Evaluation of an impulse current test generator using numerical simulation tools

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***Abstract* – In this work an extensive analysis of the impulse current generator at the high-voltage department of the TU-Graz was carried out. The aim of this work is to generate a detailed equivalent circuit for this test generator. From measured impulse currents and respective charging voltages the surge circuit elements of this model were determined by regression analysis and evaluated by numeric simulation. The individual impedance of the surge circuit components for a detailed equivalent circuit could be determined by variation of the surge circuit. At this example, the regression analysis of the test system achieved a very good agreement between measurement and simulation. With the help of the generated equivalent circuit simple and more complex surge processes can be evaluated with help of computers.**

Keywords – Impulse current generator, test field, regression analysis, simulation

I. Introduction

Rapid changing currents with high amplitude appear normally in according with high voltages and discharge of energy storages. They are frequently generated by breakdown processes combined with high forces and temperatures. In power systems and high voltage engineering these impulse currents are used for testing equipments within the effects of lightning strikes.

Particularly surge voltage protectors have to be tested with double exponential impulse currents to determine the thermal, mechanical and electrical consequences.

The principle design of a test generator for double exponential impulse currents with capacitive energy storage is shown in Figure 1. The test generator is series with additional components and the test sample.

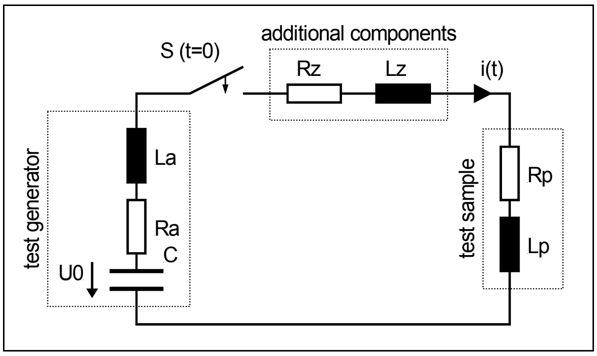

Fig. 1 Impulse current generator with capacitive energy storage

The resistors and the inductivities in combination with the pulse capacity influences the waveform of the impulse current significantly. If the impedance of the test sample is much lower than the remaining impedance, the test generator works like an ideal current source. If a non-linear element like a varistor is under test, the resulting waveform is affected by the test sample. For effective test procedure in the laboratory it is necessary to know the test circuit impedances and their variation possibilities to achieve the claimed waveform.

II. Object of Analyses

The Department of High Voltage Engineering in Graz uses an impulse current generator of Haefely. This generator is able to stress the test sample with energies up to 100kJ at system voltages of 50, 100 or 200kV. The main components of the test circuit are:

- Surge capacitors
- Connection cables
- Selection unit under oil
- Triggerable spark gap
- Coaxial sample cage with common return

By adjustment of the surge circuit impedance various waveforms can be generated like of 1/20, 4/10, 8/20, 10/350, 10/1000µs with amplitudes up to 165kA. Additionally rectangular waveforms 0.5, 1 and 2ms up to 2.2kA can be generated. All parameters of the different waveforms are based on IEC 60060-1 [1].

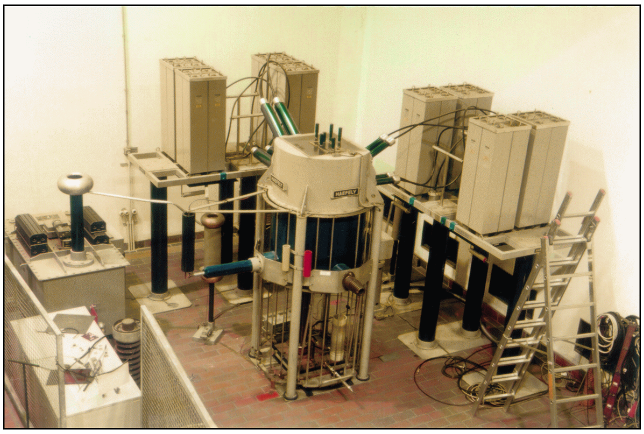

Fig. 2 Impulse current generator, TU-Graz

III. THEORY

By means of the equivalent circuit as shown in Figure 1 the differential equation for the current *i(t)* can be nominated. Depending on the damping resistor $\left(R=\Sigma R_i\right)$ of the surge circuit three different current waveforms results (see Figure 3).

