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CONSIDERATIONS REGARDING RI LIMITS FOR HIGH VOLTAGE HVDC OR FACTS STATIONS

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SUMMARY

In line with the EU EMC Directive in 1996 there have in the last ten years been a lot of standardisation activities in the field of electromagnetic compatibility (EMC). Most of those activities have been related to emission and immunity regarding low voltage equipment for domestic or industrial use. Some work has also been done regarding immunity requirements for equipment in high voltage power stations and substations. Very little has been done regarding how to specify and verify emission requirements from high voltage substations, especially when power electronic equipment is involved.

The characteristics of radio interference (RI) from high voltage lines due to corona are well known and documented in the CISPR 18 series. The less well-known characteristics of RI due to sparks are also indicated in the CISPR 18 series. During the past decades a third source of RI has become more and more important, i.e. power electronic equipment. The characteristics of RI from large power electronic equipment can be very different depending on system design and type of semiconductor elements used. For controlling the RI emission, both the formulation of the requirements and the methodology for verification measurements have to be reconsidered. Regarding RI from power electronics it is not sufficient to measure the emission at 0.5 MHz, as is sometimes done for controlling RI due to corona. The complete frequency range of interest has to be scanned.

With emphasis on power electronics of high MVA rating (HVDC and FACTS) this paper describes the characteristics of the RI emission from different sources in a substation. The description is based on measurements in a large number of HVDC and FACTS installations, both with conventional line commutated converters and with forced commutated voltage source converters (VSC), HVDC Light® and SVC Light®. Suitable methodologies for verification of the RI performance are proposed and justified. Some aspects related to the measurement methodology of outgoing lines and substations are: measurement procedure, measurement distance and number of measurement positions.

The paper finally discusses the various factors to be considered when formulating the RI requirements. One very important aspect is how to define the limits (or combination limit/measurement distance) for a substation with power electronic equipment of high MVA rating.

KEYWORDS

Radio Interference – EMC – High Voltage – HVDC – FACTS – Forced Commutation – Power Electronics - Substation – Measurement

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1. INTRODUCTION

The purpose of emission limits in the radio frequency bands is to provide protection for radio receivers against excessive noise emitted by various kinds of equipment. The emission limits are not justified by the immunity requirements, which serve the purpose of protecting equipment from transmitters that are allowed to transmit at their allocated frequency. Therefore, when defining design criteria and the verification procedure for radio frequency electromagnetic emission from HVDC and FACTS installations, the emphasis should be to manage the risk for radio frequency interference experienced during real operation. It is not the emission level outside the fence but the field levels, for radio frequencies used, at the location of sensitive radio receivers that matters. Elimination of all emission outside the fence would result in significant costs without a corresponding decrease in the risk for radio interference (RI) during operation. Thus, one should consider which frequency bands are used by radio receivers that may be interfered and where they are located. The requirements on high voltage installations also have to be balanced against the RI requirement on other equipment regarding actual interference. It can be mentioned that the broadband power line communication (PLC) being discussed for use in the low voltage distribution systems would cause an RI level inside domestic buildings that is higher than some standards specify for locations 20 m outside the fence of a high voltage substation.

The purpose of this paper is to identify and justify factors that must be considered when defining the design criteria and the measurement procedure for RI from HVDC and FACTS installations. Experience from measurement of the RI emission from a large number of HVDC and FACTS installations is the basis for this work. One such important factor is the "respect distance" between the high voltage equipment and possible radio receivers suffering interference, as the attenuation with distance is very significant close to the source. One other important factor is that power electronic equipment, including HVDC and FACTS, may have very irregular emission amplitude with respect to the frequency. Thus, it is not sufficient to check the emission at one single frequency, the complete frequency range of interest has to be defined and scanned.

The requirements and verification procedures for low voltage equipment such as vacuum cleaners and computers are well established and specified in various standards. Verifications of both emission and immunity are performed in well-screened test rooms under well-controlled conditions. Although, the EMC 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 described in IEC 61000-6-5. However, the conditions for emission and emission verification differ completely between power systems and low voltage equipment, and therefore specific emission standards for power systems are needed. The most important aspects that differ from low voltage applications are:

- All metallic equipment energised to high voltage radiate due to corona and maybe even sparking.
- The physical size of the installation can be very significant.
- For low voltage equipment RI limits are specified for frequencies above 30 MHz. For lower frequencies only limits of noise induced on the power supply cable are specified. For high voltage installations RI limits (combined with the PLC noise limits) cover the full frequency range.
- At HVDC and FACTS installations not only the valves but also all connecting bus-work are radiating due to circulating high frequency currents. Thus, the source of the RI emission is not individual 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.

