Effect of Radio Interference in 765kV Zebra Conductor with Different Bundle Configurations

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Abstract - Voltage gradient is the important parameter to be considered for designing the transmission line conductors to avoid the corona effect. Radio Interference and corona loss can be reduced by minimising the voltage gradient of the conductor. Voltage gradient of 765kV ACSR Zebra conductor (Aluminium 54 strands and steel 7 strands) was analysed using matlab software with different bundle configurations such as single, twin, triple, quad and hex. Effect of Corona Inception voltage (CIV), Corona Extinction voltage (CEV), Capacitance (C), Inductance (L) and RIV (Radio Influence Voltage) were analysed by increasing the number of sub-conductors in a bundle. Quad and hex bundle configurations had RIV value within the limit. Among different configurations the hex bundle has low RIV. The best configuration (hex) was tested practically in the laboratory. Experimental result of zebra conductor - hex bundle configuration was reported for CIV, CEV and RIV.

Keywords - Voltage gradient; Maxwell potential coefficient method; Markt and Mengele’s method; Peek’s formula; Maximum surface voltage gradient; Radio Influence Voltage

I. INTRODUCTION

Electric field distribution in the vicinity of the conductor surface induces corona discharge. Corona discharge starts when the electric field strength exceeds 20-30kV/cm (breakdown strength of air). During this corona discharge phenomenon noise can be heard, ozone gas could be smelled and glow could be seen which consumes power from the transmission line. The power consumed is corona loss. Increasing diameter of a conductor and increasing spacing between the conductors reduces the power loss of corona. Corona occurs in all types of transmission line but it is more noticeable under wet and humid conditions.

Conductor design is based on the current handling capacity. A 1200kV transmission line has the capacity to handle power of three 765kV bundle conductors. A 765kV line has the capacity to handle power of four 400 kV bundle conductors. If the diameter of the conductor is increased, then the transmission RIV and power loss can be reduced [1]. To reduce corona discharge, diameter of the conductor can be increased to a certain limit, beyond that number of conductors can be increased i.e by using bundle conductors.

The intensity of corona discharge, Audible noise (AN) and Radio Interference (RI) of four-conductor bundle was investigated and compared with single conductor by Xingming Bian et al. [2]. As the surface roughness becomes higher the electric field distortion level of the single or four bundled conductor increases for long-term operated rough surface conductor.

X. M. Bian et al [3] compared the corona-generated RI and AN of the long-term operated conductors and new conductors. For long term operated conductor corona discharge intensity was stronger, and the corona inception voltage was low.

Deng Jun et al [4] analysed RI of a HVDC by superposition of the electromagnetic field (due to corona current) using phase-model transformation. Deng Jun concluded that RI increased with temperature, altitude, and varies with relative humidity.

Lan Chen et al [5] used ultraviolet imager, a partial discharge detector, a current-measuring radiofrequency interference receiver, and a sound level meter to observe the transition region between non corona and strong corona for two practical conductors LGJ500/35 and LGJ400/50. The number of photons released from corona discharges on the aged conductors are much greater and the discharging area much larger, under similar applied high voltages [6].

II. VOLTAGE GRADIENT

The voltage gradient should be under control to maintain the radio interference (RI), corona loss (CL) and audible noise (AN) within the limit. Choosing suitable conductor configuration for 765kV is the problem to be resolved. According
to Hydro-Qubec [7] the acceptable level of audible noise is about 60dB above 2x10^{-5}N/m^2 at 100 feet and radio interference should not be higher than 67dB above 1µV/m. For every 300m increase in elevation above the sea level, the RIV increases by 1dB.

For each conductor bundle capacitance, inductance, radio interference and corona loss were measured with respect to voltage gradient. The basic assumption made is that the ground is assumed to be an infinite horizontal conducting plane surface with zero potential. Conductor surface voltage gradient is proportional to the operating voltage. Increasing number of sub-conductors in a bundle reduces surface voltage gradient.

