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Impact of Ambient Atmospheric Conditions on Radio Frequency Interference Emission of HVDC Converter Valve Stations

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Abstract

In recent years, advancements in high-power electronics, particularly in High Voltage Direct Current (HVDC) converter technology, have encouraged utilities to opt for HVDC transmission lines to transfer bulk power economically to longer distances. That, due to unique advantages, worldwide, Modular Multilevel Converter (MMC) stations are becoming more popular than conventional converter stations. Recently commissioned HVDC links in India are based on MMC technology. When such an HVDC station is in operation, it emits a spectrum of interference due to the switching operation of converter valves and electrical discharges from other energized high-voltage equipment in the station. These interferences shall be within permissible limits. Direct interference emission from valves is suppressed by valve hall shielding. If it is not properly suppressed, the interference propagates to station equipment and transmission lines as well. These transmitted interferences may affect the operation of vital equipment in the vicinity. To ensure the reliable operation of station vital equipment and validation of station design, interference emission assessment is mandatory. Emissions from conventional converter valve stations were studied and reported in the literature. As MMC technology recently emerged, only a few *in-situ* measurements of interference emission are reported. In this present work, interference emitted from two identical ±320 kV MMC technology-based HVDC converter valve stations and HVDC transmission lines, which are placed at two different ambient atmospheric conditions, are presented. Remarkably, the ambient atmospheric condition of the station has considerable influence on the interference emitted from the station and transmission lines. The influence was predominant at lower frequencies. Moreover, it was observed that the level of interference emission from transmission lines and at a location near the station on the contour of the performance perimeter has distinct characteristics. Apart from the fast-switching operation of MMC, the corona and spark or gap discharges are possible sources of interference emission and are weather-dependent. Stations located in humid weather have more corona discharges compared to the same rated station located in dry weather conditions, which in turn emits more interference. Moreover, the gap discharges are higher under dry weather compared to humid weather. A similar trend was observed in *in-situ* recorded spectra. In the case of HVDC transmission lines, the lines which are passing through humid weather have lower interference levels than that of the same rated line passing through a dry and windy environment. Analysis of the influence of ambient atmospheric conditions on interference emission from two identical ± 320 kV MMC technology HVDC converter stations and HVDC transmission lines are presented.

Keywords: Electromagnetic Compatibility, HVDC Transmission Lines, Interference Emission, MMC Converter Station, Radio Interference, Weather Dependent Interference Emission

1. Introduction

In many developing countries, due to industrial and economic growth, the energy demand has increased considerably. This rise in energy demand necessitates to transfer of electric energy either from generating stations or energy surplus locations to load centres. Utilities are keen on choosing economic options to transfer energy to longer distant load centres. Due to recent advancements in power electronics, for many utilities, High Voltage

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DC (HVDC) transmission is the option to transfer bulk power economically to longer distances.

Modular Multilevel Converter (MMC) based HVDC power transfer is an emerging technology and adopted in many HVDC links around the world recently[1,2]. The MMC-based transmission system consists of an Insulated Gate Bipolar Transistor (IGBT), converter transformer, reactor, etc[3,4]. IGBT has fast switching characteristics compared to conventional and light-triggered thyristors. Due to these fast-switching operations, these IGBTs emit higher amplitude current pulses with a faster-rising edge. These high-speed transient current pulses generate conductive disturbances and a wide spectrum of radiations in the system. The majority of these emit direct radiations which are suppressed by the shielding of valve halls. But, any inefficient suppression of these emissions by valve hall shielding results in the transfer of these interferences into switch yard equipment, and further on to the transmission lines, etc.

MMC-HVDC converter have many sub-modules and each module will contribute to the total radio frequency interference emission from that station. Several sub-modules for a particular converter station depend on the system voltage. These sub-modules with their suitably designed self-shielding are independently in compliance with the requirements of electromagnetic, electrostatic and fast transient/burst immunity. However, assessing the operation as a whole system, electromagnetic disturbance from the station becomes inevitable. If the emitted electromagnetic interferences exceed the maximum permissible limits specified in CIGRE 391, in addition to affecting the operation of nearby equipment, it may disturb the functioning of high-power electronics devices installed in the valve hall itself[5]. Hence, for reliable operation of HVDC converter stations, it is mandatory to suppress the electromagnetic emission using suitable mitigation arrangements. Studies and analyses of interference on conventional HVDC stations are reported in the literature[6]. MMC-HVDC converter station is a new technology and is recently getting commissioned in HVDC stations and very few studies, based on theoretical calculations on radio frequency interference are reported[7-10].

CIGRE 391, in general, characterized the sources of radio frequency interference from substations, and the relative strength of each source along with its dominated frequency ranges. Other than the operation of switching/power electronic devices installed in the valve hall, the discharge activities in the air from installed high voltage electrical equipment at the station, viz. corona, sparking or gap discharge and arcing, have a considerable contribution to interference emission from the substation. Among these three discharge activities, corona and gap or spark discharge are weather-dependent. Corona activities are higher during bad weather, viz. fog or drizzling or humid conditions. On the contrary, the spark discharges under dry weather are higher compared to those under wet weather conditions. These weather-dependent discharge activities make the interference level emission from the station weather-dependent. Arcing is a short-duration activity in a power supply system and is not of concern during analysis of interference emission.

