25] and ICES-004 [15].

When recalculating the RFI level at one distance for a level at another distance, not only the attenuation versus distance must be considered, but the fact that the antenna sees a larger portion of the switchyard should also be considered. This means that radiations from more sources are measured by the receiver. It can be defined as a mass effect.

D.2 Substations

D.2.1. Mass effect

A power plant installation contains several apparatus complying with the domestic or industrial requirement. Consequently, the impact on the surroundings, seen at a distance from the installation, is that the radiation from all equipment adds up leading to a higher level than the radiation from a single piece of equipment, considering the attenuation with distance. Ten pieces of equipment means an increase with 10 dB, hundred pieces means an increase with 100 dB etc. This is just by adding the radiated power (not the amplitude). Typical equipment that may be used in a large number in an installation is lighting equipment, computers, motor drives etc. Therefore, the respect distance, i.e. the distance between the source and the border where the radiation is reduced to the reference level, must be larger for an installation than for a single piece of equipment.

The mass effect also impacts the measuring result at measurements of an extended subject such as a substation, as demonstrated in Figure D1, which indicates the area seen by the antenna at different measuring distances.

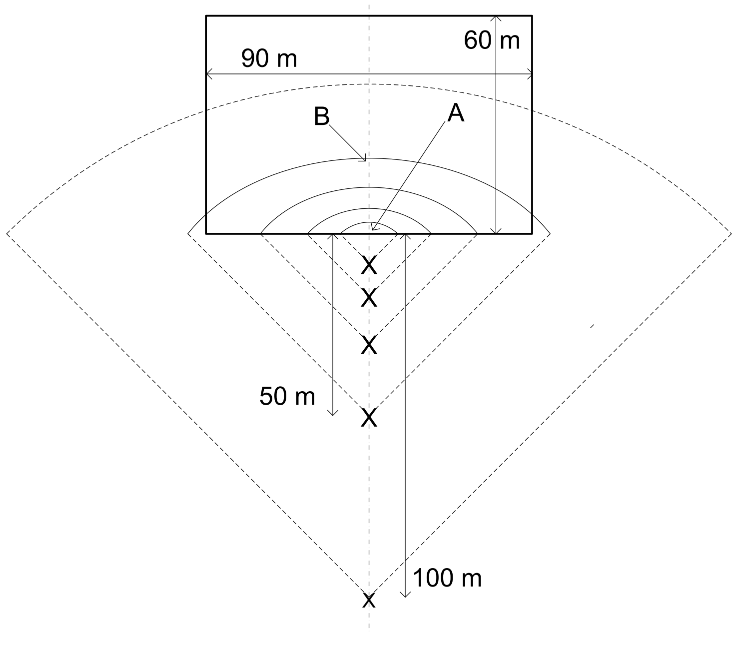

Figure D.1: What the antenna sees at different measuring distances from a substation. Measurement distances in the Figure are 7 m, 17 m, 30 m, 50 m and 100 m. Area of the active part 60x90 m.

The assumption for Figure D.1 is that the main coverage of the antenna reaches a distance 1.41 times the shortest distance to the active area. Measurement distance of 50 m: In the case that the amplitude-attenuation varies with $1/r^2$, the amplitude at point (B) is 50 per cent of the amplitude at point (A). That means that each square meter in the most remote point (B) adds 25 per cent of the radiation power from the closest square meter at point (A). The number of remote square meters is significantly higher than the number of close square meters, based on the assumption that the radiation is homogeneous in the complete active area.

Table D.1: RFI source area for measurement distances in accordance with Figure D.1.

	d_m = 7 m	d_m = 17 m	d_m = 30 m	d_m = 50 m	d_m = 100 m
Covered area of source	22.5 m^2	162 m^2	505 m^2	1378 m^2	3400 m^2
$C_A = A(d_m)/A(d_m=17)$	0.17	1.00	3.11	8.51	21.1
10*LOG(C_A)	-7,7 dB	0 dB	4,9 dB	9,3 dB	13,2 dB

As the measurement distance for IEC 62236-2 is interpreted to be 17 m from the active part (10 m outside the fence) the measurement distance of 17 m is taken as reference. With reference to Figure B.1, the coverage increases significantly when the antenna is moved to a larger distance, especially for a large substation. The expected increase of RFI due to the fact that the antenna sees a larger part of the substation when the measurement distance is increased from 17 m to 100 m or more is:

- 0 dB – If the area of the active part of the substation has a size in the order of 20x10 m or less
- +5 dB – If the area of the active part of the substation has a size in the order of 50x30 m
- +10 dB – If the area of the active part of the substation has a size in the order of 90x60 m or more

The result is not very sensitive for variation of about 1.41 of the factor between the remote border for the antennae coverage and the closest distance.

The fact that the increased coverage of the antenna compensates for the distance attenuation when the measurement distance is increased is observed during measurements reported in [37][40].

D.2.2. Recalculation of limits in IEC 62236-2 for longer distances

Figure D.2 shows the limits from IEC 62236-2 recalculated for longer distances by using Equation (9.3) in Section 9.1. Good soil is assumed, with h_1 = 15m and h_2 = 1.5 m.

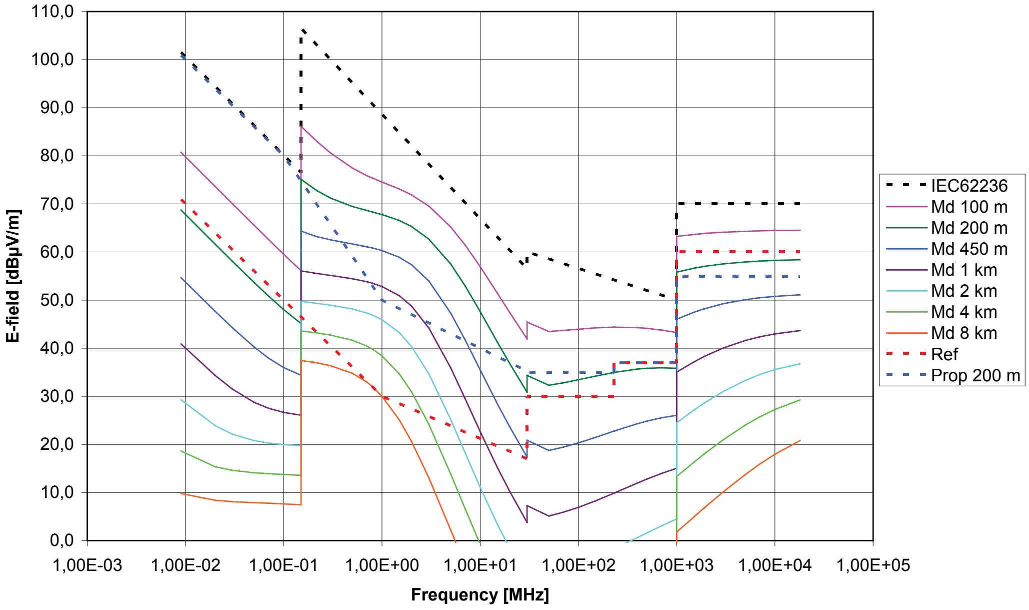

Figure D.2: Recalculation of the limits in IEC 62236-2 for longer distances

As the measurement distance is increased from 17 m to 100 m and more, 10 dB has been added for compensation for the larger coverage of the antenna as per Section D.2.1. The preferred measuring distance is 200 m. For frequencies above 1 GHz, IEC 62236 has no stipulated limit. Instead, the limit in Table 6 of CISPR 11 [4] with addition of 10 dB has been used, just for having something to compare with. The curve “Ref” is the proposed limit or designed objective in accordance with Figure B.2 in Appendix B.

There are three important conclusions which can be drawn from Figure D.2:

For frequencies above 30 MHz, IEC 62236-2 gives a level at 200 m which is close to the reference limit at the location of the radio receivers. This is the most important frequency range regarding interference.

For frequencies around 1 MHz, IEC 62236-2 gives a level significantly above the reference level for radio receivers even at a distance of 1 km.

Compared with the frequency range 150 kHz to 30 MHz, IEC 62236-2 overprotects the frequency range 9-150 kHz, which is very rarely used, see Appendix E.

Therefore it is proposed that the limit at a measurement distance is adjusted in accordance with the curve Prop 200 m. The levels in the curve Prop 200 m is normally sufficiently high to prevent it being masked by the background noise, see Figure 2.1 in the guide. However, the level may be somewhat low for frequencies above 30 MHz.

As one basic consideration regarding a proposed limit is how well it suits the reference limit at the location of the radio receivers, the proposed limit at 200 m is recalculated for some other distances. For frequencies below 10 MHz, the level at 1 km fits quite well to the reference level. In the frequency range 10-30 MHz, the level at about 600 m will be at the reference level. For frequencies above 30 MHz the level at 200 m will be practically at the reference level. Compared with engineering practice in accordance with Section 1.5, 40 dBµV/m at a distance of about 450 m, the proposed limit means a more stringent requirement for frequencies above 1.5 MHz, a frequency range of importance for modern radio communication. For lower frequencies the requirement is relaxed. This lower frequency range is of less importance for radio communication. On the other hand, countermeasures for lower frequencies cost more.

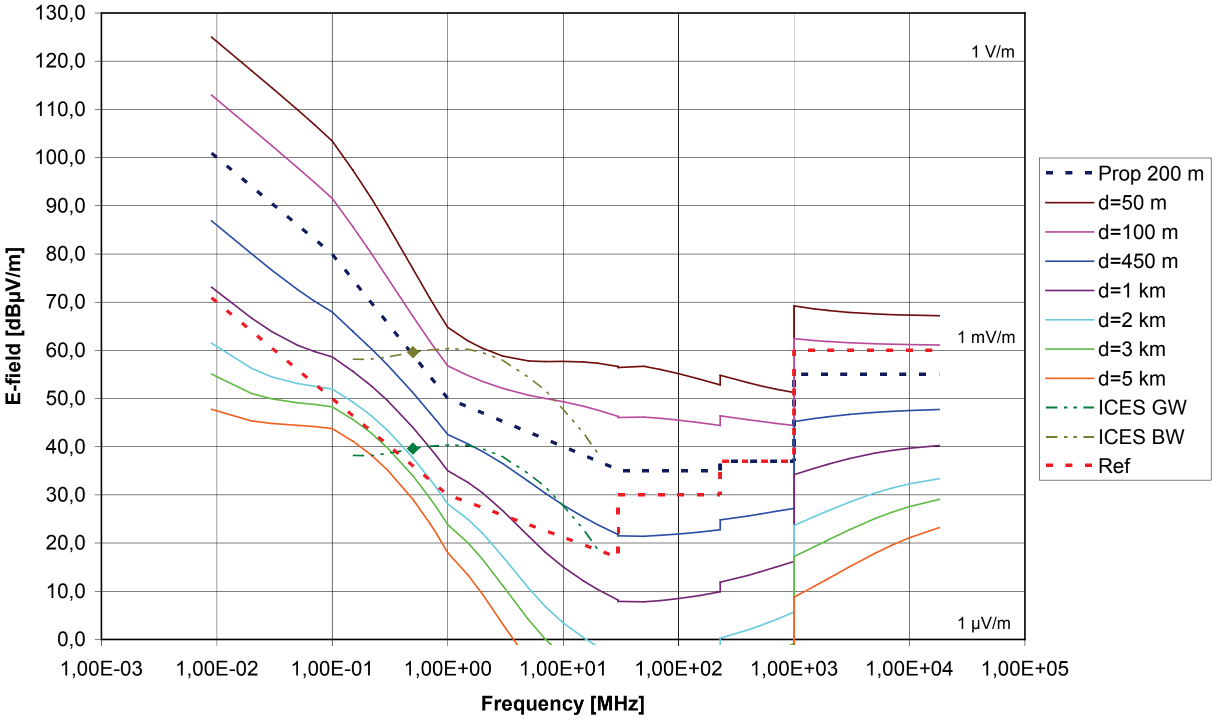

Figure D.3: Recalculation of the proposed limit in Figure D.2 for other distances

Figure D.3 also shows the level for 400 kV substations in accordance with Schedule I and Schedule II of ICES-004 [15], recalculated for 200 m. As the base level is assumed to be 55 m in accordance with Section 10.3.1 of the guide, no addition is made for increased coverage of the antenna. As 0.5 MHz is the only frequency, where measurement is performed, those points are marked. The curve ICES GW is the curve for Good Weather, in accordance with ICES-004. For the Bad weather curve ICES BW 20 dB is added to the ICES GW curve in accordance with the difference between good weather and bad weather in Figure B7 of CISPR 18-1 [8]. For good weather condition, the corona level will be below the proposed limit at 200 m. However, in bad weather conditions the corona level will be above the proposed 200 m limit for the frequency range 0.5-2 MHz. All limits are compromises and the proposed 200 m limit is considered as a fair compromise for 400 kV level. The conclusion according to measurements reported in [37] was that IEC 62236-2 seems to be a good base for the disturbance level of existing 400 kV substations.

