INVESTIGATION OF OVERVOLTAGES IN A GAS INSULATED SUBSTATION (G.I.S.) CAUSED BY A LIGHTNING STROKE

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Abstract—A back flashover for a shielding failure can be caused by a lightning stroke, which will damage equipment and devices in a gas insulated substation if the devices' maximum voltages are exceeded.

In this study, the branch timetable method, which is implemented from the lattice diagram method, is used in a computer program for the calculation of overvoltages in the gas insulated substation, as a result of a shielding failure, so that the gas insulated substation performance under lightning stroke can be determined. The study of the lightning performance of a gas insulated substation is very important for the purpose of designing lightning overvoltage protection systems.

Electrical power systems  Gas insulated substation (G.I.S.)  Lightning surges  Back-flashover
Shielding failure

INTRODUCTION

Lightning

There are different theories of charge formation in clouds[1]. An electrically charged cloud induces an opposite polarity charge in adjacent clouds or on the earth. A potential gradient then exists between them. The more the concentration of charge, the higher the potential gradient that exists[9]. Atmospheric conditions can increase considerably the cloud charge. If the potential gradient is so high that the breakdown strength of the air, which is about 30 kV/cm[9], is exceeded, a lightning discharge occurs. The methods for measuring lightning storms and describing the characteristics of lightning strokes are given in Ref. [2]. The effects of a lightning stroke on high voltage lines can be observed using a cathode-ray oscillograph. If a lightning surge wave, which travels along a line struck by lightning, was not mutilated by a flashover or modified by reflections, it has a simple wave shape. Four characteristics specify the wave shape[2]: the crest, the front, the tail and the polarity of the wave. The crest of the wave is the amplitude, which is represented in kV. The front of the wave is the time from its beginning to the crest and is measured in μs. The effective front is determined by a straight line between the 10 and 90% points. The polarity of the wave is the polarity of the crest.

A lightning surge wave can be represented mathematically by writing it as a summation of two exponential curves[1, 2, 8],

\[ e = E(e^{-\alpha t} - e^{-\beta t}). \]  

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Table 1. Lightning surge parameters

<table>
<thead>
<tr>
<th>Wave shape</th>
<th>E</th>
<th>α (μs)⁻¹</th>
<th>β (μs)⁻¹</th>
<th>Actual time to peak (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/1</td>
<td>1.0</td>
<td>0.6931</td>
<td>∞</td>
<td>0</td>
</tr>
<tr>
<td>0/5</td>
<td>1.0</td>
<td>0.1386</td>
<td>∞</td>
<td>0</td>
</tr>
<tr>
<td>0/50</td>
<td>1.0</td>
<td>0.01386</td>
<td>∞</td>
<td>0</td>
</tr>
<tr>
<td>0/100</td>
<td>1.0</td>
<td>0.000693</td>
<td>∞</td>
<td>0</td>
</tr>
<tr>
<td>1/5</td>
<td>1.81</td>
<td>0.253</td>
<td>1.35</td>
<td>1.52</td>
</tr>
<tr>
<td>1/50</td>
<td>1.036</td>
<td>0.0146</td>
<td>2.56</td>
<td>2.029</td>
</tr>
<tr>
<td>1.2/50</td>
<td>1.035</td>
<td>0.046</td>
<td>2.61</td>
<td>1.575</td>
</tr>
<tr>
<td>1/∞</td>
<td>1.0</td>
<td>0.0</td>
<td>2.746</td>
<td>∞</td>
</tr>
</tbody>
</table>

From this equation, the wave crest or the maximum value and the time to crest value can be calculated. The crest value occurs when,

\[
\frac{de}{dt} = E(-\alpha e^{-\alpha t} + e^{-\beta t}) = 0. \tag{2}
\]

The time value, therefore, has a relation as:

\[
t = t_1 = \frac{\ln(\beta/\alpha)}{\beta - \alpha} = \frac{1}{\alpha} \frac{\ln(\beta/\alpha)}{\alpha(\beta/\alpha) - 1} = (B/\alpha) \tag{3}
\]

The crest value, therefore, has a relation as:

\[
E_t = E(\epsilon^{-\alpha t_1} - \epsilon^{-\beta t_1}) = E(\epsilon^{-B} - \epsilon^{-B(\beta/\alpha)}). \tag{4}
\]

There is another way to determine the lightning surge specifications using Table 1 [8].

