Equivalent Circuit Modelling for Pulsed Bipolar Plasma Electrolytic Oxidation Process

Azamat R. Fatkullin, Evgeny V. Parfenov, and Aleksey Yerokhin

***Abstract*—The paper discusses modelling and simulation problems for the technological process of plasma electrolytic oxidation (PEO) of light alloys, presented as an electric load, for the purposes of the process understanding and control. It is shown that the transient processes of voltage and current during PEO can be simulated by a second order nonlinear circuit consisting of resistors, capacitors, an inductor and ideal diodes. The properties of the circuit components follow the coating growth; this dependency can be used for the process control.**

***Index Terms*—Equivalent circuit, modelling, plasma electrolytic oxidation, transient process.**

I. Introduction

Currently plasma electrolytic technological processes attract significant attention as efficient and environmentally friendly alternatives to conventional electrochemical processes [1]. Plasma electrolytic processes operate at high voltages from 100 to 1000 V which generate microdischarge plasma at the interface layer between the liquid electrolyte and a metal workpiece surface [2]. In the process of plasma electrolytic oxidation (PEO), the major voltage drop occurs on a thin oxide layer generally possessing n-type of conductivity which leads to a reversely biased Schottky barrier under anodic polarization [3]. Resulting high field strength promotes electric discharge evolution within the oxide layer, boosting its growth. As a result, the mechanism of plasma electrolytic oxidation involves complex combination of electrochemical, electrophysical, plasma and metallurgical processes, full understanding of which has not yet been reached. One of the recently proposed approaches to solve this problem bases on in-situ evaluation of PEO frequency response, yielding impedance spectra of the electrolyzer [4]. However, so far this method has not led to a development of an equivalent circuit for the PEO electrolyzer using a methodology of impedance spectroscopy [5], due to the high complexity of PEO process. The aim of this paper is to propose and justify an equivalent circuit model for simulation of PEO electrical characteristics based on transient analysis.

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II. Experimental Results

A. PEO Process Setup

For the plasma electrolytic oxidation, the pulsed power supply setup included two MDX II (Advanced Energy) units as programmable dc sources for the positive and negative voltages, and one pulse unit SPIK 2000 (Melec, Gmbh) combining the dc sources into a half bridge inverter circuit connected to the load. The voltage rating of the dc sources is 0 to 1000 V, rated power 20 and 10 kW for the positive and negative pulses respectively. The rated power of the pulse unit is 40 kW. As the load, 2-liter water-cooled stainless steel tank (cathode) with a specimen (anode) immersed into conventional alkaline electrolyte was used. BS6082 aluminium alloy specimens 25 mm × 20 mm × 6 mm in size were used. The other experimental details can be found elsewhere [6].

B. Voltage and Current Acquisition

For the PEO process, bipolar pulses with positive voltages Up ranging from 400 to 600 V, negative voltages Un from 5 to 200 V were used with the frequency varied from 20 Hz to 20 kHz according to the design of experiments. The positive and negative pulses were separated with a zero pause when both dc sources are disconnected from the load by the pulse unit. One positive and one negative pulse occurred during the period, both centered on the corresponding half-period, with duty cycle 45…55% and 20…30% respectively.

For the data acquisition, a National Instruments platform with PXI-5922 dual-channel flexible-resolution digitizer and Tektronix high voltage (P5205A) and current (A6302) probes were used. The in-house developed software Oscope allowed saving simultaneous frames of the voltage and current with memory buffer of up to 2 Mb per channel. The waveforms of length N =120000 samples were acquired in 8-bit resolution at sampling frequency fs = 250 kHz every Δt = 10 s, in "slow" discrete time tm, $m = 0 \ldots M$. With the measurement ranges of 1000 V and 100 A this provided 4V and 0.4 A accuracy errors respectively; this is close to the stabilization properties of the dc sources.

C. Transient Waveforms

Typical digitized waveforms of the voltage and current are shown in Fig. 1. It is clearly seen from the figure that the voltage pulses are not ideally square, especially at the falling edge of the positive pulse. This can be attributed to the circuitry of the pulsed unit which disconnects dc source from

the load during the pause that exhibits zero power supply current at this stage. This preliminary analysis shows that the equivalent circuit of the PEO process is quite complex.