D.2.3. Limits related to digital radio systems

In the same way, the limit related to digital radio systems and proposed in Section B2 of Appendix B is recalculated for some other distance. The proposed level at 200 m is the same as the reference level at the location of radio receivers.

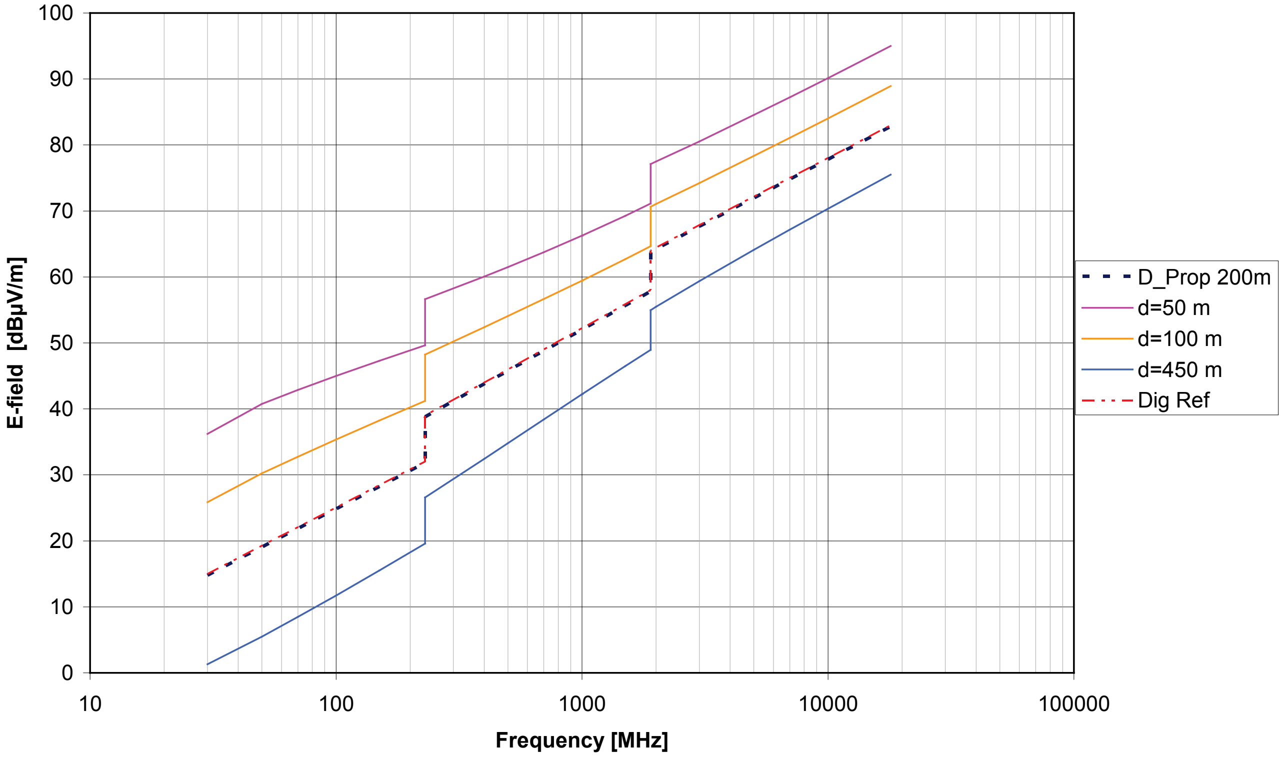

Figure D.4: BB limit in accordance with Section B.2 recalculated for other distances

D.2.4. Variation with voltage level

In order to estimate how the RFI level varies with the voltage levels, Schedule I of ICES-004 [15] was used as base. The values in schedule I were recalculated for different distances under the assumptions defined in Section 10.3 of the guide and Equation (9.3). The recalculation was performed for 0.5 MHz only.

For 400 kV, the good weather level is recalculated for 40 dB at 200 m. Figure D.5 shows the distances versus voltage curve. ICES-400 only gives the figures in the voltage range 200 kV to 800 kV. The values have been extrapolated down to 100 kV and up to 1200 kV.

The curve will be exactly the same if the bad weather value has been used, provided that the 20 dB difference has been used for all voltage levels. The value in CISPR 18-1 varies between 20 dB and 24 dB.

The purpose of Figure D.5 is to estimate how the measuring distance shall be varied versus voltage level, if the same level requirement is used. A measuring distance of 200 m for the 400 kV level is used as a base.

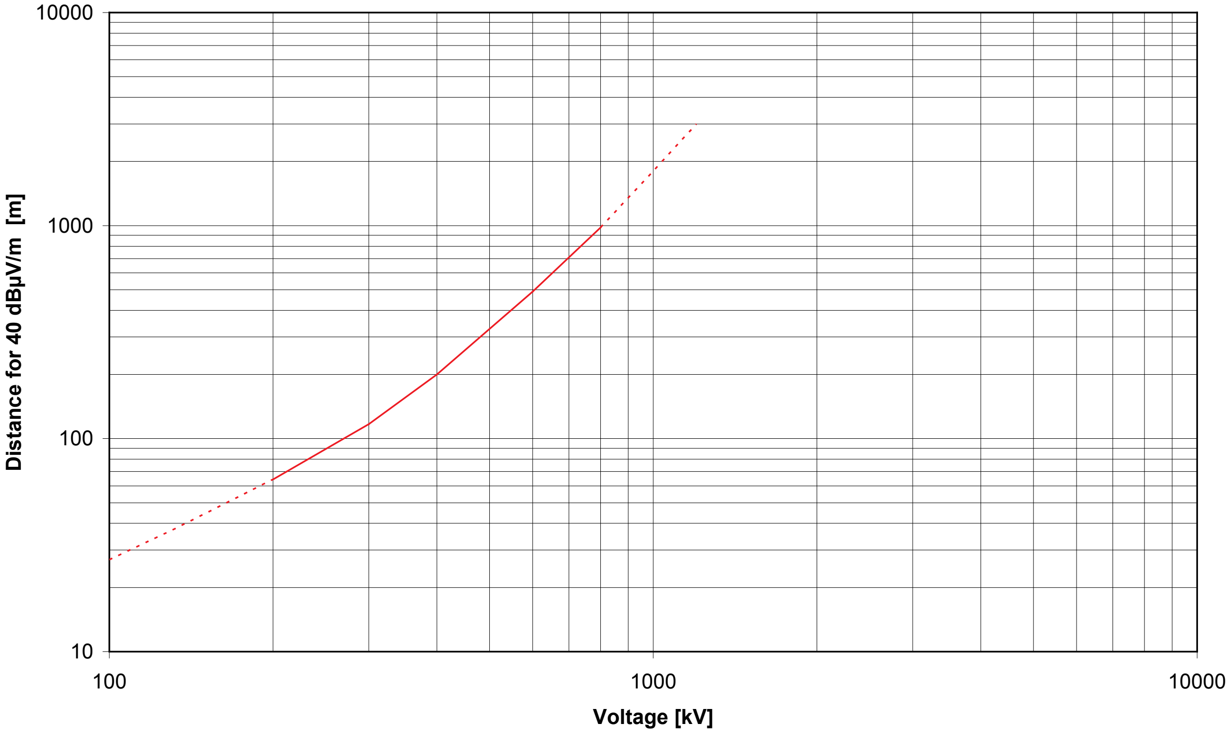

Figure D.5: Distance versus voltage when the RFI level at 0.5 MHz is 40 dB, see Schedule 1 in ICES-004.

Figure D.5 shows that if the same requirement level shall be used, the measuring distance for voltages above 600 kV will be too far to be practical. Further, the respect distance for the RFI level to be at the reference level, will be very large, which is hardly acceptable. One conclusion that can be drawn from Figure D.2 and IEC 62236-2 is that a respect distance of 8 km for frequencies up to 1 MHz is acceptable provided that the respect distance for higher frequencies is significantly shorter. This is the base for the proposed limit in Figure D.6 for the Ultra High Voltage (UHV) limit at a measurement distance of 200 m.

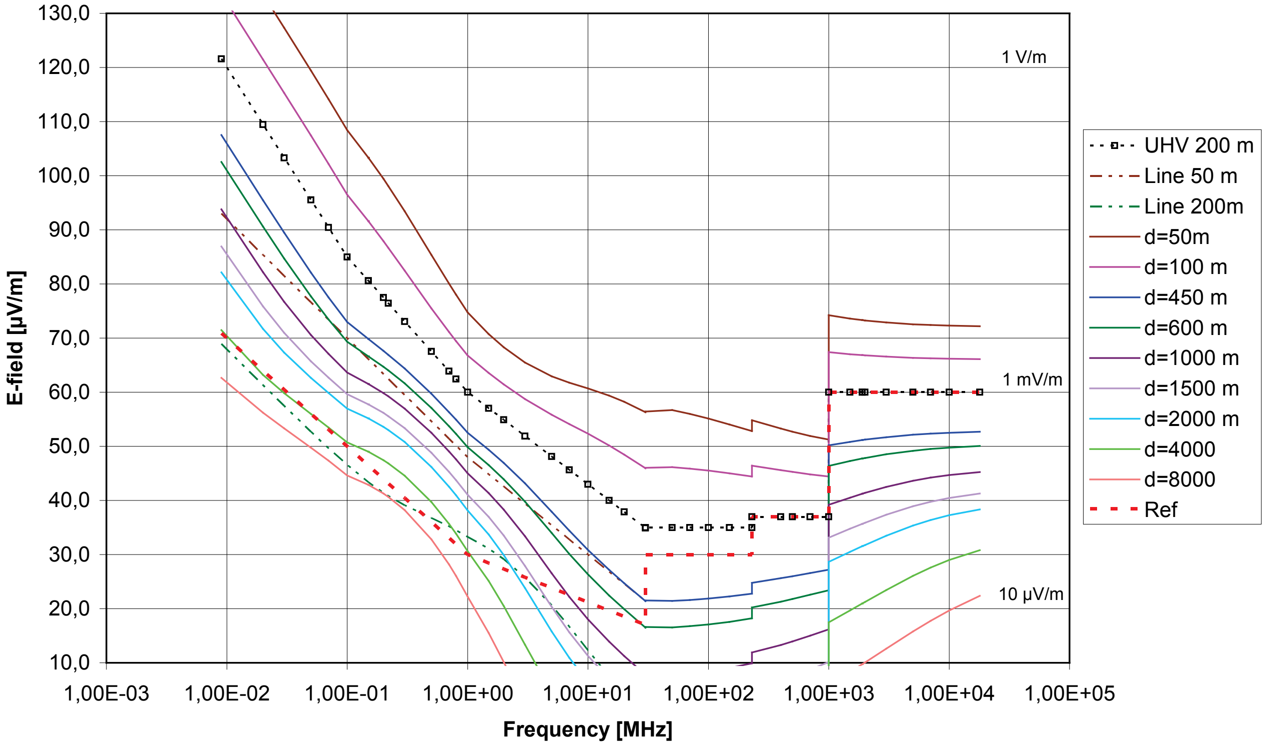

Figure D.6: Proposed limit at 200 m for Ultra High Voltage

For 30 MHz and above, the limit is the same as proposed for 400 kV, see Figure D.3. The levels at lower frequencies are increased somewhat. Figures D.3 and D.6 also illustrate how the field is attenuated at longer distances. The proposed limit at 50 m for a 1200 kV line and corresponding field level at 200 m is also included in Figure D.6 for comparison.

