Estimation of load capacitance and stray inductance in lightning impulse voltage test circuits

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ABSTRACT

In order to obtain the lightning impulse voltage waveshape regarding front time, time to half and relative overshoot magnitude within the limits prescribed by IEC 60060-1, it is useful to accurately estimate the test circuit parameters, e.g. load capacitance and circuit inductance. A stray inductance consists of the inductance of impulse generator and the inductance of connecting leads. Load capacitance consists of voltage divider capacitance, test object and parasitic capacitances. In practice, the test object capacitance is often unknown. Capacitance measurement takes time and makes testing procedure more complex. Also, it is very difficult to estimate parasitic capacitances although their influence can sometimes be significant.

This paper presents a new genetic algorithm (GA) based method for fast and accurate estimation of load capacitance and circuit inductance during lightning impulse voltage testing of a capacitive load. Computational and experimental verification of the method is successfully performed for standard and non-standard lightning impulse waveshapes with various relative overshoot magnitudes.

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1. Introduction

High voltage equipment has to be tested with lightning impulse (LI) voltage in order to prove the capability against such overvoltages. In order to simulate the effect of transient overvoltage on high voltage equipment the various national and international standards define the impulse voltages and their appliance to a test object. Time parameters of lightning impulse voltage are shown in Fig. 1 according to IEC standard [1]. Tolerances of 1.2 μs ± 30% for front time $T_1$ and 50 μs ± 20% for time to half-value $T_2$ are permitted. The test circuit has an inductance which consists of the inductance of impulse generator, ground leads and the connecting leads. In some cases inductance causes overshoot and oscillation at the crest of the lightning impulse voltage waveform.

Overshoot usually occurs when the connecting leads from impulse generator to test object are very long and the inductance is comparably high. In case of a test object with high capacitance, low values of the impulse generator front resistors are used which in some cases can lead to oscillations occurrence. Fig. 2 shows the overshoot $\beta$ which represents the increase of amplitude of an impulse voltage due to a damped oscillation (frequency range usually 0.1–2 MHz) at the peak caused by the inductance of the test circuit and the load capacitance.

Overshoot magnitude $\beta$ is the difference between the extreme value of the recorded impulse voltage curve and the maximum value of the base curve. The base curve is an estimation of a full lightning impulse voltage without a superimposed oscillation. The relative overshoot magnitude $\beta'$ represents the ratio of the overshoot magnitude to the extreme value and it is defined by expression (1).

$$\beta' = 100 \cdot \frac{U_e - U_b}{U_e} \cdot 100$$. (1)

According to Ref. [1], the relative overshoot magnitude shall not exceed 10%.

In high voltage laboratories, lightning impulse voltages are most commonly produced using the Marx lightning impulse generator [2]. Equivalent circuit of the impulse generator is shown in Fig. 3.

The generator capacitance $C_1$ is slowly charged from a DC source until the spark gap $G$ breaks down. Resistor $R_1$ primarily damps the circuit and controls the front time $T_1$, while resistor $R_2$ discharges the capacitors and controls the time to half $T_2$. $C_2$ represents the capacitance of test object and all other capacitive elements which are in parallel to the test object (e.g. capacitor voltage divider used...
for measurement, additional load capacitor, sometimes used for avoiding large variations of $T_1$ and $T_2$ if the test objects are changed, and parasitic capacitances). $L$ represents the inductance of impulse generator and the connecting leads.

Available values of $R_1$ and $R_2$ are limited in practice and therefore the standardized nominal values of $T_1$ and $T_2$ are difficult to achieve. Changing these resistors on the generator usually requires a trial-and-error process or accumulated experience with previous impulse tests on similar equipment. For this reason it is obvious that the simple and easy-to-use method for generator parameter determination would make lightning impulse testing procedure less complicated and less time-consuming.

Many published papers deal with the calculation of impulse generator parameters; Thomason [3] determined circuit formulas of the most commonly used impulse generators circuits; Feser [4], Kannan and Narayana [5] and Del Vecchio et al. [6] investigated circuit design for the lightning impulse testing of transformers; Khalil and Metwally [7] developed a computerized method to reconfigure the impulse generator for testing different types of objects. Methods described in the previously mentioned papers use $C_2$ as an input parameter which means that the load capacitance should be known or measured before testing. In practice, test object capacitance is often unknown and the measurement of it takes time and makes testing procedure more complex. Also, parasitic capacitances cannot be taken into account by this approach although their influence can be significant especially when testing low capacitance objects of large dimensions.