Maxwell potential coefficient method (MPCM) and Markt and Mengele’s method are analytical methods for calculating electric field strength. Successive image method, charge simulation method (CSM), boundary element method and finite element method (FEM) are numerical methods to find electric field strength.

A. Maxwell potential coefficient method

Basic assumption made in this method is that around each conductor, surface charges are uniformly distributed. Each conductor is represented as single line charge. The result produced by this method is accurate for single conductor. For multi-conductors with non-uniform conductor surface charge, this method becomes inaccurate [8].

B. Markt and Mengele’s method

Markt and Mengele’s method [9, 10] can be used for bundled conductors. Maxwell potential coefficient method (MPCM) is modified in Markt and Mengele’s method.

A bundle of conductor is replaced by a single conductor with an equivalent radius (req = \(R[N \frac{r}{d}]^2\)). Markt and Mengele’s method is used to compute charge density Q/2\(\pi\varepsilon_0\). Charge density is equally split to sub-conductors to calculate surface gradient. This is accurate method for calculation of surface voltage gradient for bundled conductors. As the distance between the sub-conductors in the bundle is small, error occurs in electric field distribution.

Further changes were introduced by king with the basic assumption, line charges of each sub-conductor is not located at the centre of the conductor but a small distance is away from central point [11]. Small distance is the function of bundle geometry. King made modifications in this method by replacing each sub-conductor by two line charges symmetrically displaced from the centre of the conductor.

C. Charge simulation Method

Charge Simulation Method is numerical method based on fictitious charges. In CSM discrete fictitious charges are used to replace the non-uniformly distributed surface charge [12]. Fictitious charges are flexible in both location and shape.

D. Boundary Element Method

BEM is effective in open field problem but it has the limitation of coupling with different fields.

E. Successive Images Method

Successive Image method is an iterative procedure. In this method central line charge is simplified to calculate the charge density of each conductor. Non-uniform distribution of surface charges on each conductor is considered for this method [1].

F. Finite Element Method

FEM used for field computation of irregular geometric shapes. Accuracy is improved by iterative process. It results in best fit boundary for FEA.

III. MATHEMATICAL ANALYSIS

B: Bundle Spacing(cm)
R: Bundle Radius(cm)
r: Radius of sub-conductor (cm)
d: Diameter of sub-conductor(cm)
N: Number of sub-conductors in a bundle
req: Geometric Mean Radius of bundle conductor (cm)
pb: Maxwell’s coefficient of bundle conductors
H: Height existing between centre of bundle conductor and ground (m)
L: Inductance of a bundle conductor (H)
Lc: Inductance of sub-conductor in a bundle (H)
C: Capacitance of bundle conductor (F)

A bundle of radius R and N sub-conductors can be replaced by a single conductor with equivalent radius called Geometric Mean Radius (GMR)

\[\text{req} = R[N \frac{r}{d}]^2\] (1)

GMR is used for calculating inductance, capacitance charge and many other line parameters. Inductance of a bundle conductor is

\[L = \frac{\mu_0 N}{2\pi} \ln \left(\frac{2H}{\text{req}}\right)\] (2)

Distance between adjacent sub-conductor in a bundle is called bundle spacing (B). Radius of a circle where the sub-conductors are placed is called Bundle radius (R).
The sub-conductor inductance is $N$ times that bundle inductance because all the sub-conductors are connected in parallel. When the number of sub-conductors is increased, the GMR decreases which in turn increases the line inductance and decreases power handling capacity. Capacitance of the bundle conductor is

$$C = \frac{2\pi \varepsilon_o}{\ln(\frac{2H}{req})}$$

(4)

For a $n$ phase conductor system

$$[C]_{nn} = 2\pi \varepsilon_o [P]_{nn}^1$$

(5)

$$[L]_{nn} = \frac{\mu_o}{2\pi} [P]_{nn}$$

(6)

$[L][C]$ gives velocity of light $(3 \times 10^5 \text{ km/sec})$. $P_b = \ln(\frac{\frac{2H}{req}}{2})$ is Maxwell’s coefficient [1]. When the number of sub-conductors is increased, the GMR increases which in turn increases the capacitance.