National transmission utility in India has established an 1850 km UHVDC transmission corridor to facilitate the transmission of 6000 MW of power from the northern region to the southern region. This facility involves 1650 km length ± 800 kV, 6000 MW as well as 200 km length ± 320 kV, 2000 MW transmission corridors. Since, 2021 this corridor has been fully functional. Both sending and receiving end stations of ± 320 kV HVDC section of this facility are identical, and are using MMC based converter technology, which is of interest for emission analysis because these 200 km apart ± 320 kV HVDC converter valve stations are geographically located at places having two different ambient atmospheric conditions.

MMC technology in HVDC transmission is the latest and only a few HVDC stations around the world have this technology. However, till today, no *in-situ* measurement results on radio frequency interference emission from this latest MMC technology converter stations have not reported. In addition to the *in-situ* measurement of interference, an attempt is made to analyse the weather dependency on interference emission from, two identical converter valve stations and transmission lines, located in two different extreme weather conditions.

In-situ interference emission is measured as per CISPR 18-2[11] and CIGRE 391[5]. The method of measurement, choice of measurement location, permissible limits, and equipment used for recording interference emission are given in Section II. Recorded interference from two stations and transmission lines and its analysis is reported in Section III followed by conclusions discussed in Section IV.

2. *In-situ* Measurement Methodology

2.1 Method, Antenna, Detector and EMI Receiver Used for Interference Measurement

Radio interference emissions originating from the converter station are measured/recorded at identified

locations around the shielded valve hall and on the route transmission line using an antenna and EMI receiver. As the switching operation of IGBT emits a wide spectrum of radiations, the radiated disturbance is also measured in the wide frequency range. However, in the present study, at very high frequencies, particularly above 1 GHz, no significant variation in the recorded interference emission was observed compared to that of background emission recorded at that measuring location when the converter valves are in OFF condition[5]. Moreover, the interference emission recorded till 1 GHz is sufficient to analyse the characteristics emission from converter valve station. Hence, in the present study, for analysis, the interference is recorded from 150 kHz to 1 GHz frequency range on both stations.

An EMI test receiver along with three different antennas, viz. loop, bi-conical and logarithmic antenna are used to record *in-situ* interference emission. For a single sweep of interference measurement in the frequency of interest, i.e., till 1 GHz, three independent spectra are recorded, in three spans of frequencies, using one of the three antennas independently. The frequency range of each antenna, their height during measurement and bandwidth in each span of measurement used for this *in-situ* measurement is given in Table 1. The antenna specifications comply with the requirement of CISPR 16-1[12].

Table 1. Details of antenna, bandwidth and frequency range of measurement used for interference measurement

Sl. No	Range of Frequency (*MHz*)	Band width (*kHz*)	Antenna to be Used	Height at which the antenna is to be placed (*m*)
1	0.15 to 30	9	Loop	1.75
2	30 to 300	120	Bi-conical	3.5
3	300 to 1000	120	Logarithmic	3.5

In general, the interference emission at lower frequencies will be higher compared to that of other frequencies of measurement interest due to the commutation process of power electronics devices. In many cases, the magnitude and pattern of disturbance recorded in this lower frequency range are the deciding factors on the effectiveness of valve hall shielding. For measurement of interference emission at lower frequencies, till 30 MHz, the loop antenna is used in conjunction with the EMI test receiver. Antennas are polarization/orientation sensitive. To record the interference preciously, the orientation of the antenna is adjusted as guided by CISPR 18-2 in such a way that it will record the actual value of interference emitted.

As per CISPR 18-2, at the location of measurement interest, the loop antenna is placed at 1.75 m in height from the ground on a tripod, and there is a provision to adjust the orientation of the antenna around 360 degrees on its horizontal axis. As stated in CISPR 18-2, the EMI receiver is set to record interference emission at 500 kHz and the antenna orientation is adjusted from 0 to 360 degrees. On the recorded interference from 0 to 360 degrees of orientation, at one orientation of the antenna recorded interference emission will be maximum, that orientation had received maximum value of interference is considered as worst-case polarization of loop antenna and further measurement in this measuring location is performed at that identified worst case polarization of loop antenna only.

The same procedure is followed for bi-conical and logarithmic antennae too. For the bi-conical antenna, at 150 MHz frequency, the orientation at which the receiver reads the highest values of interference is considered worst-case polarization and further measurement at that location is performed in this polarization. For the logarithmic antenna, the worst-case orientation is identified with a 500 MHz frequency. Both bi-conical and logarithmic antennae were placed at 3.5 height from ground level. CIGRE 391 states that the interference must be recorded both on the horizontal and vertical positions of antennas. However, in this present study, interference is recorded with those three orientations of antenna, in the horizontal, vertical and worst case, and the highest interference recorded among the three considered for analysis. The same procedure is applied for measurement at other measuring locations of interest in a converter valve station. For a single sweep of interference measurement from 150 kHz to 1000 MHz, all three antennas are used independently in the designated frequency ranges as given in Table 1. Measured/recorded interference level is represented in dBμV/m against frequency.