Genetic algorithm [8,9] and other optimization methods [10,11,12] have already been used for curve fitting based estimation of lightning impulse parameters such as peak value, front time and time-to-half-value.

However, the aim of this paper is to introduce a new genetic algorithm [13] (GA) based method for obtaining test circuit parameters in case of a capacitive load testing. The main advantage of this method is a fast estimation of the load capacitance and test circuit inductance from the recorded lightning voltage impulse and from the known values of generator capacitance, front and discharge resistance. Once when all circuit parameters are known it is less complicated to determine circuit elements which will provide $T_1$, $T_2$ and $\beta$ that are within limits prescribed by Ref. [1]. Hence, the presented method saves time and makes the reconfiguration of impulse generator easier.

2. Analysis of the lightning impulse voltage test circuit

The method presented in this paper estimates lumped stray inductance and load capacitance in a test circuit. In the real situation, a stray inductance consists of the inductance of impulse generator and the inductance of connecting leads while load capacitance consists of voltage divider capacitance, test object capacitance and their parasitic capacitances. By taking this into account a more realistic equivalent scheme of the test circuit would be obtained. However, this model is more complex and solving it would take more time and the algorithm has to be fast in order to be applied in practice. The presented method cannot differentiate all individual inductances and capacitances mentioned above. However, estimation of lumped inductance and capacitance in a test circuit proved sufficient for practical application. In Refs. [2,14,3] it is demonstrated that the calculations can be made much more easily if certain approximations are used, and these are found not to introduce appreciable errors in practice. Even more complicated circuit representations have been examined, particularly by Thomason [3], but the resulting expressions are of little more than academic or mathematical interest, especially as the stray capacitances and inductances are distributed throughout the circuit and no precise numerical values can be assigned to them. Therefore in practice it is convenient to simplify the calculations and use equivalent circuit shown in Fig. 3. Since in this paper excellent results were obtained by using equivalent circuit shown in Fig. 3 it is not convenient to take into account a more realistic equivalent scheme of the test circuit because it would not significantly improve the results. For that reason, a simplified circuit represented in Fig. 3 was used. The capacitances of the test object and of the voltage divider (and their stray capacitances) were lumped together in $C_2$, while the total inductance within the generator – load circuit is combined to a single inductance $L$.

Laplace transform of the circuit for lightning impulse voltage testing form Fig. 3 is shown in Fig. 4.

Voltage $U_1$ is determined by using the expression (2).

\[
U_1(s) = \frac{U_0 \cdot Z_2}{s(Z_1 + Z_2)}.
\]
where
\[ Z_1 = \frac{1}{sC_1}; \quad Z_2 = \frac{R_2 \cdot (R_1 + sL + (1/sC_2))}{R_1 + R_2 + sL + (1/sC_2)} \]

The output voltage \( U_2 \) is calculated in frequency domain using the expression (4),
\[ U_2(s) = \frac{U_1(s) \cdot Z_4}{Z_3 + Z_4} \]

where
\[ Z_3 = R_1 + sL; \quad Z_4 = \frac{1}{sC_2} \]

The output voltage is expressed in the time domain using the inverse Laplace transform:
\[ U_2(t) = L^{-1}(U_2(s)) \]

3. Method for estimation of circuit inductance and load capacitance

Exact values of all circuit parameters are unknown in practice. Nominal test circuit parameters and their tolerances are given by manufacturers or can be more or less accurately measured, but always with measurement uncertainty. The charging voltage \( U_0 \), also, is not exactly known. GA based method determines circuit inductance \( L \) and load capacitance \( C_2 \) for standard and non-standard lightning impulse waveforms. GA selects \( L \) and \( C_2 \) in a wide boundary range of values and \( R_1, R_2, C_1 \) and \( U_0 \) in a narrow boundary range around nominal values. All these parameters form a vector \( V_i \), an individual solution, while a group of vectors forms a population in GA terminology. Fig. 5 shows the flowchart of the described method.

The first step is to obtain the input data consisting of the recorded impulse voltage form the measuring system, \( R_1, R_2, C_1, U_0 \) and their tolerances. GA generates the initial population of vectors \( V_i \), \( i = 1, \ldots, n \). Population size \( n \) specifies how many individuals there are in each generation. Initial population is created randomly and it satisfies the defined bounds of parameters \( R_1, R_2, C_1, U_0, L \) and \( C_2 \). After the creation of the initial population, the output voltage \( U_2 \) is determined in time domain for each \( V_i \).

