Analysis of Arrester Energy for 132kV Overhead Transmission Line due to Back Flashover and Shielding Failure

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Abstract- This paper presents analysis of lightning arrester energy due to back flashover and shielding failure for the purpose of installing transmission line arrester (TLA). This study simulated, analysed and validated with the installed lightning arresters on the 132kV transmission line in Malaysia by using PSCAD/EMT DC software. The arrester is based on IEEE frequency dependent model. The simulation result shows that the lightning arrester energy obtained through simulation is less than the rating installed at site.

Index Terms- Arrester, Back Flashover, Shielding Failure, Bergeron model

I. INTRODUCTION

The use of line arrester is to decrease or eliminate lightning flashover on transmission lines [1]. The purpose of line arrester installation is to improve the performance of overhead lines with poor shielding or with very high tower footing impedance [2]. Arresters avoid lightning flashovers since transmission lines insulation voltage is higher than the residual voltage developed across the arresters, whether due to back flashover or shielding failure. However, the arresters have to withstand the energy discharged by the lightning stroke.

Shielding failure occurs when lightning strikes of 20 kA and below bypass the overhead shield wires. It is always designed such that overhead ground wires are located at positions which provides least shielding failure. Thus, majority of lightning will terminate on the shield wires and build up a voltage across line insulation when large currents flow through the tower. Flashover occurs when these voltages exceed the insulator critical flashover voltage (CFO) and this flashover is called back flashover [1]. When back flashover occurs, part of the surge current will be transferred to the phase conductors through insulation string [3].

This paper presents the application of PSCAD to estimate the arrester energy due to back flashover and shielding failure. The current stroke range in the simulation which contributes back flashover is 20kA, 34.5kA, 50kA, 150kA and 200kA. When shielding failure phenomena occurs due to the current stroke to phase conductor, the range of current is 3kA, 5kA, 10kA, 15kA and 20kA.

For modelling, PSCAD has been utilized. The CIGRE simulation method for 132kV has been developed and the arrester was based on frequency dependent model, which is represented with IEEE two sections of nonlinear resistance. Since the Maximum Continuous Operating Voltage (MCOV) of this transmission line is 96kV, 2P Class 3 type of arrester has been chosen because the rated voltage is between 15kV to 168kV as in the datasheet of modular polymeric surge arrester, by Tyco Electronics.

II. MODELLING

The overhead lines are represented by multi-phase model considering the distributed nature of the line parameters due to the range of frequencies involved. Phase conductors and shield wires are modelled in detail between the towers. PSCAD/EMTDC version 4.2 is used to carry out the modelling of transmission line, towers and surge arresters.

A. Transmission Line and Tower Model

Transmission line is modelled based on standard double circuit line geometry drawings and conductor data of a typical 132kV line. The transmission towers are represented geometrically similar to that of the single-storey lattice tower as shown in Fig. 1 [4]. The lowest conductor from the ground is 14.01 m and the span length of the transmission line is 300m. The line geometry is shown in Fig. 2. The average tower surge impedance is calculated based on the tower dimension using (1) [5].

$$Z_r = 60 \ln \left( \cot \left( 0.5 \times \tan^{-1} \left( \frac{r_{avg}}{H_t} \right) \right) \right)$$

(1)

$$r_{avg} = \frac{r_{h_1} + r_{h_2} (h_1 + h_2) + r_{h_1}}{h_1 + h_2}$$

(2)

where
$Z_T$ = the average tower surge impedance,
$r_1$ = the tower top radius, $r_2$ = the tower mid-section radius,
$r_3$ = the tower base radius, $h_1$ = the height from base to mid-section,
$h_2$ = the height from mid-section to top

Five transmission towers are modelled as single conductor distributed parameter line (Bergeron model travelling wave) segments of ‘transmission lines’ in PSCAD. When using the Bergeron model, since the line parameters are constant at the chosen frequency, the user may choose the R, L and C values. Line termination at each side of the model is necessary to avoid any reflection that might affect the simulated over voltages around the point of impact [6].