**Travelling waves and Bewley Lattice Diagram [2, 3]**

When an electrical source is connected to a transmission line, the voltage does not appear immediately in it because there are distributed line capacitances. The voltage wave that travels along the transmission line then suffers attenuation and distortion as energy losses exist, and there are variations in the inductances and capacitances. If attenuation and distortion do not exist, the waves are propagated with the equations as follows:

\[
V = F_1(x - vt) + F_2(x + vt) \tag{5}
\]

\[
i = \left(\frac{F_1(x - vt) - F_2(x + vt)}{Z_0}\right) \tag{6}
\]

where, \( V = \) voltage, \( i = \) current, \( x = \) the distance measured along the line, \( v = \) velocity of propagation, and \( t = \) time.
These two components depend on the reflection and refraction (transmission) coefficients $K_R$ and $K_T$ which can be written as:

$$K_R = \frac{Z_c - Z}{Z_c + Z}$$

(7)

$$K_T = \frac{2Z_c}{Z_c + Z}$$

(8)

where

$$K_R = K_T - 1.$$  

(9)

Based on the reflection and refraction of travelling waves, Bewley proposed a graphical method (Bewley Lattice Diagram method) for calculating the variation of voltage at any point in cables or long lines at any time. The length of the lines and cables are represented as their travel times, which can be found from the facts that the wave propagation in overhead lines is about the speed of light, and the propagation in cables is less than that in overhead lines. In this method, the lines are supposed lossless, but the effects of the attenuation of the waves as they travel along the lines may be included. This method can be used easily when the system is simple. In large systems in which many components are involved, such as busbars, mutual surge impedances, surge impedances of towers, attenuation and distortion of travelling waves, using the Bewley Lattice Diagram is not practical. To overcome this difficulty, Barthold and Carter, McElroy et al. and Bickford and Doepel have used the Bewley Lattice Diagram with a digital computer by which the voltage at any point at any time in a large system can be accurately calculated. This can be done by using the Branch Timetable [3].

The branch timetable is the heart of the Bewley Lattice Diagram and its digital computation.

Fig. 3. A single line diagram of a G.I.S. in a shielding failure.
Protection against overvoltages by an arrester [2, 4-6, 10, 11]

A lightning surge wave travelling to a substation may cause an overvoltage at the substation and damage devices. To prevent this bad situation, the overvoltage should be limited so that, in the protected area, the overvoltage can be maintained within acceptable values, i.e. below the insulation strength of the devices.

The application of surge arresters provides voltage limitation at devices, as surge arresters have a low resistance discharge to earth during transient currents. After the transient current, after which only the normal voltage is applied back to the system, the surge arresters provide high impedances. The transient currents, therefore, are limited and interrupted. This makes the system return to a normal condition. There are two types of surge arresters which can be used for protection.

1) The conventional arresters [4, 10].

The arresters most widely used on EHV and UHV power systems are current limiting types. These consist of spark gaps and valve blocks. The valve block is represented by the equation:

\[ V = a_0 + a_1 I + a_2 I^2. \]  \hspace{1cm} (10)

2) Gapless arresters [6].

A new generation of surge arrester uses a zinc oxide non linear resistor in which the air gap has been eliminated. Compared with a conventional arrester, the gapless arrester offers outstanding features. For this study, the conventional type was applied.

