An Optimised High Current Impulse Source

S. Kempen, D. Peier

Institute of High Voltage Engineering , University of Dortmund, Germany

Abstract

Starting from a predefined 8/20 µs impulse current, the design and construction of an impulse current source is derived. In the first step an equivalent circuit is defined that meets exactly the predefined impulse current. In the next step the components that are required to realise the equivalent circuit diagram are chosen and modelled by their equivalent circuit diagrams. As far as the components do not show ideal behaviour, the stray parameters of the components are determined by calculation and measurement. Further on, the construction parameters for the geometric structure of the plant are derived from the equivalent circuit diagram of the entire impulse generating network. Finally it is shown that the measured current of the realised impulse current generator meets exactly the desired predefined impulse current.

Keywords:

Impulse current source, Electromagnetic high-speed forming, Optimisation

1 Introduction

During a high-speed forming process the workpiece has to be fed with the forming energy $W_{\mathrm{form}}(t)$ following ideally a certain time function. This function is determined by the material parameters of the workpiece and by the desired forming result. In the case of the electromagnetic high speed forming the required forming energy $W_{\mathrm{form}}(t)$ is provided by a time variable magnetic field $B_{\mathrm{form}}(t)$. Co-action between the magnetic field $B_{\mathrm{form}}(t)$ and the eddy currents in the workpiece result in Lorentz forces causing the forming process. The interrelation between the desired forming result and material parameters on the one hand, and the therefore required time dependent magnetic field $B_{\mathrm{form}}(t)$ on the other is matter of the actual research activities.

The time variable magnetic field $B_{\mathrm{form}}(t)$ can be generated by a defined time variable current $i(t)$ flowing through a forming coil which operates as part of an impulse-generating electric network. A schematic drawing of the setup is given in Figure 1. The impulse-generating network consists of an energy storage device which is discharged over impulse forming circuit elements initiated by a certain circuit breaker. Thereby, the forming coil is one of the impulse forming circuit elements. After the desired magnetic field $B_{\mathrm{form}}(t)$, and therewith the current *i*(*t*), have been defined, an optimised high current impulse source can be designed.

At present, the impulse current *i*(*t*) for an optimised forming result can not be specified. It is the matter of actual research. Alternatively, a standardised 8/20 µs impulse current is used to demonstrate the design method for an optimised impulse current source anyhow. This current is a common used test impulse in the field of electrical power engineering. Typical peak values range from 5 kA to 100 kA. The curve progression is exactly defined in [1] and simulates the load type due to switching operations in power lines and indirectly impact of lightning strokes. The time characteristic of this impulse may be also similar to the time characteristic of impulse currents used for electromagnetic high speed forming.

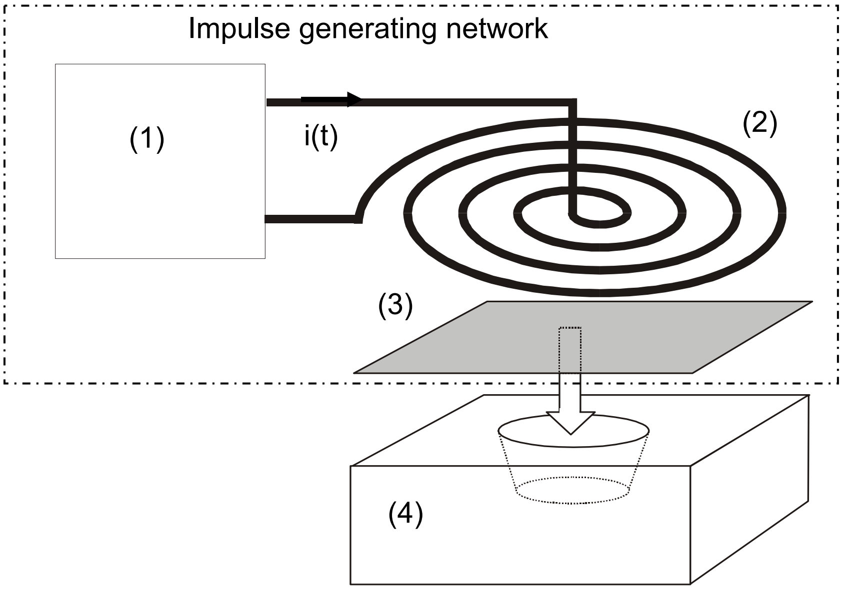

Figure 1: *Schematic drawing of a plant for electromagnetic high-speed forming. The main parts of the plant are: Impulse forming network with energy storage device and circuit breaker (1), forming coil (2), workpiece (3), cavity (4)*