2. BACKGROUND NOISE LEVELS

The background noise sets a sensitivity limit of receivers, and it needs to be considered for the planning and evaluation of in situ measurements. Figure 1 shows a frequency scan obtained using an EMC test receiver in peak detection mode and with typical EMC measuring antennas.

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.

The spectrum in Figure 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 [1] 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 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.

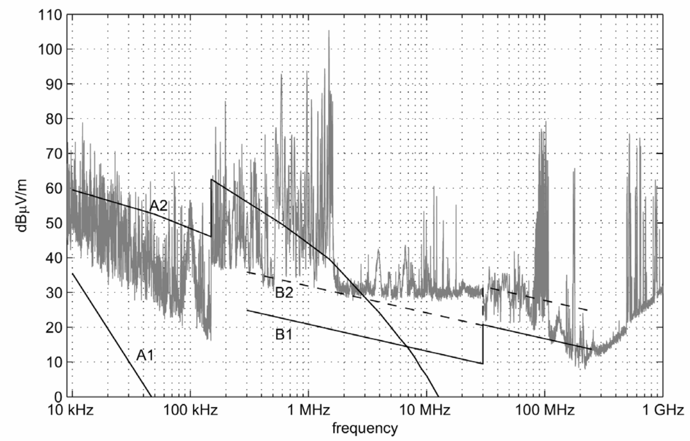

Figure 1. The figure shows the result of a frequency scan with an EMC measurement system, including radio noise curves from Rec. ITU-R P.372-8: A: atmospheric noise, value exceeded 99.5% of time (A1), exceeded 0.5% of time (A2)
B: business area man-made noise, exceeded 50% of time (B1), exceeded 10% of time (B2)

3. CHARACTERISTICS OF THE EMISSION SOURCES

Corona discharge and sparks emit RI fields due to the discharge activity. This is relevant for all equipment energised to high voltage, both lines and substations. The activity may be more pronounced in substations with high concentration of equipment. Disconnectors are critical items. The RI propagations are mostly via direct radiation. However, emission from strong local sources may also propagate via high frequency currents injected into connecting lines. It can be mentioned that the expected corona level increases with the voltage level. The aspects of RI due to corona and sparks are very well covered by the CISPR 18 series. As the broadband RI spectra due to corona are very well defined, the level at 0.5 MHz is used as reference. Sometimes only the RI level at 0.5 MHz is specified.

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 antennas 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. 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.

For schemes utilising forced commutation, such as voltage source converters e.g. STATCOM, HVDC Light® and motor drives, 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 on 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 RI and PLC disturbances, as well as the transient oscillations caused by single commutation events.

The RI due to the commutation process from HVDC and FACTS installations can reach surrounding radio receivers both as direct radiation and as radiation from high frequency currents induced in the connecting transmission lines. As a first approximation within a distance of $\lambda/2\pi$ from a substation, the attenuation of the field strength decreases as $1/r^2$ [2]. For a larger distance, the attenuation is proportional to $1/r$ where r is the distance to the installation. However, at distances smaller than the physical size of the installation, the field level may be very irregular with significant local variation. RI 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 RI criteria regarding the acceptable amount on induced high frequency currents in the line.

The measures employed to reduce RI due to corona are to use better electrode configurations and larger corona rings. CISPR 18 gives good guidance. It is reasonable to think, that equipment, which passes the RIV test defined in IEC 60694, also has an acceptable corona level from an RI point of view. (However, the authors are not aware of any written support for such an assumption.) Measures employed for reduction of directly radiated RI due to the commutation process are based on reduction of the antenna area of the loops with high frequency currents, and shielding. Countermeasures against the high frequency currents induced in the connected lines are RI and PLC filters, effective at high frequency.

The lower RI frequency band, 9 kHz and upwards, also covers the frequency band used for HV line PLC communication (30-500 kHz). It should be noted that RI levels and the PLC noise levels for lines are dependent on each other. For both, the basic criterion is that the additional noise shall not increase the total noise level above the noise level due to corona. This is important for maintaining the signal to noise ratio for the PLC communication. However, PLC and RI filters have to be economically considered, especially for the lower frequency range. For PLC it is obvious that specification of a very stringent PLC noise limit for frequencies not used is an uneconomical solution. The same should be valid also for RI.