SYSTEM TO BE ANALYSED

The circuit diagram shown in Fig. 1 is a transmission line which is connected to a gas insulated substation. This type of substation has some essential features. Its surge impedance is lower than that of the overhead lines. This makes overvoltages in it lower. Further, the average bus run for a compact G.I.S. is much less than the one for a conventional station. In addition, the G.I.S. is totally enclosed and, therefore, is free from any atmospheric contamination. Furthermore, the number of lightning arresters required is less than that for a conventional substation.

Looking at the above essential features, the G.I.S. has become a serious competitor where land cost is high and atmospheric problems are severe.

Fig. 4. Voltage-time characteristics of busbars under a shielding failure for the conditions where no C.V.T., \( C_T = 0.0008 \) \( \mu \)F and G.I.S. trunk length = 40 m are used: (a) busbar 1, (b) busbar 3, (c) busbar 4, (d) busbar 5.
The G.I.S. seems to be an automatic choice to be placed inside buildings in big cities or underground.

In this study, the system shown in Fig. 1 has been investigated for its lightning overvoltage performance. Overvoltages at the transformer (point 4) caused by a lightning stroke at the phase line (point 1) that produces a shielding failure will be observed when a particular characteristic of a lightning arrester is connected at the G.I.S. entrance (point 3).

The overvoltages have also been investigated by varying the value of the capacitor voltage transformer (C.V.T.) for measuring purposes, the length of the G.I.S. trunk (the length between points 3 and 4) and the capacitance of the transformer (C_T). From these investigations, it can be determined the acceptable values for C.V.T., C_T and G.I.S. trunk length for design purposes.

**DATA PREPARATION**

The important data required for calculations using the computer program are described in the following sections:

1. **Base voltage.** Voltages are represented in per unit value of voltage between the line and neutral. A voltage of a transmission line of 400 kV is chosen as the voltage reference.

2. **Busbar numbering.** In the system of the study, eight busbars are used, a busbar consists of three individual phase busbars.

3. **Single circuit transmission lines.** A transmission line is specified by its sending and receiving end busbars, its length and surge impedance matrix. In this system, there are six single circuit transmission lines. The assumptions chosen for calculation have no mutual impedances, and no attenuation and distortion in the transmission lines. The velocity of wave propagation is taken equal to the velocity of light in air which is 300 m/μs.

4. **Shunt capacitances.** There are two capacitances used. One is for the transformer representation in a short time transient, and the other is a capacitor voltage transformer which is used for measuring purposes.

5. **Shunt resistance data.** The data required for the shunt resistances are similar to that for the surge impedances in that both are assumed to have no mutual effects. The number of shunt resistances is two, one at the 1st tower base and the other at the 2nd tower base.

![Fig. 5. Voltage-time characteristics of busbars under a shielding failure for the conditions where C.V.T. = 0.004 μF, C_T = 0.0008 μF, G.I.S. trunk length = 40 m are used: (a) busbar 1, (b) busbar 3, (c) busbar 4, (d) busbar 5.](image)
Table 2. Comparison of data calculated between G.I.S. without and with C.V.T. in a shielding failure, where \( C_T = 0.0008 \mu F \)

<table>
<thead>
<tr>
<th>No.</th>
<th>C.V.T.</th>
<th>Time for 1st wave (( \mu s ))</th>
<th>( V_{\text{at} 1\text{st wave}} ) (p.u.)</th>
<th>( V_{\text{max}} ) (p.u.)</th>
<th>( V_{\text{min}} ) (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>8.2395</td>
<td>-4.7157</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.23</td>
<td>1.5512</td>
<td>5.1233</td>
<td>-1.4981</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.38</td>
<td>1.1385</td>
<td>2.1928</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.53</td>
<td>1.1399</td>
<td>2.7420</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.73</td>
<td>1.1734</td>
<td>3.3486</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>8.240</td>
<td>-4.72</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.23</td>
<td>1.5512</td>
<td>5.055</td>
<td>-1.51</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.38</td>
<td>1.0052</td>
<td>2.190</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.53</td>
<td>1.0074</td>
<td>2.800</td>
<td>0.78</td>
<td></td>
</tr>
</tbody>
</table>