2 Definition of the equivalent circuit diagram according to the desired impulse characteristic

2.1 Definition of the standardised 8/20µs impulse current

The standardised 8/20µs impulse current [1] possesses a characteristic which rises in a very short time period from zero to the peak value î and falls back to zero following an exponential or aperiodic sinusoidal time characteristic (Figure 2). The curve is characterised by the virtual front time T_1 and by the virtual time to half value T_2. In the case of the 8/20 µs impulse current, T_1 amounts 8 µs and T_2 amounts 20 µs. The curve can be analytically approximated by Equation (1).

$$i(t) = i_0 \cdot e^{-t/\tau_1} \cdot \sin\left(\frac{t}{\tau_2}\right) \tag{1}$$

Attention should be paid to the fact that there is no oscillation, under- or over-shooting in the progression of the curve.

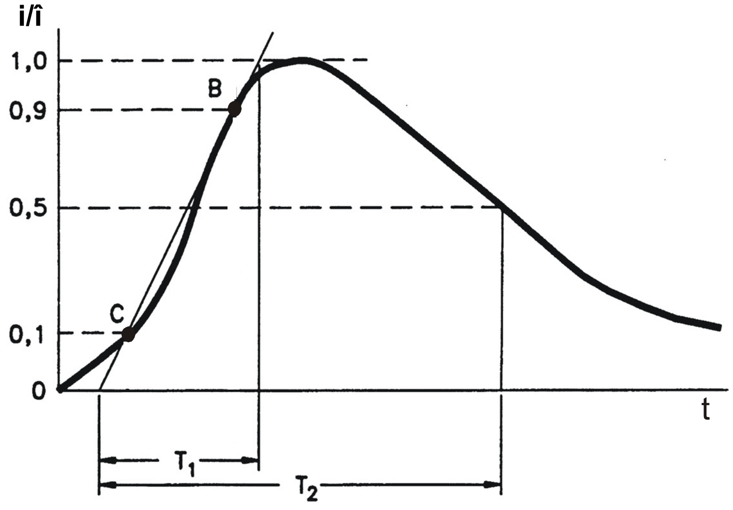

***Figure 2:** Definition of the standardised exponential impulse current [1]: T_1: virtual front time, T_2: virtual time to half value, î: current peal value*

2.2 Structure of the equivalent circuit diagram

The structure of an impulse generating electrical network can be derived from the impulse describing equation. The sinusoidal term in Equation (1) leads to the demand for two energy storage devices of different type. Therefore, the resulting circuit is able to oscillate. To avoid these undesired oscillation of energy between the two storage devices, a damping device has to be part of the circuit. The damping function is represented by the exponential term in Equation (1). These conclusions lead to a basic equivalent circuit with a least 4 elements including a switch. The different types of energy storage devices are displayed by a capacitance and an inductivity. At the beginning, the only known element of the circuit is the forming coil which is displayed mainly by its inductivity. Damping devices are displayed by resistances. The catenation of the elements leads to the series resonant circuit (Figure 3).

Further on, it has to be decided which of the both energy storage devices has to be carried out as the primary energy storage device. According to the duality principle it would be possible to choose either the inductivity *L* or the capacitance *C* as the primary energy storage device [2]. With regard to the demand of calculability of all components, including the switch, the choice of the capacitance as primary energy storage device is advantageous. In the case that for the primary energy storage an inductivity would be chosen, a properly defined non ideal behaviour of the switch is required. The switch behaviour determines mainly the rise in current in this case [2]. This would make the calculability and the later construction of the switch extremely difficult. In the case that the capacitance is chosen to be the primary energy storage, the switch behaviour is approximately ideal. Therefore, the capacitance *C* is chosen to be the basic energy storage device in this case. So the charging circuit is carried out as a DC voltage source which is connected over a charging resistance R_L to the capacitance (Figure 3). The task of the charging resistance is to decouple the two circuit loops.

