Process analysis using adapted Rogowski coil for non-conventional processes

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Keywords: Rogowski Coil, Hybrid Processes, Process Analysis, Current Rise Time

Abstract. The process analysis of non-conventional processes is very complex because many critical subprocesses can occur. These subprocesses can be determined among other things, by their positive and negative current increases. A process adapted Rogowski coil is particularly suitable for analyzing the current increases. Using the example of plasma electrolytic polishing, it will be shown how pulse typical effects can be distinguished from process typical effects. The boundary condition for this development was that the size of the measuring sensor had to be adapted to the system conditions of the plasma electrolytic polishing process. It was not necessary to calculate the real current, but rather to recognize the process situation very quickly. For this purpose, a higher signal amplification must be carried out during the polishing process and the initialization phase must be hidden. The example of experimental test setup shows, which analyzes can be carried out. The influence of the process disruption on the result can also be determined through comparisons with the processed final results.

Introduction

Process monitoring and process control are important components of process optimization for non-conventional machining processes such as electrical discharge machining (EDM), electrochemical machining (ECM), Plasma-electrolytic polishing (PeP), and the hybrid derivatives of these processes. The primary pulse analyses for these processes are performed by determining the measurable current and voltage pulses [1-3]. Another way to characterize the process is to measure the current changes. The current increases di/dt are typical for certain ablation mechanisms or process disturbances and can be recorded quickly. Fast data acquisition also makes it possible to react to the process disturbance or process change more quickly than with the usual parameters.

Rogowski coils are best suited for measuring these current increases, which ever have to be adapted to the process and the system technology. For this purpose, a study was conducted to investigate the possibilities of size adjustment and process parameter acquisition. Plasma-electrolytic polishing (PeP) was used as a test procedure on a test system.

Figure 1 shows how the current change can be considered as a part of the process analysis. It is also crucial whether the process is directly influenced by the sensor or not. Only current measurement using shunts directly influences the process, but it has the advantage that all frequency components can be recorded.

The current measurement with the Rogowski coil is indirect. It has no influence on the process but is frequency-dependent and shows linear behavior up to the cutoff frequency. Up to this frequency, the output signal of the Rogowski coil is proportional to the derivative of the current di/dt. Certain process types such as EDM and arc can be analyzed by the current rise. Similarly, there are differences in the different types of short circuits resulting from a metallic short circuit between anode and cathode, metallic bridging from ablation particles/additives or partial discharges between metallic particles/gas bubbles.

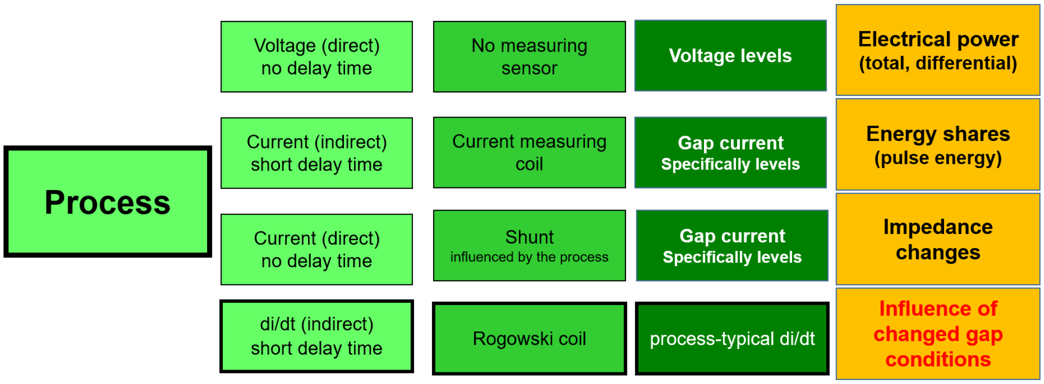


Figure 1: Components of process analysis for non-conventional machining processes [4]

The analysis of the machining process is not only used for process control but also allows conclusions to be drawn about the machining quality, for example by determining the frequency of the process types during machining. The short circuit types, the discharges, and the main removal types play a decisive role here.