(6) **Arrester.** A conventional active gap arrester is applied at the entrance of the G.I.S. The 80% arrester rating is used with the section rating of 6 kV. The voltage–time characteristic of this arrester is shown in Fig. 2, where \( T_1 = 400 \mu s, T_2 = 900 \mu s, T_3 = 1100 \mu s \) and \( V_D = 2.2 \) p.u. The arrester is simulated by a glock characteristic which has the constants: \( a_0 = 5.2698, a_1 = 0.83374, a_2 = -0.042453. \)

(7) **Initial voltage conditions.** Each busbar must be given initial voltage conditions (frequency in Hz, phase magnitude in p.u. and phase angle in degrees). The initial conditions given to the busbars in the phase lines are 1 p.u. for voltage, 50 Hz for frequency and \( -30, 210^\circ \) for phase angles in phases A, B and C, respectively.

(8) **Lightning surge.** The lightning surge wave applied in the program calculation is the one which has a waveshape of 1/50. The value of 3 MV/\( \mu s \) is taken as its rate of rise. Therefore, the crest value is 7.5 p.u.

(9) **Basic time interval and final time** [4]. There are three criteria governing the choice of the basic time interval required for the branch time table. Those are:

(i) The travel time of each transmission line ideally should be an integer number of the basic time interval chosen. It should be more than half the basic time interval.

(ii) At the value chosen, any applied voltage wave must be adequately represented.

(iii) The time constant associated with the surge impedances of the transmission lines and shunt resistors and any lumped reactive element should satisfy the relation, \( \theta < T/3 \), where \( \theta \) is the basic time interval. Looking at these three criteria and the circuit diagram of the system in Fig. 1, the value of \( \theta = 0.01 \mu s \) is chosen as the basic time interval throughout the calculation. The time of interest of the final time is 10 \( \mu s \).

The behaviour of the G.I.S. that will be investigated is its performance under a lightning stroke at the second tower with a steep front of 1 \( \mu s \). It is assumed that the maximum voltages which will exist in each point of the circuit is within 10 \( \mu s \) duration. The final time chosen for the calculation is 30 \( \mu s \) in order to observe the behaviour after 10 \( \mu s \).

**SHIELDING FAILURE**

**Circuit diagram**

In a shielding failure, a lightning surge strikes the phase lines directly. In this computer program calculation, it is supposed that no flashover occurs. The lightning surge wave applied has the

Table 3. Absolute values of maximum voltages in a G.I.S. in a shielding failure for a G.I.S. trunk length = 40 m

<table>
<thead>
<tr>
<th>C.V.T. (( \mu F ))</th>
<th>( V_{\text{max}} ) (p.u.)</th>
<th>( t ) (( \mu s ))</th>
<th>( V_{\text{max}} ) (p.u.)</th>
<th>( t ) (( \mu s ))</th>
<th>( V_{\text{max}} ) (p.u.)</th>
<th>( t ) (( \mu s ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>2.6724</td>
<td>2.58</td>
<td>2.6271</td>
<td>1.88</td>
<td>2.6294</td>
<td>1.93</td>
</tr>
<tr>
<td>0.001</td>
<td>2.8450</td>
<td>1.78</td>
<td>2.6618</td>
<td>1.93</td>
<td>2.6810</td>
<td>2.02</td>
</tr>
<tr>
<td>0.002</td>
<td>2.8008</td>
<td>1.83</td>
<td>2.7472</td>
<td>1.88</td>
<td>2.6671</td>
<td>2.08</td>
</tr>
<tr>
<td>0.003</td>
<td>2.7979</td>
<td>1.88</td>
<td>2.8171</td>
<td>1.93</td>
<td>2.6309</td>
<td>1.92</td>
</tr>
<tr>
<td>0.004</td>
<td>2.7999</td>
<td>2.58</td>
<td>2.8903</td>
<td>1.98</td>
<td>2.6715</td>
<td>1.98</td>
</tr>
</tbody>
</table>
specifications as follows:

(1) waveshape 1/50
(2) rate of rise 3 MV/μs
(3) crest value 3 MV = 7.5 p.u.