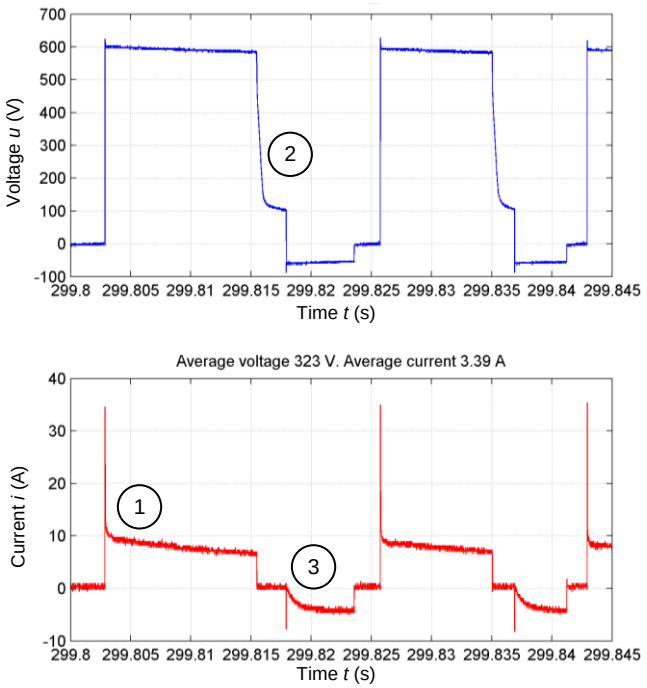

Fig. 1. Waveforms of the voltage and current during PEO of aluminium at U_p = 587 V, U_n = 57 V, t_m = 5 min.

The waveforms feature four pulse edges, three of them have significant time constants compared to the pulse period. The corresponding transient processes are numbered from 1 to 3 in Fig. 1. The first transient is a current reaction of the load to switching on the positive dc voltage source. The second one is a voltage reaction of a generally capacitive load to switching off the positive dc source. The third transient process occurs after the first pause and reflects a current reaction of the load to switching on the negative dc voltage source. The fourth edge after switching off the negative dc source does not show any significant transient process.

Investigation of the transients over all the experimental design shows that the time constants and steady values vary with the PEO treatment time and with the positive and negative pulse voltages. Therefore, the transient analysis of the waveforms will help to uncover the PEO electrolyzer equivalent circuit, and the evolution of its component values will help to evaluate the coating thickness and other surface properties during the treatment.

III. Transient Process Modelling and Discussion

A. Approximation of the Waveform Transients

All three characteristic parts of the acquired waveforms have been picked out and averaged over the measurement frame of length N in order to minimize random noise effects. Then the transients have been approximated using Curve Fitting Toolbox of MATLAB by non-linear least squares method with the following functions:

$$i_1 = A_1 e^{p_1 t} + A_2 e^{p_2 t} + D_1, \quad (1)$$

$$u_2 = A_3 e^{p_3 t} + A_4 e^{p_4 t} + D_2, \quad (2)$$

$$i_3 = A_5 e^{p_5 t} + A_6 e^{p_6 t} + D_3. \quad (3)$$

TABLE I: Approximation Coefficients for Transient Process 1

Time t_m (s)	A_1 (A)	p_1 (s^{-1})	A_2 (A)	p_2 (s^{-1})	D_1 (A)	R^2
5	31.46	–87400	2.644	138	6.242	0.95
10	27.51	–55500	1.522	359	4.777	0.93
20	26.10	–49060	1.119	1107	4.005	0.89
40	32.20	–74380	0.9643	1485	3.183	0.87
60	23.05	–85560	1.257	2622	2.626	0.90

TABLE II: Approximation Coefficients for Transient Process 2

Time t_m (s)	A_3 (A)	p_3 (s^{-1})	A_4 (A)	p_4 (s^{-1})	D_2 (A)	R^2
5	417.1	–3593	63.28	–969900	105.9	0.99
10	404.9	–2440	61.63	–704700	120.5	0.99
20	353.1	–2325	66.15	–359200	168.7	0.99
40	291.4	–1882	78.11	–89470	215.7	0.99
60	232.2	–2583	100.7	–378	200.2	0.99