Since the GA performs many calculations finding an acceptable solution, it is very important to minimize the execution time. To achieve this, it is helpful to reduce the number of calculations by comparing measured waveform with GA results in several representative points only. Therefore, characteristic points \( (t_{cp}, U_{cp}) \) are selected on measured waveform front (at 10%, 30%, 50%, 75%, 90% and 100% of the amplitude), tail (at 90%, 75%, 60%, 50%, 40% and 30% of the amplitude) and at the local extremes in case of oscillatory impulses. For each \( t_{cp} \), voltage \( U_2 \) is calculated with circuit parameters selected by GA and compared to measured values. Describing the waveform by characteristic points is a great advantage because it significantly reduces calculation time and enables this method to be used during laboratory impulse testing.

The fitness function is the objective function minimized by the GA [15]. In this case, the fitness function takes into account the voltage percentage error for each characteristic point. Fitness function is calculated using the expression (7),
\[ e = \left| \frac{U_{2calculated}(t_{cp}) - U_{2opt}(t_{cp})}{U_{2opt}(t_{cp})} \right| \times 100(\%) \]

The algorithm stops when the voltage percentage errors of all characteristic points are lower than the user defined limit value or when a certain time elapsed. All calculations are performed using Matlab software on PC Intel core i5 CPU, 2.53 GHz with 4 GB RAM and a selected time period of 1 min was enough to reach the stopping criteria.

If stopping criteria is not fulfilled, then selection, crossover and mutation are performed. The stochastic uniform selection function chooses the parents for the next generation based on fitness results. The elite count specifies the number of individuals that are guaranteed to survive to the next generation (in this case 50). Crossover fraction specifies the fraction of the next generation, other than elite individuals, that are produced by crossover (in this case 80%). The remaining individuals are produced by mutation. The scattered crossover function creates a random binary vector. It then selects the genes for which the vector value is a 1 from the first parent, and the genes for which the vector value is a 0 from the second parent, and combines the genes to form the child. Mutation functions create small random changes in individuals from a population, and they provide genetic diversity and enable the GA to search a broader space. Adaptive feasible mutation was used which randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation. A step length is chosen along each direction so that bounds are satisfied.

If \( T_1, T_2 \) or \( \beta \) are not acceptable, it is necessary to modify the test circuit parameters. This usually requires changing \( R_1 \) and/or \( R_2 \) and/or introduction of additional capacitor \( C_{ad} \) in parallel with the test object. Now, with known \( L \) and \( C_2 \), one can easily calculate output voltage using the finite pool of \( R_1, R_2 \) and \( C_{ad} \) available in a high
voltage laboratory instead of trial-and-error voltage applications in actual test circuit.

In case of a purely capacitive test objects, maintaining the $T_1$ is much more complicated than maintaining the $T_2$. Stray inductance $L$ and front resistance $R_1$ tend, in general, to retard the length of the wave front. The inductance also introduces oscillations in the wave [3]. It may be impossible to realize standard waveforms within the standard tolerances for certain test circuits and test objects. In such cases extension of front time $T_1$ or overshoot may be necessary (guidance for such cases should be given by the relevant Technical Committee).

Of all parameters used in the GA based method it is noticed that only the population size significantly affects the GA convergence rate and execution time, while the influence of other parameters is small. At first, a smaller population sizes were used but the convergence rate was slow and the execution time was long. Execution time of this algorithm should not be longer than a few minutes (in this paper 1 min criterion adopted) in order to be applied in practice. It is noticed that the increase of population size to a certain value improves the convergence rate and shortens the execution time to an acceptable value. Satisfactory convergence rate and acceptable execution time were achieved with the population size of 500 in case of computational verification and with the population size of 2000 in case of experimental verification.

4. Verification of the presented method

The presented method is verified in the following sections:

4.1 Computational (numerical) test.
4.2 Tests with recurrent surge generator.
4.3 Tests in high voltage laboratory.

4.1. Computational verification

All circuit parameters are exactly known in this example and the method’s ability to determine $L$ and $C_2$ is tested. The following cases are examined:

(a) $U_2$ without oscillations, $L = 0$, GA selects only $C_2$.
(b) $U_2$ with oscillations $L = 26.5–1950 \mu H$, relative overshoot $\beta = 9.09–33.33\%$, GA selects $L$ and $C_2$.