D.2.5. Proposed limits for substations and equipment

A proposal for measurement distances and level limits for substations and equipment is worked out in Table D.2. Limit 1 is the proposed reference level at the location of the radio receivers in accordance with Figure B.2 and Table B.1 combined with the broadband RMS BB limit in accordance with Figure B.3 and Table B.2. Limit 2 is the Prop 200 m curve in Figures D.2 – D.3 combined with the same broadband limit RMS BB considering digital radio systems. Limit 3 is the limit proposed in Figure D.6 for frequencies below 30 MHz. The intention is to obtain a consistent set of limits covering all voltages levels and all ratings of power electronic equipment, including HVDC and FACTS. The levels for low voltage domestic and industrial equipment are known and used as reference at the lower end of the scale. For the voltage range 100 kV to 1200 kV the levels and measurement distance is based on results provided in Section D.2. The levels for 2-30 kV and 31-100 kV is fitted in to obtain a reasonable transition.

An overview of the limits, graphical and numerical, is given in Appendix F.

Table D.2: Proposed measurement distances and limits for substations and equipment

Voltage level	**Rating of PE1) equipment**	**Measurement distance**	**Limit curve**		**REMARK**
			9 kHz to 30 MHz	**> 30 MHz**	
LV Domestic	Domestic: ≤1 kVA	10 m	(Limit 1)2)	Limit 1	IEC 61000-6-3 applies
LV Industrial	Industrial: ≤100 kVA	30 m	(Limit 1)2)	Limit 1	IEC 61000-6-4, CISPR 11 apply
2 – 30 kV	0,11 - 1 MVA	30 m	Limit 1 + 10 dB	Limit 1	
31 – 100 kV	1,0 - 7 MVA	30 m	Limit 2 - 5 dB	Limit 1	
101 – 170 kV	8 - 40 MVA	50 m	Limit 2	Limit 2	
171 – 250 kV	41-200 MVA	100 m	Limit 2	Limit 2	
251 – 420 kV	201 - 1000 MVA	200 m	Limit 2	Limit 2	
421 – 620 kV	1.1-5 GVA	200 m	Limit 2	Limit 2	
621 – 800kV	6-25 GVA	200 m	Limit 3	Limit 2	
801 – 1000 kV	26-100 GVA	200 m	Limit 3	Limit 2	
1001 – 1200 kV	> 100 GVA	200 m	Limit 3	Limit 2	

Notes: 1) Power Electronic equipment including HVDC and FACTS
2) Tentative proposal which may be applied.

Regarding the ratings of power electronic equipment they shall be seen as an attempt to get a consistent set of limits. Reported measurements [32], [37], [40] shows that RFI from PE-equipment with rating of 50 to 5000 MVA is consistent with the limits stipulated in IEC 62236-2. However, the size of the installation is much larger for a 1000 MVA installation than for a 50 MVA. Considering the mass effect described in Section D.2.1 the classification in accordance with Table D.2 is made. The selected classification of rating gives about the same factor in MVA rating between each step.

For dc voltage installations, the common relevant parameter is the amplitude of the phase-to-earth or pole to earth voltage. Thus, for high voltage dc installations the equivalent ac voltage level is in accordance with Equation (D.1).

$$U_{ACequiv} = U_{DC} * \sqrt{\frac{3}{2}} \qquad \text{(D.1)}$$

Thus 800 kV DC corresponds to 980 kV AC regarding field strength around the conductors. 500 kV DC corresponds to 610 kV AC.

D.3 Connecting lines

It should be noted that the RFI limits for the lines are not for controlling the RFI from the line itself, but for controlling the guided RFI due to RFI sources in the substations.

D.3.1 Recalculation of limits in ICES-004 for larger distances

Schedule I combined with Schedule II in ICES-004 [15] RFI from ac lines of different voltages. Section 4.2 of ICES-004 stipulates a minimum distance of 5 km from the substation. As the limits in Schedule I in accordance with Section 5.1.1 of the Standard relates to good weather conditions 20 dB is added to the levels in Schedule I, as for the substation, see Section D.2.2.

As for the substation, a 400 kV line is taken as the starting point. Figure D.7 shows the requirement in ICES-004 [15], compensated for bad weather conditions, and recalculated for different measurement distances.

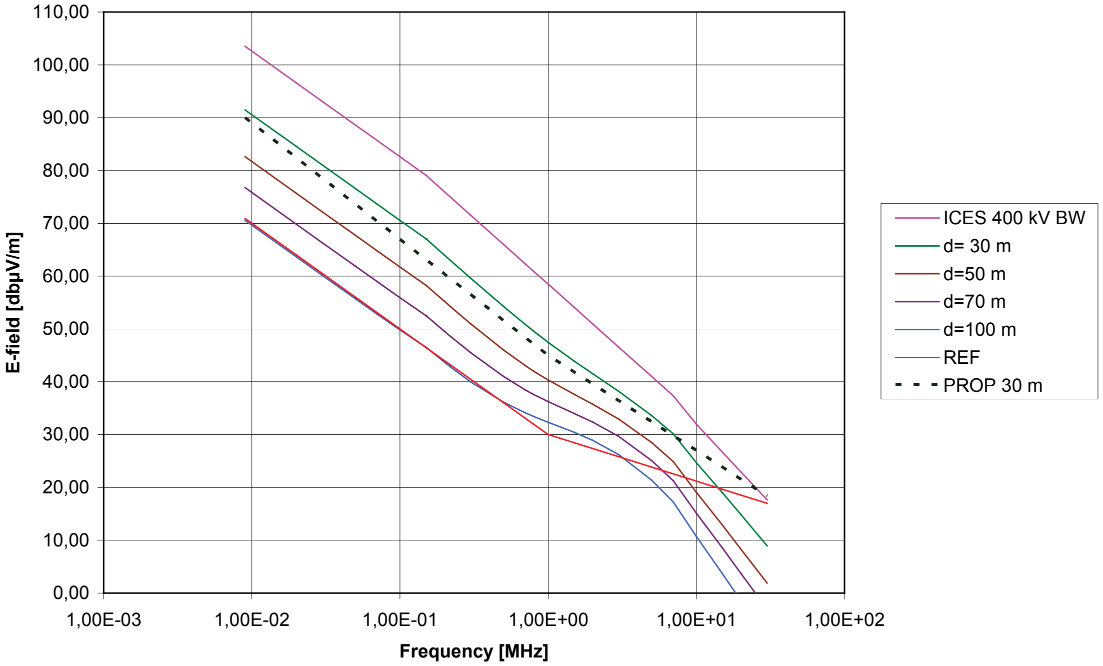

Figure D.7: The values in ICES-004 for 400 kV, compensated for bad weather condition, recalculated for longer distance. The values in ICES-004 refer to a distance of 15 m from the outer phase conductor.

ICES 400 kV is the ICES-004 requirement at a distance of 15 m, with an addition of 20 dB for representing the bad weather condition. The curve is extrapolated down to 9 kHz. The curves d= 30 m to d= 100 m are the values in ICES 400 kV BW recalculated for longer distances, as for the substations, see Section D.2.2. The curve Ref is the reference level at the location of the radio receivers defined in Figure B.2 and Table B.1. The curve PROP 30 is the proposed limit at a measuring distance of 30 m

Compared to the REF level, ICES-004 is more restrictive for frequencies above around 3 MHz. The attenuation in the line is higher for higher frequencies than for lower frequencies, see Section C.3 and [37]. Therefore, it can be justified to reduce the distance to the substation to 4 km when the PROP 30 m limit is used. Nevertheless, the limit is reduced above 1 MHz, in relation to the reference curve.

D.3.2. Variation with voltages

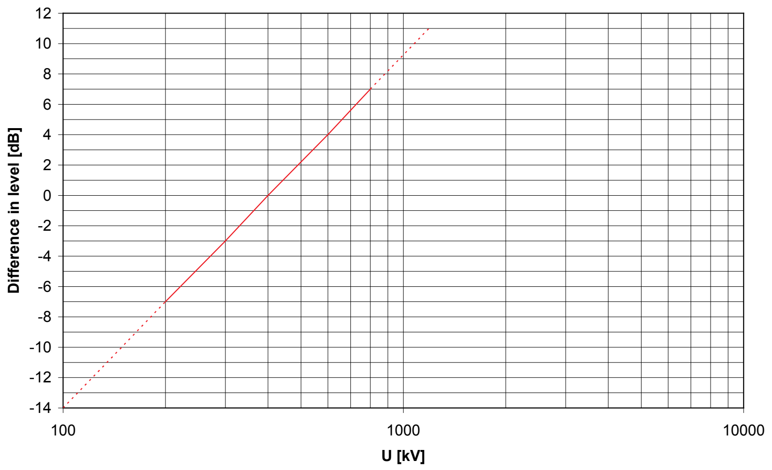

Figure D.8: Variations in ICES-004 at 0.5 MHz versus voltage levels. Levels outside 200 kV to 800 kV are extrapolated

Figure D.8 shows how the RFI levels vary with voltage levels, in accordance with ICES-004 [15]. When combined with the fact that the attenuation between 30 m and 50 m in Figure D.7 is 8 dB in the complete frequency range, it is the base for the proposed limits in Table D.3.

Table D.3: Proposed measurement distances and limits for connecting lines

Voltage level	Rating PE equipment in connected substation	Measurement distance	Applied Limit		REMARK
			9 kHz to 30 MHz	> 30 MHz	
LV Domestic	Domestic: ≤1 kVA	3 m	Limit 1	Limit 1	ECC/REC/(05)04 applies
LV Industrial	Industrial: ≤100 kVA	10 m	Limit 1	Limit 1	
2 – 30 kV	0,11 - 1 MVA	30 m	Limit 1	Limit 1	
31 – 100 kV	1,0 - 7 MVA	30 m	Limit 4 - 13 dB	Limit 1	
101 – 170 kV	8 - 40 MVA	30 m	Limit 4 - 9 dB	Limit 1	
171 – 250 kV	41-200 MVA	30 m	Limit 4 - 5 dB	Limit 1	
251 – 420 kV	201 - 1000 MVA	30 m	Limit 4	Limit 1	
421 – 620 kV	1.1-5 GVA	30 m	Limit 4 + 4 dB	Limit 1	
621 – 800kV	6-25 GVA	50 m	Limit 4 - 1 dB	Limit 1	
801 – 1000 kV	26-100 GVA	50 m	Limit 4 + 1.5 dB	Limit 1	
1001 – 1200 kV	> 100 GVA	50 m	Limit 4 + 3 dB	Limit 1	

Limit 1 is the proposed reference level at the location of the radio receivers in accordance with Figure B.2 and Table B.1 combined with the broadband RMS BB limit in accordance with Figure B.3 and Table B.2. Limit 4 is the PROP 30 m curve in Figures D.7. An overview of the limits is given in Appendix F.

