A Simple Surge Arrester Model Extracted from Experimental Results

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SUMMARY

This paper presents a simple model of a ZnO surge arrester extracted from experimental results. The parameters in the proposed model are estimated from the experimental results. The current generation circuit is considered in the algorithm for the parameter estimation. The generation circuit is composed of a charging capacitor and an associated inductor for producing the standard lightning impulse current waveform of 8/20 μs. The experiment on injection of 8/20 μs waveform current to the surge arrester under test was carried out in a real HV laboratory. Injected currents and residual voltages calculated the IEEE, modified IEEE, and proposed models, and from experiment are compared in this paper. From the compared results, the proposed model shows better performance than the other models. It is simpler, faster in calculation, and more accuracy than the other models. From this achievement, the accurate arrester model can be readily applied in a circuit simulator in insulation coordination design.

KEYWORDS

Current generation circuit–Parameter estimation–Standard lightning impulse current
- Surge arrester model

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1. Introduction
Lightning strike has been one of the major factors that lead to failure of electrical power system. In recent years, metal oxide surge arrester has been widely used and it is now an essential item in the insulation coordination for power systems based on its promising electrical characteristics. Surge protections of power systems are now commonly examined based on the results of their network simulation of their responses to the electrical overstresses. Accurate simulation needs an accurate model of the network elements and this includes an accurate arrester model. The study of dynamic lightning model of metal oxide surge arrester has been conducted to provide an accurate performance in the operation. Several accurate models have been proposed to describe the arrester characteristics for different kind of electrical stress. The significant dynamic characteristic is that the voltage across the arrester increases as time to crest of the arresters current decreases and that the voltage reaches a peak before the arresters current reaches its peak. Therefore, the arrester can not only be modeled by a non-linear resistance. This dynamic study may be found useful in the insulation coordination studies. The purpose of this paper is to present parameter estimation of an arrester model for typical lightning surges of 8/20 μs from experimental results and the current generation circuit is considered in the parameter estimation algorithm. Effectiveness and accuracy of the estimated model is verified by comparing the experiment results from the residual voltage test and the result of the estimated model.

2. The IEEE Arrester Model
One of the models shown in Figure 1 was proposed by IEEE W.G.3.4.11 [1]. The model is represented by two nonlinear resistors (A₀ and A₁) in parallel separated by an R-L filter. This filter represented dynamic (frequency dependant) characteristics that are significant for lightning and other fast wave-front surges, which have their peak in the range of 8 μs or faster. Later Pinceti et al. [2] proposed the simplified model as shown in Figure 2. The model is very close to the previous model. The parallel resistors (R₀ and R₁) were removed and the resistor (R) was connected at the sending end of the arrester model. In the two models the nonlinear resistors can be modeled by using the data provided in their papers. Sometimes effect of the nonlinear resistors cannot reproduce the residual voltages according to the manufacturer data. The other parameters have to be adjusted to get good agreement to the manufacturer data. To overcome this difficulty Fernandez et al. [3] proposed the model that the inductor (L₁) was removed. The model is shown in Figure 3. The nonlinear resistors (A₀ and A₁) can be estimated from the manufacturer data or experimental results. There are many literatures show that those models are quite effective to reproduce the residual voltage peak after a process of parameter adjustment. However, the entire waveforms are deviated from the measured waveform. In this paper, the simple model as shown in Figure 4 is proposed to increase accuracy of the arrester model.

![Figure 1. IEEE model.](Image)

![Figure 2. Pinceti’s model.](Image)

![Figure 3. Fernandez’s model.](Image)

![Figure 4. Proposed and simple model.](Image)
3. Experimental Set Up

The lightning impulse current can be generated by a transient RLC circuit as shown in Figure 5, where, $V_C$ stands for a DC charging voltage source, $R_L$ stands for a current limiting resistor, $C_s$ stands for a charging capacitor, $L_s$ stands for an inductor, $R_{SH}$ stands for a shunt resistor for current measurement, $i(t)$ stands for impulse current, and EUT stands for equipment under test.