In both cases other parameters are $C_1 = 50 \mu F$, $C_2 = 1 \mu F$ while $R_1$ and $R_2$ are varied to provide standard and non-standard waveforms with $T_1 = 0.6–1.8 \mu s$ and $T_2 = 30–70 \mu s$.

GA input values are $R_1$, $R_2$, $C_1$, $U_0$ and characteristic points from $U_2$. The size of GA population in each generation is $n = 500$. GA task is to choose $L$ and $C_2$ in a fairly wide range of values (boundaries $0.1–20 \mu H$ for $C_2$ and $10–4000 \mu H$ for $L$) and to find the output voltage which best fits the inputted $U_2$. Table 1 shows estimated $C_2$ for case (a). Tables 2–6 show estimated $C_2$ and $L$ for case (b).
Figs. 6–8 show comparison between input (original) waveform and calculated waveform obtained with estimated $L$ and $C_2$.

Fig. 9 shows the change of fitness value $\epsilon$ throughout generations for waveform 1.2/50 $\mu$s and relative overshoot $\beta = 9.09\%$.

In all cases algorithm successfully estimates $C_2$ and $L$ with high precision within the following stopping criteria: a time period of 1 min elapsed or the fitness value of 0.2% is achieved. The largest percentage differences between estimated and known $C_2$ and $L$ are 0.16% and 0.24%, respectively.

4.2. Tests with RSG

RSG is a low voltage single stage equivalent of a high voltage impulse generator. It is usually used to study the voltage distribution in high voltage windings during impulse voltage stresses.

Parameters of impulse circuit are in fact parameters of RSG so, in this case, the exact values of circuit parameters are unknown, but the nominal values are stated by RSG manufacturer. Fig. 10 shows the test setup. The impulse voltages are recorded using a digital oscilloscope (500 MHz, 1 G/s) connected to PC.

RSG parameters are $U_0 = 250$ V, $R_1 = 6.8 \Omega$, $R_2 = 100 \Omega$, $C_1 = 470$ nF, $C_2 = 100$ nF and $L$ is varied (10 $\mu$H, 20 $\mu$H and 30 $\mu$H). GA selects $L$ from 0.1 $\mu$H to 2 $\mu$H and $C_2$ from 10 nF to 200 nF. The size of GA population in each generation is $n = 2000$. Fig. 11 shows the comparison between measured and calculated (GA obtained) waveforms. Measured and GA obtained waveforms show excellent agreement.

Percentage differences between real and estimated $C_2$ and $L$ cannot be exactly determined because the exact values of circuit parameters are unknown, but only the nominal values are stated by RSG manufacturer. Nevertheless, comparison of estimated and nominal values shows a good agreement (Table 7).

4.3. Tests in high voltage laboratory

In Section 4.1 the exact values and in Section 4.2 the nominal values of all circuit parameters were known. In this case $L$ and $C_2$ are unknown. The tests are performed on oil-paper insulated inductive
voltage transformer $U_m = 245 \text{kV}$ and SF6 insulated current transformer $U_m = 765 \text{kV}$. The measurement of impulse voltages was carried with measurement systems consisting of digital impulse analyzing system and capacitor voltage divider which fulfill the requirements of [1,16,17]. The size of GA population in each generation is $n = 2000$.

### 4.3.1. Oil-paper insulated inductive voltage transformer

$U_m = 245 \text{kV}$

Fig. 12 shows the test setup for lightning impulse voltage testing of an oil-paper insulated inductive voltage transformer in high voltage laboratory. Parameters of the test circuit are: $U_0$ (618–798 kV), $R_s = 1600 \Omega$, $C_1 = 50 \text{nF}$ and $R_1$ is varied. GA selects $L$ from 0.1 μH to 1 mH and $C_2$ from 0.5 nF to 10 nF.

$C_2$ consists of voltage divider capacitance (nominal value 817 pF), test object capacitance (unknown) and parasitic capacitances (unknown). At first the impulse voltage is recorded with $R_1 = 142 \Omega$ (yellow curve in Fig. 13). This waveform contains some oscillations with front time $T_1 = 0.77 \mu s$ and tail time $T_2 = 42.4 \mu s$. According to Ref. [1] $T_1$ is too short.

