Current Passing Through Grounding System of High Voltage Transformer Substation and Parameters Impacting on It When Lightning Strikes on the Grounding Wire of Transmission Line

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(Abstract) Current injecting a grounding system of high voltage transformer substation decides the amplitude and the voltage distribution along the grounding grid [1]-[2]. Therefore, the determination of short circuit current at substation is always cared by the designers. [9] suggested a new method to calculate the current passing through grounding system of high voltage substation when lightning strikes on the grounding wire of transmission line regardless of the impacting parameters. This paper studied clearly the influence of above parameters and from this, some interesting results were received.

Keywords: Grounding System; High Voltage Transformer Substation; Grounding Wire.

1. INTRODUCTION

This paper presents some new formulas to calculate the current passing through grounding system of high voltage substation and its dangerous zone when lightning strikes on the grounding wire of transmission line.

Based on transmission line models [3]-[5], the grounding wire system can be modeled as equivalent circuit (Fig.1).

Fig.1 Equivalent circuit of grounding wire line

Based on transmission line models [3]-[5], the grounding wire system can be modeled as equivalent circuit (Fig.1). Where, \( n \) is the number of span, each span is represented by a pi-circuit. The shunt impedance \( Z_p \) is the grounding impedance of electric pole and the series impedance \( Z_s \) is the impedance of grounding wire of each span (if the transmission line has two grounding wires then this series impedance will be \( Z_s/2 \)). \( Z_1 \) is the impedance of grounding system of the first substation and \( Z_2 \) is the impedance of grounding system of the second substation. In case of open-ended grounding wire line, \( Z_2=\infty \). The system of grounding wire and impedance of electric pole can be modeled as a series of connected \( n \) pi-elements equivalent circuit with lumped \( Z_s-Z_p \). So, the calculation of lightning current will be a process to solve this \( n \) pi-elements equivalent circuit.

2. CALCULATING THEORY

2.1 Impedances

From [6]-[7], in case of open-ended grounding wire line, we get the Thevenin impedance (seeing from the position that lightning strikes to the end of the grounding wire line) as follows:

\[
Z_{\text{th}} = \frac{\alpha_1 \left( b - \sqrt{4Z_pZ_s + Z_1^2} \right) - \alpha_2 \left( b + \sqrt{4Z_pZ_s + Z_1^2} \right)}{\left( b + \sqrt{4Z_pZ_s + Z_1^2} \right) - \left( b - \sqrt{4Z_pZ_s + Z_1^2} \right)}
\]

where:

\[
b = 2Z_p + Z_s
\]

\[
\alpha_1 = \frac{-Z_s + \sqrt{4Z_pZ_s + Z_1^2}}{2}
\]

\[
\alpha_2 = \frac{-Z_s - \sqrt{4Z_pZ_s + Z_1^2}}{2} \quad \text{or} \quad \alpha_2 = -\left( \alpha_1 + \alpha_2 \right)
\]

In case of the end of the grounding wire line connecting with the grounding system impedance \( Z_1 \), [8], [9] we get the Thevenin impedance as follows (see Appendix):

\[
Z_{\text{th1}} = Z_{\text{th}} - \frac{Z_{\text{pTD}}^2}{Z_{\text{th}} + Z_1}
\]

where:

\[
Z_{\text{pTD}} = \frac{2Z_s^2 + 4Z_pZ_s + Z_1^2}{\left( b + \sqrt{4Z_pZ_s + Z_1^2} \right) - \left( b - \sqrt{4Z_pZ_s + Z_1^2} \right)}
\]

2.2 Calculation of currents

We consider two cases (Fig. 1):

Case one: When lightning strikes at the gate pole of the first substation, we have the following equivalent circuit:
Current passing through grounding system of substation 1 (Fig. 2) is calculated as follows:

\[ I_{z1} = \frac{Z_{th2}}{Z_1 + Z_{th2}} I \]  

(4)

where \( Z_{th2} \) is the Thévenin impedance of the grounding wire of transmission line (seeing from the position that lightning strikes to the second substation) (Ω). \( Z_1 \) is the grounding system impedance of first substation (Ω). \( I \) is the lightning current value (kA).