The second possible use of the Rogowski coil is as a safety sensor in processes in which the di/dt can be used to detect and prevent very high current values from being reached at an early stage. In order to prevent very high current values from being reached, the output signal of the Rogowski coil will be transmitted to the control element, whereby purely mechanical solutions have a response time in the higher ms range, hydraulic solutions in the higher µs-range, and the electrical solution in the lower µs-range. The excess power must be then stored or disposed.

Fundamentals of the Rogowski coil

The characteristics of the Rogowski coil can be derived from the equivalent circuit diagram (Figure 2).

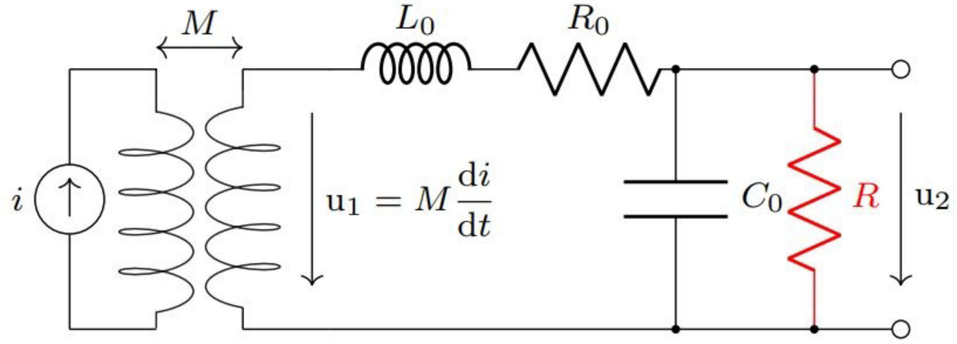


Figure 2: Geometric parameters of the Rogowski coil and characteristics of the output voltage vs. frequency with the first resonance frequency

The equivalent circuit diagram contains the parameters mutual inductance M, inductance L_0, capacitance C_0, ohmic resistance R_0, operating current i, and measuring voltage u_2. The geometric parameters of the Rogowski coil are shown in Figure 3 as well as the qualitative characteristic curve of the amplitude as a function of frequency. The following equations apply to a coil with rectangular windings and are valid only up to the first resonant frequency [1-3].

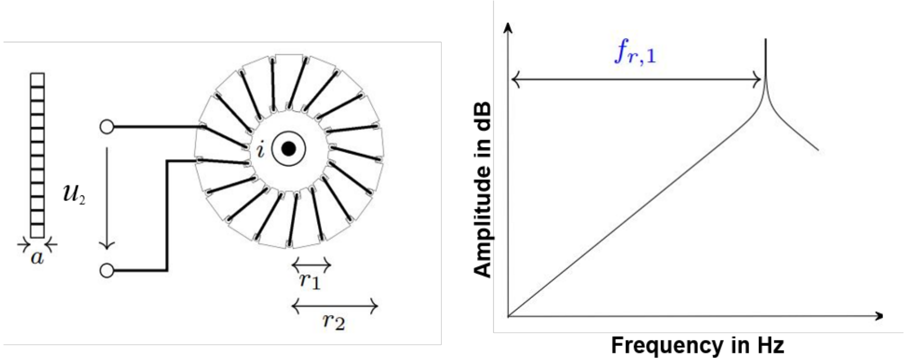


Figure 3: Geometric parameters of the Rogowski coil and characteristics of the output voltage vs. frequency with the first resonance frequency

$$\mathbf{M} = \mathbf{N}\frac{\mu_0\,\mu_r}{2\pi}\mathbf{a}\,\ln\left(\frac{r_2}{r_1}\right) \tag{1}$$

$$\mathbf{L_0} = \mathbf{N}\frac{\mu_0\,\mu_r}{2\pi}\mathbf{a}\,\ln\left(\frac{r_2}{r_1}\right) \tag{2}$$

$$\mathbf{C_0} = 4\pi^2\epsilon_0\epsilon_r\,\frac{r_1+r_2}{\ln\left(\frac{r_1+r_2}{r_2-r_1}\right)} \tag{3}$$

$$\mathbf{R_0} = \frac{l}{\kappa A} \tag{4}$$

$$\frac{U_2}{I} = \frac{\frac{R}{R+R_0}j\omega M}{\frac{RL_0C_0}{R+R_0}(j\omega)^2+\frac{L_0+RR_0C_0}{R+R_0}j\omega+1} \tag{5}$$

$$\mathbf{f_{r1}} = \frac{1}{2\pi}\sqrt{\frac{R+R_0}{RL_0C_0}} \tag{6}$$

$$\boldsymbol{\sigma} = \pi\frac{L_0+RR_0C_0}{R+R_0}\mathbf{f_{r1}} \tag{7}$$

The parameters in Equations (1) to (7) are shown in Figure 2 and Figure 3, where N represents the number of turns, σ denotes attenuation and f_{r1} is the resonant frequency.