D.3.3. Controlling the RFI from the line closer to the substation

For controlling the RFI from outgoing lines close to the station, it is proposed to apply the same limits as for the substation also for the outgoing lines, but at a shorter measurement distance, see Section 12.2. The measuring distance at the line exit is one third of the measuring distance for the substation.

D.4. Respect distances

For justification of the proposed limits, the respect distances have been evaluated by recalculating the limits for longer distances. The respect distance is when the level is down to the reference level. The same methodology as used for Figure D.3.

D.4.1. Substations and equipment

Figures D.3 and D.6 shows the field levels for different distances. From the figures it can be seen that the attenuation per unit length is more significant at shorter distances than at longer distances. Therefore, when moving out from the station, the levels fairly quickly drop significantly below the limit value. However, the distance required for the level to fall below the reference value is a bit longer, especially in the frequency range 0.1-1.0 MHz. For frequencies above 1 MHz the attenuation is much higher. This is favourable as the frequency ranges above 1 MHz are much more important for wireless communication than frequencies below.

Table D.4 shows the respect distances for substations and equipment, when the limits in accordance with Table D.2 are applied. The limits are defined in Appendix F.

Table D.4: Respect distances for substations and equipment with limits as per Table D.2.

Voltage level	**Rating of PE equipment**	**Measurement distance**	**Respect distance [m]**			
			9 kHz to 1 MHz	1-30 MHz	30-230 MHz	> 230 MHZ
LV Domestic	Domestic: ≤1 kVA	10 m	10	10	10	10
LV Industrial	Industrial: ≤100 kVA	30 m	30	30	30	30
2 – 30 kV	0,11 - 1 MVA	30 m	55 (30)	60 (30)	30 (10)	30 (10)
31 – 100 kV	1,0 - 7 MVA	30 m	300 (160)	100->80 (30)	30 (10)	30 (10)
101 – 170 kV	8 - 40 MVA	50 m	300 (160)	300->170 (120->80)	70 (35)	50 (20)
171 – 250 kV	41-200 MVA	100 m	1000 (300)	1000->300 (300->140)	150 (70)	100 (50)
251 – 620 kV	201 - 5000 MVA	200 m	3000 (900)	2000->600 (500->359)	300 (150)	200 (100)
621 – 1200kV	>5 GVA	200 m	7000 (2000)	4000->600 (1500->350)	300 (150)	200 (100)

Note: The distances within brackets are the distances where the level is less then 10 dB above the reference value.

D.4.2. Lines

Figure D.7 shows the field level for different distances when the limit in accordance with Table D.3 is applied for a 400 kV line, measured at least 4 km from the substation. The right part of Table D.5 shows the corresponding respect distances, when the field level is down to the reference level. The left part shows the respect distances at exit from the substation. The distances between brackets are when the field level is less than 10 dB above the reference level.

Table D.5: Respect distances for lines, with limits according to Section D.3.

Voltage level	Respect distances for line [m] At the exit from the substation			Respect distances for lines [m] More than 4 km from the substation		
	9 kHz to 3 MHz	3-30Mz	> 30 MHz	9 kHz to 3 MHz	3-30Mz	> 30 MHz
LV Domestic	3	3	3	3	3	3
LV Industrial	10	10	10	10	10	10
2 – 30 kV	25	25	15	30	<20	10
31 – 100 kV	30	30	15	40	<30	15
101 – 170 kV	90 (50)	90->75 (50)	20 (10)	50 (30)	30->20 (20->10)	20 (10)
171 – 250 kV	200 (100)	220->120 (70->50)	40 (20)	60 (40)	50->25 (25->10)	30 (15)
251 – 420 kV	450 (200)	450->200 (200->100)	70 (45)	85 (50)	65->35 (40->15)	30 (15)
421 – 620 kV	450 (200)	450->200 (200->100)	70 (45)	100 (60)	100->50 (50->25)	30 (15)
621 – 800 kV	1000 (500)	1000->200 (450->100)	70 (45)	130 (70)	130->55 (50->25)	50 (30)
801 – 1000 k	1000 (500)	1000->200 (450->100)	70 (45)	150 (90)	170->60 (70->25)	50 (30)
1001 – 1200 kV	1000 (500)	1000->200 (450->100)	70 (45)	170 (100)	200->70 (90->30)	50 (30)

Note: The distances within brackets are the distances where the level is less then 10 dB above the reference value.

For the UHV lines (>620 kV), with a measuring distance of 50 m, the field level at frequencies around 1 MHz is a few dB above the reference value at the distance defined as the respect distance, see Figure D.9 and compare the Ref curve with the curve d=130 m. For the distance within brackets, the +10dB distance, there is no such negative margin.

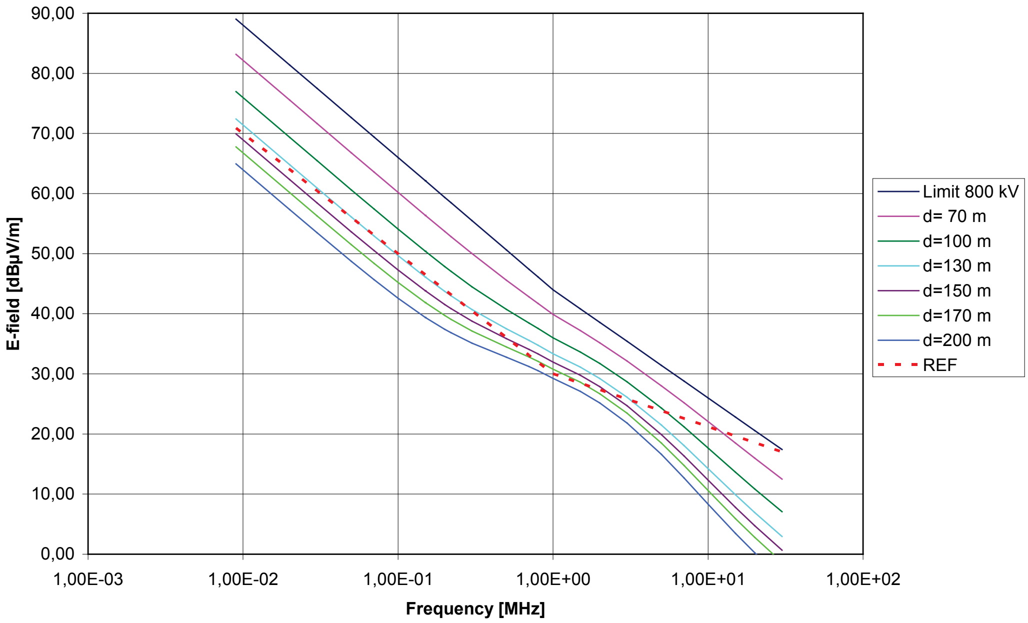

Figure D.9: Field levels at different distances when the limit in Table D.3 is applied for an 800 kV line.

D.5. Comments

It should be noted that the limits in ECC/REC/(05)04 [10] do not constitute any hard limits. However, in case of interference, if the measured levels are higher than those defined in ECC/REC/(05)04, mitigation measures are needed. In that case, only frequencies of conflict should be evaluated.

The practical implication is that even if some peaks in the frequency characteristic of RFI from a substation are above the reference level in accordance with ECC/REC/(05)04 the probability for an interference conflict is still low. The conflict may occur if a radio receiver operates at that frequency listening to a very weak transmitter, on the border for operation limit. With the applied measurement methodology, the respect distances are applicable for the highest peaks in the frequency characteristics. For most frequencies, the level will be down to the reference level at a much shorter distance. The respect distances are not further than the ones obtained when IEC 62236-2 [25] is applied. That Standard has been in force for several years. Besides, the levels correspond well to RFI from existing substations [37].

For frequencies above 30 MHz the respect distance is fairly short due to the soil attenuation. This is a very good outcome as those frequencies are important for modern wireless communication.

It is not straight forward to verify corona by RFI measurements as the proposed limits correspond to bad weather. Corona levels in good weather should be 20 dB below. Thus, if corona is felt to be the only source, the RFI level shall be about 20 dB below the proposed limits. However, it must be noted that gap discharges may be a source in dry weather, at least in older substations.

The radio spectrum from 9 kHz to 150 kHz

E.1. Introduction

The purpose of this Appendix is to describe the radio communication characteristics in the frequency range 9 kHz to 150 kHz regarding background noise levels and frequency usage. Background noise levels have been obtained from International Telecommunication Union (ITU) documents and converted in order to be comparable with EMC requirements in this frequency range. The frequency usage has been described both as the frequency allocation as stated by ITU and as examples of the actual frequency utilization.

This frequency range is typically used for long distance communication, and especially where the long-range ground wave coverage of low frequencies is important, such as for radio navigation. Reception of the ground wave is possible up to about 1000 km from the transmitter. Ionospheric reflection enables the communication distance to be further extended. The performance of radio receivers in this frequency range is limited by background noise, consisting of atmospheric and man-made noise.

E.2 Background noise

Figure E.1 shows the highest and lowest background noise levels given in ITU-R P.372-8 [27], from 10 kHz to 1 MHz, converted to a bandwidth of 200 Hz for frequencies below 150 kHz and a bandwidth of 9 kHz for frequencies above 150 kHz. In the frequency range from 50 kHz to 150 kHz the atmospheric noise is dominant but man-made noise may limit performance in some locations [54]. The values given by ITU are rms-values. The diagram also includes existing limits, and some measurement results obtained by STRI at a rural location on the shore of a lake just outside the small city of Ludvika using different detectors. The difference between the response of peak, quasi-peak and rms detectors decrease with increasing noise pulse repetition rate. If noise pulse repetition rate is much higher than the measurement bandwidth, then the response of different detectors should be approximately the same. This is due to the fact that all detectors are calibrated to give the RMS-value of a sine wave. Thus, if the pulse-repetition rate is higher than the measurement bandwidth, only one Fourier (sine wave) component will reach the detector. Therefore, with a bandwidth of 200 Hz, the difference between detectors is often not so large. An example is given by the measurement results in Figure E.1.