Radio interference is recorded using one or a combination of the different detectors of the EMI receiver, viz. RMS, average, peak, quasi-peak, and CISPR average, etc., as per requirements. Each detector has its independent characteristics and is used for specified measurements. As specified in CISPR 18-2 and CIGRE 391, the radio interference is to be measured with either a Quasi-peak detector peak detector or a combination of these two detectors. Interference measurement with a Quasi-peak detector with linear frequency steps in the span of 150 kHz to 1 GHz consumes more time than that of other detectors

and getting such a long shutdown time of the station for background measurement is challenging. At the same time, measurement with a peak detector will be faster and less time-consuming compared to other detectors. For the same bandwidth, the peak detector reads a higher value than that of the quasi-peak detector. Hence, for accurate measurement, as suggested in CISPR 18-2 and other literature, the measurement is performed with a peak detector and on the measured spectrum, peak search is performed using a Quasi-peak detector[11]. This combination will reduce the overall measurement time.

R&S-made ESR 3 model of EMI test receiver is used for interference measurement in this present study. This receiver follows the requirement of CISPR 16-1 and CIGRE 391 for RI measurement in the frequency range of 9 kHz to 3.6 GHz[12]. The EMI receiver used for this measurement is calculated as per CISPR 16-1 in an ISO/IEC 17025-certified laboratory.

At one identified location, Radio Frequency Interference (RFI) is recorded in two different conditions of converter valves, viz. with converter valves ON and OFF conditions. During ON condition, out of two poles of the station, one pole is energized at its full capacity along with reactive power, e.g., 1000 MW with 330 MVAr capacitive load for this HVDC station. Another pole is compensated with inductive load, e.g., at 330 MVAr. Interference emission measured during the OFF condition of converter valves is considered as background emission at that location.

2.2 Selection of Measurement Location

Based on the station operating voltage level, CIGRE 391 has tabulated, the radius of performance perimeter, *d1*, along which the emission shall be less than the specified maximum permissible limit. Identified measuring points for ±320 kV converter valve station are shown as a schematic representation in Figure 1[5]. Identified value of d1, $d2 = d1/3$, and d3 is 200 m, 66.7 m, and 50 m to 60 m (at 1 km distance), respectively[5].

In this present study, a comparison of interference emission from two identical stations located at two different ambient atmospheric conditions, measuring points for both stations are also chosen identically. These points are earmarked as MP1 and MP2 in Figure 1. To measure the emission en route to the transmission line, location MP3 is chosen at a 1 km distance from the energized part of the valve hall. In all three measuring points, interference emission was measured in the frequency range of 150 kHz to 1000 MHz with HVDC converter values in ON and OFF conditions. Photograph of antenna arrangement for RFI measurement at different measuring points, viz. MP1 to MP3 is shown in Figure 2.

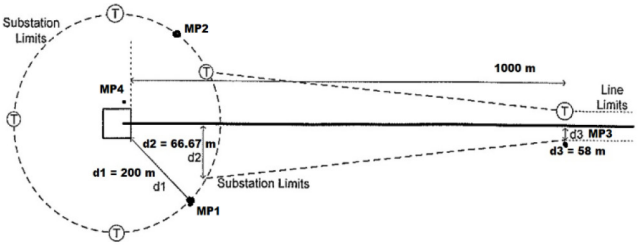


Figure 1. Schematic representation of the location of measuring points for ±320 kV HVDC converter station as per CIGRE 391[5].

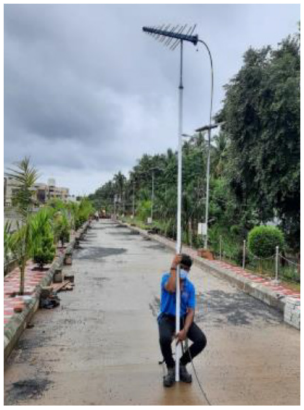


Figure 2. Photograph of logarithmic antenna arrangement for interference measurement at the station located in the humid weather environment.

2.3 Maximum Permissible Limits of Interference Emission

CIGRE 391 has specified maximum permissible limits of RFI emission from a substation based on their power rating and operating voltage levels. For stations operating in the voltage range of 251 to 420 kV with 1000 MW capacity, CIGRE 391 has specified the maximum permissible limit[5]. Following these guidelines, the utility has earmarked the permissible interference emission from ±320 kV HVDC stations for the frequency range from 150 kHz to 1 GHZ as given in Table 2. Measured interference emission at any ambient atmospheric conditions shall be within this permissible limit and any deviation requires proper precautionary measures to reduce the interference within the permissible limit.

Table 2. Specified maximum permissible limits of interference emission of ± 320 kV HVDC converter valve station

Sl. No.	Frequency (MHz)	Specified Maximum permissible limit of interference emission from HVDC station in line with CIGRE 391(dBμV/m)
01	0.10	90.0
02	0.15	117.8
03	1.00	93.1
04	30.00	84.3
05	230.00	86.3
06	1000.00	86.3

2.4 Ambient Atmospheric Conditions of Chosen HVDC Converter Stations

Chosen HVDC converter stations for interference measurement have identical voltage levels, designs, technology, equipment, and construction and are located at 200 km distance from each other. Station I, is located at a place, where the relative humidity, varies from 85% to 90%. Average annual rainfall and number of rainy days are 386 mm and 245.91 days, respectively[13]. Measurement was performed during monsoon season and it was drizzling during measurement. It was observed during measurement, that waterdrops precipitation all around the energized parts of the station. A satellite view of Station I, located in humid weather conditions, is shown in Figure 3[14]. On the contrary, the other station, Station II, is located in a dry and windy environment with an average rainfall of 132.36 mm and 148.44 days, respectively[13]. It is a windy area, due to which a few windmills are also installed around the HVDC converter station. Average relative humidity is in the range of 60% to 65%[13]. When the measurement was performed, it was clear, windy, dry and sunny weather. A satellite view of HVDC Station II, located in a dry-weather environment, is shown in Figure 4[14]. Stations are in two different weather conditions.