Figure 1. 132kV double circuit tower dimension

B. Insulator String Model

The insulator is modelled as a stray capacitance connected between respective phases and the tower. The tower model in PSCAD is shown in Fig. 3. The string which comprises of glass insulators provides an equivalent capacitance used in this model. The insulator itself contributes mechanical support to the conductors and all the current carrying parts subjected to normal operating and transient voltage. The voltage withstand capability of the insulator is calculated using (3),

$$V_{\text{flashover}} = K_1 + \frac{K_2}{t^{0.75}}$$  \hspace{1cm} (3)

where

$K_1 = 400 \times L$

$K_2 = 710 \times L$

$L$ = insulator length in meter

t = time elapsed after lightning stroke in $\mu$s [7,8]

Figure 2. 132kV double circuit tower configuration

Figure 3. PSCAD tower model

C. Line Arrester Model

The line arrester characteristics selected for the simulation are as follows:

<table>
<thead>
<tr>
<th>TABLE I.</th>
<th>ARRESTER CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage (kV)</td>
<td>120</td>
</tr>
<tr>
<td>MCOV (kV rms)</td>
<td>96</td>
</tr>
<tr>
<td>Voltage(kV) for 10 kA, 8/20$\mu$s</td>
<td>303</td>
</tr>
<tr>
<td>Energy absorption (kJ/kV)</td>
<td>8.0</td>
</tr>
<tr>
<td>Length of arrester column (m)</td>
<td>1.268</td>
</tr>
<tr>
<td>No. of parallel column of disks</td>
<td>1</td>
</tr>
</tbody>
</table>

The non-linear characteristic of the line arrester is modelled as recommended by the IEEE W.G 3.4.11(IEEE
Working Group 3.4.11, 1992) [9]. The frequency-dependent model consists of two non-linear resistors, $A_0$ and $A_1$, which are separated by R-L filter, as shown in Fig. 4. The I-V characteristics of $A_0$ and $A_1$ shown in Fig. 5 are obtained from 8/20 µs impulse data as supplied by the manufacturer.

The resistor and inductor initial parameters are calculated based on an estimated height of the arrester and the number of parallel columns of metal-oxide disks using the following equations [10]:

$$
L = 15d/n \mu H
$$

$$
R = 56d/n \Omega
$$

$$
L_s = 0.2d/n \mu H
$$

$$
R_s = 100d/n \Omega
$$

$$
C = 100n/d \mu F
$$

where

- $d$ = the estimated height of the arrester in meter (overall dimensions from data sheet)
- $n$ = the number of parallel columns of metal oxide in the arrester

The calculated parameters have been adjusted to obtain the best behaviour for the frequency-dependent model as suggested by the Working Group 3.4.11 [11].

III. LIGHTNING

Lightning source used in this study is modelled based on the IEC triangular wave shape as shown in Fig. 6 [12]. The lightning stroke is modelled by a current source parallel with lightning-path impedance (Fig. 7). The lightning-path impedance is represented as a parallel resistance of 400Ω [13]. Peak current source of different magnitudes have been used to investigate the effects of back flashover and shielding failure phenomenon on the arrester discharge energy. Simulation of back flashover is carried out by injecting single stroke current of 20kA, 34kA, 5kA, 50kA and 100kA to the top of the third tower.

IV. ARRESTER ENERGY

A. Stroke to Ground Wire

The energy discharged by the surge arrester, $W_a$, during back flashover can be estimated by the following equations [1]:

$$
W_a = i_4 E_4 \tau
$$

where

- $i_4$ = arrester current
- $E_4$ = arrester discharge voltage
- $\tau$ = time constant

The time constant of the arrester current, $\tau$, is estimated by:

$$
\tau = \frac{Z_s}{R_s} T_s
$$
where

\[ Z_g = \text{ground wire impedance} \]
\[ R_f = \text{footing resistance} \]
\[ T_s = \text{span length divided by the velocity of light} \]

B. Stroke to Phase Conductor

The arrester current and discharge voltage can be related as [14]:

\[ i_A = k \left( e_A \right)^\alpha \]  \( (7) \)

The energy discharged by the surge arrester, \( W_A \), during shielding failure can be estimated by the following equations [1]:

\[ W_A = \int_0^\infty i_A e_A dt \]
\[ W_A = \frac{K_1 E_{A1} \tau_1 + K_2 E_{A2} \tau_2 + K_3 E_{A3} \tau_3}{1 + 1/\alpha} \]  \( (9) \)

where \( E_{A1}, E_{A2}, \) and \( E_{A3} \) are the discharge voltages for currents of \( K_1, K_2, \) and \( K_3 \).

V. RESULTS AND DISCUSSION

Presently, the 132kV transmission lines are equipped with 5.1kJ/kV energy of surge arrester. Thus, the comparison between calculated and simulation were developed for both conditions:

a) back flash over for stroke current range of 20kA to 200kA
b) shielding failure for stroke current range of 0kA to 20kA

Over 50% of the lightning strokes contain more than one stroke which is also known as multiple strokes lightning (MSL). For this study, only single stroke lightning (SSL) current magnitude is considered.