As a conclusion, there are measures available for reducing the RI level from HVDC and FACTS installations. However, filters and screening have to be economically evaluated against the benefit.

4. IMPACT SURFACE

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

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

Some general aspects for different equipment and installations regarding impact surface are:

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 and each line occupies a much larger area than a substation. Thus, the lines have a much 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 densely populated areas.
4. The 70-130 kV lines may crisscross densely populated areas.
5. There is a significant number of 10 kV substations, often located very close to 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 surface of these distribution networks is many orders of magnitude larger than the impact surface for 400 kV substations.

It is reasonable that the RI requirements for different items reflect the difference in impact surface: 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 locations. This harmonizes well with the corona emission criteria as per CISPR 18.

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

5. VERIFICATION PROCEDURE

An often-used method is that the measurement positions around an installation are selected along the outer borders of the contour as shown in Figure 2.

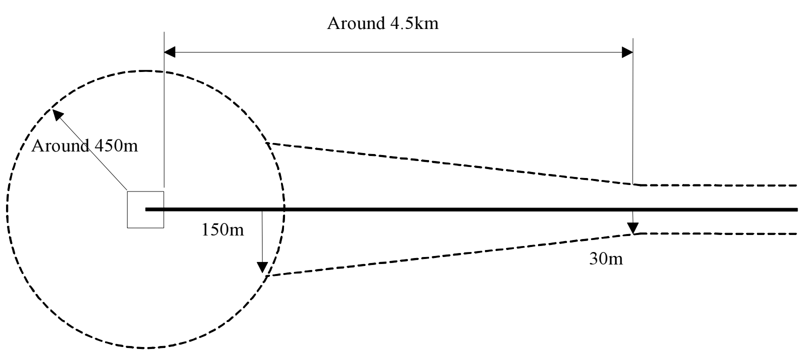

Figure 2. Typical contour curve for RI verification of a substation with connecting line.

According to general praxis, the requirement limit is 40 dBμV/m at the border, and the frequency range is somewhere between 150 kHz – 1 GHz. Some standards state the same requirement limit, 40 dBµV/m, but at a much shorter distance to the installation (e.g. down to 10 m from the fence around the installation). At shorter measurement distance to the source, the limit should be increased to compensate for the attenuation due to distance, see section 3. Above 30 MHz a normal measurement distance is 30 m from the installation. Sometimes requirements exist from 9 kHz and upwards.

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 total RI level in a wider surrounding 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 [2].

Measurements performed too close to the source will give local variations as per Figure 5, and they will not be representative for the total RI emission from the installation. The measurement distance should therefore be greater than the physical dimension of the installation. Measurements should neither 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 generated noise level has to be compared with the background noise level, which is significant in most locations. The background level is obtained when measuring with the installation not in operation, or by performing the measurement at a greater distance to the installation than the propagation of the generated noise.

In some standards the amount of measurement locations is not realistic to fulfil due to the physical dimension of the installation (for example measurements at each 10 m around an installation). Practical issues and the fact that the measurements would be very time consuming will finally limit the amount of locations in reality.

Based on our experience, Figure 2 shows a very good approach for RI verification of an installation. We have found that it is sufficient to measure at four different directions around the substation and at one location at each outgoing line. A measurement distance of 50-100 m may be a better compromise than 450 m regarding signal level and relevance for the more remote surroundings, see Figure 6. The attenuation effect must be considered when defining the limit for the E-field at that measuring distance.

6. MEASUREMENT RESULTS

Several measurements have been performed around HVDC and FACTS installations, both with conventional line commutated converters and with the forced commutated VSC. A frequency spectrum of a typical installation with a line commutated SVC converter is illustrated in Figure 3. The frequency range shown is 9 kHz – 30 MHz and the H-field measured with a loop antenna is given, converted to an equivalent E-field. As seen the converter generated noise is exceeding the background noise level in the frequency range 9 kHz – 3.5 MHz. The step in level at 150 kHz is due to change in bandwidth.