Figure 3. Satellite view of Station I, located in a humid and wet environment[14].



Figure 4. Satellite view of Station II, located in a dry and windy environment[14].

2.5 Characteristics of Sources of Radio Frequency Interference (Interference Emissions)

In an electrical power supply system, there are several sources of radio frequency interference emissions. High-frequency current pulses emitted during the commutation process of high-power electronic equipment, viz. HVDC converter valves and FACTS are among the major contributing sources[5]. Other considerable contributing sources are corona and sparking or gap discharges of switchyard equipment[5]. The relative frequency spectra of interference emission from some influential contributing sources of electric power systems are shown in Figure 5. Among possible sources, corona and sparking or gap discharge, i.e., electrical discharge activities in energized substation equipment, are weather-dependent. In foul or humid weather conditions, the corona is approximately 10 times higher than that in good weather conditions[5]. Though the corona emission is prevented by adopting proper size conductors and accessories, for this operating voltage level when the substation is energized, the corona discharges from other equipment are inevitable. This is due to the compact placement of station equipment in the switchyard and other energized high-voltage equipment/ accessories. Both chosen stations have having open switchyard, and weather-dependent corona discharge will influence the level of interference emission from stations. As given in Figure 5, corona discharge is one of the contributing factors of interference emission in the frequency range from 0.1 MHz to about 12 MHz.

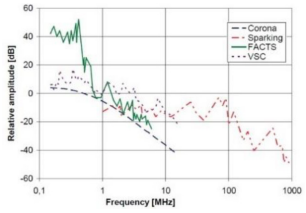


Figure 5. Sources of interference emission and its relative frequency spectra[5].

The electrical breakdown between two metallic contacts is referred to as sparking or gap discharge. Non-conducting parts of transmission lines or fittings of substations or nearby metallic fences, when exposed to a strong electric field may experience sparking. The occurrence of sparking is weather-dependent. In wet weather, as the water molecules/particles bridge the gap between two contacts the probability of sparking at that gap reduces considerably. But in dry-weather environments, more gap discharge activities are observed. CIGRE 391 has reported that 15 dB higher radio interference emission is recorded in dry weather conditions than that of the same station located in a humid or foul weather environment. Moreover, the gap discharge is the source of interference emission in the entire frequency range from 1 MHz to 1000 MHz.

Operation of FACTS devices, viz. static VAR compensators, which use thyristors, commutation and control of these reactive power compensation devices is another source of RFI emission, particularly in the lower frequency range from 0.1 MHz to about 12 MHz[5]. The commutation of high-power electronic devices also contributes to interference emission in the frequency range from 0.1 MHz to about 12 MHz[5]. These RFI emissions from the commutation of power electronic devices, which were installed in shielded valve hall and are not weather dependent.

For analysis of interference emission at a particular location, the emission has to be recorded with converter valves in ON and OFF conditions. Recorded emissions during the valves in OFF condition are considered background emissions of that particular location. This background emission depends not only on the energization of the HVDC station of interest but also on other possible sources of RFI emissions nearer to that station, viz. mobile communication base stations, towers, other vital communication devices, radio stations, nearby transmission lines, etc. For any analysis, background interference at that location during measurement is mandatory and it is possible only by *in-situ* measurement. Hence, in the present study, all the interferences are recorded in *in-situ* only. This background interference varies with operating conditions of nearby possible sources, to avoid this variation, interferences are recorded more-or-less at same the period and environmental conditions.

To characterize /identify the sources of interference emission from the HVDC station more preciously, in the present study, in addition to regular measurement at MP1 and MP2, *in-situ* emission measurement was performed at 1 m distance from the HVDC station fence, with converter valves ON and OFF conditions. Using a loop and bi-conical antenna, the interference is recorded from 150 kHz to 300 MHz frequency range in two sweeps. The arrangement of the loop antenna near the station fence for the characterization of the interference source is shown in Figure 6. An overlapped screenshot of the recorded interference emission of the EMI receiver using a loop antenna in the frequency range from 150 kHz to 30 MHz with converter valves in ON and OFF conditions at the specified time instant and more-or-less similar environmental conditions, is given in Figure 7.

In the screenshot shown in Figure 7, the yellow colour spectrum line represents the radio interference, emission measured using a peak detector and the red colour '+' symbol indicates the obtained peak search in the recorded spectrum using a quasi-peak detector[12]. As mentioned, to reduce measurement time, interference is recorded using a peak detector and peak search on the acquired spectra is performed with the quasi-peak detector. The x and y-axis in the screenshot are frequency (MHz) and magnitude of RFI (dBμV/m), respectively.