TABLE III: Approximation Coefficients for Transient Process 3

Time t_m (s)	A_5 (A)	p_5 (s^{-1})	A_6 (A)	p_6 (s^{-1})	D_3 (A)	R^2
5	4.53	–1178	-6.21	$-1.4 \cdot 10^7$	-4.72	0.86
10	3.80	–697	-7.32	$-1.3 \cdot 10^7$	-4.48	0.87
20	3.54	–410	-10.12	$-0.2 \cdot 10^7$	-3.57	0.94
40	2.82	–394	-12.61	$-1.7 \cdot 10^7$	-2.47	0.92
60	2.32	–410	-9.36	$-3.4 \cdot 10^7$	-2.32	0.8

The goodness of fit has been evaluated using coefficient of determination R^2, which is a squared coefficient of paired correlation between the experimental and approximated data. For all transients the first order functions containing only one exponential component have shown poor approximation $R^2 < 0.85$; the third order appeared to be excessively complex. Therefore functions (1)-(3) being the solutions for second order aperiodical transient process problem have been used for the analysis. The average value of R^2 for all the fits is 0.94 which is consistent with the accuracy of the voltage stabilization. Functions (1)-(3) do not have time shift to the start of the corresponding edge since it is not necessary for the equivalent circuit synthesis.

The coefficients of approximation for all the three transient processes occurring during pulsed bipolar PEO process at U_p = 587 V, U_n = 57 V, at different instants t_m are given in Tables I, II, and III, along with the goodness of fit R^2.

B. Equivalent Circuit Diagram

The schematic of the equivalent circuit has been proposed after the structural analysis of the waveforms in Fig. 1 and functions (1)-(3).

The first transient current looks typical for a capacitor charge through a resistance; non-zero steady state implies that another resistor should be placed in parallel with the capacitor to form a voltage divider. The second order of the transient suggests two parallel *RC* branches. This part is implemented by R_0, R_1, C_1, R_2, and C_2 components in Fig. 2.

The second transient is a typical voltage decrease during discharge of a capacitor via a resistor. This transient occurs during the first pause when both power switches S_1 and S_2 are

shut off by the pulse generator described as ideal sources V_1 and V_2. During this transition, capacitors C_1 and C_2 discharge through resistors R_1 and R_2 respectively. Because R_0 is not involved into this process, roots p_1 and p_2 differ from p_3 and p_4.

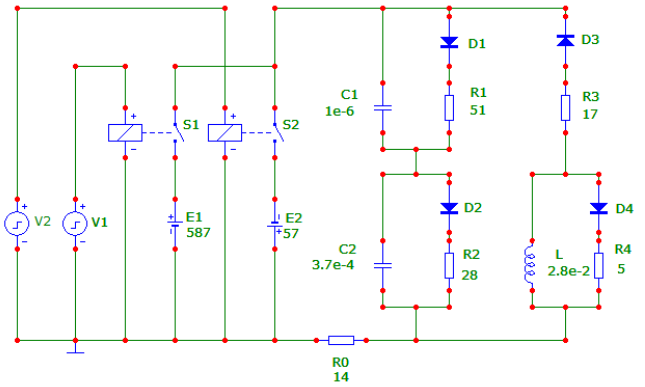

Fig. 2. Equivalent circuit of the bipolar pulse power supply and the PEO process of aluminium at U_p = 587 V, U_n = 57 V, t_m = 5 min.

The third transient exhibits a sharp peak at the rising edge of the current and further rather slow exponential current growth. The peak can be attributed with the capacitors recharge to the negative source voltage through a rather small resistor R_0. The exponential growth can be described with an inductor L charging through resistors R_0 and R_3. These two processes have significantly different roots p_6 and p_5 respectively, and constants A_6 and A_5 having different sign. The fourth transient is virtually absent; this can be achieved by putting R_4 in parallel with the inductor for its discharge during the second pause.

The current-voltage characteristic of the PEO process is significantly nonlinear [7] because of the difference between cathodic and anodic electrochemical and plasma processes on the aluminium workpiece with porous oxide ceramic coating. All the transients are therefore separated from each other by diodes D_1, D_2, D_3, and D_4. This makes the equivalent circuit nonlinear.