In the program calculation, a lightning stroke with the above specifications is applied at a phase line at a second tower from a G.I.S., as shown in the circuit diagram in Fig. 3.

Overvoltages at the transformer (busbar No. 5) then are investigated. The influences of varying C.V.T., \( C_t \) and the length of the G.I.S. upon the overvoltages at the transformer are also observed.

Voltage–time characteristics

Using a transformer capacitance of 0.0008 μF with a 40 m G.I.S. trunk length, the voltage–time characteristics at the busbars (shown as numbers in Fig. 3) without and with a C.V.T. of 0.004 μF appear in Figs 4 and 5, respectively. The data listed in Table 2 can be found from calculation by means of the computer program.

From Table 2, it is obvious that the propagation times for both G.I.S. with and without C.V.T. are the same throughout the same single circuit transmission line.

Looking at Fig. 4, the voltage–time characteristics in a shielding failure can be explained. When a lightning surge with a rate of rise of 3 MV/μs is applied to a phase line at the second tower (busbar 1 in Fig. 3), its steep front is transmitted to the G.I.S. When this travelling wave arrives at busbar 3, it is reflected and refracted. The reflected wave from busbar 4 (where an arrester is connected) reduces the voltage at busbar 1 sharply for the first time. This sharp fall starts to occur at \( 2 \times 1.38 = 2.76 \) μs (see Table 2 for busbar 4). There is another reflected wave that comes from busbar 5 that also reduces the lightning surge wave sharply to a value of \( -4.7157 \) p.u. This reflected

<table>
<thead>
<tr>
<th>C.V.T. (μF)</th>
<th>( C_t = 0.0008 ) μF</th>
<th>( C_t = 0.002 ) μF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>2.9159 3.78</td>
<td>2.9147 2.43</td>
</tr>
<tr>
<td>0.001</td>
<td>2.8974 3.83</td>
<td>2.8958 2.48</td>
</tr>
<tr>
<td>0.002</td>
<td>2.8221 3.88</td>
<td>2.8604 2.53</td>
</tr>
<tr>
<td>0.003</td>
<td>2.9042 2.08</td>
<td>2.8053 2.58</td>
</tr>
<tr>
<td>0.004</td>
<td>2.9868 2.13</td>
<td>2.7231 2.58</td>
</tr>
</tbody>
</table>
wave arrives at busbar 1 at $2 \times 1.53 = 3.06 \mu s$ (see Table 2 for busbar 5). This rapid reduction is transmitted to the G.I.S., and it will reduce the voltages in busbars 3, 4 and 5.

After the value of $-4.7157 \text{ p.u.}$ has been reached, because of the tail part of the lightning surge wave, the voltage at busbar 1 increases steeply to a second peak which is less than the first one. The effect of this steep increase of voltage waveform upon the busbars is similar to the one that previously occurred.

From Table 2 and both Figs 4 and 5, it is clear that the application of the C.V.T. results in less smooth waveforms. Further, the minimum voltage at the transformer is less but the maximum voltage is higher than the G.I.S. without the C.V.T.

**Effects of varying C.V.T. upon overvoltages at transformer**

Taking a value of the G.I.S. trunk length of 40 m, the overvoltages at the transformer caused by a lightning surge wave applied at a phase line at the second tower from the G.I.S. can be calculated for a particular value of $C_T$. The results are given in Table 3 and illustrated in Fig. 6 for values of $C_T = 0.0008$, 0.002 and 0.0014 $\mu F$.

Beyond point B of Fig. 6 (when the C.V.T. is 0.0026 $\mu F$), the overvoltages at the transformer will decrease by increasing the value of $C_T$ because the bigger the value of $C_T$, the longer the voltage build up at $C_T$ is. This relation is valid for values of C.V.T. less than 0.0026 $\mu F$ and for both $C_T = 0.0008 \mu F$ and $C_T = 0.002 \mu F$. For $C_T = 0.0014 \mu F$ and $C_T = 0.002 \mu F$, however, it is only valid beyond point A (C.V.T. = 0.00135 $\mu F$).