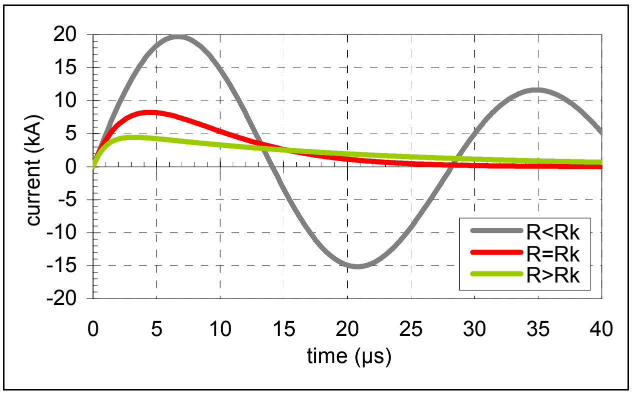

Fig. 3 Current waveforms, depending on the damping resistor

If the resistance is lower than the critical resistance (see equation (1)) a damped sin-waveform results. If it is bigger an unipolar current waveform result, which convergent after endless time to zero.

At the investigated test generator the ohmic resistance is very low, which results in a damped sin-waveform (the waveform can be described by equation (2)-(4)).

$$R_K = 2 \cdot \sqrt{L/C} \tag{1}$$

$$i(t) = \frac{U_0}{L \cdot \beta} \cdot e^{-\alpha \cdot t} \cdot \sin\left(\beta \cdot t\right) \tag{2}$$

$$\alpha = \frac{R}{2 \cdot L} \tag{3}$$

$$\beta = \sqrt{\frac{1}{L \cdot C} - \frac{R^2}{4 \cdot L^2}} \tag{4}$$

With these equations the waveform will be reproduced exactly (all circuit elements are constant with time). The waveform can also be explicit described by peak value $\hat{i}$, attenuation factor α (see equation (3)) and radian frequency β (see equation (4)).

Based on a measured current waveform the circuit elements can be evaluated. The system is now underdetermined and an infinite variety of results occur. This is also obvious because four circuit elements (U_0, L, C, R) have to be determinate out of three impulse waveform parameters ($\hat{i}, \alpha, \beta$). So at least one more parameter has to be determined.

Therefore the charging voltage U_0 is measured with high accuracy and low expense. It's also a linear parameter which gives the peak value of the resulting waveform.

The evaluation of the circuit elements using the current waveform and the charging voltage was solved by the use of regression analyses with the program TableCurve [2]. This program performs a least squares minimization of the sum of squares of the residuals between measurement and computed model.

The first four half-waves of the measured currents were used as a uniform range of values. The terminated values from the circuit parameter evaluation have been verified with the simulation program PSPICE [3] (see Figure 4).

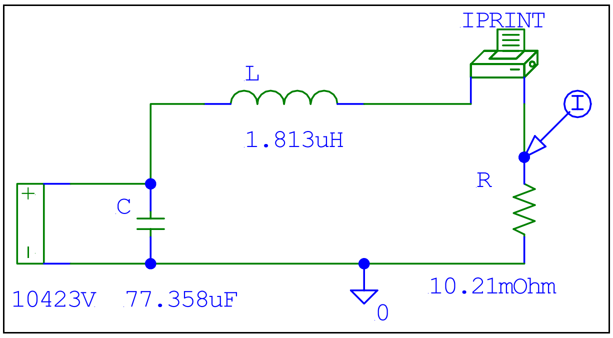

Fig. 4 Simulation circuit in PSPICE

A comprehension of the measured and the simulated current waveform is shown in Figure 5 and Figure 6 with good similarity and low relative deviation.

