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Calculation of Audible Noise and Radio Interference for Unconventional High Surge Impedance Loading (HSIL) Transmission Lines

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***Abstract-* Corona discharges cause power loss, audible noise (AN), radio interference (RI), and television interference (TVI), all of which should be considered during transmission line design. Unconventional high surge impedance loading (HSIL) lines have been shown to have the potential to produce greater natural power than conventional lines and conventional HSIL lines. More than one conductor is used in conventional extra high voltage (EHV) lines, typically more than 300 kV, to form bundled conductors which reduce the electrical field on the subconductors and, as a result, reduce corona effects. In conventional lines, the number of subconductors symmetrically placed on a circle and bundle radius are determined based on corona effects considerations. Using a larger bundle circle and increasing the number of subconductors lead to greater natural power, resulting in conventional HSIL lines. Therefore, in conventional HSIL lines, bundled conductors are used not only to address corona effects but also to increase natural power. Using smaller conductors for conventional HSIL lines keeps costs close to conventional lines. In conventional HSIL lines, subconductors are still symmetrically placed on a circle while unconventional HSIL lines have subconductors placed at any point in space. Unconventional HSIL lines can lead to more natural power than conventional HSIL lines. In this paper, AN and RI for unconventional HSIL lines are calculated and discussed.**

I. Introduction

Corona discharges in the air are caused by the partial breakdown of air around high-voltage conductors, resulting in various problems such as corona loss, audible noise (AN), radio interference (RI), and television interference (TVI).

Corona discharges produce positive and negative charges that are alternately attracted and repelled by periodic polarity reversals. The sound-pressure waves produced by their movements have frequencies from twice the power frequency to about 20 kHz [1]. AN level also rises in amplitude during bad weather. Studies show that nearby residents around high-voltage lines may suffer from insomnia caused by AN. By keeping the AN level below 52.5 dB or lower, this problem can be dealt with as given by the Perry Criterion.

Receivers on radio stations detect noise from corona discharges on transmission lines, causing RI problems. This will occur if receivers are not located at a distance where noise becomes lower than a threshold.

The load flow pattern of some lines has changed significantly as a result of deregulation, uncoordinated long-term planning for expansion of the generation and transmission sectors, and the inclusion of renewable resources in some places, resulting in some lines being overloaded and others working below capacity. With these factors coupled with delayed investments in the transmission sector due to deregulation, the U.S. power system is very close to reaching its maximum loadability and stability margins. A recent study has also shown that to reach net-zero emissions in America by 2050, the transmission capacity has to increase by about 60% by 2030 and triple by 2050, to connect further wind and solar energy resources to the US power grid [2]. Considering the restrictions and targets mentioned above, it is necessary to increase transmission lines' power delivery capabilities. Therefore, the power delivery capability of EHV AC transmission lines must be increased. This goal has traditionally been achieved by incorporating capacitor banks in series and shunt, which can decrease line reactance and inject reactive power, respectively. This results in increased transient stability and voltage-drop limits. However, this solution would be costly [3].

High surge impedance loading (HSIL) lines may have the potential to naturally increase power delivery capability without conventional reactive compensation apparatuses [3]. HSIL line designs can be divided into conventional HSIL lines and unconventional HSIL lines. An unconventional HSIL line has an irregular arrangement of bundled subconductors in space as opposed to conventional HSIL lines that place subconductors symmetrically on bundle circuits.

To realize these new unconventional HSIL line designs, many design criteria would need to be met, including corona discharge effects. So, accurate estimation for AN and RI, targeted in this paper, is necessary during the design phase. If the electric field on and around the surface of subconductors increases above a specific threshold value which is determined from the corona onset gradient, the effects of corona become greater than acceptable levels. As a result, it is crucial to calculate the surface electric field accurately. We accomplish this by employing a new method we presented in our other paper [4].

In this paper, the AN and RI of unconventional HSIL lines are calculated and discussed.

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II. METHOD

A. Line Model and Design

Designing an unconventional HSIL line requires various constraints to be met, which initially lie on the maximum surface electric field strength, E_{max} limited by the corona onset gradient. For dry air at atmospheric pressure, the breakdown level is approximately 30 kV/cm. With this under consideration, the threshold for the surface electric field is often set at 20 kV/cm during the design stage [5].