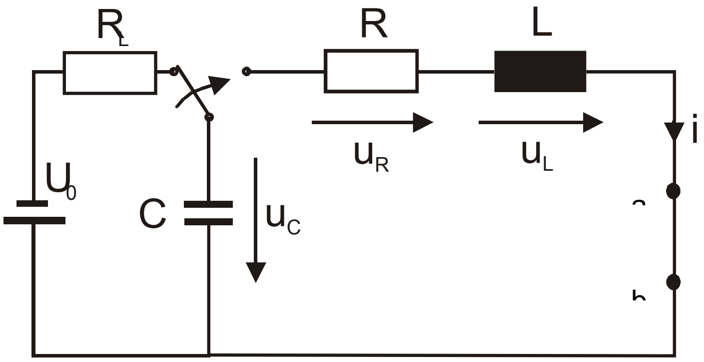

Figure 3: *Basic equivalent circuit diagram of the impulse current source with charging circuit*

The equivalent circuit represents graphically the differential equation of the electric network. In the present case, the circuit is described by a linear 2nd order differential equation for the current *i*(*t*).

$$\frac{d^2i}{dt^2}+\frac{R}{L}\cdot\frac{di}{dt}+\frac{1}{LC}\cdot i=0 \tag{2}$$

Equation (1) displays the periodic damped solution for this differential equation. It appears if the network parameters comply with condition (3)

$$R<2\cdot\sqrt{L/C} \tag{3}$$

To avoid undesired oscillation of the current, the circuit resistance *R* has to be carried out in the way that the circuit operates in, or at least near the aperiodic limiting case which results if the circuit parameters comply with Equation (4).

$$R=2\cdot\sqrt{L/C} \tag{4}$$

The voltage U_0 of the source determines the initial condition of the capacitance. It is assumed that the circuit breaker only is switched at the time t_0 after the charging current has become zero, and so the initial voltage of the capacitance is $U_C = U_0$, although there is a charging resistor R_L between the source and the capacitance.

2.3 Calculation of parameters in the equivalent circuit diagram

The desired 8/20 µs impulse current can be analytically described by Equation (1) as mentioned. In the first step, the parameters i_0, τ_1 and τ_2 have to be fixed. Therefore, the analytic current function has to be fitted to the standardised 8/20 µs current impulse (Figure 2). For a 17,3 kA – 8/20 µs impulse current the curve fitting results in the values: i_0 = 86,0 kA, τ_1 = 9,071 µs, τ_2 = 0,1586 µs

In the next step, the circuit parameters R, C, L, and the operation parameter U_0 have to be calculated from the impulse current parameters. The special solution of the differential equation leads to the following equations which assign the interrelation between the current parameters and the circuit parameters.

$$i_0 = \frac{U_0}{L \cdot \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \tag{5}$$

$$\frac{1}{\tau_1} = \frac{R}{2L} \tag{6}$$

$$\frac{1}{\tau_2} = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{7}$$

With (5,6,7), a system of three implicit equations with four unknowns is given. For the solution of the system of equations, a further condition to one of the parameters has to be fixed by a technical boundary condition. This might be, for example, the capacitance of the available impulse capacitors. In the present case, the capacitance is fixed to the value of C = 74,7 µF. After this, a system with three equations and three unknowns remains. The solution of the equation system leads to the following set of circuit parameters: U_0 = 4,5 kV, L = 830 nH, R = 183 mΩ

By fixing one of the circuit parameters, the following further aspects should be taken into account:

- maximum available and economic charging voltage
- required forming energy plus electrical and mechanical losses
- compliance with condition (3,4)

Hence, the free parameter can be used to optimise the system under the mentioned aspects.

3 Design and construction of the impulse current source

The realisation of the calculated equivalent circuit to an impulse current generator construction which meets exactly the desired current function demands that the equivalent circuit displays all of the electric properties of the construction, including the electric properties of the components. From this it follows that the electrical properties of the components and the structure of the plant have to be known.

3.1 Structure of the impulse current source and choice of components

From the demand that the electrical properties of the construction have to be known follows that it has to be possible to calculate the electrical properties from the geometric data of the structure. The choice of the structure determines significantly the inductivity of the structure. The relatively low value of the calculated inductivity (L= 830 nH) and the consideration that the other required components bring additional inductivity into the circuit (e.g. the forming coil) lead to the demand of an overall low inductive plant structure. In reference to the great storage capacitance (C = 74,7 µF) the stray capacitances of a geometric structure are negligible. The requirements of low inductivity and calculability lead to a coaxial geometric structure which is carried out as weir. The geometry data of the structure is determined in the way that the inductivity of the coaxial weir structure displays the desired inductivity of the calculated equivalent circuit together with the inductivity of the other required components.

Other required components are the capacitive energy storage, damping resistance, a current measurement resistor, circuit breaker, and the forming coil.