Specific requirements were defined for the development of a suitable process analysis sensor. These include a sensor size that allows integration into industrial systems, a wide operating frequency of up to 10 MHz, very good linearity of the sensor output voltage with the frequencies, and an analyzable, measurable output signal.

Structure of various Rogowski coils

As part of the study, various sensors (Rogowski coils) were constructed and tested using a test procedure (PeP). Figure 4 shows the three most important solutions with their geometric parameters.

Coil 1 has a non-ferromagnetic printed core with guide slots for the winding. The advantage of this coil is the geometrically exact and homogeneous winding, which can also be implemented in a concrete calculation or simulation. Comparisons between calculations and measurements are provided below.

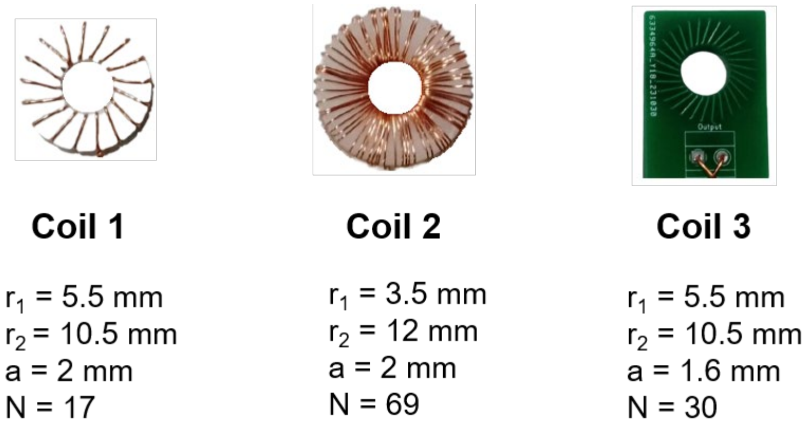


Figure 4: Test coils for different application

Coil 2 has a larger ratio between outer and inner diameters with a significantly higher number of turns, which leads to overlaps on the inside radius and unequal spacing on the outside radius. This means that the calculation equations for the equivalent circuit diagram (ECD) in Figure 2 are only partially applicable.

Coil 3 is a printed circuit board Rogowski coil. The advantage of this coil is the higher manufacturing accuracy, which leads to a more precise calculation or simulation.