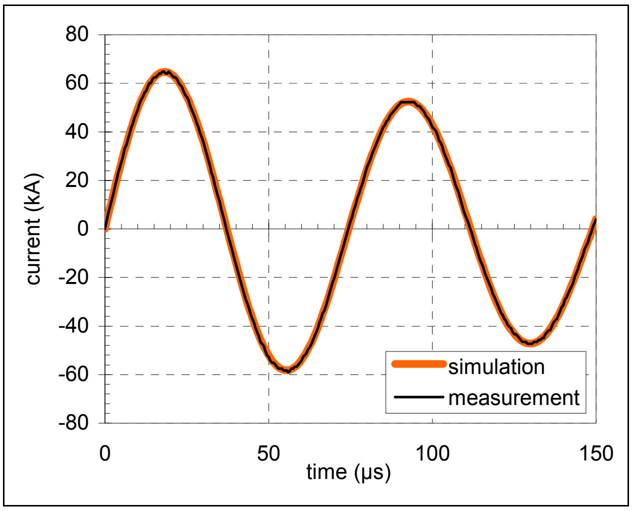

Fig. 5 Simulated and measured current waveform

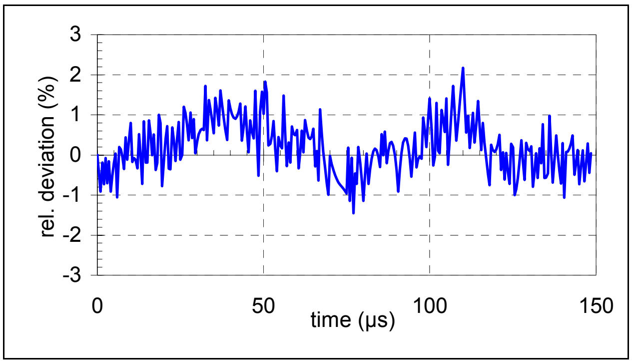

Fig.6 Relative deviation of simulation and measurement

The deviation can be split in a high frequency and a low frequency part. The high frequency part is caused by the digitalisation of the recording system (Digital Storage Oscilloscope). The low frequency part is caused by the non-linear behaviour of the used spark gap to initiate the surge.

The average of the absolute value of the relative deviation is 0.54% and is in the range of uncertainty of the circuit elements (in this case the uncertainties were lower than 0.2% for L and C, and lower than 1% for R).

IV. SYSTEMATIC ANALYSIS OF THE IMPULSE GENERATOR

With the aid of the previous developed tool of the regression analysis the whole impulse current generator was analysed systematically. Only skin effect and other non-linearity were neglected for further investigations. Figure 7 shows current waveforms by variations of the surge capacity between 10 and 80µF by using one to eight capacitor elements.

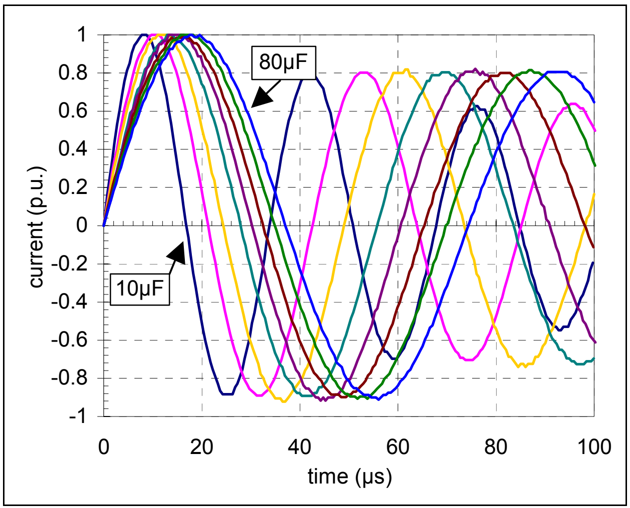

Fig. 7 Measured discharge currents with variation the surge capacity (normalized to peak value)