**Case two:** When lightning strikes at the \( k^{th} \) electric pole on the grounding wire of transmission line.

\[ I_{z1} = \frac{Z_{th2}}{Z_1 + Z_{th2}} I \]  

Fig. 3 Equivalent circuit model

We alter the circuit in (Fig.3) for (Fig.4).

\[ I_{z1} = \frac{Z_{th2}Z_p}{Z_pZ_{th1} + Z_{th1}Z_p + Z_{th1}Z_{th2}} I \]  

(5)

\[ I_{z2} = \frac{Z_{th2}Z_p}{Z_pZ_{th2} + Z_{th2}Z_p + Z_{th2}Z_{th2}} I \]  

(6)

\[ I_{z3} = \frac{Z_{th2}Z_p}{Z_pZ_{th2} + Z_{th2}Z_p + Z_{th2}Z_{th2}} I \]  

(7)

where \( Z_{th1} \) is the Thévenin impedance of the grounding wire of transmission line (seeing from the position that lightning strikes to the first substation) (Ω). \( Z_p \) is the shunt impedance at electric pole that lightning stroke (Ω).

We consider \( T \)-circuit equivalent impedance (seeing from the position that lightning strikes to the second substation) (Fig. 3).

Current passing through grounding system of substation 1 (Fig. 2) is calculated as follows:

\[ I_{z1} = \frac{Z_{th2}}{Z_1 + Z_{th2}} I \]  

(4)

Current passes through grounding system of first substation as follows:

\[ I_{z1} = \frac{Z_{pTD1}}{Z_1 + Z_{th01}} I \]  

(8)

where \( Z_{pTD1} \) is the elementary impedance of \( T \)-equivalent circuit to the left of the position that lightning strikes (Ω) (Fig. 5). \( Z_{th01} \) is the Thévenin impedance of the grounding wire of transmission line (seeing from the position that lightning strikes to the first substation) in case of open-ended grounding wire line at this substation (Ω). \( Z_2 \) is the grounding system impedance of second substation (Ω).

Similar calculation:

\[ I_{z2} = \frac{Z_{pTD2}}{Z_2 + Z_{th02}} I \]  

(9)

where \( Z_{pTD2} \) is the elementary impedance of \( T \)-circuit equivalent to the right of the position that lightning strikes (Ω). \( Z_{th02} \) is the Thévenin impedance of the grounding wire of transmission line (seeing from the position that lightning strikes to the second substation) in case of open-ended grounding wire line at this substation (Ω). \( Z_2 \) is the grounding system impedance of second substation (Ω).

Substituting the above formulas (8), (9) into equations (5), (6) we obtain:

\[ \begin{align*}
I_{z1} &= \frac{Z_{th2}Z_p}{Z_pZ_{th1} + Z_{th1}Z_p + Z_{th1}Z_{th2}} I \\
I_{z2} &= \frac{Z_{th2}Z_p}{Z_pZ_{th2} + Z_{th2}Z_p + Z_{th2}Z_{th2}} I \\
I_{z3} &= \frac{Z_{th2}Z_p}{Z_pZ_{th2} + Z_{th2}Z_p + Z_{th2}Z_{th2}} I
\end{align*} \]  

(10)

**2.3 Summary**

From the above analysis, we have a method to calculate the current value passing through the grounding system impedance of substation when lightning strikes at any point on the grounding wire of transmission line as follows:

(i). We determine the Thévenin impedance (seeing from the position that lightning strikes to the substations) in case of open-ended grounding wire line at the substations, with the number of nodal point is \((k-1)\) and \((n-k)\) as follows:

\[ \begin{align*}
Z_{th01} &= \frac{\alpha_1}{\beta + \sqrt{\gamma Z_p + Z_{th1}^2}^{\frac{1}{4}}} - \frac{\alpha_2}{\beta + \sqrt{\gamma Z_p + Z_{th1}^2}^{\frac{1}{4}}} \\
Z_{th02} &= \frac{\alpha_1}{\beta - \sqrt{\gamma Z_p + Z_{th1}^2}^{\frac{1}{4}}} - \frac{\alpha_2}{\beta - \sqrt{\gamma Z_p + Z_{th1}^2}^{\frac{1}{4}}}
\end{align*} \]  

(11)

where \( \alpha_1, \alpha_2 \) and \( \beta \) was considered in formula (1).
(ii). Determine the Thevenin impedance (seeing from the position that lightning strikes to the substations) in case of grounding wire line connecting with grounding system of these substations, with the number of nodal point is \((k - 1)\) and \((n - k)\) as follows:

\[
Z_{th1} = Z_{th01} - Z_{pTD1}^2 / (Z_{th01} + Z_1) \quad \text{(12)}
\]

\[
Z_{th2} = Z_{th02} - Z_{pTD2}^2 / (Z_{th02} + Z_1) \quad \text{(12)}
\]

where \(Z_{pTD1}, Z_{pTD2}\) have form as formula (3)

(iii). The current which passes through the grounding system impedance of substations when lightning strikes at any point on the grounding wire of transmission line is calculated as follows:

\[
I_s(k) = \frac{Z_{pTD1}}{Z_1 + Z_{th01}} x \frac{Z_p}{Z_{th01} + Z_{th1} + Z_{th2} + Z_1} x Z_{th1} I \quad \text{(13)}
\]

\[
I_s(k) = \frac{Z_{pTD2}}{Z_1 + Z_{th02}} x \frac{Z_p}{Z_{th02} + Z_{th1} + Z_{th2} + Z_1} x Z_{th2} I \quad \text{(13)}
\]

where \(Z_{th01}, Z_{th02}, Z_{th1}, Z_{th2}, Z_{pTD1}, Z_{pTD2}\) was considered in above formulas.

3. APPLICATION

1. Current passing the grounding system of substation with impact of \(R_p\): a). \(R_p\) is constant.

Surveying the following parameters:

Grounding resistance of electric pole changes from 5 to 40(Ω),

Grounding resistance of substation 1: \(R_1 = 1(Ω)\),

Grounding wire TIC-25: \(R_s = 6.32(Ω/km)\),

Number of span: \(n = 50\).

Results received as follows:

![Graph of Current (%) passing the grounding system of substation 1 in term of lightning position k](image)

![Graph of (% ) of current at grounding system of substation in terms of lightning position k](image)

- The more the grounding resistance of the electric pole is, the higher the current passes through grounding system of substation.
- The more the grounding resistance of the electric pole is, the larger the dangerous zone for substation.
- We can clearly determine the lightning position that creates a risk to substation.

<table>
<thead>
<tr>
<th>Lightning position</th>
<th>(%I) (R_p=5)</th>
<th>(%I) (R_p=10)</th>
<th>(%I) (R_p=15)</th>
<th>(%I) (R_p=20)</th>
<th>(%I) (R_p=25)</th>
<th>(%I) (R_p=30)</th>
<th>(%I) (R_p=35)</th>
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<td>-5.20</td>
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<td>-1.29</td>
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<td>-5.31</td>
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<td>-5.86</td>
<td>-5.96</td>
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<td>-0.99</td>
</tr>
</tbody>
</table>

Surveying the current through grounding system of substation (see Fig.7 and Table T2), we obtained: the faster the current decreases, the smaller the grounding resistance of electric pole is.

b). Changing \(R_p\) of electric pole close to substation

Surveying the following parameters:
Fixing grounding resistance of electric pole from 10 to 40(Ω), only changing grounding resistance of electric pole close to substation
Grounding resistance of substation 1: \( R_1 = 1(Ω) \).
Grounding wire \( \text{PIC-25} \): \( R_s = 6.32(Ω/km) \).
Number of span: \( n=50 \).
Results received as follows:

**Surveying at first electric pole with \( R_p = 5(Ω) \)**

Fig.8: Graph of Current ( %) passing the grounding system of substation 1 in term of lightning position \( k \) with resistance of first electric pole \( 5Ω \).