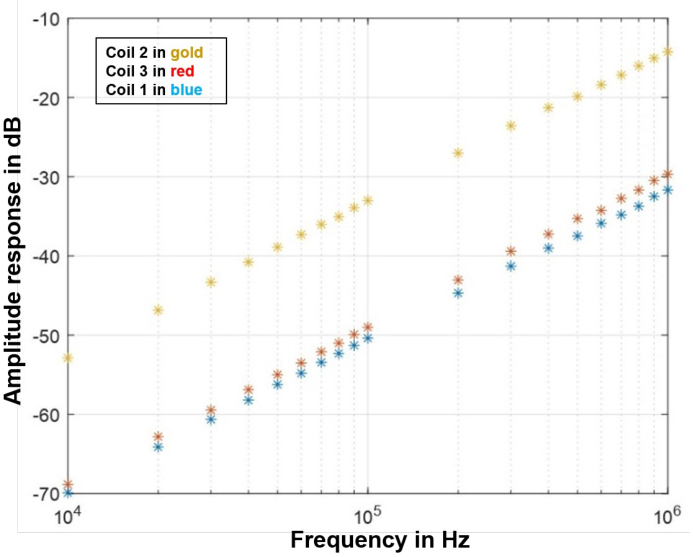


Figure 5: Amplitude response for the three test coils up to 1 MHz

In Figure 5 the linearity of the three coils was tested from 10 kHz up to 1 MHz, as a result. All tested coils have been shown a very good linearity. The influence of increasing the number of turns on the sensitivity can be clearly seen in Figure 5. The sensitivity M of coils 1 and 3 are almost similar, where the sensitivity M of coil 1 is 1.6 dB higher than that of coil 3. Coil 2 has a significantly higher sensitivity M than both coils 1 and 3. The sensitivity M of coil 3 is 17.7 dB higher than that of coil 1 and 16.1 dB higher than that of coil 3. Therefore, a higher number of windings is preferred. However, due to manufacturing limitations during the 3D printing of coil 1 and the PCB fabrication of coil 3, a higher number N of windings could not be achieved. In Figure 6 the calculated and measured frequency response for coil 1 are compared.

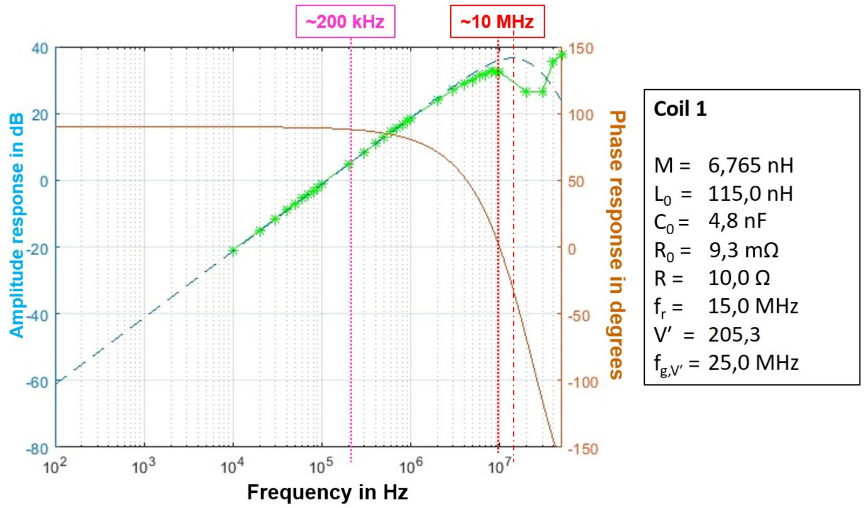


Figure 6: Amplitude response and phase response in the frequency range from 10 kHz to 10 MHz, calculated (blue, red) and measured (green) for coil 1

Figure 6 shows an agreement between the measured and calculated amplitude response up to 10 MHz. The cutoff frequency is around 10 MHz. The requirement for the measuring sensor (coil) has been met.

Experimental setup

The experimental setup is intended to show that both the initialization conditions of plasma electrolytic polishing (PeP) and the process transitions of the ECM can be determined at different voltage levels. PeP initialization requires the use of higher currents and larger voltage changes. In this case, the coil can be used without further amplification. With EC processing, however, significantly smaller current changes are to be expected, so that amplification of the coil output signal is necessary.