Figure 6. Loop antenna placed at 1 m distance from station fence to characterize the sources of RFI emission.

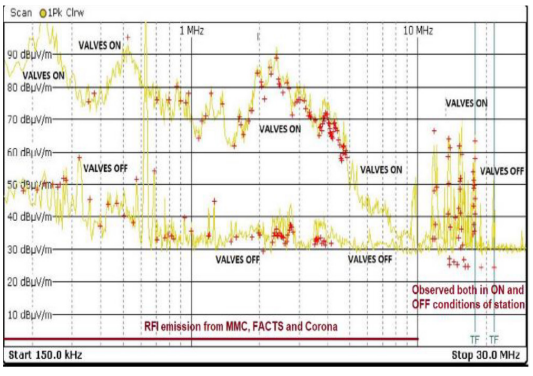


Figure 7. Overlapped screenshot of interference emission recorded at 1 m distance from station fence using loop antenna from 150 kHz to 30 MHz frequency with converter valves in ON and OFF conditions.

It is evident from Figure 7 that, when valves are ON, a higher value of RFI is recorded, viz. 107.58 dBμV/m and 92.93 dBμV/m at frequencies 222 kHz and 526 kHz, respectively. These higher values are due to inevitable corona discharges and commutation of power electronics devices, viz. FACTS and MMC. Some spikes were observed around 10 to 20 MHz frequency both in the ON and OFF condition of converter valves. This is due to discharges from switchyard equipment. These spikes were not observed, on the recorded interference emission at en route of transmission lines. When the HVDC station is not in operation, a nominal magnitude of interferences is observed in these frequencies. These nominal values may be due to electrical discharges from energized switchyard equipment.

At the same location, using a biconical antenna, the emission is recorded from 30 MHz to 300 MHz with converter valves in ON and OFF conditions and a screenshot of overlapped spectra of recorded interference is shown in Figure 8. It is evident from the recorded emission that, in the 40 to 50 MHz range and at around 200 MHz, a marginal difference is observed. As per CIGRE 391, the emission at this frequency is due to spark discharges. As the measuring point was located close to the station's fence, though the station is newly commissioned, some discharge activities occur when the valves are ON and the station is energized.

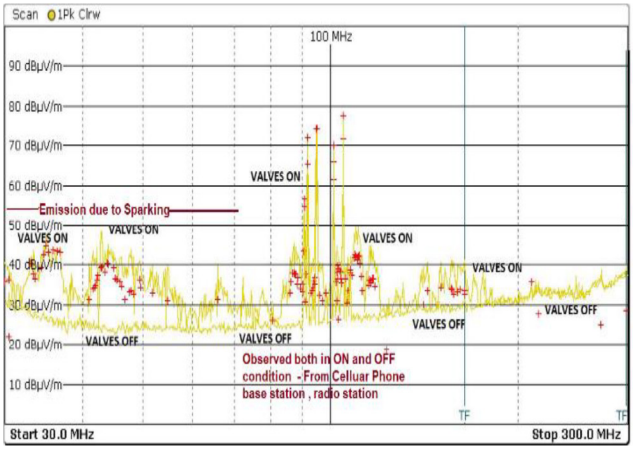


Figure 8. RFI was recorded at a 1 m distance from the station fence using a Bi-conical antenna in 30 to 300 MHz with converter valves ON and OFF condition.

Further, some spikes were observed around 80 to 100 MHz during both conditions of converter valves, this is due to the operation of nearby cellular phone base stations, and radio stations[15]. The radio station was in operation by turning the radio receiver to that band of frequencies. At higher frequencies, from 300 MHz to 1000 MHz, recorded spectra with converter valves in ON and OFF conditions were more-or-less similar, i.e., at higher frequencies the contribution from station operation on interference is negligible, whatever recorded is from operation of external sources. It is observed that the trend of emission recorded from the station is in line with the pattern given in Figure 5.

3. Analysis of *In-situ* Radio Interference Emission Recorded

3.1 Interference Emission Recorded at 200 m Distance Ffrom Energized Parts of Valve Station Along the Contour Performance Perimeter

Interference emission from MMC technology-based, two-pole, bi-directional ±320 kV HVDC stations having the facility to exchange a maximum of 1000 MW of power per pole and are located 200 km apart in two extreme weather conditions, viz. humid and dry, is considered for analysis. When the stations are operated at their full capacity, one pole of the stations will be energized at 1000 MW power with 330 MVAr capacitive load and consequently, another pole is compensated with 330 MVAr inductive load. Both stations have newly commissioned necessary electrical equipment along with switchyards nearby. Irrespective of condition converter valves, ON or OFF, part of essential electrical equipment along with its switch yard will be in energized condition.