B. Audible Noise (AN)

The audible noise from overhead line corona discharge comprises two components: a 120 Hz hum and a broadband component. The generated AN depends on the conductor surface voltage gradient, the number of subconductors in the bundle, the diameter of the conductor, atmospheric conditions, and the distance between the conductor and the point of noise measurement. Additionally, AN is perceived to have a greater impact during night-time when the sound decibel level is lower. According to the defined "Day-Night Criterion", the AN level limit is set to be 55 dB. The sound pressure level (SPL) is the noise level relative to a reference pressure level of 20 μPa and is found in dB by

$$SPL\ (dB) = 10\log_{10}\left(\frac{SPL}{20\times10^{-6}}\right) \quad (1)$$

The L_{50} level is the reference noise level that is exceeded during rainfall or bad weather for half a year (or a certain period). For the L_5 level, the limit is exceeded only 5% of the time. The BPA developed a formula for calculating the AN level. For N, the number of subconductors, less than 3, it is

$$AN(n) = 120\log_{10}E_{am}(n) + 55\log_{10}d - 11.4\log_{10}D(n) - 115.4\ \ dB \quad (2)$$

For N more than 3, the formula becomes:

$$AN(n) = 120\log_{10}E_{am}(n) + 55\log_{10}d - 11.4\log_{10}D(n) + 26.4\log_{10}N - 115.4\ \ dB \quad (3)$$

where n refers to the n-th phase, $E_{am}(n)$ is the mean of the maximum electric field on subconductors of the n-th phase, d is the subconductor diameter in cm, and $D(n)$ is the distance of the testing point to the n-th phase in m. The AN values for phases are then added to obtain the AN level for the line. Eqs. (1) and (2) are valid for conventional EHV lines from 230 kV to 1500 kV with $N \leq 16$, and for subconductors having diameters between 2 and 6.5 cm.

C. Radio Interference (RI)

According to the classification of corona discharges as glow and streamer types, only the latter causes RI between 0.5 and 1.6 MHz while the former causes power loss. This is due to pulses that are formed because of electron avalanches during corona discharge. When designing EHV overhead lines, the right-of-way (ROW) should be determined by examining the lateral RI profile as shown in Fig. 1. RI can be estimated by empirical formulae made by applying data gathered by many countries. One of them is the CIGRE formula.

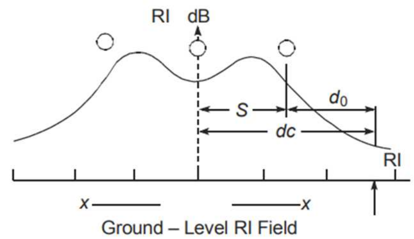

Fig. 1. Lateral profile for RI for a 3-phase line.

It shows that RI is dependent on conductor radius, maximum surface voltage gradient, distance from the conductor to the point of measurement, frequency, and weather conditions. RI for a particular conductor, i, is found as:

$$RI_i(dB) = 3.5g_m + 6d - 33\log_{10}\frac{D_i}{20} - 30 \quad (4)$$

where g_m is the effective maximum surface voltage gradient in kV/cm, d is the conductor diameter in cm, D_i is the distance from the point of measurement to the conductor i in m. It gives a good estimate provided that D_i is greater than 20 m, the frequency is 0.5 MHz, the number of subconductors is equal to or below 4, B/d ranges from 12 to 20 where B is the bundle spacing, moderate weather conditions, and if the RI level disperses by ±6 dB. Since this only works for $N \leq 4$, it cannot be used for unconventional HSIL lines targeted in this paper having more than 4 subconductors per phase.

For our 500 kV unconventional HSIL line, the empirical formula developed at the Bonneville Power Administration (BPA) has been considered [6]. To allow for these empirical formulae to be applied to our unconventional HSIL line, we have used the new method we have developed to find the maximum surface electric field for each phase [4].

$$RI = 46 + 120\log_{10}\left(\frac{E_{max}}{17.56}\right) + 40\log_{10}\left(\frac{2r}{3.51}\right)\ \ dB(1\mu V/m) \quad (5)$$

where, E_{max} is the maximum surface electric field for each phase, and r is the radius of the subconductors. Eq. (5) can calculate the noise from a single-phase conductor measured by a CISPR standard quasi-peak receiver at 1 MHz with a horizontal loop antenna fixed at 1 m above the ground, and 15 m from the phase conductor for fair weather conditions. To consider measurable rain conditions, 25 dB can be added to Eq. (5). It is also assumed to be at 0 m altitude above sea level, thus, to consider higher altitude levels, a factor of $A/300\ dB$ can be added to Eq. (5), where A is the altitude above sea level in meters. For measuring frequencies different from 1 MHz, a factor of $10[1-(\log 10f)^2]\ dB$ is added. If the measuring distance is changed, the correction factor of $-C_1 + C_2\ dB$ is required, where C_1 is the constant for the reference line and the latter is a constant for the new line. Both these values can be found as follows.