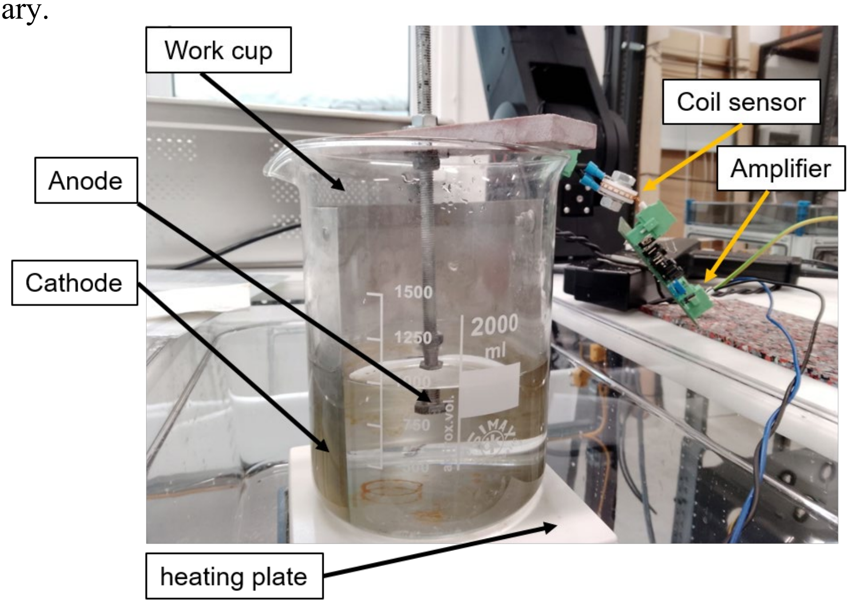


Figure 7: Experimental setup for PeP/ECM

The basic structure of the experiment corresponds to that of a PeP and the electrolyte used (Beckmann Institute) is also used for PeP processing. Figure 7 shows the key elements of the experiment.

The workpiece electrode (anode) is located in the center of a 61 mm radius work cup filled with a special electrolyte from the Beckmann Institute. The cathode plate is placed circumferentially against the inner wall of the cup. This configuration results in an anode-to-cathode ratio of 1 to 10, which is required for plasma polishing. Two series-connected programmable power supplies were used, each capable of supplying 300 VDC for the process. The cup filled with the electrolyte was brought to a temperature of 80 °C ± 5 °C using a heating plate. The coil was placed around the wire connected to the anode. Voltage, current and current change di/dt were recorded with an oscilloscope.

To analyze the switching behavior of the process, the voltage provided by the two power supplies was switched from an offset of 100 V/6 A to a typical PeP voltage of 348 V/396 V, pulsed for repeated generation of current increases.

Results of the current change analysis at different voltage jumps in arrangements (PeP/ECM)

Figure 8 shows the performance of test coil 1 and test coil 3 when the supply voltage changed from 100 V to 348 V. The current changes di/dt were measured in two different experiments under the same conditions, resulting same process current and process voltage. It can be seen that the measured current changes with test coil 3 lead to significantly larger peak values. The beat (~8 kHz) on the di/dt peaks (~40 kHz) can be seen with the coil 3 also more clearly. There is still no clear initialization of the PeP process in the voltage switching range. There is no light effect on the anode that would indicate plasma formation. The di/dt peaks are caused by the power supplies used. This also proves the high performance of the test coil.

