The measurement of powerful high-frequency current pulses

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samenvatting

A description is given of a shunt-resistor capable to measure current pulses with amplitudes up to 50A. As the inductive time constant of the shunt is very low (1 ns), pulses with very steep edges can be measured without distorsion.

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The measurement of powerful high-frequency current pulses

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Introduction

In the research of electro-erosion machining the determination of the amplitude and the shape of the current pulses is necessary. The shapes may resemble a half or full-sine wave, rectangles, trapezoids and not being unimportant: e-power shaped pulses. The amplitude ranges from 1 up to 1000 A at frequencies of up to 1 MHz, with rise-times as low as 50 ns.

The general method of measuring pulses is to convert the current into a voltage, either with the aid of a shunt-resistor (Ohm's law: $V=I.R$), or with the aid of a current coil. In this latter case the voltage induced in the coil (according to Faraday's law: $V=-M\frac{di}{dt}$) has to be integrated in order to get a voltage proportional to the current. The voltage thus obtained can easily be measured and displayed, for instance with the aid of a suitable oscilloscope.

The current-coil method is not very attractive because of the difficulties of integrating low-frequency phenomena; so the direct-current component of a pulse train cannot be measured.

Another difficulty with this system may arise in the case of inevitable stray capacities (C_s) which may disturb the measurement (see Fig. 1).

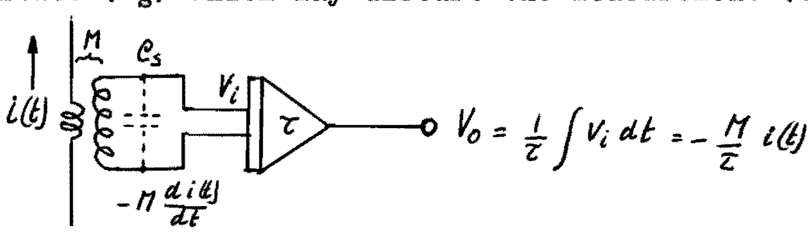

Fig. 1. Current measurement with the aid of a current coil and integrator.

A more direct measurement is possible with the current shunt with the only requirement of constructing a frequency-independent resistor in fulfilment Ohm's law. A commonly constructed resistor normally has a series self-inductance (L_s) and a parallel capacitance (C_p) (see Fig.2). Since the resistance of the shunt generally is relatively low ($1 m\Omega - 1\Omega$), the influence of parallel capacitance can be neglected, whereas self-inductances may cause serious mismeasurements.

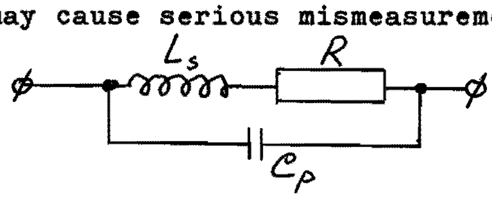

Fig. 2. Representation of a non-ideal shunt with series self-inductance (L_s) and parallel capacitance (C_p).

The influence of self-inductance in a shunt resistor with high-frequency pulses.

Self-inductance is the effect of a conductor being in its own maggnetic field which is proportional to the current through the same conductor. The magnetic energy stored in this field is delivered by a source connected to the conductor. A varying magnetic field induces a voltage in the conductor.

The voltage V_s across a resistor R with series self-inductance L is found through

$$V_s = R.i + L\frac{di}{dt}, \text{ where } i = i(t)$$

Generally, it is not easy to give figures of arbitrary pulse shapes. Apart from the actual wave-form the most relevant parameters are the amplitude, rise-time and the current-time area of the pulse, the latter being represented by the charge $Q = \int i(t)\,dt$.

The shapes of the pulses are often representable by trapezoidal wave forms. In this case the voltage across the shunt resistor will be as in Fig. 3.