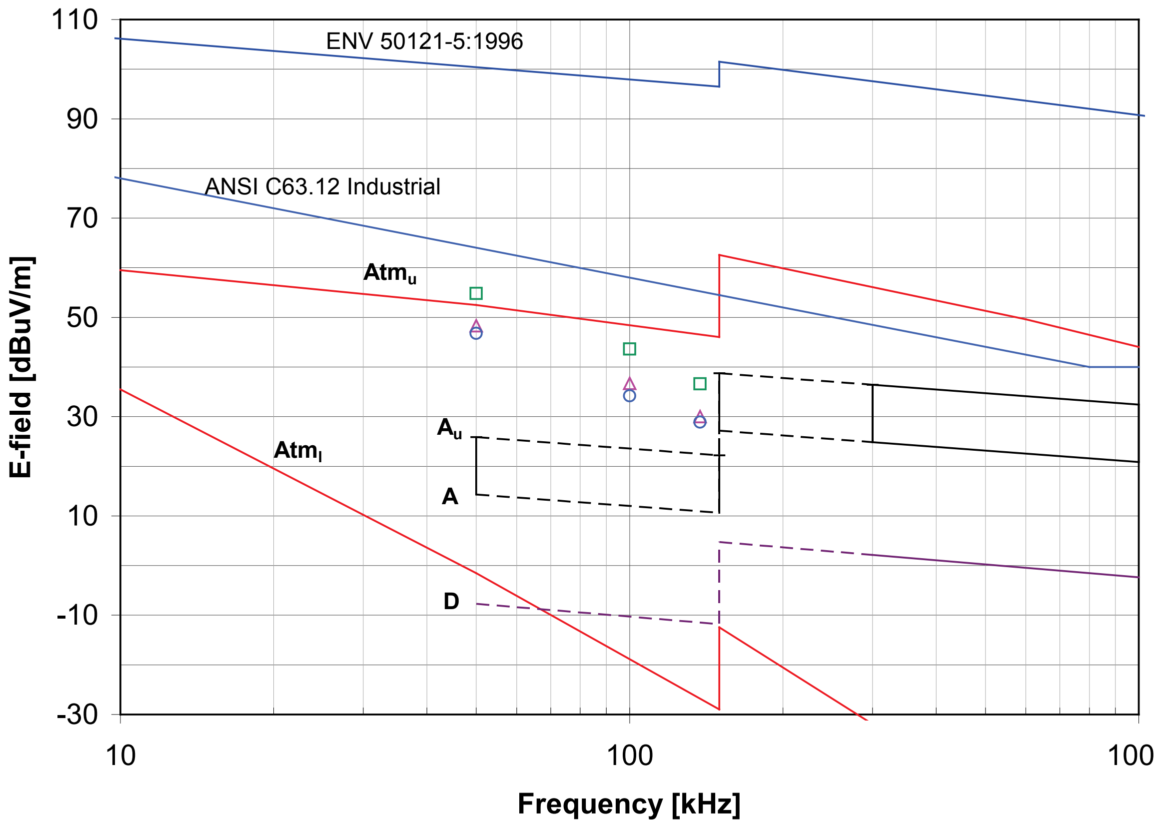

Figure E.1: Range of noise levels from ITU Rec. P.372-8, converted to 200 Hz/9 kHz bandwidth, including existing limits and some measurement results.

Atm_u	atmospheric noise, value exceeded 0.5% of time
Atm_l	atmospheric noise, value exceeded 99.5% of time
A	man-made, business areas, median
A_u	man-made, business, upper decile (the value exceeded 10% of time)
D	man-made, quiet rural areas, median

Background noise measured by STRI in Ludvika:

□	Peak
Δ	Quasi-peak
○	RMS

ENV 50121-5:1996 emission limit [11].

ANSI C63.12 Industrial emission guideline [2] (Domestic is 10 dB lower).

The dashed part of the curves for man-made noise indicates extrapolated values. The ITU report gives values of man-made noise down to 300 kHz.

For the atmospheric noise curves, all times of day, seasons, and the entire Earth’s surface have been taken into account. Atmospheric noise levels are generally higher closer to the equator.

The guideline according to ANSI C63.12 assumes a bandwidth of 10 kHz. No method for bandwidth correction is specified. Correcting the bandwidth according to 10×log(10000/200) gives 17 dB lower values for the frequencies below 150 kHz.

The correction for bandwidth is further discussed in Section E.5.

E.3. International frequency allocation

National frequency allocation is based on the ITU international frequency allocation. The table below is a reproduction of the ITU table of frequency allocations [29] for the frequency range 9 – 150 kHz, excluding footnotes. Capital letters means primary service. Lower case letters indicate secondary serviceand primary service has priority in case of interference.

Region 1 Europe, Africa and Russia	Region 2 North and South America	Region 3 Asia and Australia
9-14 RADIONAVIGATION		
14-19.95 FIXED MARITIME MOBILE		
19.95-20.05 STANDARD FREQUENCY AND TIME SIGNAL (20 kHz)		
20.05-70 kHz FIXED MARITIME MOBILE		
70-72 kHz RADIONAVIGATION	70-90 kHz FIXED MARITIME MOBILE MARITIME RADIO-NAVIGATION Radiolocation	70-72 kHz RADIONAVIGATION Fixed Maritime mobile
72-84 kHz FIXED MARITIME MOBILE RADIONAVIGATION		72-84 kHz FIXED MARITIME MOBILE RADIONAVIGATION
84-86 kHz RADIONAVIGATION		84-86 kHz RADIONAVIGATION Fixed Maritime mobile
86-90 kHz FIXED MARITIME MOBILE RADIONAVIGATION		86-90 kHz FIXED MARITIME MOBILE RADIONAVIGATION
90-110 kHz RADIONAVIGATION Fixed		
110-112 kHz FIXED MARITIME MOBILE RADIONAVIGATION	110-130 kHz FIXED MARITIME MOBILE MARITIME RADIO-NAVIGATION Radiolocation	110-112 kHz FIXED MARITIME MOBILE RADIONAVIGATION
112-115 kHz RADIONAVIGATION		112-117.6 kHz RADIONAVIGATION Fixed Maritime mobile
115-117.6 kHz RADIONAVIGATION Fixed Maritime mobile		
117.6-126 kHz FIXED MARITIME MOBILE RADIONAVIGATION		117.6-126 kHz FIXED MARITIME MOBILE RADIONAVIGATION
126-129 kHz RADIONAVIGATION		126-129 kHz RADIONAVIGATION Fixed Maritime mobile
129-130 kHz FIXED MARITIME MOBILE RADIONAVIGATION		129-130 kHz FIXED MARITIME MOBILE RADIONAVIGATION
130-148.5 kHz FIXED MARITIME MOBILE	130-160 kHz FIXED MARITIME MOBILE	130-160 kHz FIXED MARITIME MOBILE RADIONAVIGATION
148.5-255 kHz BROADCASTING	160-190 kHz FIXED	160-190 kHz FIXED Aeronautical radionavigation

E.4. Frequencies in use

It is not possible to find a complete and reliable list of frequencies in use in the LF band. The organization Klingenfuss is a well-established source of updated information regarding radio spectrum usage, but covers mainly the HF spectrum and gives only a few examples of LF applications. The information in the tables below has been compiled from the Internet. It is far from a complete listing. More information can be found on different amateur radio web pages, which is probably the best source in this case. Two examples of links to such web pages are given in Section E.6.

Time signals

Frequency (kHz)	Station	Region	Station location
40	JJY	Japan	-
50	RTZ	Russia	Irkutsk
60	JJY	Japan	-
60	WWVB	North America	Boulder Colorado
60	MSF	Europe	Rugby England
66.66	RBU	Russia	Mendeleevo, Moscow
68.5	BPC	China	Lintong
75	HBG	Europe	Prangins Switzerland
77.5	DCF77	Europe	Mainflingen Germany

Radio navigation

Frequency (kHz)	System	Region
90-110	LORAN-C	North America, Russia, Europe

The previous European radio navigation system Omega and Decca are closed down.

Miscellaneous (a few examples)

Frequency (kHz)	Station	Type	Region
53,8	RDD 78	Weather reports	Russia, Moscow
68.0	GBY	Broadcasting	Great Britain
82.8	MKL	Military	Great Britain
122.5	CFH	Military	Canada
123.7	DCF 42	Accurate Positioning	Germany, Berlin
129.8	Danish Navy	Military	Denmark
135.7-137.8	-	Amateur radio	Europe
139	DCF 39	Remote control	Germany, Magdeburg
147.3	DDH 47	Weather reports	Germany, Hamburg
148	UTW	Weather reports	Russia, Pevek

There is a tendency that this frequency range is becoming less important for communication. An important use of these frequencies has previously been communication and navigation at sea. This is now being taken over by satellite services, and telegraphy is not used for emergency communication at sea any more.

E.5. Bandwidth correction

Since bandwidth correction is dependent both on the signal characteristics and the detector used, the statistical or wave-form properties of the atmospheric noise must be known. At frequencies below 20 MHz, the natural atmospheric noise is dominated by the noise from lightning strikes in thunderstorms all over the world. One model of atmospheric noise proposed is a low level Gaussian noise (representing far-distant effects), plus a high-level impulse noise process to represent more local effects. The difficulty with this model, from a bandwidth point-of view, is that the bandwidth correction is different for these two noise models according to the following.

E_1 is the reading in dB of the detector with bandwidth BW_1

E_2 is the reading in dB of the detector with bandwidth BW_2

For broadband Gaussian noise, the conversion between different measurement bandwidths is [5].

- RMS detector: $E_2 = E_1 + 10 * \mathrm{LOG}_{10}(BW_2 / BW_1)$
- Average detector: $E_2 = E_I + 10 * \mathrm{LOG}_{10} (BW_2 / BW_1)$
- Quasi-peak detector: $E_2 = E_1 + 10 * \mathrm{LOG}_{10} (BW_2 / BW_1)$
- Peak detector $E_2 = E_1 + 10 * \mathrm{LOG}_{10} (BW_2 / BW_1)$

For pulsed interference the dependence of measurement bandwidth is [6]

- RMS detector: $E_2 = E_1 + 10 * \mathrm{LOG}_{10} (BW_2 / BW_1)$
- Average detector: The response is not dependent of the measurement bandwidth (only on the pulse repetition frequency)
- Quasi-peak detector: $E_2 = E_1 + 20 * \mathrm{LOG}_{10} (BW_2 / BW_1)$
- Peak detector $E_2 = E_1 + 20 * \mathrm{LOG}_{10} (BW_2 / BW_1)$

A measure of the relative amplitude between the two interference components is the impulsiveness ratio [7]. The impulsiveness ratio IR is defined as

$$IR = 20 \log \frac{E_{\mathrm{RMS}}}{E_{average}}, \tag{E.1}$$

In [27], bandwidth conversion as a function of IR is plotted in a diagram to simplify bandwidth conversion for atmospheric noise modelled as a mix of Gaussian and impulsive noise.

E.6. Internet links

http://www.pacificsites.com/~brooke/FA.shtml (frequency allocation)
http://www.npl.co.uk/time/time_trans.html (time signals)
http://www.boulder.nist.gov/timefreq/ (time signals)
http://www.navcen.uscg.gov/loran/default.htm (Loran C)
http://www.lwca.org/mb/index.htm (general about VLF)
http://www.m1cvc.uklinux.net/radio_frqlst_spct.html (online frequency allocation table)
http://www.provcomm.net/pages/joe/introvlf.htm#Frequency%20Allocations%20for%20LF%20and%20VLF%20operation (frequency list and information about VLF)
http://www.klingenfuss.org/ (an organization that provides information about radio transmission in the frequency range 0 – 30 MHz)

http://www.qsl.net/g4cnn/lf/lf.htm (An amateur radio site including a list of active LF frequencies)

http://beaconworld.org.uk/files/lfguide.pdf (An amateur radio site including a list of active LF frequencies)

Overview of proposed limits

Appendix F gives an overview of the limits proposed in Appendix D. The limits are given in graphical form in Figure F.1 and in numerical form in Tables F.1 and F.2. The measurement distances and additions are given in Appendix D.