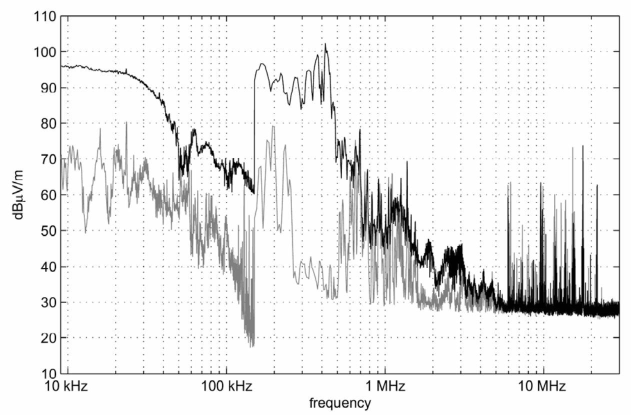

Figure 3. Frequency spectrum about 13 m from building or apparatus of installation with line commutated SVC, measured with a loop antenna. Black – with converter running, grey – background measurement.

A measurement around an installation with a forced commutated VSC is shown in Figure 4, in the frequency range 9 kHz – 30 MHz. Above 30 MHz it is not possible to distinguish the level generated by the installation from the background noise level, therefore no measurement plot is shown in that frequency range.

In close vicinity to large HVDC and FACTS installations, there may be significant local variations as illustrated in Figure 5. At a certain distance from the installation though (when reaching the far field and at a distance larger than the physical size of the installation), the level becomes almost equal in all directions. The attenuation due to distance from the installation is illustrated in Figure 6. At 460 m distances from the converter building, the level could not be distinguished from the background noise level. As seen, several radio transmitters are identified in Figure 5 and Figure 6 in the frequency range 0.54 MHz – 1.6 MHz.

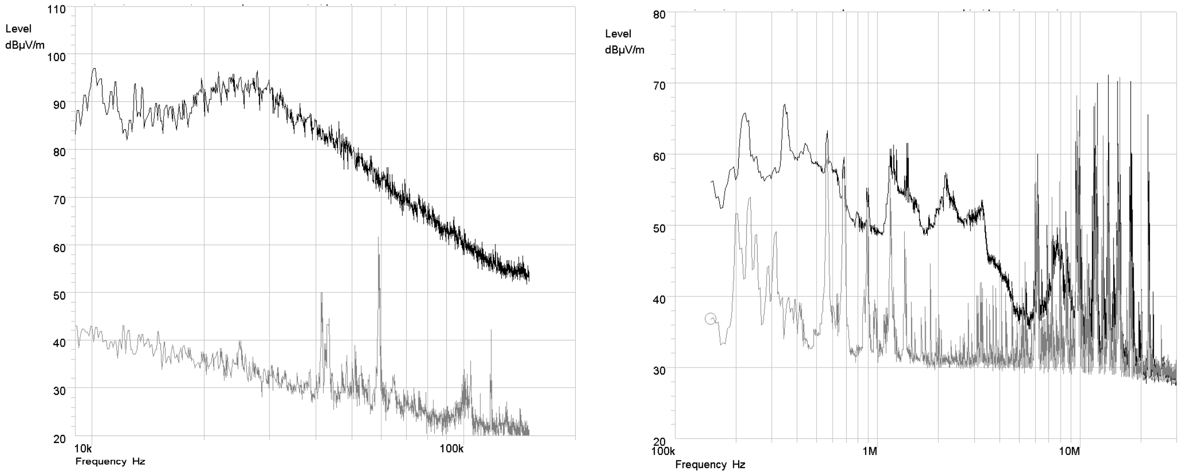

Figure 4. Frequency spectrum around an installation with forced commutated VSC. Measurement with a loop antenna 8 m from the wall of the installation. Black – with converter running, grey – background measurement.

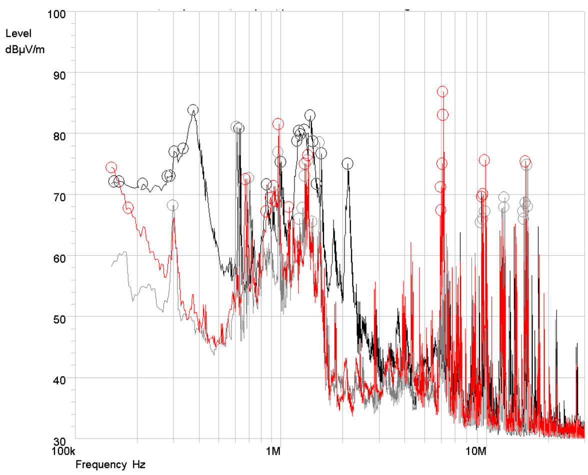

Figure 5. Significant local variations in close vicinity to an installation with a forced commutated VSC. Measurement with a loop antenna in three different positions around installation, 20 m from the wall of the installation.