A. Peek’s formula

The corona inception gradient ($E_{or}$) given by peek’s formula. Peek [13] formulated empirical equations for the corona inception voltages of a cylindrical conductor that laid basic for foredooming researchers in corona.

$$E_{or} = 29.8 \ m \delta \left(1 + \frac{0.301}{\sqrt{\delta}}\right) \text{ kV/cm}$$

(7)

$$\delta = \frac{P^2 \ v_0}{T_0 \ 273 + t} = \frac{2.89P^2}{273 + t}$$

(8)

$m$: Surface irregularity factor
$\delta$: Relative density of the air
$t$: Ambient temperature (Kelvin)
$P$: Atmospheric pressure (kPa).

$m=0.75$ for standard and tension strung,
$m=0.55$ for stranded and dragged conductors,
$m=0.3-0.6$ for water drops in heavy rain condition and $m=0.4$ for bundle conductors at approximately $18 \text{mm/h}$ rain rate.

B. Maximum surface voltage gradients

An assumption is made that the voltage gradient on the surface of bundle is only due to the charges on the sub-conductors in that bundle. Other charges are neglected. The sub-conductors are placed at a distance such that a uniform electric field exists. Stress doubling is used. In table the surface voltage gradient occurs at point $P$ for $N$ number of sub-conductors. Maximum surface gradient ($E_p$) at $P$ is obtained as

$$E_p = \frac{g}{2\pi \varepsilon_o} \left[1 + \frac{(N-1)^r}{r}\right]$$

(9)

Surface voltage gradient from surface of conductor to ground ($V$) is

$$V = E_{or} \cdot r \cdot \ln\left(\frac{2H}{\tau}\right)$$

(10)

<table>
<thead>
<tr>
<th>N</th>
<th>B and R relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$R = B/2$</td>
</tr>
<tr>
<td>3</td>
<td>$R = B/\sqrt{3}$</td>
</tr>
<tr>
<td>4</td>
<td>$R = B/\sqrt{2}$</td>
</tr>
<tr>
<td>6</td>
<td>$R = B$</td>
</tr>
</tbody>
</table>

C. Radio Interference

Pulse less / glow corona and pulse type / streamer corona are the two types of corona discharge in ACSR conductor. Pulse type corona interfere radio broadcast in the range of $0.5\text{MHz}$ to $1.6\text{MHz}$. CIGRE formula to calculate radio interference upto four conductor bundle is

$$RI = 3.5 \ gm + 6d - 33 \log\left(\frac{d}{20}\right) - 30$$

(11)

gm: Maximum surface voltage gradient on the conductor (KV/cm)
$D$: Aerial distance (m), $D \geq 20m$

IV. SIMULATION AND RESULTS

The effect of increasing the number of sub-conductor in a bundle for a ACSR zebra conductor with $765\text{KV}$ was simulated using Matlab software. Diameter of the conductor is $0.03177\text{m}$. Conductor was placed at a height of $15\text{m}$ above the ground and the spacing between two adjacent sub-conductors in the bundle was $457\text{mm}$.

A. Simulation

Programming was done by using following sequence.

Step1: Equivalent radius (req) of bundle conductor was calculated.
Step2: Bundle radius ($R$) was determined.
Step3: Maxwell’s potential coefficient ($P_b$) was obtained.
Step4: Inductance ($L$) and Capacitance ($C$) values were calculated.
Step5: By using peek’s formula corona inception voltage ($E_{or}$) was obtained.
Step6: Maximum surface voltage gradient (gm) of the bundle conductor was extracted.
Step7: Radio Influence voltage (RIV) in dB was predetermined by using CIGRE formula.

The above steps were repeated for all configurations (N=1,2,3,4 and 6) of conductor and the results were plotted graphically.
B. Simulated Results

In Fig.1 Inductance of the bundle conductor decreases when number of conductors in the bundle increased. It increases the power handling capacity for the transmission line. In Fig.2 Capacitance of the bundle conductor increases when number of conductors in the bundle increased.