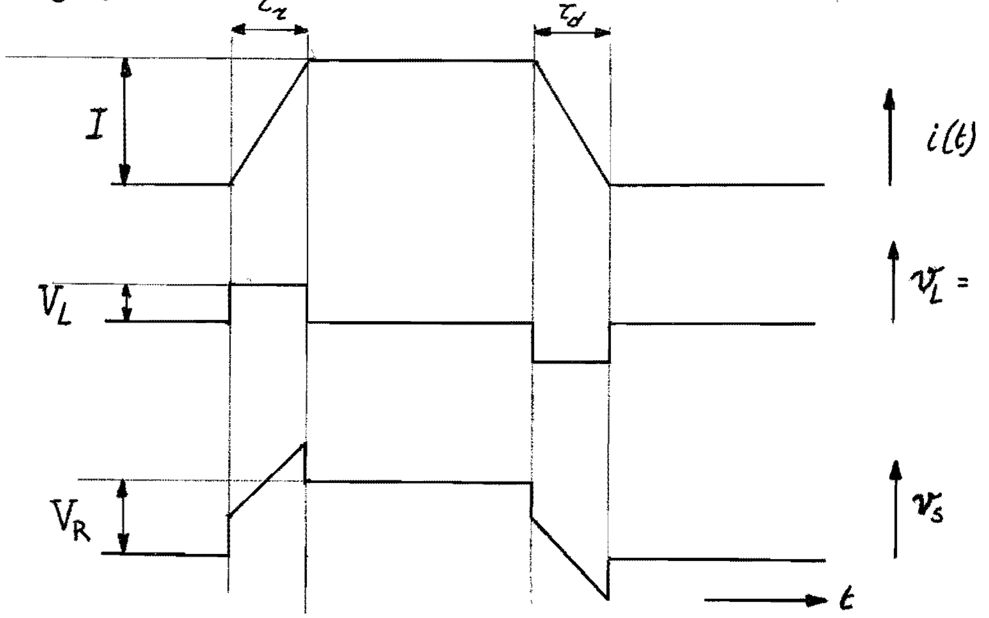

Fig. 3. The occurrence of the voltage V_s across a shunt-resistor with self-inductance in case the current i(t) has a trapezoidal pattern.

The voltage across the shunt must be $V_R = I.R$, but self-inductance introduces distorsion according to $V_L = L\frac{di}{dt}$. In this case, trapezoids with amplitude I and rise-time τ_r, the amplitude V_L will be

$$V_L = L\frac{I}{\tau_r}$$ whilst the amplitude of the correct voltage

must be

$$V_R = I.R.$$

The relation

$$\frac{V_L}{V_R} = L\frac{I}{\tau_r}\,\frac{1}{I.R.} = \frac{L}{R}\cdot\frac{1}{\tau_r} = \frac{\tau_L}{\tau_r}$$

is a measure for the relative distorsion, where $\tau_L = \frac{L}{R}$ is called the inductive time-constant of the shunt. It is clear that if $\tau_L \gg \tau_r$, serious mistakes in the interpretation of the measurements can be made. Although the mid-part of the pulse is unaffected, the actual amplitude is not easy to be determined. With rise-times of 50 ns, time constants of 10 ns or lower seem reasonable.

The presence of inductance in a shunt resistor has no influence on the measurement of the area of the time-current product (the passed charge) of a pulse with arbitrary shape; this is physically clear if it is taken into account that magnetic energy stored in the coil is supplied back when the current pulse is past. Mathematically: the area of the current-time product of the pulse is

$$Q = \int_0^T i(t)\,dt \quad \text{where } T \text{ is the duration of the pulse.}$$

The observed voltage across the shunt results from

$$v(t) = L.\frac{di(t)}{dt} + R.i(t)$$

The measured area of the voltage-time product is

$$A_v = \int_0^T v(t)\,dt, \text{ hence}$$

$$A_v = \int_0^T \left\{ L.\frac{di(t)}{dt} + R.i(t) \right\} dt = L\left[i(t)\right]_0^T + R\int_0^T i(t)\,dt.$$

Since $i(o) = i(T) = 0$, $A_v = R.\int_0^T i(t)\,dt = R.Q.$

From this it follows that the area of the voltage across the shunt is in linear relationship with the charge which has passed the shunt and in consequence the shape is not important for this measurement.