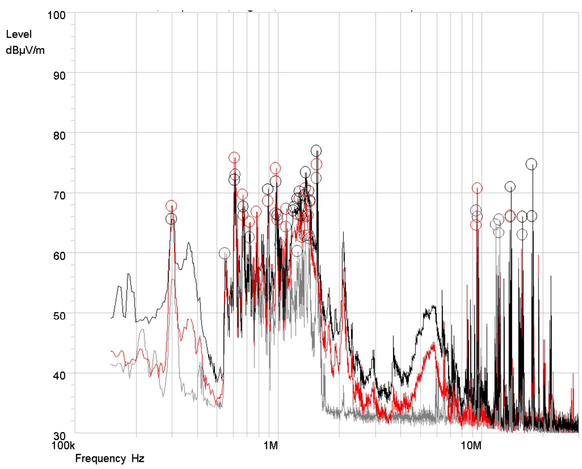

Figure 6. Illustration of the attenuation with distance from an installation with a forced commutated VSC. 50 m (black curve), 100 m (red curve) respectively 460 m (grey curve) from the wall of the installation. Grey curve is identical with the background noise level.

7. DISCUSSION AND CONCLUSIONS

The RI requirements and the RI verification procedures for HVDC and FACTS installations should be related to the risk for realised disturbances of sensitive radio receivers in the surroundings. Furthermore, HVDC and FACTS are installations of significant physical size and connected to HV or MV ac power systems. Thus, the verification of the RI emission levels cannot be verified in a shielded laboratory but only in the field by in situ measurements. This means that the background noise has to be considered in the evaluation process.

Due to the irregular emission pattern from power electronic equipment such as HVDC and FACTS the complete frequency range of interest has to be scanned.

The emission level from an installation must always be expressed as a combined figure defining both the field level and the measurement distance relatively to the active part of the installation. As an example: if a limit of 40 dBμV/m at a distance of 450 m for 0.5 MHz is replaced by a limit of 40 dBμV/m at a distance of 15 m it means that the allowed source must be reduced with about 45 dB or with a factor of about 180, expressed as allowed magnetic moment Am^2 for the antenna [2].

The measurement distance is always a compromise between signal level and relevance for a wider surrounding. The measurement distance should not be shorter than the physical size of the installation. Furthermore, for being relevant, the measurement distance shall refer to the closest active part of the installation. See also the proposal in the last paragraph of section 5.

The RI limits for one type of equipment should reflect the impact surface of that specific equipment, i.e. the number of receivers that could be disturbed if the limit is too high. The impact surface of lines is larger than that of substations. The impact surface of low voltage equipment is larger than that of high voltage equipment. The justification for this is that the number of sensitive receivers close to low voltage lines is much higher than the number of receivers close to high voltage substations.

The limit for a specific frequency range should reflect both the background noise level and the characteristics of the radio traffic using this frequency range. Reasonably, stringent limits should only be required for frequencies used by sensitive receivers in the close surroundings.

There are areas where further investigations are needed.

- The quasi-peak detector specified in CISPR 16 is mainly intended to be representative for analogue AM radio communication. It may not be the best detection principle for verification of RI with more broadband digital radio communication. It is likely that a complementary detection principle is needed for relevant coverage of both narrowband, broadband and radio communication. For being useful for in situ measurements the detector should be able to detect an RI emission in a frequency band with several radio transmitters in the background such as the frequency bands 0.54 MHz to 1.6 MHz and 10 MHz to 20 MHz in Figure 6.
- The RI requirement for an installation is expressed as a maximum field level in μV/m while the corresponding requirement for high voltage equipment in IEC 60694 is expressed as a minimum voltage for the RIV criteria of 2500 μV. Some translation functions for these two worlds should be of value. Probably also the physical size and the amount of equipment play a role.
- CISPR 18 covers mainly RI from HV lines due to corona. There is a need of complementary emission standards for high voltage substation and lines considering also all aspects relevant for RI from power electronics i.e. HVDC and FACTS. Many of these aspects are discussed in this paper.

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