C. Equivalent Circuit Component Values

The first transient process describing by Kirchhoff's law

$$E_1 = u_{C_1} + u_{C_2} + i_1 R_0 \tag{4}$$

starts from the zero independent initial conditions

$$u_{C_1}(-0) = u_{C_1}(+0) = 0, \tag{5}$$

$$u_{C_2}(-0) = u_{C_2}(+0) = 0. \tag{6}$$

The value of R_0 can be estimated from (1) at t = +0 as

$$R_0 = \frac{E_1}{A_1 + A_2 + D_1} \tag{7}$$

For $t = +\infty$ the value of $R_1 + R_2$ can also be estimated from

$$D_1 = \frac{E_1}{R_0 + R_1 + R_2} \tag{8}$$

Differentiating (4) at t = +0

$$\left.\frac{du_{C_1}(t)}{dt}\right|_{t=+0} + \left.\frac{du_{C_2}(t)}{dt}\right|_{t=+0} + \left.\frac{di_1(t)}{dt}\right|_{t=+0} \cdot R_0 = \left.\frac{dE_1(t)}{dt}\right|_{t=+0} \tag{9}$$

and substituting (1) yields

$$\frac{i_{C_1}(+0)}{C_1} + \frac{i_{C_2}(+0)}{C_2} + (A_1 \cdot p_1 + A_2 \cdot p_2) \cdot R_0 = 0. \tag{10}$$

The characteristic equation for this transient is

$$Z(p) = R_0 + R_1/(1 + pC_1R_1) + R_2/(1 + pC_2R_2). \tag{11}$$

Solving equations set (8)-(11), the values of R_1, R_2, C_1, and C_2 can be obtained.

TABLE IV: EQUIVALENT CIRCUIT COMPONENT VALUES

Time t_m (s)	R_1 (Ω)	C_1 (μF)	R_2 (Ω)	C_2 (μF)
5	50.68	1.02	27.87	370.0
10	73.63	1.30	30.63	121.0
20	88.26	13.7	37.98	31.3
40	112.4	1.01	53.89	17.0
60	120.5	0.70	90.90	6.63

TABLE V: EQUIVALENT CIRCUIT COMPONENT VALUES

Time t_m (s)	R_0 (Ω)	R_3 (Ω)	L (mH)	R_4 (Ω)
5	14.37	17.17	27.2	5
10	17.15	16.32	48.4	5
20	18.57	23.43	103.0	5
40	15.95	44.75	154.3	5
60	21.53	43.09	157.9	5

The second transient process (2) (assuming its start at t = 0) can be split into two independent ones – discharging C_1 via R_1 and C_2 via R_2 described by equations:

$$u_{C_1} = A_3 e^{p_3 t}, \tag{12}$$

$$u_{C_2} = A_4 e^{p_4 t} + D_2, \tag{13}$$

with non-zero initial conditions of the capacitors' voltage left after the first transient. This allows evaluating roots p_3 and p_4:

$$p_3 = -1/(R_1C_1),\ p_4 = -1/(R_2C_2), \tag{14}$$

which, in turn, helps to correct the values of R_1, R_2, C_1, C_2.

The third transient process (again assuming its start at t = 0) can be described by Kirchhoff's law

$$i_3 = i_{C_2} + i_L, \tag{15}$$

where i_{C_2} can be seen as a very short peak and i_L – as exponential negative current growth (see Fig. 1). Considering significantly different time constants, which absolute values are reciprocal to p_5 and p_6 (see Table III), these transients again can be treated as independent:

$$i_{C_2} = A_6 e^{p_6 t}, \quad (16)$$

$$i_L = A_5 e^{p_5 t} + D_3. \quad (17)$$

This assumption yields

$$p_5 = -(R_0 + R_3)/L, \; p_6 = -(C_1 + C_2)/(R_0 C_1 C_2), \quad (18)$$

which allows estimation of L and R_3.

The transient processes have been analyzed for different time instants t_m and the corresponding equivalent circuit component values have been calculated (Tables IV and V).