To analyse the impact of ambient atmospheric conditions, interference emissions around both stations are independently recorded, in the frequency range from 150 kHz to 1 GHz, with converter valves in ON and OFF conditions. Emission is recorded at three identified measuring points as shown in Figure 1, viz. at 200 m distance from energized parts of a valve station on both sides along the contour of performance perimeter and third one on the route of transmission line at 1 km distance from the station. After carefully analyzing the emission for a week duration at a particular measuring location, a time slot is identified, during which the emission is more-or-less similar and has lower as well as a consistent contribution from other possible sources of interference, which are not in our control, viz. operation of the nearby radio station, cellular phone tower base station, FM radio broadcast, and operating conditions of nearby switchyard, etc. Actual emissions were recorded at the identified time slots only. This procedure is followed

for all measurements at both stations and all identified measuring points. A combination of peak and quasi-peak detectors was used for emission measurement. As discussed earlier, repeated measurements were performed by placing the antenna in different polarizations, viz. vertical, horizontal and worst-case polarization. Spectra with a higher level of interference observed at the respective locations are considered for analysis. For ease of analysis, screenshots of recorded emissions at stations located in two different extreme weather conditions are overlapped, on the yellow colour represents the magnitude of emission recorded using the peak detector and the '+' symbol represents identified peaks in recorded emission by using the quasi-peak detector.

A direct screenshot from the EMI receiver on interference recorded at stations located in dry and humid weather environments is given in Figures 9 and 10, respectively. Using a loop antenna, in an identified time slot, at a 200 m distance from energized parts of the station on one side along the contour of the performance perimeter, the emission is recorded in *in-situ*. When recording the station is operating to its full capacity with required compensation at an alternate pole. Overlapped screenshots of emissions recorded from humid and dry weather conditions from 150 kHz to 30 MHz are shown in Figure 11. As described earlier, the design, technology, equipment used and its arrangement and voltage level are identical, except they are in two different weather conditions.

For analysis, overlapped *in-situ* interference emissions recorded from stations located in two extreme weather conditions are divided into a few regions in line with source characteristics as shown in Figure 5. At the outset, it is evident that the pattern of recorded emission from stations is more-or-less similar and has considerable magnitude difference, particularly at lower frequencies. From 200 kHz to 1 MHz frequency range, interference emitted from stations located in a humid weather environment is about 17 dBµV/m higher compared to that of other stations. At this frequency range, apart from the commutation of power electronics devices, corona discharges are the major contributing factor. For a station located in humid weather conditions, till few MHz frequencies, apart from common factors, a major source for emission is from corona discharges. In humid weather, the water droplets deposited on the surface of energized equipment will modify the electric field significantly and create more corona discharges. Though the operating voltage levels of both stations are the same, these modified fields make discharges happen even at operating voltages. If the ambient conditions are normal, both stations may have more or less the same pattern of emission except for the contribution of other sources about that geographical position.

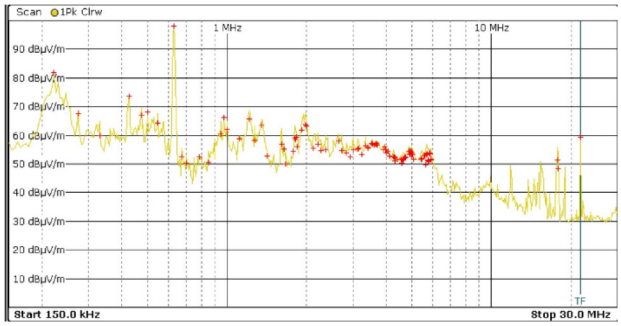


Figure 9. Screenshot of *in-situ* interference emission recorded when converter valves are ON using loop antenna at 200 m distance from energized parts of HVDC station located in dry weather environment.

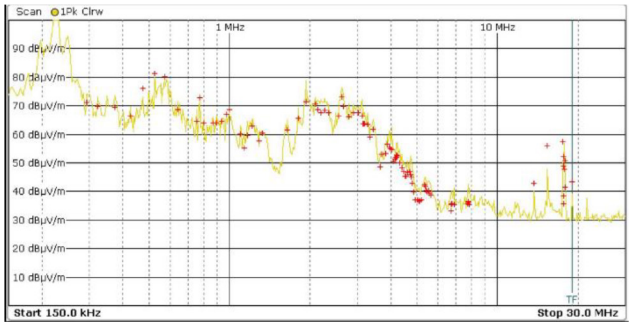


Figure 10. Screenshot of *in-situ* interference emission recorded when converter valves are ON using loop antenna at 200 m distance from energized parts of HVDC station located in the humid weather environment.

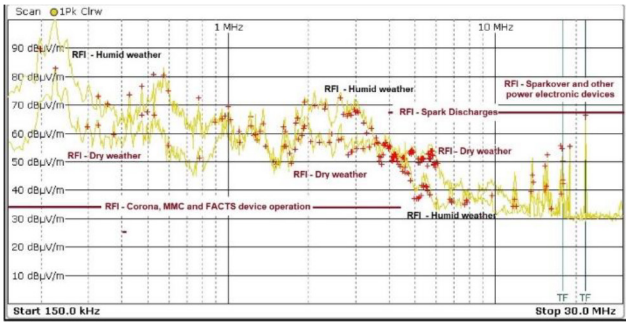


Figure 11. Overlapping screenshot of *in-situ* interference emission recorded from an HVDC station located in a dry and humid weather environment.