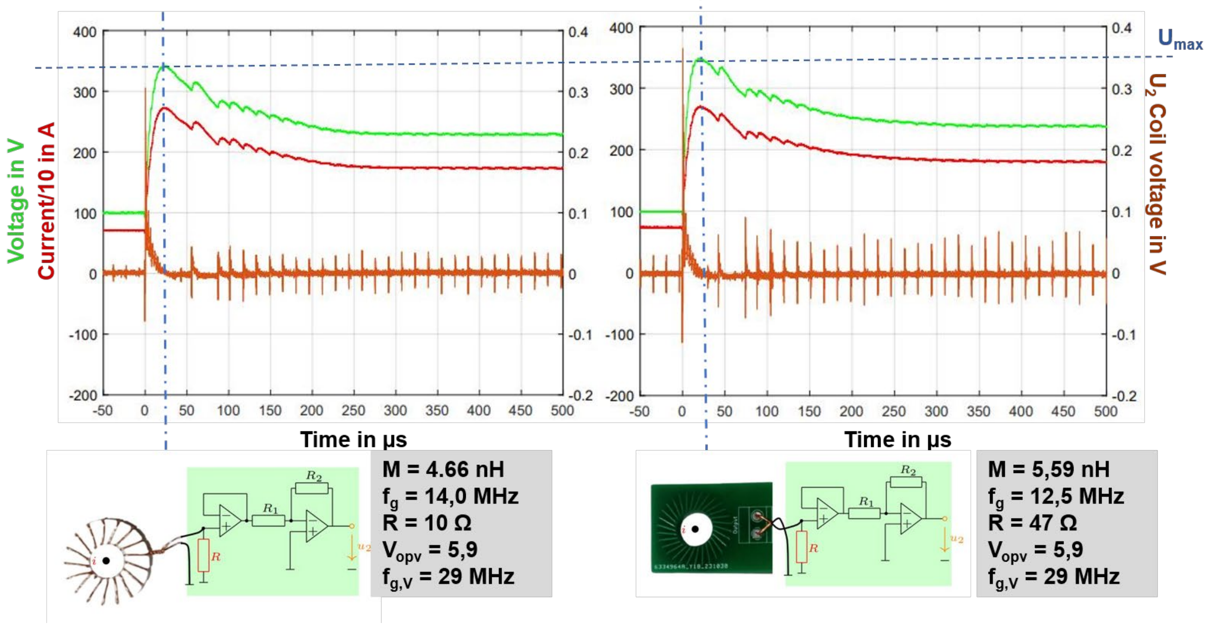


Figure 8: Voltage changes from 100 V to 348 V measured with test coils 1 and 3 for two different tests

On the 100 V level, a pure heating effect of the electrolyte can be assumed. The introduced power is approximately 600 W. In the 348 V level, the current density increases to 2 A/cm², and the power rises to approximately 5.9 kW after reaching a steady state. Due to the 6.1 cm distance between the anode and cathode, a low current yield is expected, minimizing the possibility of an electrochemical effect.

In Figure 9, the transient conditions are compared for two different voltage steps. In the left diagram, the voltage step of 248 V is smaller. After a current peak of 17 A, the current drops to approximately 7.5 A before approaching the stable final value of 17 A. The u_3 value in this case is 2.55 V. In the case of the 296 V voltage step, the current peak is 62 A, and the later settling final value is 17 A. The maximum u_3 value is 3.35 V. After reaching the stable final value, the di/dt peaks remain constant, indicating no additional processes contributing to the electrolyte's warming.

