Calculation of Multistage Impulse Circuit and Its Analytical Function Parameters

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Abstract

A new approach has been proposed for the evaluation of multi stage impulse circuit parameters from known rise or peak time and tail time (physical parameters) using Nelder-Mead algorithm (NMA). Results of five stage (n=5) impulse circuit parameters such as $C_1$, $C_2$, $R_1$, $R_2$ & $R_s$ are reported for generating full lightning impulse (LI) and full switching impulse (SI) as given in standards (IEEE 4-2013 and IEC 60060-1). The determined circuit parameters are validated for practical applications through the impulse circuit developed in MATLAB/Simulation for 150kV peak impulse signal. The presented method enables accurate estimation of unknown impulse circuit parameters from the known physical parameters. Impulse wave (LI & SI) attained using double exponential expression and through simulation circuits are reported. The closeness in peak time, rise time, tail time and peak voltage between the output of double exponential function and Simulink model for both standard LI (1.2/50µs) and standard SI (250/2500µs) are also described.

Key Words:- Analytical function parameters, circuit parameters, full lightning impulse (LI), Nelder-Mead algorithm (NMA), full switching impulse (SI).

1 Introduction

In recent years, lightning and switching over voltages have been considered to be the major reason of damage or destruction to power system apparatus. Lightning impulse and transient switching over voltages can cause great damage to insulation of power apparatus used in its network [1-2]. Hence, the power apparatus used in power system network should be designed and constructed to withstand against such lightning
and switching over voltages. Power system network mainly concern with reliability of each apparatus used in it. In order to maintain the reliability of power system against lightning and switching over voltages, it is important to test and verify the electrical breakdown strength or capability of insulation of high voltage power apparatus before introducing into power system network [3-6]. International standards such as IEC 60060-1 [7] and IEEE std 4-2013 [8] describes both full lightning impulse (LI) and switching impulse (SI) voltage tests normally performed on insulation of power system apparatus, in order to check the dielectric strength. According to these standards 1.2/50μs and 250/2500μs impulses are considered for full LI and SI. Hence, it is essential to check the shape and properties of the both LI and SI before applied to the test object in the laboratory. [9].

Standard full LI and SI waveforms shown in Fig. 1 and Fig. 2 are characterized by three parameters: peak value (V<sub>peak</sub>), time to rise (t<sub>rise</sub>) (for full LI) or time to peak (t<sub>peak</sub>) (for full SI), and time to half peak value (t<sub>tail</sub>). According to IEEE standards IEEE std 4-2013, full LI has t<sub>rise</sub> = 1.2μs and t<sub>tail</sub> = 50μs with tolerances of ±30% for t<sub>rise</sub> and ±20% for t<sub>tail</sub> [10]. According to IEC standards IEC 60060-1, full SI has t<sub>peak</sub> = 250μs and t<sub>tail</sub> = 2500μs with tolerances of ±20% for t<sub>peak</sub> and ±60% for t<sub>tail</sub> [11]. These parameters can be termed as physical parameters because these are generally determines from the impulse waveforms (both full LI and SI).

![Fig.1 Double exponential wave with t<sub>rise</sub> and t<sub>tail</sub> of the standard full lightning impulse voltage [12]](image1)

![Fig.2 Double exponential wave with t<sub>peak</sub> and t<sub>tail</sub> of the standard full switching impulse voltage wave [12]](image2)

Standard full LI and SI waveforms are mathematically expressed by double exponential function (1).

\[ V(t) = V_0K\left(e^{-\alpha t} - e^{-\beta t}\right) \]

(1) Where V<sub>0</sub> is amplitude, α and β are the analytical (double exponential) function parameters. To keep the pulse positive polarity, the analytical (double exponential) function constant parameters α and β should satisfy the condition that β > α > 0, t ≥ 0 [13]. K is the amplitude modifying factor [14].

Proper physical parameters can be achieved through the selecting the suitable values of circuit parameters. In the same manner, it is also important to determine proper analytical function parameters (α, β) from known physical parameters. Hence this paper, a new approach for aforementioned transformation from physical parameters to multi stage impulse circuit parameters for both full LI and SI has been attempted and explained in Section 3 and reported in section 4. Results of circuit
parameters are validated through simulation impulse circuit designed in the MATLAB is explained in Section 5.

2 Details of Multi Stage Impulse Circuit and Its Parameters

Simulation and practical multi stage impulse circuit consisting of parameters \( (C_1', C_2', R_1', R_2' & R_s) \) as shown in fig.3 has been considered for generation of standard full LI and SI [15-16]. Double exponential function (1) is commonly used for generation of both full LI and SI voltages. The shape properties of standard full LI and SI voltages using (1) are given in Fig. 1 and Fig. 2 respectively.