A. Stroke to Ground Wire

The stroke current strikes directly to ground wire, creating back flashover phenomena. Fig. 8 shows 20kA stroke current to the ground wire whilst Fig. 9 indicates the voltage across the surge arrester during the lightning. The virtual time to crest or front time and tail time concerning both Fig. 8 and 9 is 8\( \mu \text{s} \)/20\( \mu \text{s} \). It is set since it is the standard lightning wave shape impulse. The energy dissipated by the frequency-dependent model consists of two non-linear resistors namely \( A_0 \) and \( A_1 \) are shown in Fig. 10 and 11 separately. The total of these two energies discharged by the line arrester is shown in Fig. 12.
Table II shows comparison between calculated energy values using (5) and values obtained from simulation result using PSCAD for different stroke currents between 20kA and 200kA. It was found that the simulated energy is slightly less than the calculated energy. Fig. 13 depicts understandably the comparison and differences value both calculated and simulation energy results.

Table II. Energy of arrester during back flashover

<table>
<thead>
<tr>
<th>Stroke Current (kA)</th>
<th>Calculated Energy (kJ/kV)</th>
<th>Simulated Energy (kJ/kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.01</td>
<td>0.006</td>
</tr>
<tr>
<td>34.5</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>50</td>
<td>0.09</td>
<td>0.05</td>
</tr>
<tr>
<td>100</td>
<td>0.24</td>
<td>0.19</td>
</tr>
<tr>
<td>150</td>
<td>0.41</td>
<td>0.35</td>
</tr>
<tr>
<td>200</td>
<td>0.58</td>
<td>0.51</td>
</tr>
</tbody>
</table>

B. Stroke to Phase Conductor

Direct lightning stroke to phase conductor may result in shielding failure phenomena. This occurs when the lightning current of 20kA and below bypass the overhead shield wire.

For this case, only SSL current magnitudes between 10kA to 20kA are simulated and analysed since shielding failures tend to occur between these values. The designed line arrester is placed on the top phase $A_1$ of the third tower and different SSL currents are injected to the top phase conductor.

Fig. 14 shows the 20kA stroke current used for this analysis. The waveform of discharge voltage across the phase $A_1$ when 20kA lightning stroke terminates on the top conductor is shown in Fig. 15.

Figure 12. Energy discharged by the line arrester

Figure 13. Comparison of arrester energy during back flashover

Figure 14. 20kA lightning stroke current

Figure 15. Voltage across surge arrester during 20kA stroke to the phase conductor

The energy discharged by the non-linear element of $A_0$ and $A_1$ obtained from the simulation when the peak current magnitude is injected to the conductor are shown in Fig. 16 and Fig. 17.

Figure 16. $A_0$ energy waveform
Figure 17. A1 energy waveform

Both A0 and A1 do not share the discharge energy equally because of the inductance between the elements. The sum of the two energy results in the total energy absorption of the line arrester due to shielding failure as shown in Fig. 18.

Figure 18. Energy discharged by the line arrester

To calculate the arrester energy analytically, the stroke current is assumed to have an exponential tail decay. The time to half value of the stroke current is taken to be 20μs, hence the tail time constant, , is 72μs. Assuming the arrester discharges the entire stroke current, the energy dissipated can be calculated from (8) and (9).

Table III summarises the results obtained of the total energy dissipated by the arrester in kJ/kV of MCOV for different peak current magnitudes. Increase in lightning current results to a higher energy discharged by the arrester.

<table>
<thead>
<tr>
<th>Stroke Current (kA)</th>
<th>Calculated Energy (kJ/kV)</th>
<th>Simulated Energy (kJ/kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.76</td>
<td>1.16</td>
</tr>
<tr>
<td>13</td>
<td>1.09</td>
<td>1.58</td>
</tr>
<tr>
<td>15</td>
<td>1.31</td>
<td>1.86</td>
</tr>
<tr>
<td>17</td>
<td>1.53</td>
<td>2.01</td>
</tr>
<tr>
<td>20</td>
<td>1.87</td>
<td>2.44</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

This paper presents the findings of the study carried out to investigate the capability of the installed arresters in withstanding single stroke lightning (SSL) discharged energy caused by back flashover and shielding failure phenomena. Determination of arrester energy during lightning has been performed by analytical method and simulation using PSCAD/EMTDC. The designed arrester has been found capable of withstanding the discharged energy from the lightning current and complies with the design requirement of 5.1kJ/kV of MCOV as specified by the national grid in Malaysia.

REFERENCES