**Surveying at first 2 electric poles with \( R_p = 5(Ω) \)**

Fig.9: Graph of Current ( %) passing the grounding system of substation 1 in term of lightning position \( k \) with resistances of first 2 electric poles \( 5Ω \).

**Surveying at first 3 electric poles with \( R_p = 5(Ω) \)**

Fig.10: Graph of Current ( %) passing the grounding system of substation 1 in term of lightning position \( k \) with resistance of first 3 electric poles \( 5Ω \).

Comparing the values of current passing grounding system of substation 1 in Fig. 6, 8, 9 and 10 we saw that: this current fast decreases (decreasing dangerous zone) and only in some spans it will goes out of the dangerous zone.

2. **Current passing the grounding system of substation with impact of \( R_s \):**

Surveying the following parameters:

Changing grounding wire: \( \text{PIC-25} : R_s = 6.32(Ω/km), \text{PIC-35} : R_s = 4.47(Ω/km), \text{PIC-50} : R_s = 3.45(Ω/km), \text{PIC-70} : R_s = 2.19(Ω/km), \text{PIC-95} : R_s = 1.88(Ω/km) \).
Grounding resistance of substation 1: \( R_1 = 1(Ω) \).
Grounding resistance of electric pole: \( R_p = 5(Ω) \).
Number of span: \( n=50 \).
Results received as follows:

**Surveying at first 2 electric poles with \( R_p = 5(Ω) \)**

Fig.11: Graph of Current ( %) passing the grounding system of substation 1 in term of lightning position \( k \).

From Fig.11 (and from Table T3) we saw that:

- The more the grounding resistance of the electric pole is, the higher the current passes through grounding system of substation.
- The smaller the grounding wire is, the higher the current passes through grounding system of substation.
- We can clearly determine the lightning position that creates a risk to substation.

**Table T3: Current ( %) passing through grounding system of substation 1 in terms of lightning position \( k \)**

<table>
<thead>
<tr>
<th>Lightning position</th>
<th>%I (PIC-25)</th>
<th>%I (PIC-35)</th>
<th>%I (PIC-50)</th>
<th>%I (PIC-70)</th>
<th>%I (PIC-95)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>78.7668</td>
<td>74.9228</td>
<td>71.8485</td>
<td>66.1107</td>
<td>64.1047</td>
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<tr>
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<td>45.2183</td>
<td>46.8990</td>
<td>47.5679</td>
<td>47.5563</td>
<td>47.2339</td>
</tr>
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<td>31.4927</td>
<td>34.2093</td>
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<tr>
<td>3</td>
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</table>

Fig.12: ( % ) of current at grounding system of substation in terms of lightning position \( k \)
In general, when surveying a dangerous zone for substation, we obtained that, this dangerous zone only lies in first some spans of transmission line and the designers have to pay attention to it while designing transmission lines.

From Fig.12 (and from Table T4), We received, the bigger the values of current passing grounding system of substation are, the larger the grounding wire is.

**3. Current passing the grounding system of substation with impact of \( R_1 \):**

Surveying the following parameters: Changing grounding resistance of substation 1 from 0.1 to 1(Ω).

Resistance of grounding wire ICC-25: \( R_s = 6.32(Ω/km) \).

Grounding resistance of electric pole: \( R_p = 5(Ω) \).

Number of span: \( n = 50 \).