For the realisation of the capacitive energy storage, certain impulse capacitors are needed. With regard to the mentioned demands the most important criterion in choosing the capacitors is a self-inductance which is as small as possible. The entire required capacitance should be displayed by several capacitors which can be arranged to a circular structure. Parallel connection of these capacitors reduces additionally the resulting inductivity of the storage. In the present case, 10 impulse capacitors with a nominal capacitance of C = 7,74 µF are used (Figure 4). They can operate up to a maximum charging voltage of U_{LMax} = 24 kV and have therefore each a maximum stored energy of 2,15 kJ.

The required value of the damping resistor is in the range of 100 mΩ. During a discharge it has to absorb the energy

$$W = R_{Damping} \int i^2(t)dt \tag{8}$$

This leads to an extreme warming of the resistor material. Also the damping resistor should be constructed as low inductive as possible. In this case, it is realised by parallel connection of two or more carbon rods for arc lamps (Figure 5). The resistance value can be adjusted by varying the length and the number of the rods. With regard to the high voltages which have to be expected during the high current discharge, the design of the carbon rod connecting electrodes is optimised for high voltage application.

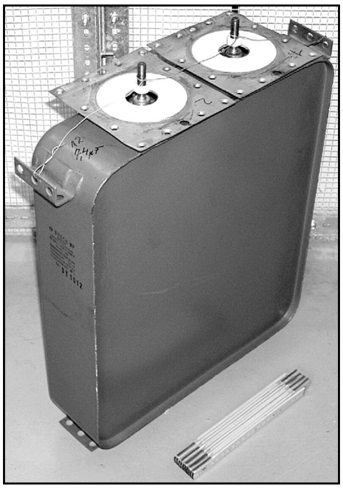

***Figure 4:** Impulse capacitor with C_N = 7,47 µF*

***Figure 5:** Damping resistor with 2 carbon rods*

***Figure 6:** Vacuum circuit breaker tube*

The current $i(t)$ flowing through the test object, which is the forming coil in this case, is detected with a coaxial foil measurement resistor. The shunt resistor is designed to be able to absorb the entire energy stored in the capacitor battery without bringing out irreversible damage to the resistor in the case of failure.

For starting the transient discharge in the circuit, one or more circuit breakers are needed. The use of only one central circuit breaker has the advantage that difficulties with isochronous switching do not have to be expected. Taking the operating parameters of the impulse current source into account, the switch has to be designed for high current applications and should have a sufficiently high isolation voltage. Further, the switching behaviour should be preferably ideal. Therefore, a vacuum circuit breaker is chosen (Figure 6). It can be opened pneumatically and can be closed by an electric trigger signal.
The design and the properties of the forming coil are described in [3].

3.2 Electric properties of the components and the geometric structure

The electrical behaviour of the impulse capacitors can be modelled by the equivalent circuit diagram in Figure 7. The time parameters of the equivalent circuit elements are determined by measuring of the charge and discharge characteristics with different resistors in series to the capacitor. The most important parameter is the value of the series inductivity which amounts L_C = 228 nH. The value of series resistance is very small (several of 10 µΩ) in comparison to the required circuit resistance. In order to that it can be neglected for modelling the impulse generating network. The value of the parallel resistance R_{C2} determines the self discharging time constant of the capacitor. The time constant amounts several 10 minutes so that it can also be neglected.

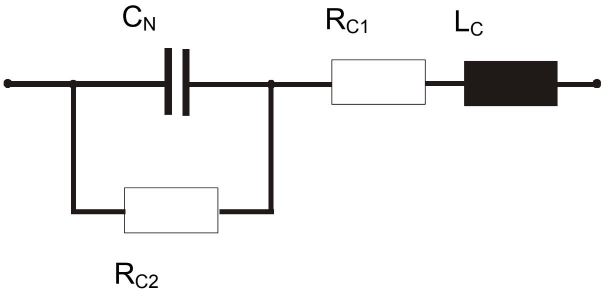

Figure 7: *Equivalent circuit diagram of an impulse capacitor [4]*

The required circuit resistance amounts R = 183 mΩ. It is primary built by the resistances of the shunt and the damping resistor. Additionally, the relevance of the parasitic resistances of the forming coil, the impulse capacitors, and the structure itself have to be considered. In the present case, the circuit resistance is built by the damping resistor (R_{Damping} = 182,8 mΩ) and the shunt resistor (R_{Shunt} = 0,185 mΩ). In comparison to this, the other components have negligible values of their parasitic resistances. Due to their construction the damping resistor and the shunt resistor can be modelled as quasi ideal ohmic resistances. The experimental determined bandwidth of the shunt amounts B = 2 MHz.