Above 1 MHz frequency, in addition to corona and commutation of devices, the spark over is also contributed. The fog or water droplet of humid weather bridges the potential sources of gap discharges and consequently, the emission due to bad metallic contact or other spark over places becomes null. It is evident from Figure 11 that, the emitted interference

from stations located in humid weather started decreasing from 3 MHz and after about 12 MHz, the magnitude and pattern of emitted interference from both stations are more-or-less similar. The trend of recorded interference from both stations at the same operating conditions follows a similar trend reported in the literature. In both stations recorded interference emission at this frequency range, i.e., till 30 MHz, is less than the maximum permissible limit specified in Table 2. From recorded interferences, it is evident that the weather conditions of the station have a definite impact on the intensity of interference emissions, it is proposed to have weather weather-dependent maximum permissible limit while deciding the limits of interference level emission from converter valve stations.

It is also observed from spectra of *in-situ* emission recorded from two stations located in two different weather conditions shown in Figures 12 and 13, that the trend and magnitude of emission are almost identical from the 30 MHz to 1000 MHz frequency range and no noticeable difference was found. The few spikes observed around 100 MHz from both stations are due to the operation of nearby cellular phone base stations. Similarly, the spikes observed in spectra from 850 MHz to 1000 MHz are from broadcasting and mobile communications[15]. It is evident from in-site measurement of emission at both stations that the emission at higher frequencies is not influenced by weather conditions.

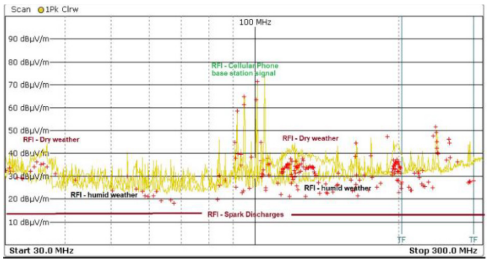


Figure 12. Overlapped screenshot of *in-situ* interference emission in 30 MHz to 300 MHz frequency from HVDC station located in dry and humid weather environment.

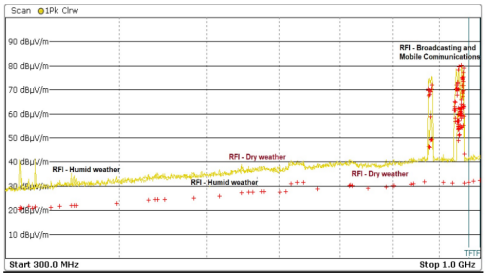


Figure 13. Overlapped screenshot of *in-situ* interference emission in 300 MHz to 1 GHz frequency from an HVDC station located in a dry and humid weather environment.

3.2 RFI Measured in Route of Transmission Line at a 1 km Distance from Converter Station

The effectiveness of the converter valve hall shielding on suppression of disturbances emitted from commutation of converter valves and other high-power electronic devices is assessed by performing RFI measurement at a 1 km distance from the valve hall building on the route of the transmission line[5]. In an HVDC system, an inefficient/improper shield of the valve hall injects high-frequency current pulses originating from the commutation process of high-power electronics devices into the busbar of the switchyard through established high-voltage connections. These high-frequency current pulses and energized bus structure combinedly act as a magnetic dipole antenna and emit interferences. Additionally, from the switchyard, some fraction of these high-frequency current pules will penetrate further as guided waves into transmission lines. To assess the effectiveness of shielding valve halls the *in-situ* interference emissions from transmission lines are recorded.

As with other measuring points on the contour of performance perimeter, the maximum permissible limit specified in Table 2 is applicable for emission from transmission lines also. If the valve hall shielding is effective or sufficient, then the magnitude of emitted interference will be smaller, on the contrary, if the shielding is not properly designed, the magnitude of radiated emission will be higher. In this work, as with interference measurement in an HVDC station, en route to the transmission line also the emission is recorded with converter valves in ON and OFF conditions, following the same procedure. For HVDC lines the main sources of interference emissions are corona discharges at the conductor surface, discharges from some portion of insulators which are highly stressed, spark discharges from imperfect or lost contacts, design parameters of transmission line, surface voltage gradient or line voltage, polarity and weather conditions[16]. Only a few theoretical studies are available in CISPR 18-1 on interference emission and characteristics of sources of emission from HVDC transmission lines. Photographs of the localization of the loop antenna at a 58 m lateral distance from the transmission line passing in humid and dry weather environments are shown in Figures 14 and 15, respectively. *In-situ* interference emissions recorded from respective locations are shown in Figures 16 and 17.

It was observed from recorded emissions that, under similar operating conditions, i.e. when converter valves are

in ON conditions, a higher level of interference magnitude was observed from a line passing in dry weather conditions than that of one passing in wet weather conditions. Normally, water drops form on the surface of HVDC conductors passing through humid weather conditions. In general, with the influence of an electric field, these water drops deposited on the conductor's surface will deform and become a pointed object. This deformed pointed water drop produces corona at a value of electric field much lower than the surface electric field in fair weather conditions. The electric field required to produce corona at fair weather is around 25 kV/cm, but, if water drops are present, the corona appears at about 10 kV/cm electric field range itself. This pointed water drop corona, in humid weather, ionizes the air around the surface of the transmission line and due to this considerable quantity of space charge will be produced. This space charge forms an ion cloud around the conductor, consequently, the surface gradient of the conductor becomes much lower than the corona onset field, which is required to produce a corona from a deformed water drop. Now the surface gradient is lower and hence, there will not be any corona discharges from the line and thereupon, the level of interference emission will also decrease. However, at the beginning of drizzling or precipitation of snow, for a short time, it seems the interference level increases due to humid weather, but once the space charges are produced, then the conductor is fully covered with a uniform ion cloud, which reduces corona discharges, indeed the level of interference emission will also decrease.