$$C_i = 10\log_{10}(DW^2 + ESU^2 + EIND^2)\ dB,\ \ i = 1,2 \quad (6)$$

where DW, ESU, and $EIND$ represent the direct wave, surface wave, and induction field components. Each of these can be calculated as shown below.

$$DW = \begin{cases} \dfrac{H}{k_0 D}\,, & for\ D \le \dfrac{12Hh_a}{\lambda} \\ \dfrac{H}{k_0 D}\dfrac{12Hh_a}{\lambda D}\,, & for\ D > \dfrac{12Hh_a}{\lambda} \end{cases} \quad (7)$$

where H, h_a, and D represent the height of the conductor, the height of the antenna, and the distance between the antenna and the conductors, all in meters, respectively. λ is the wavelength in meters, and $k_0 = 2\pi/\lambda$. ESU and $EIND$ can be found as:

$$ESU = \frac{g(\Delta)H}{k_0 D} \quad (8)$$

where $g(\Delta) = (2 + 0.3\Delta)/(2 + \Delta + 0.6\Delta^2)$ and $\Delta = 52.5D/\sigma_g\lambda^2$. Here, σ_g is the ground conductivity in mS/m.

$$EIND = \frac{H}{(k_0 D)^2} \quad (9)$$

To find C_1, $D = 21.04$ m, $f = 1\,MHz$, $\sigma_g = 4\,mS/m$ and $h_a = 1\,m$. The RI level for each of the phases is calculated using this method. The net RI level for the 3-phase line is then given by the highest value at each of the distances considered.

III. Simulation Results

A. Geometries of Conventional 500-kV Line and Unconventional HSIL Line with N=8

Fig. 2 shows the geometry of a conventional 500-kV line which we consider as our base case for calculating AN and RI. The conductor considered here has a diameter of 26.82 mm.

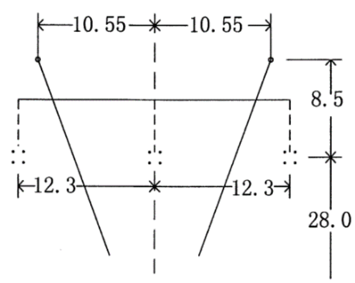

Fig. 2. Configuration for the 500-kV conventional line.

Fig. 3 shows the geometry of an optimal unconventional HSIL line with 8 subconductors per bundle resulting from our previous studies [4]. Here, the conductor has a diameter of 20.93 mm, the distance between phases is about 8.12 m, the average height of the outer phases is 31.37 m and that of the middle phase is 24.29 m. $\sigma_g = 10\,mS/m$ was assumed for both lines.

B. AN and RI for the conventional line and unconventional HSIL line

The AN profiles and the phase locations for the conventional 500 kV shown in Fig. 2 and the unconventional HSIL line shown in Fig. 3 for a corridor of width 160 m centered on the middle phase have been shown in Figs. 4 and 5. The RI profile for the conventional line for a frequency of 0.5 MHz with the distance considered from the center of the middle phase has been shown in Fig. 6.

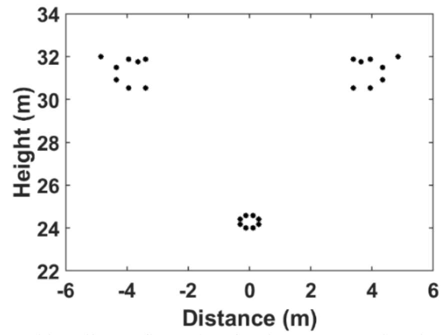

Fig. 3. Line and bundle configuration for the unconventional HSIL line.

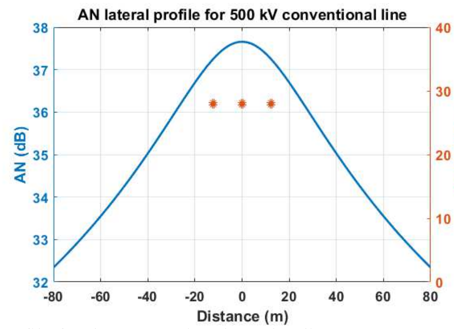

Fig. 4. AN profile for the conventional 500 kV line.