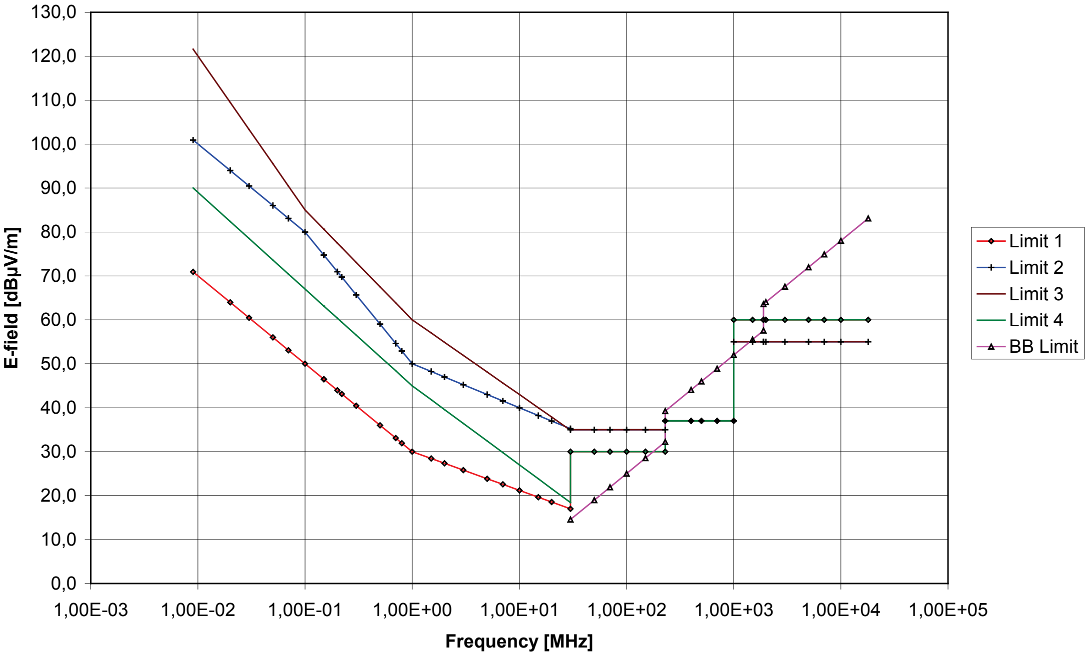

Figure F.1: Overview of limits defined in Appendix D. Numerical values in Tables F1-F2.

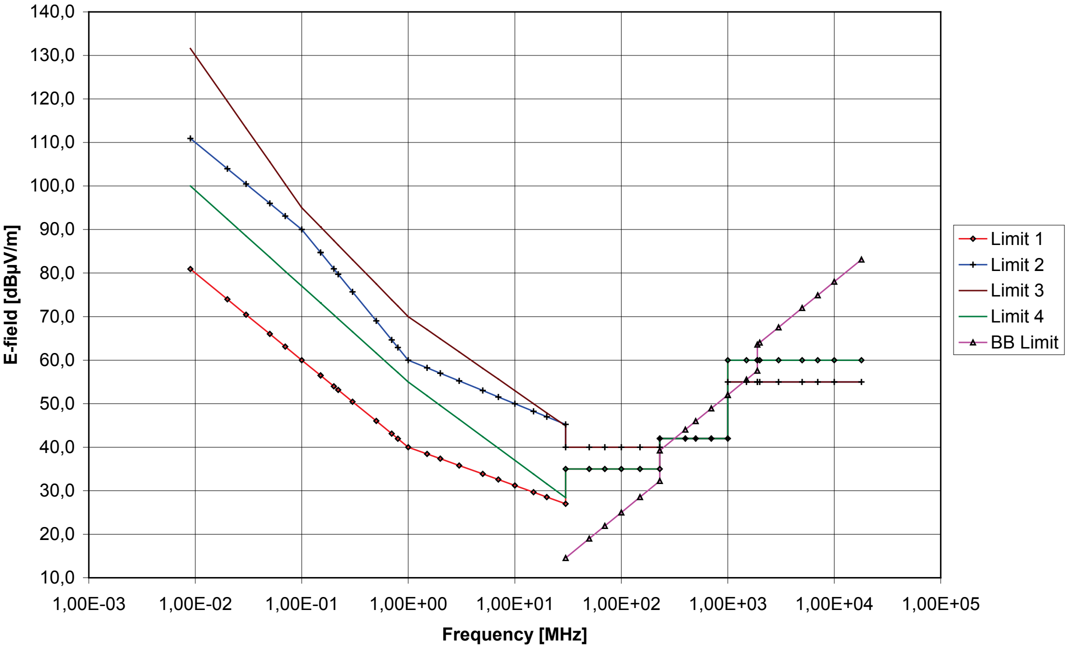

Figure F.2: Alternative limits for measurement with peak detectors

Figure F.2 shows an alternative set of limits related to measurement with a peak detector instead of an quasi-peak detector, for speeding up the measurement procedure, as justified below.

Table F.1: Overview of proposed limits for MV and HV substations and lines, CISPR 16 Bandwidths

DEFINITIONS	**PROPOSED LIMITS IN [dBμV/m]**						
Frequency ranges, frequency in [MHz]	0.009 – 0.1	0.1 - 0.15	0.15 - 1	1 - 30	30 -230	230 - 1000	1000 - 18000
Limit 1 and Reference Substations and lines, $U \leq 30$ kV	$30 - 20\cdot\log(f)$	$30 - 20\cdot\log(f)$	$30 - 20\cdot\log(f)$	$30 - 8.8\cdot\log(f)$	30	37	60
Limit 2; Substations 30 kV $<U\leq$ 620 kV	$60 - 20\cdot\log(f)$	$50 - 30\cdot\log(f)$	$50 - 30\cdot\log(f)$	$50 - 10\cdot\log(f)$	35	37	55
Limit 3; Substations $U >$ 620 kV	$50 - 35\cdot\log(f)$	$60 - 25\cdot\log(f)$	$60 - 25\cdot\log(f)$	$60 - 17\cdot\log(f)$	35	37	55
Limit 4; Lines $U >$ 30 kV	$45 - 22\cdot\log(f)$	$45 - 22\cdot\log(f)$	$45 - 22\cdot\log(f)$	$45 - 18\cdot\log(f)$	30	37	60
Bandwidth	200 Hz	200 Hz	9 kHz	9 kHz	120 kHz	120 kHz	1 MHz
Detector	Quasi-peak	Quasi-peak	Quasi-peak	Quasi-peak	Quasi-peak	Quasi-peak	Peak

NOTES: $\log(f)$ is $^{10}\log(f)$ with f in [MHz]
The reference is the limit at the location of the radio receivers as per Appendix B.
The measurement distances are defined in Appendix D

Table F.2: Proposed Broadband limits related to interference with digital radio systems

DEFINITIONS	**PROPOSED LIMITS IN [dBμV/m]**			**REMARK**
Frequency ranges, frequency in [GHz]	0.03 – 0.23	0.23 – 1.9	1.9-18	
BB Limit related to digital radio systems All substations ands lines	$45 + 20\cdot\log(f)$	$52 + 20\cdot\log(f)$	$58 + 20\cdot\log(f)$	f in GHz
Bandwidth	1 MHz	5 MHz	20 MHz	
Detector	RMS	RMS	RMS	

NOTE: The measurement distances are defined in Appendix D

Table F.3: Alternative limits for MV and HV substations and lines, CISPR 16 Bandwidths, Peak detector

DEFINITIONS	**PROPOSED LIMITS IN [dBµV/m]**						
Frequency ranges, frequency in [MHz]	0.009 – 0.1	0.1 - 0.15	0.15 - 1	1 - 30	30 -230	230 - 1000	1000 - 18000
Limit 1 Substations and lines, $U \leq 30$ kV	$40 - 20\cdot\log(f)$	$40 - 20\cdot\log(f)$	$40 - 20\cdot\log(f)$	$40 - 8.8\cdot\log(f)$	35	42	60
Limit 2; Substations 30 kV $<U\leq$ 620 kV	$70 - 20\cdot\log(f)$	$60 - 30\cdot\log(f)$	$60 - 30\cdot\log(f)$	$60 - 10\cdot\log(f)$	40	42	55
Limit 3; Substations $U >$ 620 kV	$60 - 35\cdot\log(f)$	$70 - 25\cdot\log(f)$	$70 - 25\cdot\log(f)$	$70 - 17\cdot\log(f)$	40	42	55
Limit 4; Lines $U >$ 30 kV	$55 - 22\cdot\log(f)$	$55 - 22\cdot\log(f)$	$55 - 22\cdot\log(f)$	$55 - 18\cdot\log(f)$	35	42	60
Bandwidth	200 Hz	200 Hz	9 kHz	9 kHz	120 kHz	120 kHz	1 MHz
Detector	Peak	Peak	Peak	Peak	Peak	Peak	Peak

NOTES: $\log(f)$ is $^{10}\log(f)$ with f in [MHz]
The measurement distances are defined in Appendix D

Measurement in quasi-peak mode takes much longer than measurement in peak detector mode. Therefore, for practical reasons it is favourable to have the limits related to peak values.

In the frequency range 9 kHz to 30 MHz the levels are based on the levels in ECC/REC/(05)04 [10], see Section B1 of Appendix B. The values in ECC/REC/(05)04 are originally related to peak values and reduced by 10 dB. Therefore, in the frequency range 9 kHz to 30 MHz it is fully justified to use the peak values in Table F.3 instead of the quasi-peak limits in Table F.1. In the frequency range 9 kHz to 30 MHz the levels in Table F.3 and Figure F.2 is 10 dB above the values in Table F.1 and Figure F.1.

In the frequency range 30 MHz to 1 GHz, the limits are originally in quasi-peak values. However, experience shows that quasi-peak values are always more than 5 dB below the peak values [37]. Therefore it is justified to use the alternative limits in Table F.3 also in the frequency range 30 MHz to 1 GHz. In this frequency range the values in Table F.3 and Figure F.2 are 5 dB above the values in Table F1 and Figure F.1. However, in case of a conflict, the quasi-peak values in Table F.1 have precedence.

The limits above 1 GHz and the broadband RMS-limits in accordance with Table F.2 are not affected. However, Appendix G can be consulted if background noise makes the broadband measurement difficult.

Measurement with a smaller bandwidth

G.1. General

Certain situations require the measurements, for practical reasons, to be performed with a much narrower bandwidth then that specified in the requirement specification. The reason may be the ability to discriminate between background noise and noise from the EUT (Equipment under test) when performing in situ testing.

Described below is an example when a measurement is preformed with the CISPR 16 bandwidth of 120 kHz [5] while the specified bandwidth is 3 MHz, i.e. 25 times wider.

G.2. Assumptions

It is assumed that an RMS-detector was used at the measurements and that the specification (or Standard) also calls for an RMS-detector. This allows the measurement values to be well defined and lets the user know how the bandwidth impacts the measurement result.

Additionally, it is assumed that we have a true frequency characteristic curve of the RFI noise from the EUT. The impact of background noise from radio transmitters have been eliminated in one way or another. The measurement is performed with an RMS detector and a bandwidth of 120 kHz. The result is presented in dBμV/m.

The requirement is assumed to be a measurement using an RMS-detector with a bandwidth of 3 MHz.

It is assumed that the stepping required for the measurement is 1.5 MHz.

If the spectrum is flat, the measurement with 3 MHz bandwidth will be 10log(3/0.12)=14 dB higher than the measurement with a bandwidth of 120 kHz, provided RMS detectors are used in both cases.

G.3. Transformation procedure

The required measurement is divided into n interval with an amplitude E_{1i} at the midpoint of interval i and a bandwidth BWI for each interval. The measurement is performed with a bandwidth BW_1. The measurement result at the midpoint of the interval is M_{1i}. We have:

$$\sum_{i=1}^{n} BWI = n \cdot BWI = BW_2 \qquad \text{(G.1)}$$

$$M_2 = 10 \cdot \log\left\{\frac{BWI}{BW_1}\sum_{i=1}^{n} 10^{(M_{1i}/10)}\right\} \qquad \text{(G.2)}$$

Where M_2 is the estimated result with bandwidth BW_2.