Results received as follows:

**Table T5: (%) of current decrease at grounding system of substation in terms of lightning position \( k \)**

<table>
<thead>
<tr>
<th>Lightning Position</th>
<th>( %I ) (( R_1=0.1 ))</th>
<th>( %I ) (( R_1=0.2 ))</th>
<th>( %I ) (( R_1=0.3 ))</th>
<th>( %I ) (( R_1=0.4 ))</th>
<th>( %I ) (( R_1=0.5 ))</th>
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</tr>
</tbody>
</table>

The smaller the grounding resistance of substation is, the larger the value of current passing grounding system of substation is. However, this change is not large and, thus, in this case, the dangerous zone can be considered to be unchanged.

**Fig.14: (%) of current at grounding system of substation in terms of lightning position \( k \)**

Surveying the current decrease at grounding system of substation (see Fig.14), we obtained: the faster the current decreases, the smaller the grounding resistance of substation is.

**3. CONCLUSIONS**

This paper presents some formulas to calculate current passing through grounding system of high voltage substation and determines a dangerous zone of high voltage substation when lightning strikes at any point on the grounding wire of transmission line. It provides designers with information to design transmission lines properly.

**REFERENCES**

To determine the equivalent impedance in case of the end of the grounding wire line connecting with a grounding system impedance \( Z_1 \), we turn \( n \) pi-elements equivalent circuit into the \( n \) \( T \)-elements equivalent circuit and use characteristic matrix method.

If we consider elementary parameters of each span to be equal, then each \( T \)-circuit will be considered as a two-terminals network having the same characteristic matrix, as follows:

\[
A = A_1 = \ldots = A_n = A = \begin{bmatrix}
2Z_p + Z_s & 4Z_pZ_s + Z_s^2 \\
2Z_p & 4Z_p \\
1 & 2Z_p + Z_s \\
Z_p & 2Z_p 
\end{bmatrix}
\]

If we transform \( n \) series two-terminals networks into one then this equivalent two-terminals network will have the characteristic matrix as follows:

\[
A_{TD} = A_1 \times A_2 \times \ldots \times A_n = A^n (A.1)
\]

Applying the Cayley-Hamilton theorem to solve (A.1), we have:

\[
\Rightarrow A_{TD} = \begin{bmatrix}
\beta_0 + \beta_1 A(11) & A(12) \\
A(21) & \beta_0 + \beta_1 A(22)
\end{bmatrix}
\]

where

\[
\begin{align*}
\beta_0 &= \frac{\lambda_1 \lambda_2 - \lambda_2 \lambda_1}{\lambda_2 - \lambda_1} \\
\beta_1 &= \frac{\lambda_1^2 - \lambda_2^2}{\lambda_2 - \lambda_1}
\end{align*}
\]

and

\[
\begin{align*}
\lambda_1 &= \frac{2Z_p + Z_s + \sqrt{4Z_sZ_p + Z_s^2}}{2Z_p} \\
\lambda_2 &= \frac{2Z_p + Z_s - \sqrt{4Z_sZ_p + Z_s^2}}{2Z_p}
\end{align*}
\]

The two-terminals network with the characteristic matrix determined at (A.2) is transformed inversely into \( T \)-elements equivalent circuit as in Fig. A.1

Fig. A.1 Equivalent Thevenin circuit where parameters of \( T \)-elements equivalent circuit as follows:

\[
\begin{align*}
Z_{th0} &= Z_s + Z_p \left( 1 + \frac{\beta_0}{\beta_1} \right) \\
Z_{th1} &= Z_{th0} - \frac{Z_{pTD}^2}{Z_{th0} + Z_1}
\end{align*}
\]

where:

\[
Z_{pTD} = \frac{2^n Z_p \sqrt{4Z_sZ_p + Z_s^2}}{\left( b + \sqrt{4Z_sZ_p + Z_s^2} \right)^n - \left( b - \sqrt{4Z_sZ_p + Z_s^2} \right)^n}
\]

and

\[
b = 2Z_p + Z_s.
\]

**BIography**

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