Generation of full lightning and switching impulses as per the standards in laboratory, it is necessary to determine the suitable multi stage impulse circuit parameters \( (C_1, C_2, R_1, R_2 & R_s) \) corresponds to physical parameters \( (t_{\text{rise}} \text{ or } t_{\text{peak}} \text{ and } t_{\text{tail}}) \) rather than single stage impulse circuit parameters because single stage impulse circuit generates voltage up to certain limit, beyond that voltage, a single capacitor and its charging unit used in single stage impulse circuit become too costly. In order to production of 150kV (peak) impulse voltage (full LI or SI), charging capacitor \( (C_1') \) of each stage in multi stage impulse generation circuit (5 stages) is charged to \( K \times 30kV \) in parallel and discharge them in series. In this regard, the charging resistance \( (R_s) \) is chosen for charge the capacitors in parallel to supply voltage in about 1 minute and limits the charging current to about 50 to 100mA [17]. Initially, charging capacitor \( (C_1) \) of single stage impulse generation circuit is selected based on maximum charging voltage \( (V_{0\text{max}}) \) and impulse energy \( (W) \) of the generator as given by (2). Then, single stage charging capacitor \( (C_1) \) is converted into multistage charging capacitor \( (C_1') \) according to [12]. In this paper, impulse energy of 150kV (peak) impulse generator (full LI or SI) is chosen as 225J.

\[
C_1 = \frac{(2 \times W)}{(V_{0\text{max}}^2)} \tag{2}
\]

![Fig.3. Multi stage impulse generator circuit (n=5)](image-url)
3 Proposed Impulse Circuit Parameter Estimation Technique

The proposed technique for estimating multi stage (n=5; where n is the number of stages) impulse circuit parameters (C₁, C₂, R₁, R₂ & Rₚ) from known physical parameters has two major parts, one is Nelder-Mead algorithm (NMA) to determination of analytical (double exponential) function parameters (α, β) from the initially defined physical parameters (t_{rise} and t_{tail}) and second one is determination of multi stage impulse circuit parameters from α, β for the multi stage (n=5) impulse generation circuit is shown in Fig. 3.

Nelder-Mead algorithm is used for determination of analytical (double exponential) function parameters (α and β) from known (target) physical parameters (t_{rise} and t_{tail}). The initial approximations given in [18] by (3) are used to initiate the algorithm

\[
\alpha_{init} = \frac{1}{t_{tail}} \quad \text{and} \quad \beta_{init} = \frac{1}{t_{rise}}
\]  

(3)

![Flowchart for determination of multi stage impulse circuit parameters from physical parameters using Nelder-Mead algorithm](image)

Fig. 4. Flowchart for determination of multi stage impulse circuit parameters from physical parameters using Nelder-Mead algorithm
Then, the algorithm is continued for searching the close value of analytical function parameter $\alpha$ and $\beta$ corresponding to the given $t_{\text{tail}}$ and $t_{\text{rise}}$ respectively. Values of $\alpha$ and $\beta$ are moderately changed in a specific interval upward or downward in each step, then $t_{\text{tail}}$ and $t_{\text{rise}}$ are calculated corresponding changes in the $\alpha$ and $\beta$. These calculated tail and rise times are compared to the known physical parameters for each changes of $\alpha$ and $\beta$. At the end of each step, the $\alpha$ and $\beta$ are taken and chosen as the start of next step. If the values of $\alpha$ and $\beta$ are same as that of the previous $\alpha$ and $\beta$, then specific interval is decreased by half. This process is repeated until the desired target parameters $t_{\text{tail}}$ and $t_{\text{rise}}$ are achieved with smaller relative error (between tail and rise time of final $\alpha$, $\beta$ and given target) than the preset accuracy [19]. This algorithm is quite simple and gives more precise results near the end. This process offers the possibility for transform physical parameters of the impulse wave to analytical function parameters. Complete steps involving to find the multi stage ($n=5$) impulse circuit parameters from the known rise or peak time and tail time (physical parameters) using Nelder-Mead algorithm (NMA) are given in the form of flow chart in Fig. 4.

4 Results of Proposed Technique

The circuit parameters ($C_1$, $C_2$, $R_1$, $R_2$ & $R_s$) for multi stage impulse generator and analytical (double exponential) function parameters ($\alpha$, $\beta$) are obtained from Section 3 and reported in section 4, are validated through simulation using impulse circuit implemented in MATLAB/Simulation [23]. The circuit parameters have been derived for the generation of standard full lightning impulse (IEEE std 4-2013) voltage signal (1.2/50$\mu$s) with 150kV peak results are given in table 1. Similarly circuit parameters are also derived for the generation of 150kV peak standard full switching impulse (IEC 60601) voltage signal (250/2500$\mu$s) is tabulated in table 2.