If the bandwidth of the intervals BWI differs from the measurement bandwidth BW_1 a correction with BWI/BW_1 is needed to estimate of the power in each interval. This procedure is applied for three examples.

G.4. Examples

In the examples that follow, M_1 represents the assumed measured RMS-values with a bandwidth $BW_1$of 120 kHz and M_2 is the estimated values if the measurement had been performed with a bandwidth BW_2 of 3 MHz. The stepping is 1.5 MHz. BW_{2Req} is the requirement at the bandwidth M_2.

In the examples, there are three RFI sources with different bandwidth. All three have a maximum value of 80 dBµV/m measured with a bandwidth of 120 kHz. The requirement when using a bandwidth of 3 MHz is assumed to be 90 dBµV/m.

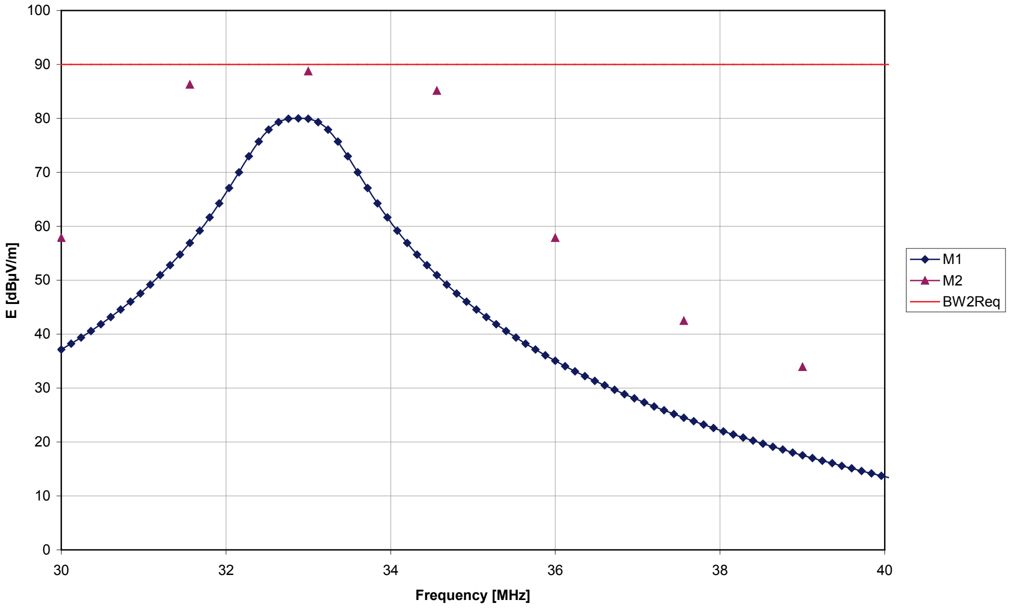

Figure G.1: A quite typical spectrum for RFI from power electronic equipment.

With the RFI spectra in Figure G.1, the change of bandwidth from 120 kHz to 3 MHz makes a difference of about 9 dB.

With a broader spectrum, as per Figure G.2, the increased level with the wider bandwidth is close to the 14 dB for a flat spectrum.

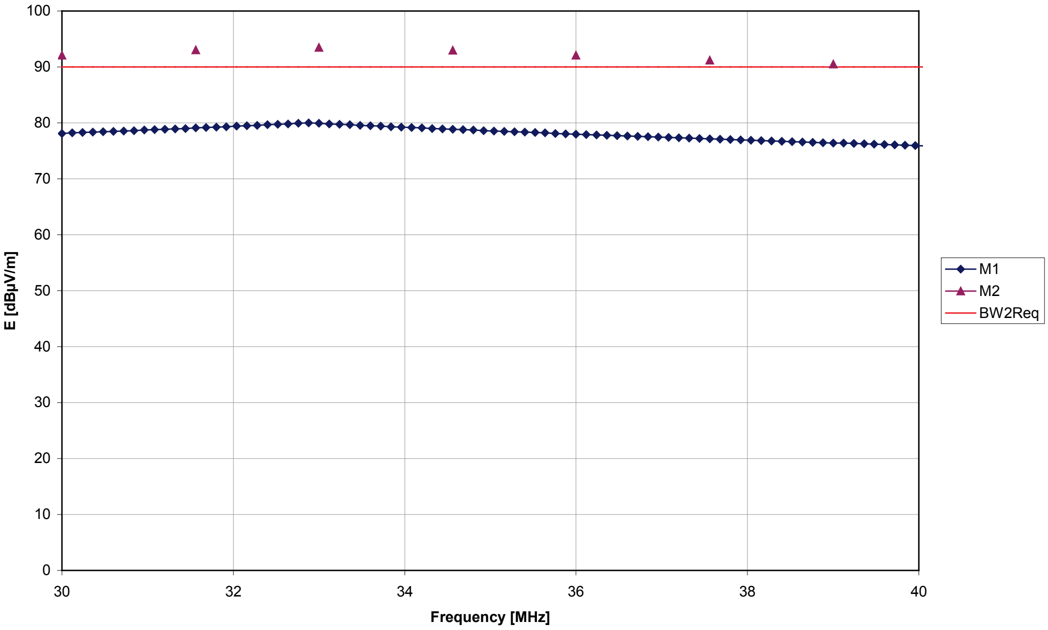

Figure G.2: A spectrum from a broadband RFI source.

If the spectrum from the RFI source is sharp, a narrowband source, the amplitude is independent of the measurement bandwidth, provided that the measurement bandwidth is the same or larger than the bandwidth of the RFI noise, see Figure G.3.

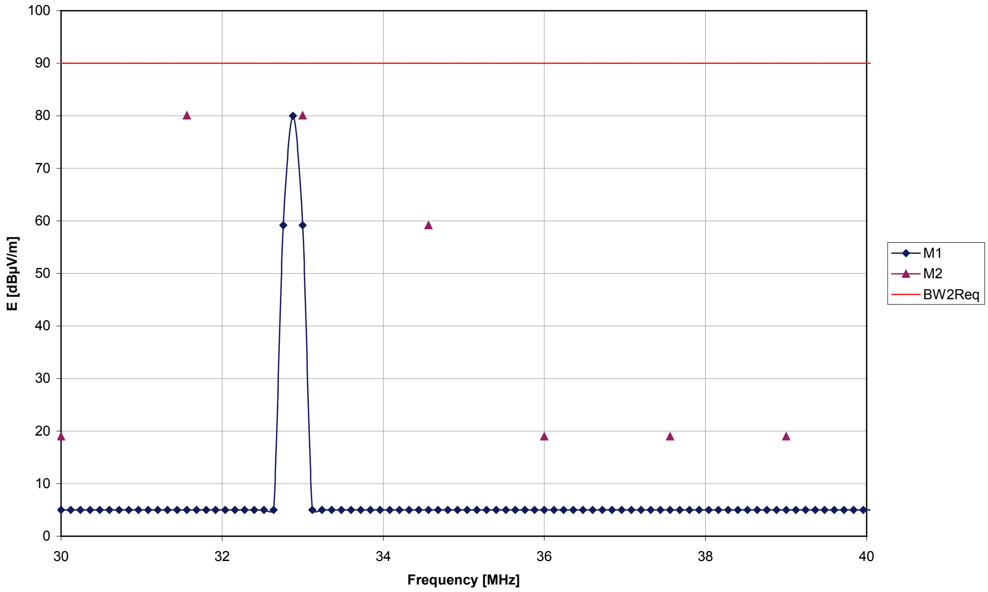

Figure G.3: A spectrum from a narrow band RFI source.

In Figure G.3 it is indicated that there always is a background noise.

G.5. Limit and noise varies with frequency

Often the limits in standards are not flat, but vary with frequency, which makes it a bit more complicated to convert measurement with another bandwidth, as indicated in Figure G.4.

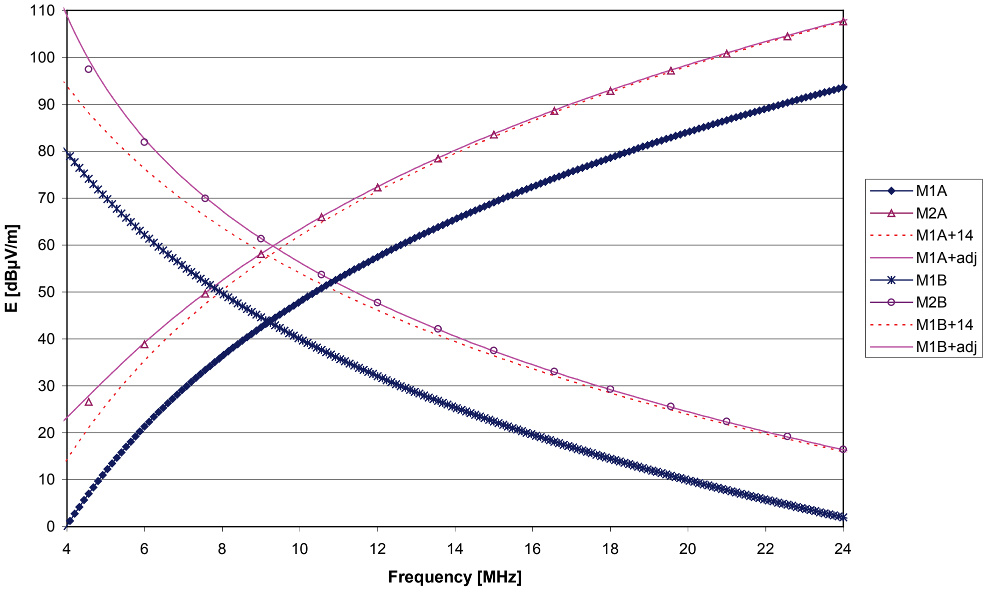

Figure G.4: Conversion to broad band measurement when noise varies with frequency.

The noise *A* with the measurement values M_{1A}, bandwidth 0.12 MHz increases as f^{6} where *f* is the frequency. The noise B with measurement values M_{1B} varies as f^{-5}. As the curves are not linear the estimated value with a bandwidth of 3 MHz will be higher than the value with a bandwidth of 0.12 MHz plus 14 dB as shown in Figure G.4.

If the frequency is much larger than the bandwidth, the difference can be neglected. In Figure G.4 the adjustment is:

$$Adj = 14 + c_c * \left| L_{f0} - \tfrac{1}{2}\left(L_{f0-\frac{1}{2}BW_2} + L_{f0+\frac{1}{2}BW_2} \right) \right| \qquad \text{(G.3)}$$

Where

- Adj is the adjustment for conversion from bandwidth BW_1 to bandwidth BW_2.
- 14 is the dB adjustment at a flat limit and a flat noise curve.
- c_c is a constant
- L_{f0} is the limit at the midpoint frequency for bandwidth BW_2
- $L_{f0-\frac{1}{2}BW2}$ is the limit at the lower end of the bandwidth

$L_{f0+\frac{1}{2}BW2}$ is the limit at the upper end of the bandwidth

In Figure G.4 the constant c_c is 2.5 for curve M_{1A+adj}, which is convex, as the value increases with frequency. For the concave curve M_{1B+adj} a value of 5 is used for c_c. This adjustment comes quite close to the calculated values M_{2A} and M_{2B} for the broader bandwidth BW_2.

G.6. Step changes of the limit

A step change in the limit might also cause problem during the evaluation of measurements performed with a smaller bandwidth, as illustrated in Figure G.5. In Figure G.5, the stepping in frequency applied for evaluation at the broader bandwidth BW_2 is significantly smaller than $BW_2/2$. The reason is to observe better the behaviour at the step change.