The impedance fractions could be separated by well-adjusted connections of surge capacitors and the connection cables to the cage. The values of the capacitor- and cable impedances, the impedance of the test sample cage, the selection unit with the spark gap and the common cable return can be terminated. By connecting two (identical) cable in parallel, the capacitor- and the connection cable impedance can be separated. With the assistance of these data it was possible to create an equivalent circuit as shown in Figure 9. It shows the detailed equivalent network of the 50kV setup using all impulse capacitors.

Possible improvement arrangements can now be considered regarding to afford and success with the knowledge of the impedance proportioning. In addition new elements can be pre-dimensioned by simulations and are not necessary to be determined by test series experimentally.

V. APPLICATIONS OF THE EQUIVALENT CIRCUIT

With this detailed knowledge of the test circuit impedances it is possible to simulate the waveform behaviour, the achievable peak values, energies and other derived factors with the help of a numerical simulation.

Various tools of simulation software with optimiser exist to determine the circuit elements for the waveform applied to a new test sample (for example the simulation tool PSPICE [3] has included an effective optimiser-tool). With specification of an available capacity value it is possible to determine charging voltage, circuit resistor and inductivity to obtain a predicted peak value and waveform.

An auxiliary program [4] for all available values of the capacity with a calculation at ones was written in MatLab [5]. This program calculates for a given peak current, front time and time to half value according to IEC 60060-1 [1] the respective charging voltage, capacity, inductivity and resistor in the system and displays the current waveform. Values for a 4/10µs waveform with 100kA peak current within the allowed time limits for this impulse are shown in Table I.

Table I Variation for a 4/10µs 100kA impulse current within the limits

T_S [µs]	T_2 [µs]	U_0 [kV]	C [µF]	L [µH]	R [Ω]	
3.5	10	151.067	5	3.089	0.869	
3.5	11	187.057	5	3.639	1.206	(*)
4	10	120.888	5	3.098	0.516	
4	11	157.078	5	3.757	0.848	(*)
4	9	85.774	5	2.431	0.200	
4.5	10	92.258	5	2.983	0.188	
4.5	11	127.061	5	3.734	0.499	(*)
4.25	10.5	123.966	5	3.409	0.507	(*)
4.25	10.75	132.935	5	3.586	0.589	(**)

These results can be compared with the values of the test generator by an estimation of the additional components or an improvement of the arrangements ((*) in Table I: possible implementation forms for this investigated test generator). The selected setup variants can be simulated numerically and their behaviour can be analysed more detailed by using a sample model [6]. These waveforms can be put into practice and tested in the field. The variant (**) was put into practice after installation of the measurement circuit and the test sample. Figure 8 shows the simulated current waveform for this setup.

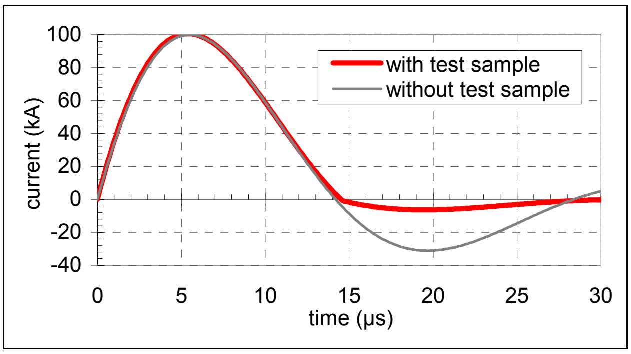

Fig. 8 Simulated 4/10µs 100kA impulse current with and without test sample (varistor)