Radio influence voltage was predetermined by CIGRE formula. Fig.3 shows RIV in dB plotted for a distance 40m from the conductor bundle of different configurations.

RIV decreased when the N increased. Single conductor (N=1) has very high RIV value which is beyond the acceptable range. Twin bundle also has high RIV value that is not preferable. Triple conductor has acceptable range of RIV at 20m away from the conductor. Quad and hex bundle has acceptable RIV range. Among the five configurations hex bundle gave best result with low RIV value. Hex bundle configuration has RIV less than 50dB. At 20m away from the conductor Hex bundle has 40dB RIV.

V. EXPERIMENTAL SETUP AND MEASUREMENT

A. Test Arrangement

ACSR zebra conductor of 0.03177m diameter held at a height of 15m above the ground. The HV coupling capacitor should be free of RIV within the voltage range of object under test. A coupling capacitor will draw a minimum current but at the lower frequencies it acts as high reactive element which produces a low RIV factor. In Fig.4 the coupling capacitor is connected to high voltage terminal of object under test and the other end is connected to ground through a non-inductive resistor. RIV is measured across the resistor.

B. RIV Measurement test procedure

The Radio Influence Voltage can be measured as per NEMA (National Electrical Manufacturers Association) publication.
Ambient RIV is measured at the required test voltage with the test object disconnected. Further RIV measurement can be performed only when the ambient RIV is less than 6dB[14]. Experimental setup was done in a virtually made dark High Voltage Lab.

Procedure for RIV dry test:
1. Pressure and temperature were measured.
2. Supply voltage was increased gradually, the voltage at which visible glow occur was recorded.
3. Voltage was increased further for 10% and held for 1 minute.
4. The supply voltage was decreased gradually and the voltage at which the glow extinguishes was recorded.
5. Step 1 to 4 repeated 3 times. The average was taken as corona inception and extinction voltage.
6. Ambient RIV was measured.
7. Voltage above the onset voltage was applied and RIV was measured.

**TABLE II. Inception and Extinction Voltage**

<table>
<thead>
<tr>
<th>Inception Voltage (KV)</th>
<th>Extinction Voltage (KV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>523</td>
<td>515</td>
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<tr>
<td>524</td>
<td>516</td>
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<tr>
<td>520</td>
<td>515</td>
</tr>
<tr>
<td><strong>Mean: 522</strong></td>
<td><strong>Mean : 515</strong></td>
</tr>
</tbody>
</table>

**TABLE III. RIV in dB Vs Voltage (kV)**

<table>
<thead>
<tr>
<th>Voltage(kV)</th>
<th>RIV(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>545</td>
<td>66</td>
</tr>
<tr>
<td>540</td>
<td>65</td>
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<td>530</td>
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<td>520</td>
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<td>515</td>
<td>56</td>
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<tr>
<td>510</td>
<td>46</td>
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<td>500</td>
<td>40</td>
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<tr>
<td>490</td>
<td>40</td>
</tr>
<tr>
<td>480</td>
<td>37</td>
</tr>
<tr>
<td>450</td>
<td>33</td>
</tr>
</tbody>
</table>

Measured RIV in dB and applied voltage in kV plotted in graph as

**VI. CONCLUSION**

Single, twin, triple, quad and hex bundle configurations of 765kV, zebra conductor(54 Al/7 st strands) were taken for analysis. Capacitance, inductance and radio influence voltage were determined analytically. All the configurations were compared. The configurations with low RIV was considered as the good configuration for corona discharge reduction. In the proposed work, hex bundle configuration gave less RIV when compare to other configurations. Hex bundle configuration was tested practically in the laboratory.

1. Inductance value decreases and capacitance value increases by increasing number of conductor in the bundle.
2. For every addition of sub-conductor in a bundle the RIV is getting decreased by 10-15dB.
3. Hex bundle configuration tested practically at specified test voltage (510kV) showed that the RIV is within the limit.

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**References**

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