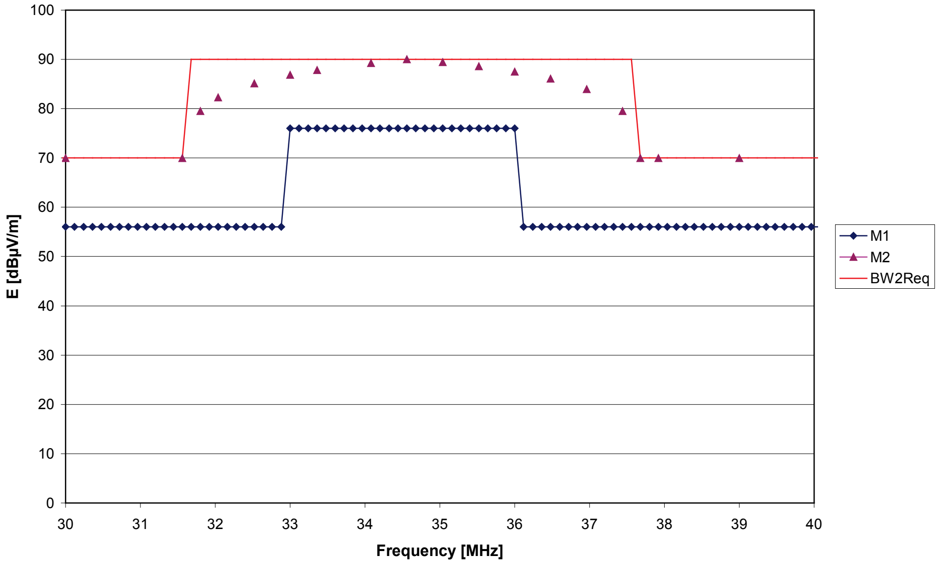

Figure G.5: Conversion between bandwidth at step changes in noise and limits

The conclusion of Figure G.5 is that, when comparing the level at the smaller bandwidth BW_1 and the limit for bandwidth BW_2, the lower level of the limit should be extended by one half of the bandwidth BW_2 into the frequency range with the higher limit.

G.7. Some conclusions

If the results from a measurement with a narrower bandwidth is above the requirement, the requirement is not met.

If the measurement with a bandwidth BW_1 always is lower than the requirement with a bandwidth BW_2 minus 10*LOG(BW_2/BW_1), then it is acceptable for a flat limit. It is also acceptable for a frequency dependent limit if the frequency is higher than about ten times the bandwidth BW_2. If there is a step change in the limit, the evaluation shall be performed as the lower level was extended with a frequency $BW_2/2$ into the frequency range with the higher limit.

If the situation is somewhere in between, a more detailed analysis is needed. The conformance depends on the bandwidth of the disturbance RFI noise.

For the purpose of evaluation, it might be more convenient to present the measurement result as E^2 in [(µV/m)^2] instead of [dBµV/m]. The requirement should be presented as $E^2_{lim}*BW_1/BW_2$. The requirement at 3 MHz bandwidth is assumed to be 90 dB. Yellow area shows 3 MHz bandwidth. The mean value between 31.5 and 34.5 MHz is below the adjusted limit, which corresponds to 90 dBµV/m.

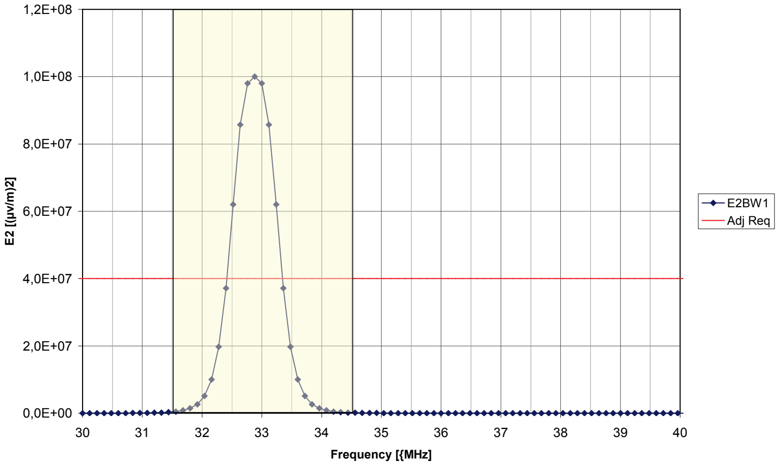

Figure G.6: Measurement value in Figure G.1 transformed to E^2 in (µV/m)^2.

An example of uncertainty budget

This appendix shows an example of a measurement uncertainty (or error) budget for measurement in the frequency range 9 kHz to 30 MHz at a distance of 200 m from an ac substation, see Table H.1.

For more background information, reference is made to CISPR 16.4.2 [7] and CISPR 16.2.3 [6]. Appendix C of CISPR 16.2.3 combined with Section 8.9 of this guide is the starting point for the uncertainty budget.

H.1: Uncertainty budget input

Table H.1: Uncertainty budget for emission measurements in the frequency range 150 kHz to 30 MHz

Component	**Probability distribution**	**Uncertainty [dB]**	**Remarks**
Antenna factor calibration	normal ($k = 2$)	± 2	
Cable loss calibration	normal ($k = 2$)	± 1	
Receiver specification according to CISPR 16-1-1	rectangular	± 1.5	Peak measurement
Antenna directivity	rectangular	0	Two orthogonal measurements
Antenna height		0	
Measurement distance uncertainty 5 %	normal ($k = 1$)	± 0.85	
Background noise, external noise	normal ($k = 1$)	-0, + 3 1)	Always too high reading
Terrain conditions	triangular	± 1.5	When normal care is used
Local variations	normal ($k = 1$)	± 0.5	At a distance of 200 m
Operation mode (turn on voltage 0.9 p.u.)	rectangular	± 0.9 3)	To be calculated case by case
Loading (80 % loading)	rectangular	± 1.9 3)	To be calculated case by case
Busbar voltage (5 % below max voltage)	rectangular	-2, +0	Only for corona and gap discharge 4)
Weather conditions	rectangular	- 20, +0 2)	Only for corona and gap discharges, always too low readings
Mismatch	U-shape	± 1.1	

Notes:

1. The background noise shall not be included when considering the total uncertainty, as this is concentrated on corrections due to a possible too low reading while background noise and disturbances always result in a too high reading.
2. The corrections for the weather conditions for corona and gap discharge are so large that they can not be combined with the other measurements uncertainties. Instead the considerations regarding consequences of the weather conditions have to be treated separately.
3. If the power electronic equipment is operated at full load and in worst continuous operation mode, these uncertainties are nil.
4. In dry weather, the voltage variation will be related to gap discharge and in bad weather it is related to corona.

The assumption for this example is that the measurements are performed in dry weather.

H.2. Standard uncertainty

In order to calculate the combined total uncertainty, the different uncertainties must be brought into a common form, the standard uncertainty, i.e. the standard deviation. The conversions factors that are deduced from information in [6][7] are shown in Table H.1.

Table H.2: Factor for standard uncertainty for different probability distributions.

Probability distribution	**Uncertainty or error**	**Standard uncertainty $u_c(x_i)$**
Normal, $k = k$	$U = \pm U_n = \pm k^* \sigma$	$u_c = U_n / k = \sigma$
Rectangular	$U = \pm U_R$	$u_c = \frac{u_R}{\sqrt{3}}$
Triangular	$U = \pm U_T$	$u_c = \frac{u_T}{\sqrt{6}}$
U-shape	$U = \pm \underline{u_U}$	$u_c = \frac{u_U}{\sqrt{2}}$

H.3. Combined uncertainty

The combined standard uncertainty $u_c(y)$ is calculated in accordance with Equation (H.1):

$$u_c(y) = \sqrt{\sum_i \left(u_c^2(x_i)\right)} \tag{H.1}$$

A coverage factor k = 2 will ensure that the level of confidence is approximately 95 %, therefore the total uncertainty U is calculated as:

$$U_{measure} = 2 * u_c\,(y) \tag{H.2}$$

With the figures in Table H.1 when the uncertainties due to background noise and weather conditions are disregarded, the standard uncertainty $u_c(y)$ is calculated in Equation (H.3), considering the factors in Table H.2:

$$u_c(y) = \sqrt{\left(\frac{2}{2}\right)^2 + \left(\frac{1}{2}\right)^2 + 0.85^2 + 0.5^2 + \frac{1.5^2 + 0.9^2 + 1.9^2 + 2^2}{3} + \frac{1.5^2}{6} + \frac{1.1^2}{2}} = 2.60 \text{ dB} \tag{H.3}$$

The total measurement uncertainty thus is:

$$U_{measure} = 2 * u_c(y) = 2 * 2.60 = 5.20 \text{ dB} \tag{H.4}$$

As $U_{measure}$ is 0.9 dB above the U_{base} value of 4.3 dB in Table 8.2 in Section 8.9.7 of this guide the measurement results in this case shall be increased by 0.9 dB.

Appendix I

Responses to the RFI questionnaire

A questionnaire was sent out in February 2006 to all SC C4 members regarding the experience of radio frequency interference in HV and MV installations, especially substations. In total four answers were received, two from South America, one from North America and one from Europe. The answers are reported in this Appendix I.

I.1. Applied Standards

In two cases, national standards were applied and in two cases international standards were applied. The international standards referred to are FCC (in general) and IEC 61000-6-5.

In one answer, the importance of the RIV test of apparatus in accordance with IEC 60694 [19], superseded by IEC 62271-1 [26], was pointed out

I.2 Enforcement of RFI limits.

The answers were as follows:

Method\Answer	**A**	**B**	**C**	**D**
By design rules, calculations	**X**	**X**		**X**
Supplier verification by measurement	**X**	**X**	**X**	
Own verification by measurement	**X**			

In one answer, design was mentioned as the preferred method.

I.3. Where RFI limits are applied

The answers are from utilities with a large amount of installation and HV lines

The table below shows the number of positive answers to the questions.

RFI verification procedure	**A.C. HV substations**	**FACTS or HVDC stations**	**A.C. HV lines**	**HVDC HV lines**	**HVDC electrode lines**
For which type of installation do you apply RFI limits?	**2**	**2**	**4**	**2**	**2**
RFI performance always verified by measurement				**1**	**1**
RFI performance often verified by measurement		**1**		**1**	
RFI performance seldom verified by measurement	**1**		**2**		
Experience of interference due to RFI			**1**		
Degree of interference on scale 1-5, 5 worst			**4**		

I.4. Relation between limits and actual RFI levels

I.4.1. Substations

The table below summarises the answers regarding the experienced of RFI from substations.

Actual RFI level in relation to stipulated RFI limits	Old a.c. installations	New a.c. installations	FACTS/HVDC installations
Below limits		**1**	
Close to limits	**1**		**2**
Above limits			
Do not know/No answer	**3**	**3**	**2**

I.4.2. Lines

The table below summarises the answers regarding the experienced of RFI from lines.

Actual RFI level in relation to stipulated RFI limits	A.C HV lines	HVDC HV lines	HVDC electrode lines
Much below limits		**1**	
Below limits	**1**		
Close to limits		**1**	**1**
Above limits			
Do not know/No answer	**3**	**2**	**3**

One specific comment regarding RFI from HV lines: “Modern lines use larger conductors as load increases and the cost of losses increases. As a consequence, the level of RFI is lower.”

I.5. Comments regarding present limits

Answer to the question: “Your opinion about the present limit:”

Too strict:	One respondent
Good:	Two respondents
Insufficient:	None.

I.6. Comments to the answers

One very valuable input was from Canada regarding the Canadian standard ICES-004. The respondent considers this standard to be good, and the opinion is supported by experience from many measurements.

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