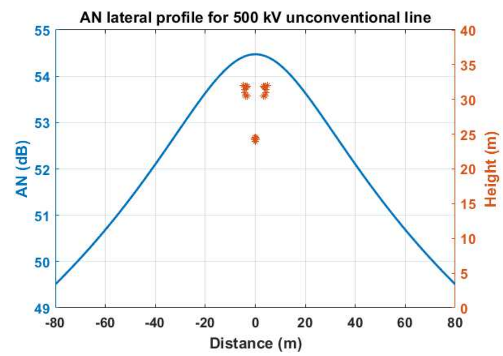

Fig. 5. AN profile for the 500 kV unconventional HSIL line.

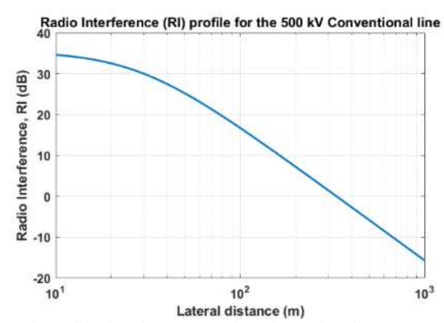

Fig. 6. RI lateral profile for the conventional 500 kV line.

Fig. 7 shows the RI profile for the unconventional HSIL line for various frequencies, where the x-axis distance is taken from the rightmost phase. Fig. 8 shows that for various altitude levels. The AN profiles for the conventional line and unconventional HSIL line show that as the number of subconductors increases from 4 to 8 going from the former to the latter configuration, the maximum AN increases by about 17 dB to a peak value of about 54.5 dB. According to the

Perry Criterion, a noise level of 52.5 dB is required to ensure no complaints from the surroundings [1]. From Fig. 4, it is seen that this criterion is met by the conventional line for any distance from the center of the line. However, the unconventional line meets this after around 30 m from the middle phase as seen in Fig. 5. According to the Day-Night Criterion, however, the no-complaint zone is met anywhere along the line.

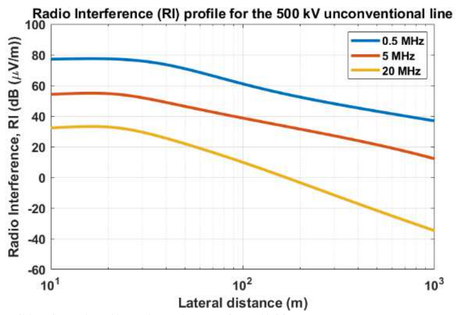

Fig. 7. RI profile for the line in Fig. 3 for different measurement frequencies.

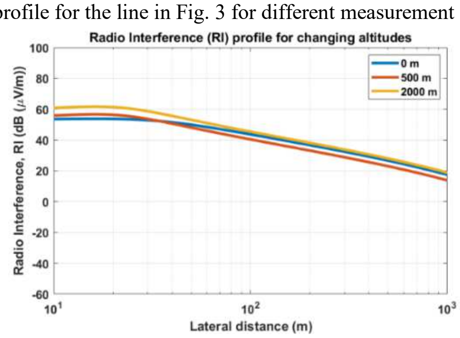

Fig. 8. RI profile for the 500 kV unconventional line for different altitudes.

For the USA, the RI limits are set by ensuring a guaranteed minimum signal-to-noise ratio (SNR) of 24 dB at the receiver, for signals that are at least 54 dB in strength [1]. However, depending on the frequency the noise level may vary, and therefore not all stations may satisfy the minimum SNR criterion [1]. For the unconventional line considered in this study, a ROW width of around 60 m would result in an RI noise level below 30 dB, thus ensuring a 24 dB SNR at the receiver for a 54 dB signal. Considering the unconventional line in our study, the minimum ROW requirement would be much higher, i.e., in the range of over 200 m (100 m on each side from the middle of the line) for 5 MHz signals.

Note that in addition to AN and RI, it is necessary to carefully examine all electrical, mechanical, and structural aspects of designing overhead lines at component level for these unconventional HSIL lines [7-13], as well as the interaction of these envisaged lines with the power system at system level [14-18], to realize such unconventional designs.

IV. Conclusions

Unconventional HSIL lines can significantly increase power transfer capability and can be a game-changing technology, especially in the direction of 100% renewable energy. In this paper audible noise (AN) and radio interference (RI) for unconventional HSIL lines are calculated and discussed. The results show that both AN and RI increase for the unconventional HSIL line considered in this paper compared to the conventional design. The next and further research should investigate mitigation methods regarding the limited ROW, if necessary.

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