Basic constructions of shunt-resistors

For direct-current and low frequencies the most common form of a shunt is a single rod or bar. The self-induction of such a shunt is relatively high, the value depends on the geometricity of the rest of the wiring; therefore exact figures can hardly be given. A rule of thumb for the self-induction of a piece of wire is 10nH (10^{-8}H) per cm. A shunt-resistor of 10mΩ with this length has a time constant of $\tau = \frac{L}{R} = 1\,\mu s$, which value is rather high.

Another basic construction in frequent use is the coaxial resistor; see Fig. 4.

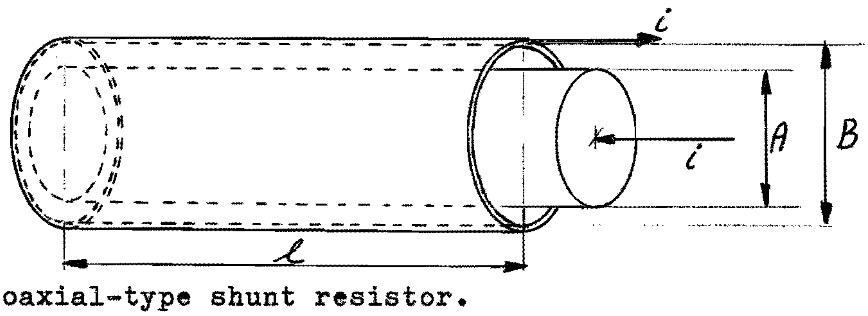

Fig. 4. Coaxial-type shunt resistor.

The current flows through the inner pipe and returns along the inner wall of the outer pipe. The inner pipe is screaned by the other; so a magnetic field can only exist in the space between the two pipes. If this space is narrow, so that the ratio of the diameters A and B is nearly 1, only a small amount of magnetic energy can be stored, and therefore this construction may have a rather low self-inductance. Its value is

$$L = \frac{l\mu_0}{2\pi} \log_e \frac{B}{A}, \; ((B-A) \ll l)$$

where $\mu_0 = 4\pi \,.\, 10^{-7}$ H/m

If, for instance, ℓ = 10cm, B = 10mm and A = 9mm the self-induction is L = 1.88nH. With a resistance value of 10mΩ this shunt has a time constant τ_L of approximately 0.2μs. This type of resistor, which is widely used, is much better than the single rod (time constant 1μs, length only 1 cm), but the construction is rather difficult and serious cooling problems may arise.

The flat-type resistor consists of two flat conductors separated by a thin insulator (see Fig. 5), so that the space between the conductors is very small, and the magnetic field of the one conductor is almost completely neutralised by the other.

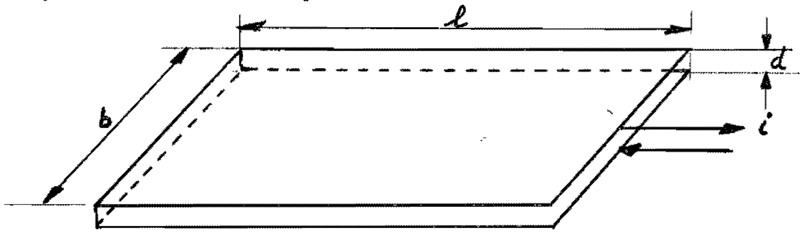

Fig. 5: The flat-type shunt resistor.

The self-induction of this resistor is given by

$$L = \mu_0 \frac{d\ell}{b}, \quad (d \ll b, \ell)$$

In the case of ℓ=10cm, b=3cm and d=20μm the self-induction is L=84pH (=84.10^{-12}H) and with a resistance of R=10mΩ this shunt has a time constant of 8.4 ns, which is a very low value.