<table>
<thead>
<tr>
<th>Length of G.I.S. trunk (m)</th>
<th>$V_{\text{max}}$ (p.u.)</th>
<th>$t$ (\mu s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>2.6672</td>
<td>2.080</td>
</tr>
<tr>
<td>50</td>
<td>2.7103</td>
<td>2.180</td>
</tr>
<tr>
<td>60</td>
<td>2.7556</td>
<td>2.230</td>
</tr>
<tr>
<td>70</td>
<td>2.7978</td>
<td>2.330</td>
</tr>
<tr>
<td>80</td>
<td>2.8343</td>
<td>2.430</td>
</tr>
<tr>
<td>90</td>
<td>2.8603</td>
<td>2.530</td>
</tr>
<tr>
<td>100</td>
<td>2.8775</td>
<td>2.63</td>
</tr>
<tr>
<td>120</td>
<td>2.9090</td>
<td>2.83</td>
</tr>
<tr>
<td>150</td>
<td>2.9321</td>
<td>3.13</td>
</tr>
<tr>
<td>170</td>
<td>2.9423</td>
<td>3.330</td>
</tr>
<tr>
<td>200</td>
<td>2.9496</td>
<td>3.63</td>
</tr>
</tbody>
</table>
Replacing the 40 m G.I.S. trunk length by 90 m, the results of the calculations can be seen in Table 4 which then are illustrated in Fig. 7. A transition section appears at the value of C.V.T. less than 0.0024 $\mu$F (point B). From Figs 6 and 7, it is clear that the G.I.S. trunk length of 40 m produces lower overvoltages than a 90 m G.I.S. trunk length up to the value of C.V.T. = 0.005 $\mu$F for $C_T = 0.002 \mu$F.

**Effects of varying G.I.S. trunk length upon overvoltages at G.I.S. transformer**

In this case of study, the G.I.S. trunk length is varied to investigate its effect on the overvoltages produced.

Making the value of the G.I.S. trunk length bigger, makes the propagation time in the G.I.S. bigger. As a result of this, the overvoltages at the transformer increase gradually. These can be seen in Table 5 which then are illustrated in Fig. 8, when a value of $C_T = 0.002 \mu$F and a value of C.V.T. = 0.0008 $\mu$F are taken for the calculation.

**CONCLUSIONS**

The application of the G.I.S. will increase because it uses less space compared with the conventional substation. The investigation of the overvoltages caused by a lightning surge in a G.I.S. has been calculated by means of a digital computer program. For these studies, the conditions of shielding failure have been simulated. The variables are the length of the G.I.S., the capacitor voltage transformer and the capacitance of the transformer. Out of these studies, the conclusions are as follows:

1. Investigation of shielding failure in the G.I.S. shows that higher overvoltages are produced when the value of the C.V.T. is increased, and shows that shielding failure has gradual fronts and wide pulses.
2. The application of C.V.T. results in less smooth waveforms. Further, the minimum voltage at the transformer is less, but the maximum voltage is higher than a G.I.S. without the C.V.T.
3. All the values of G.I.S. trunk length mentioned should be corrected by a multiplication factor 330/300 because wave propagation in the G.I.S. is 330 m/$\mu$s while that in air is 300 m/$\mu$s.
4. When an arrester is connected, the overvoltage will be reduced sharply.
5. For values of C.V.T. = 0.0026 $\mu$F, the overvoltage at the transformer will decrease by increasing the value of $C_T$ because the bigger the value of $C_T$, the longer the voltage build up at $C_T$.
6. The length of the G.I.S. trunk up to 200 m is acceptable in the condition where $C_T = 0.002 \mu$F and C.V.T. = 0.002 $\mu$F.
REFERENCES