It is also observed that the level of interference emission from HVDC conductors varies with wind speed and its direction, either from positive conductor to negative conductor or vice-versa. During onsite measurement, to get more-or-less repeatability on the level as well as the pattern of interference at particular time slots, the measurements were repeated many times. From many recorded spectra, it was observed that the wind speed has a considerable influence on the level of emission. If the wind speed is high the interference level is high and vice-versa.

In a bipolar HVDC transmission line, either on positive or negative conductors, a thin layer of respective ions forms around that conductor. When there is no sufficient wind, this layer acts as a uniform ion cloud of space charge around the conductor, as a result, the surface gradient of the conductor becomes lower than the corona onset value. This lower value of the surface gradient is not sufficient to induce corona discharge from conductors. The absence of corona discharges from conductors reduces the interference emission level. On the contrary, if the high-speed wind flows around the line conductors, formed thin layer of ions will move away from the conductor and there will not be any space charge around that, which results, in the surface gradient of the conductor increasing, on many occasions, this gradient is sufficient to initiate a dry corona discharge from conductor surface. This discharge increases the level of radio interference emission from the conductor during the windy season or when high-speed wind passes around the line. Though repeated measurements were performed, due to the random nature of phenomena and variation of meteorological conditions, it was not possible to correlate the changes in the level of interference emission with wind speed. It is observed from Figure 17 that the recorded *in-situ* interference level from lines located under dry weather conditions is higher compared to that of identical lines passing through humid weather conditions.



Figure 14. Arrangement of loop antenna on the route of transmission line at 1m distance from HVDC station located in humid weather environment.



Figure 15. Arrangement of loop antenna in dry weather and windy environments at 1m distance from HVDC station for recording emission from transmission line weather environment.

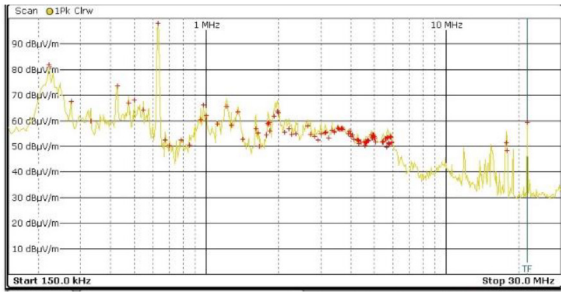


Figure 16. *In-situ* interference recorded from transmission line passing through humid weather environment with converter valve in ON condition.

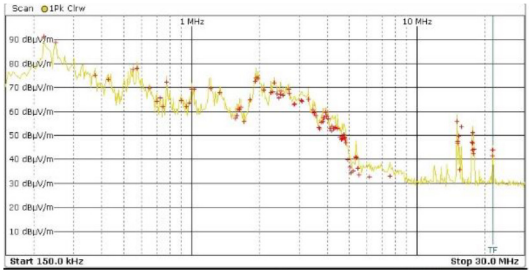


Figure 17. *In-situ* interference was recorded from the transmission line passing through dry weather and windy environments with the converter valve in ON condition.

4. Conclusions

Interference emissions from two ±320 kV Modular Multi-level technology HVDC converter stations, which are identical in voltage level, design, technology and equipment used, located at two different weather conditions, humid and dry, are recorded at *in-situ* as per CISPR 18-2 and CIGRE 391. From recorded emissions, possible sources of interference along with their characteristics were analysed. It was found that apart from the fast-switching operation of high-power electronic devices, the electrical discharges, viz. corona and spark or gap discharges from energized HV equipment are among the main sources of radio interference emission from HVDC converter stations. Each source, viz. commutation of electronic devices and discharges, is dominant in a particular range of frequencies. On that, interference emissions due to electrical discharges are weather dependent and the intensity of emitted RFI emission varies with weather conditions.

It is evident from recorded emission spectra of both stations operating at similar conditions that a difference of 17 dBµV/m in interference emission was observed between stations located in dry and humid weather environments. This weather-dependent interference emission is predominant at low-frequency levels, but, at higher frequencies i.e., above 30 MHz, a negligible difference was found. It is also observed from recorded *in-situ* interference spectra that, the influence of weather is negligible at higher frequencies. Levels of emission recorded at various locations as per CIGRE 391, were found within specified maximum permissible limits. As the weather condition has a considerable influence on emission levels at lower frequencies, while designing/deciding the equipment and technology for HVDC stations, the weather condition of the locality is also to be considered. Moreover, in this work, interference emissions from HVDC transmission lines were also presented and the influence of possible weather conditions, viz. wind speed and humidity, particularly deposition of water drops on the surface of the conductor were analysed. Due to the random nature of phenomena and meteorological conditions, quantization of the influence of weather conditions with interference emission from HVDC transmission lines was challenging. However, identification of the influence of other parameters, particularly, the condition of conductor surface and sparking from a portion of insulators were highly stressed, damaged/imperfect hardware, sparking due to losing contacts, etc. are in the future scope of work.

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