Owing to the short distance between the two conductors the capacitance of the resistor may be rather high and may cause difficulties.
The capacitance of the resistor is according to

$$C = \frac{\varepsilon_r \varepsilon_0}{2} \frac{b\ell}{d}, \quad (d \ll b, \ell)$$

where $\varepsilon_0 = \frac{1}{c^2 \mu_0} \approx \frac{10^{-9}}{36.\pi}$ and ε_r the relative dielelectric constant of the insulation material.
If Teflon is taken as insulation material (ε_r=20), the capacitance C of the above resistor is 1300pF. This seems to be a high value, but the capacitive time constant T_c=RC is 13 ps and is negligible with respect to the inductive effect.

Construction of the flat-type shunt resistor

As is always the case with low-ohmic resistors, the shunt must have separate current and voltage connectors, otherwise it is difficult to define the resistance. See Fig. 6.

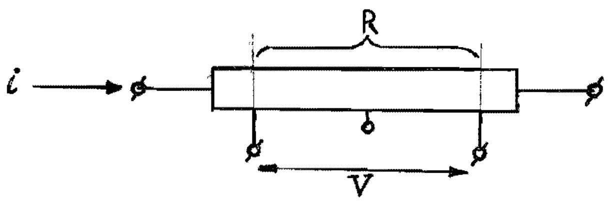

Fig. 6. Current and voltage connection configuration of a low-ohmic resistor.

An experimental shunt-resistor consists of two tantalum conductors pressed and bonded to mylar insulation (thickness d=20μm). The dimensions of each conductor are 10x2 cm. The current and voltage connector are copper bars (1x1x5 cm.). A similar set of bars is used at the bend of the resistor (Fig. 7). A photo of the resistor illustrates the construction (Fig. 8).

The resistance of this shunt is 70mΩ, the inductive time constant is 1 ns and the capacitive time constant 80 ps.

Owing to the flat construction the cooling property is well. In free air the shunt may dissipate 5 Watt and 50 Watt when cooled in paraffin (dielelectricum used with electro-erosion).

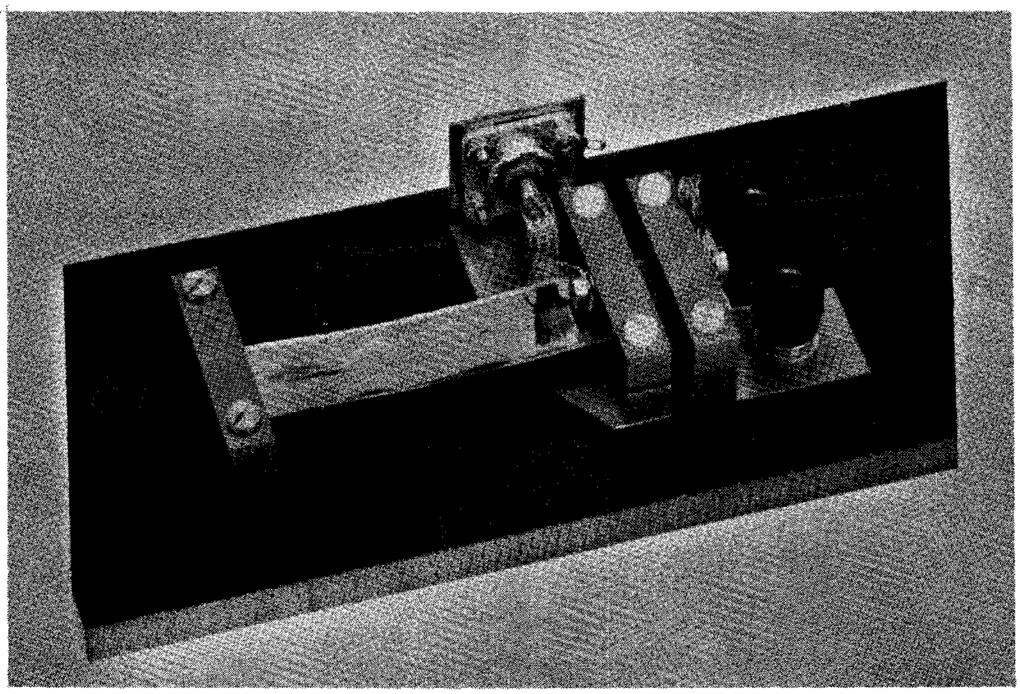

Fig. 8. An experimental model of the low inductive shunt.