![Figure 5. Circuit of impulse current generator.](image)

To meet the requirement of the standard lightning current waveform[4], the capacitance of the charging capacitor and the inductance of the inductor were set to be 2 $\mu$F and 27 $\mu$H, respectively. The arrester under test has voltage rating of 9 kV and nominal discharge current of 5 kA. The residual voltage [5] across the arrester and the current impulse are measured using the voltage divider and the non-inductive resistive current shunt, respectively. These are then measured by the digital oscilloscope. The elevated current impulse test at about 5 kA was conducted on the 5-kA arrester by adjusting charging voltages on the charging capacitor. The charging voltage was 46 kV.

4. Parameter Estimation

As the proposed model, there are five parameters composed of two resistors ($R_1$ and $R_2$), a capacitor ($C$), an inductor ($L$) and a non-linear resistance ($A_0$). The resistances of $R_1$ and $R_2$ are set to be 540 $\Omega$ and 2.5 k$\Omega$. They are used for damping voltage oscillation on calculated residual voltage. The capacitance can be obtained by measurement and it is 220 pF. The nonlinear resistance is approximated by piece-wise linear which is drawn through the center of voltage-current data from experiment as shown in Figure 6.

![Figure 6. Voltage-current data from experiment.](image)

From Figure 6, the inductance is calculated from the voltage difference ($\Delta V$) from the voltage of the piece-wise linear approximation as given in eq. (1),

$$L = \frac{\Delta V}{i_{vp}}$$

(1)

where, $i_{vp}$ is a derivative of the injected current at peak voltage.

The calculated inductance from eq. (1) and Figure 6 is equal to 1.5 $\mu$H.
5. Solution of The Computed Model

The solution of the arrester model can be calculated by using nodal analysis. In order to obtain the nodal equations in algebraic form, the differential equations describing the voltage-current relationship of resistors, inductors, and capacitors are converted into algebraic equations by utilizing the trapezoidal rule of integration. The nodal equations for the circuit in a discrete time interval can be formulated and the whole network can be represented in a discrete time interval by a system of linear algebraic equations written in the form:

\[
[G][v(t)] = [i(t)] - [I],
\]

(2)

where, \([G]\) is the nodal conductance matrix, \([v(t)]\) is the column vector of the node voltages, \([i(t)]\) is the column vector of current sources, and \([I]\) is the column vector of past history current sources. The non-linear element can be implemented in the circuit simulation by adding the current of the non-linear element on the left hand side of eq. (2) as the following.

\[
[G][v(t)] + [f(v(t))] = [i(t)] - [I]
\]

(3)

where, \([f(v(t))]\) is the column vector of currents of non-linear elements which is written in a form of function of \(v(t)\).

Solution of eq. (3) can be calculated by Newton-Raphson method and its modification. In this paper, the solution of Newton-Raphson method in a vector form can be calculated by eq. (4).

\[
[J][\Delta v(t)] = -[F],
\]

(4)

where,

\[
[F] = [G][v(t)] + [f(v(t))] - [i(t)] + [I],
\]

(5)

\[
[\Delta v(t)] = [v_{i+1}(t)] - [v_i(t)],
\]

(6)

and \([v_i(t)]\) is a vector of voltage at the \(i^{th}\) iteration, and \([J]\) is a Jacobian matrix of \([F]\).

The iteration is stopped when the \([\Delta v(t)]\) is closed to zero, then the solution of eq. (3) is obtained.

The other way for obtaining the solution of eq. (3) with higher stability and faster is approximation of \([f(v(t))]\) with piece-wise linear [6]. This approach is employed in the proposed model because it is simpler, faster in calculation and more stable.