Table 1. Analytical (Double Exponential) Function Parameters ($\alpha$ and $\beta$) & Multi Stage Impulse Circuit Parameters of Standard Full Lightning Impulse Voltage

<table>
<thead>
<tr>
<th>Standard full lightning impulse physical parameters (rise &amp; tail time) (µs)</th>
<th>Result of $\alpha$ and $\beta$ for the physical parameters using NMA</th>
<th>Multistage impulse circuit parameters corresponds to physical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha$ ($\times 10^4$)</td>
<td>$\beta$ ($\times 10^6$)</td>
</tr>
<tr>
<td>1.2/50</td>
<td>1.4912</td>
<td>1.6335</td>
</tr>
</tbody>
</table>

The circuit parameters for standard full lightning and standard full switching impulse voltage shown in table 1 and table 2 are validated through the multi stage impulse generator circuit as given in [15]. The percentage error of peak time, rise time, tail time and peak voltage between results of simulation and analytical function are calculated and reported. The charging resistance $R_s$ is chosen here for charging the each stage capacitors in parallel is calculated using (4).
Table 2: Analytical (Double Exponential) Function Parameters (α and β) & Multi Stage Impulse Circuit Parameters of Standard Full Switching Impulse Voltage

<table>
<thead>
<tr>
<th>Standard full switching impulse physical parameters peak &amp; tail time (µs)</th>
<th>Result of α and β for the physical parameters using NMA</th>
<th>Multistage impulse circuit parameters corresponds to physical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α (µF)</td>
<td>β</td>
</tr>
<tr>
<td>250/2500</td>
<td>377.54</td>
<td>6000.1</td>
</tr>
</tbody>
</table>

5 Results Validation and Discussion

The multi stage impulse generator circuit implemented in MATLAB/Simulink is shown in Fig. 5. The five stage (n=5) impulse circuit parameter (C₁ =C₂=C₃ =C₄=C₅), C₂, R₁ (R₁d₁=R₁d₂=R₁d₃=R₁d₄=R₁d₅), R₂ (R₂g₁=R₂g₂=R₂g₃=R₂g₄=R₂g₅) and R₃ given in table 1 and table 2 for standard lightning impulse voltage and standard switching impulse voltage signals are substituted in respective elements shown in Fig. 5 and its results are reported in Figs. 6 and 7.
The corresponding correction factor $k$ is calculated and incorporated in Simulink model. The percentage error is calculated for both full LI and SI waveforms by taking four parameters i.e. rise time, tail time, peak time and peak voltages. These errors are reported in table 3 and table 4 respectively. From the Figs. 6 and 7 it is observed that, the simulation output is matched well with the analytical function waveforms obtained using NMA algorithm. Hence the proposed method is validated through simulation.

![Fig.6. Standard full lightning impulse voltage waveform (1.2/50µs) using multistage impulse generation circuit and analytical function parameters.](image1)

![Fig.7. Standard full switching impulse voltage waveform (250/2500µs) using multistage impulse circuit and analytical function parameters.](image2)

Table 3: Percentage Errors between Results of Analytical (Double Exponential) Function & Multi Stage Impulse Generator Circuit of Standard Full Lightning Impulse Voltage

| Standard full lightning impulse physical parameters (rise & tail time) (µs) | Percentage Error |
|---|---|---|---|---|
| | Rise time | Tail time | Peak time | Peak voltage |
| 1.2/50 | 1.48% | 1.67% | 1.79% | -0.02% |

Table 4: Percentage Errors between Results of Analytical (Double Exponential) Function & Multi Stage Impulse Generator Circuit of Standard Full Switching Impulse Voltage

| Standard full switching impulse physical parameters (rise & tail time) (µs) | Percentage Error |
|---|---|---|---|---|
| | Rise time | Tail time | Peak time | Peak voltage |
| 250/2500 | 0.67% | 4.06% | 0.48% | -1.24% |
From the table 3 and 4, it is observed that the percentage error in rise time, tail time, peak time and peak voltage are within tolerance as provided in standards IEEE 4-2013 and IEC 60060-1 for both standard full LI and SI respectively. Also the maximum percentage error observed from proposed method for determining the impulse circuit parameter is 4%.

6 Conclusion

A new method for calculating analytical function and multi stage impulse circuit parameters are attempted and reported. Results of impulse circuit parameters are validated through simulation for both standard full LI and SI voltages. The percentage error in rise time, tail time, peak time and peak voltage between the impulse waveforms attained using circuit parameters and analytical function parameters are reported. Maximum error observed in the proposed approach is ±4%. Proposed method enables an accurate estimation of unknown impulse circuit parameters from known physical parameters. Errors appeared in proposed approach are within the tolerance as given in the standards. Hence the circuit parameters reported here can be useful in high voltage laboratory or in related applications for generating standard high voltage lightning and switching impulse signals with the peak of 150kV.

7 References