For calculating the current $i(t)$, the vacuum circuit breaker can be modelled as an ideal switch. In the opened state the resistance is in the range of several 100 MΩ and in the closed state the resistance amounts only a few mΩ. The breakdown time of a vacuum circuit breaker amounts a few nanoseconds. For calculating the voltage rise at the forming coil or at another test object in the circuit, the time and path length depending capacity $C_{Switch}(t,s)$ of the vacuum circuit breaker has to be considered. It determines the voltage rise at the test object before the voltage at the circuit breaker breaks down.

The required inductivity, which has to be displayed by the coaxial weir structure of the impulse generator, can be calculated by differencing the unavoidable inductivities in the circuit from the required circuit inductivity.

$$L_{Structure} = L - \sum L_{Components} \tag{9}$$

In the present case results a value of $L_{Structure} = 0{,}81\ \mu H$. The required geometric data of the coaxial structure can be estimated by the inductivity of a coaxial cable [5] where d is the diameter of the inner conductor and D the diameter of the outer conductor

$$\frac{L'}{nH/cm} = 2 \cdot ln \frac{D}{d} \tag{10}$$

Together with demands to the maximum possible diameter of the plant due to the limited available area in the laboratory a height of h = 1m results.

3.3 Design and construction of the impulse current generator

Figure 8 shows the resulting coaxial 100 kA- impulse current generator without charging circuit and without forming coil. The impulse capacitors at the bottom are arranged in a ¾ - circle. A 90 degree opening in the circle is needed to handle test objects in the centre of the plant. The capacitors ground terminals are connected low inductively with the circular basic earth plane. In the centre of the bottom plate the shunt resistor is mounted. The high voltage connectors of the capacitors are connected over copper tubes (length: 1 m) to the low inductive circular top plate. In the centre of the top plate the vacuum circuit breaker is mounted. Under the circuit breaker follows the damping resistor. Between the lower connector of the damping resistor and the connector of the shunt resistor the test object or a forming coil can be mounted. The horn structure that can be seen in the photography in the centre above the bottom plate displays a coaxial ohmic- capacitive voltage divider with high frequent termination. It can be used to measure the voltage at a test object with high bandwidth (B = 8 MHz).

Figure 8: Coaxial 100 kA- impulse current generator with capacitive energy storage and without charging circuit

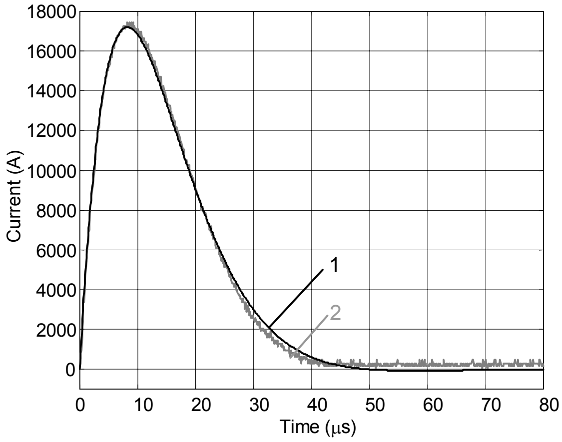

***Figure 9:** Measurement (curve 2) and calculation (curve 1) of the 8/20 μs impulse current output*

3.4 Verification of function

To verify the correct design and function of the impulse current source, the capacitor battery is charged to a voltage U_0 = 4,5 kV and discharged over a short circuit instead of the test object (without forming coil in the circuit). It is measured by the shunt resistor. The expected current can be calculated by (1,5,6,7) using the following circuit parameters:

R = 183 mΩ	(damping resistor and shunt)
L = 830 nH	(accumulated inductivities in the circuit)
C = 74,7 μF	(capacitance of the capacitor battery)

The measured and the calculated currents are plotted in Figure 9. It can be seen that both curves have nearly identical progressions. The time typical constants T_1 and T_2 meet exactly the desired values of the standardised 8/20 µs impulse current.

4 Conclusion

For high electromagnetic high-speed sheet forming an impulse current source is needed which supplies the forming coil with a certain impulse current. The design of an impulse current source can be performed in two steps. In the first step, an equivalent circuit is defined that meets exactly the predefined progression of a desired impulse current. In the second step, the equivalent circuit diagram is realised with real components. The example of a standardised 8/20 µs impulse current shows that it is possible to design a impulse current source which meets exactly the progression of a predetermined impulse current. The precondition for such a design is that the electrical properties of the geometric structure and of all used components are precisely known, or that their behaviour is quasi ideal. Only then it is possible to derive an interrelation between the construction parameters and the desired electrical parameters of the equivalent circuit.

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