D. Discussion of Equivalent Circuit

The transient processes in the equivalent circuit have been simulated using *MicroCap* software using schematic shown in Fig. 2. The simulated transients are shown in Fig. 3. The comparison of Fig. 1 and Fig. 3 shows that the equivalent circuit adequately describes the electrical characteristics of the PEO process.

Analysis of the equivalent circuit components shows that they can be attributed with certain parts of the PEO system. Series resistance R_0 having quite low value can have a physical meaning of the electrolyte equivalent resistance. Pair R_1-C_1 having higher resistance and lower capacitance compared to R_2-C_2 can represent the thick porous PEO coating, while R_2-C_2 can be attributed with a thin barrier layer in the coating/substrate interface.

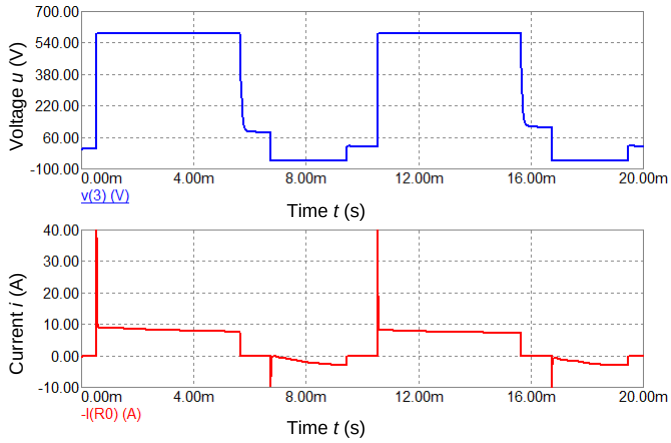

Fig. 3. Simulated transients in the equivalent circuit.

Inductor L with resistors R_3, R_4 can represent cathodic deposition of the electrolyte species during the negative polarization. The component values obtained in this research are close to the values calculated as a result of *in-situ* impedance spectroscopy of the similar PEO process [8]. Therefore, the proposed method yields verified information which can contribute to a deeper understanding of the PEO process. Analysis of the component values variation with time shows that except R_0 and C_1 all the components evolve with the coating growth. This fact supports the attribution of R_0 to the electrolyte resistance and appears to be consistent with C_1 evolution reported elsewhere [6]. Resistance R_1 attributed to the porous part of the coating increases with time and follows the coating thickness as shown in Fig. 4. Therefore, the equivalent circuit approach can be used for diagnostics of the coating thickness and other unobservable surface properties during the PEO treatment, thus, contributing to the process control.

IV. Conclusion

The transient analysis of the voltage and current waveforms recorded during plasma electrolytic oxidation of aluminium was performed. The decomposition of the experimental bipolar pulses uncovered three significant transients, two in the current, one in the voltage. The transients were approximated with a superposition of exponential functions which helped to propose an equivalent circuit diagram. An inverse problem of an equivalent circuit synthesis was solved on the base of Kirchhoff's differential equations, and its correctness was justified by a simulation using a circuit modelling software. It was shown that the components can be attributed to certain parts of the coating, and their values evolve with the coating growth. Therefore, the proposed method can be applied in a process control system for diagnostics of the unobservable surface properties during plasma electrolytic oxidation.

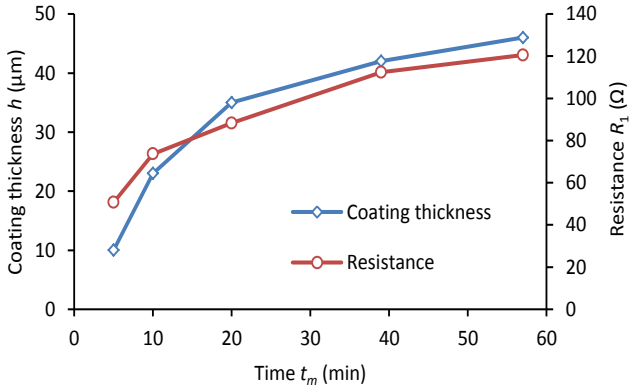

Fig. 4. Evolution of the coating thickness and resistance R1 during the PEO process of aluminium at *Up* = 587 V, *Un* = 57 V.

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