For example, the equivalent circuit of Fernandez arrester model including the current generation circuit is shown in Figure 3. The nodal equation can be written by eq. (7).

\[
\begin{bmatrix}
G_{11} & G_{12} & G_{13} & V_s \\
G_{21} & G_{22} & G_{23} & V_0 \\
G_{31} & G_{32} & G_{33} & V_i \\
\end{bmatrix}
\begin{bmatrix}
0 \\
q_0 V_0 \\
q_1 V_1 \\
\end{bmatrix}
= \begin{bmatrix}
I_s \\
I_0 \\
I_i \\
\end{bmatrix}
\]

(7)

where,

\[
G_{11} = \frac{2C_t}{\Delta t} + \frac{\Delta t}{2L_s}, \quad G_{12} = -\frac{\Delta t}{2L_s} = G_{21}, \quad G_{13} = 0 = G_{31},
\]

\[
G_{22} = \frac{\Delta t}{2R} + \frac{1}{R} + \frac{\Delta t}{2L}, \quad G_{23} = -\frac{\Delta t}{2L} = G_{32}, \quad G_{33} = \frac{\Delta t}{2L},
\]

\[
I_s = \left(2C_t \right) (V_i(t) - V_0(t - \Delta t)) + \frac{\Delta t}{2L_s} (V_i(t - \Delta t) - V_0(t - \Delta t)) + I_{C_i}(t - \Delta t) - I_{L_s}(t - \Delta t),
\]

\[
I_0 = \left(\frac{2C_t}{\Delta t} + \frac{\Delta t}{2L_s}\right) (V_0(t - \Delta t)) + \frac{\Delta t}{2R} (V_i(t - \Delta t)) + \frac{\Delta t}{2L} (V_i(t - \Delta t)) + I_{L_s}(t - \Delta t) + I_{C}(t - \Delta t) + I_L(t - \Delta t),
\]

and

\[
I_i = -\frac{\Delta t}{2L} (V_i(t - \Delta t) - V_0(t - \Delta t)) + I_L(t - \Delta t)
\]
The computer program according to the presented approach was developed based on Matlab program. The computed result by the developed program has been compared to the result calculated by EMTP/ATP. The same results have been found. The reason of using developed program is that there are many optimization methods available in Matlab, so it is readily to use the optimization methods for extracted parameters of the arrester models.

6. Computed and Experimental Results

To show the performance of the proposed model, the calculated results of the injected currents and residual voltages are compared to experimental results. From the estimated parameters in Sections 2 and 4, the residual voltages and impulse current can be calculated by using the approaches in Section 5. The charging voltages on the charging capacitor were fixed in all cases at 46 kV. In the IEEE, Pinceti, and Fernandez models, the circuit parameters were determined by a genetic algorithm [7]. The nonlinear resistances in the presented model can be found in [1]-[3]. The other circuit parameters are given in Table 1.

Table I Estimated Parameters in the presented model

<table>
<thead>
<tr>
<th>Model</th>
<th>IEEE</th>
<th>Pinceti</th>
<th>Fernandez</th>
</tr>
</thead>
<tbody>
<tr>
<td>L₀</td>
<td>0.3µH</td>
<td>1.80µH</td>
<td>-</td>
</tr>
<tr>
<td>L₁</td>
<td>2.53µH</td>
<td>0.52 µH</td>
<td>2.25µH</td>
</tr>
<tr>
<td>R₀</td>
<td>7.29Ω</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R₁</td>
<td>47.04Ω</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R</td>
<td>-</td>
<td>10 MΩ</td>
<td>114.11kΩ</td>
</tr>
<tr>
<td>C</td>
<td>67pF</td>
<td>-</td>
<td>107pF</td>
</tr>
</tbody>
</table>

Figures 7 to 10 show the comparative results of the injected impulse current and the residual voltages calculated by the presented models and those from experiment. Dash and solid lines stand for experimental and calculated results, respectively. Good agreement is observed in a case of the proposed model.
7. Conclusion
In this paper, the parameter estimation of the arrester model is presented. The computed results of the model were calculated by numerical technique based on trapezoidal rule integration and either Newton-Raphson method or piece-wise linear approximation employed to solve the nonlinear equation. The accuracy of the proposed model is validated by comparing the computed results with those from experiment. Good agreement is observed when the proposed model is applied. From this achievement, the accurate arrester model can be readily applied in a circuit simulator in insulation coordination design.

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References