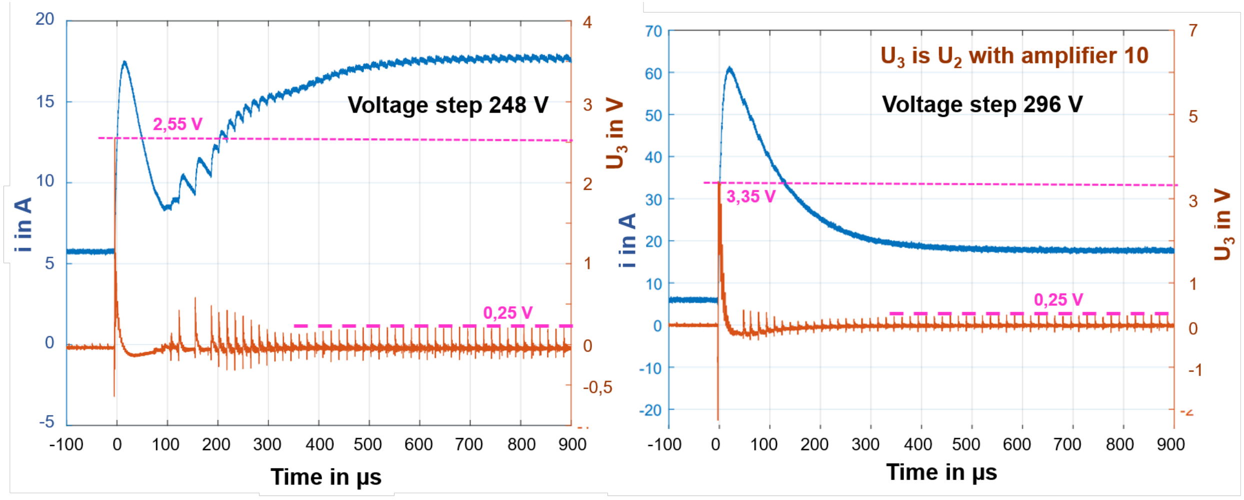


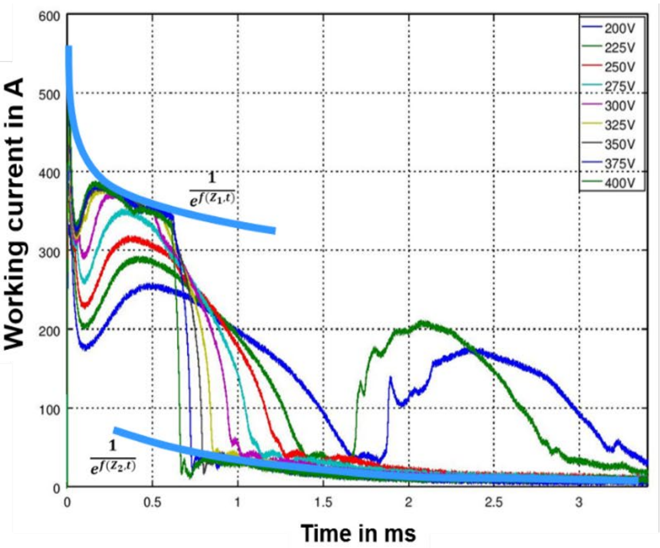
Figure 9: Transient behavior of the working current with different voltage jumps

Compared to the initialization characteristic of Bath-PeP [5], only the first two phases of this characteristic are present. This implies that no plasma area can be created. Furthermore, based on [5], it can be inferred that the absolute voltage peak value is not crucial for initialization; instead, it is the du/dt value that matters. This is evident in the fact that a voltage value of 396 V with a rise of 0 V is ideal for PeP processing. In the examined example, however, the voltage change from 100 V to 396 V is not sufficient.

Important measuring ranges of the Rogowski sensor for the Bath-PeP

In [5] different initialization curves were recorded for different voltage levels, as shown in Figure 10. The experiments involve stable PeP processing as well as unstable processes. Depending on the process energy source used to provide the voltage for the process, it is essential to initially verify whether the current overshoot in the first 50 µs is within the safe operating state and does not exceed the current limit that the process energy source can provide. Since this current value is also dependent on the immersion process, there may be larger deviations compared to the present diagram. With the di/dt sensor presented, the current overshoot can be detected within a few microseconds and appropriate measures can then be taken.

The second use of the coil occurs after the current drops after the initial current plateau, which provides information about the stability of the plasma ignition. A lower supply voltages lead to greater instabilities in the polishing process; thus, depending on the materials and electrolyte used, there must be a minimum changes in the process current di/dt to ensure a rapid and stable PeP process. For processes with greater instability, indicating potential reinitializations (plasma disruptions), as shown in Figure 10 for voltages of 200 V and 225 V, a third process evaluation can be conducted. For these process analyses and system safety considerations, Rogowski coils without amplification can be used. It is recommended to position the windings on a printed core with guide slots for the winding (coil 1) to enable the creation of reliable process analysis programs.



Current limitation in the initialization area (0 to 50 µs)

Negative current drop until the polishing current is reached (600 µs to 1700 µs)

Secondary current increase (1700 µs to 1900 µs)

Figure 10: PeP initialization diagrams for Bath-PeP at different working voltages [5]

Due to the very small current changes in the steady state, an amplifier circuit may be required for coils in order to monitor the current changes. When amplifying the coil output signal, the cutoff frequency of the amplifier circuit must be considered. To avoid influencing the cutoff frequency of the coil, the cutoff frequency of the amplifier circuits must be higher than the cutoff frequency of the coil, ensuring that the overall system's cutoff frequency remains equal to that of the coil itself. In the examples examined, the shifts in cutoff frequency were close to the required 10 MHz cutoff frequency in the worst case.

Summary

This paper demonstrates the effectiveness of the Rogowski coil in measuring transients and fast current changes. All the coils studied have shown very good linearity up to an operating frequency of 10 MHz, measuring transients as short as 100 ns. The electrical properties of the Rogowski coil are significantly influenced by its geometrical parameters. To increase the accuracy of the calculation and simulation, it is recommended to wind the coil around a printed core with guide slots or to realize a circuit board with fixed geometric dimensions. Coil parameters such as mutual inductance, inductance, resistance and capacitance have been calculated analytically. The practicality of three Rogowski coils has been tested experimentally. The function of a Rogowski coil is to recognize current changes. For processes with direct correlation to current, such as ECM or PEP, the Rogowski coil can help protect processes against overcurrent, analyze the stability of processes and act as an event detector for monitoring processes over time. Known for its scalability, the Rogowski coil offers an industrially scalable solution for accurately measuring current changes across various applications. Its adaptability to different current levels, ease of installation and precision make it an effective choice for industrial environments with different current levels and operating conditions.

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