The current connectors are at the right, the voltage connector at the middle.

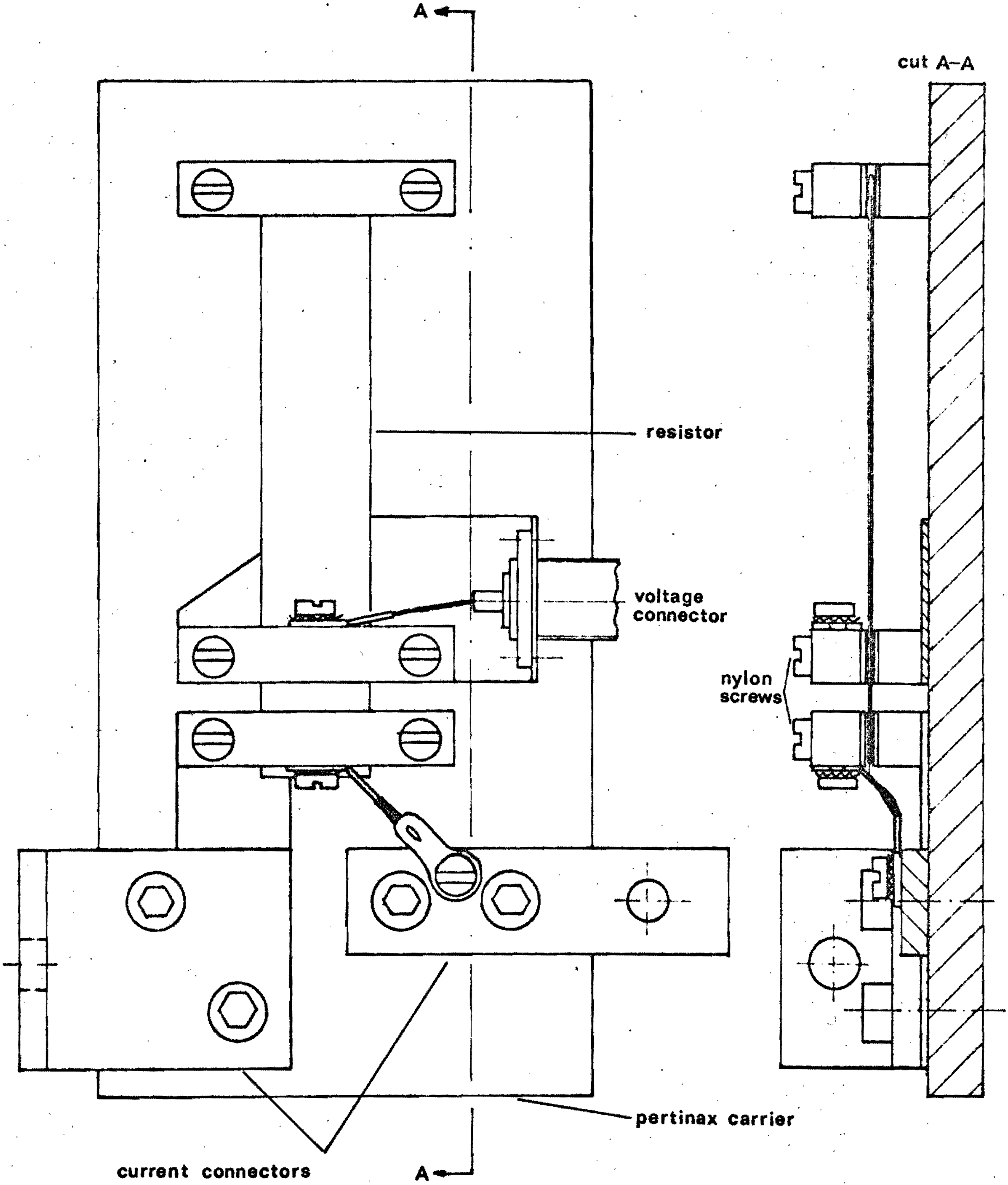

Fig. 7. Construction of the low-inductive shunt.
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