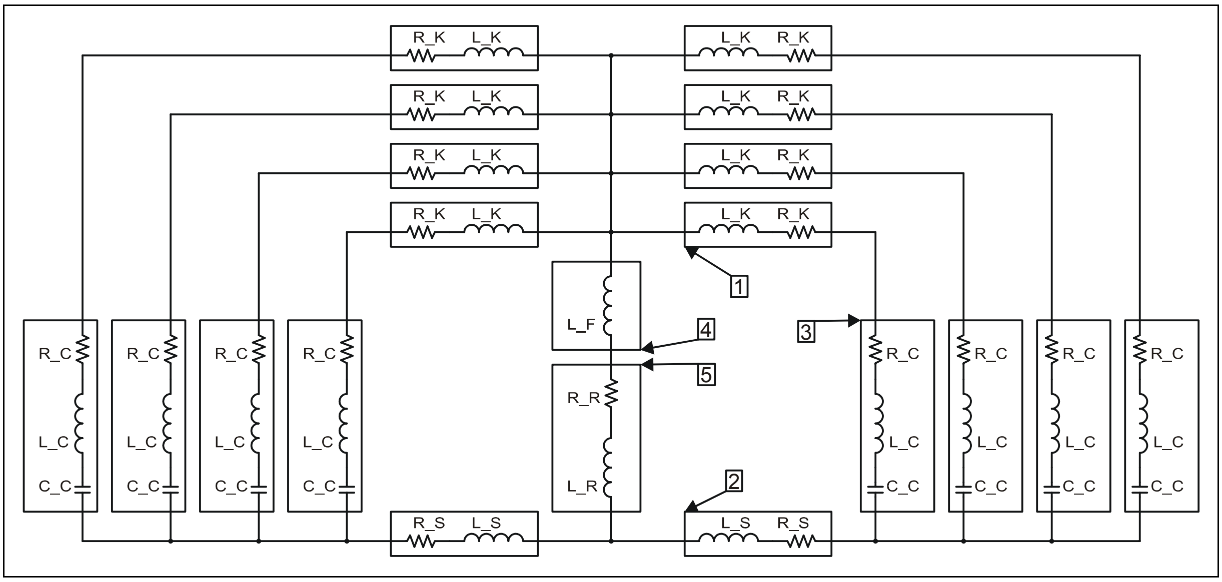

Fig. 9 Detailed equivalent network of the 50kV wiring with 80µF impulse capacity

1 Connection cable, inner conductor (R_K, L_K)
2 Connection cable, equivalent cable return of 4 connection cables (R_S, L_S)
3 Impulse capacitor á 10µF, 50kV (switchable) (C_C, L_C, R_C)
4 Selection switch unit with the controllable spark gap (L_F)
5 Test sample cage (R_R, L_R)

By using a varistor as a test sample or as an additional component (Fig. 1) the waveform is according to the IEC 60060-1 [1] (the inverse polarity peak is lower than 20% of the peak value), the waveform without the test sample is not conform to the standard. A bigger damping or the use of a bypass switch are other possibilities for a decrease of the inverse polarity peak.

VI. Conclusion

The aim of this work is to reduce the try-out time in the test field by pre-calculating the generator setup by numerical simulation. The impulse current generator can be used more efficiently without arranging mechanically and testing all setup variants. If an approved model of the test sample is given, the charging voltage and the impulse circuit parameters can be predicted by calculations. It is possible to achieve the specifications of the postulated current waveform more exactly and the peak value by a minimum of setup samples, the necessary preparation time will be reduced significantly. In this work the interplay of data acquisition by measures and statistical tool regressions analyse are shown. This allows to generate an equivalent circuit for a numerical simulation. With this detailed circuit numerical variations are possible to optimise the use of the investigated generator. Arrangements can be considered regarding to afford and success.

Improvements and new developments can be created in an efficient way with the knowledge of impedance proportioning, the strengths and weaknesses of the test generator concept. The application of new waveforms can be designed numerically according to the practicability.

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