Increasing the external front resistor $R_1$ value helps to damp oscillations while the value of external leads inductance causes an oscillatory natural response of the system. The critical serial resistance $R_c$ for the circuit to be non-oscillatory is given by the following well-known equation:

$$R_c = 2 \sqrt{\frac{L}{C}}$$

(8)

where

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

(9)

This equation is suitable for determining the limiting values for the front resistor $R_1$. In this case $R_c = 264 \Omega$. Since high voltage laboratory has a finite pool of $R_1$, the closest value obtained was $R_1 = 295 \Omega$. $L$ increases with $R_1$ due to the stray inductance of the resistors, so it is better to choose $R_1$ slightly higher than calculated $R_c$.

Measurement and simulation results are shown in Fig. 13 and Table 8. It can be seen that the oscillations are heavily damped when $R_1 = 295 \Omega$ which is close to calculated $R_c$, while $T_1$ and $T_2$ are within the limits of [1]. Other examples in Table 8 only show how front resistors introduce stray inductances and that this can be taken into account.

Estimated $C_2$ is quite stable as expected and varies from 1.80 nF to 1.96 nF. Increase of $R_1$ damps the oscillation and reduces peak voltage without affecting wave tail and, as a consequence, $T_2$ increases. In Fig. 13, the charging voltage $U_0$ of the impulse generator was increased in order to compensate the influence of $R_1$ on peak voltage reduction.

### 4.3.2. SF6 insulated current transformer $U_m = 765 \text{kV}$

Fig. 14 shows the test setup for lightning impulse voltage testing of SF6 insulated current transformer in high voltage laboratory.

Parameters of the test circuit are: $U_0 = 1640 \text{kV}$, $R_2 = 1236 \Omega$, $C_1 = 53.6 \text{nF}$ and $R_1 = 420 \Omega$. GA selects $L$ from 0.1 μH to 1 mH and $C_2$ from 0.5 nF to 10 nF. $C_2$ consists of voltage divider capacitance (nominal value 613 pF), test object capacitance (261 pF, measured with Schering bridge and standard capacitor) and parasitic capacitances (unknown value). GA simulation gives $C_2 = 1.69 \text{nF}$ and $L = 99.9 \mu \text{H}$ after 12 generations. Fig. 15 shows measured and estimated impulse waveforms.

There is a significant difference between estimated $C_2$ and the sum of capacitances of the test object and voltage divider. This implies that parasitic capacitances have great influence on $C_2$ and cannot be disregarded.
Table 8  Estimated $C_1$ and $L$

<table>
<thead>
<tr>
<th>Nominal $R_1$ (Ω)</th>
<th>Measured $T_1/T_2$ (μs)</th>
<th>$U_0$ (kV)</th>
<th>Estimated $L$ (μH)</th>
<th>Estimated $C_1$ (nF)</th>
<th>Number of generations</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>0.77/42.4</td>
<td>618</td>
<td>45.8</td>
<td>1.96</td>
<td>16</td>
</tr>
<tr>
<td>212</td>
<td>0.88/51.6</td>
<td>687</td>
<td>49.6</td>
<td>1.88</td>
<td>11</td>
</tr>
<tr>
<td>295</td>
<td>1.07/58.4</td>
<td>740</td>
<td>53.7</td>
<td>1.80</td>
<td>14</td>
</tr>
<tr>
<td>464</td>
<td>1.88/60.1</td>
<td>770</td>
<td>88.7</td>
<td>1.91</td>
<td>10</td>
</tr>
<tr>
<td>550</td>
<td>2.20/62.8</td>
<td>798</td>
<td>105.3</td>
<td>1.94</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. 14 shows a comparison between measured and estimated waveforms when parasitic capacitances are excluded from the simulation. Load capacitance is set to a sum of voltage divider and test object capacitances while circuit inductance is varied from 0 to 200 μH. It is obvious that even when test object capacitance value is known it may not be enough for accurate estimation of impulse voltage waveform.

According to the previous statement, it can be concluded that a test object capacitance measurement may give insufficient information about a total load capacitance.

5. Conclusion

The paper describes a new GA based method for estimation of load capacitance and circuit inductance in case of lightning impulse testing of capacitive loads.

The presented method enables a fast and accurate estimation of unknown circuit parameters: the total load capacitance, including parasitic capacitances which cannot be disregarded when testing low capacitance objects, and test circuit inductance. The method is successfully verified on several examples.

Future work will be focused on expanding the capabilities of the method for estimating the test circuit parameters in case of impulse testing of low inductance loads, such as low voltage windings of power transformers.

References