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USING THE NEGATIVE IMPEDANCE CONVERTER IN DEVICE FOR QUALITY TESTING OF LASER WELDING

Annotation. The paper presents a method for increasing the sensitivity of the eddycurrent probe for testing of defects of laser welding and a means for this method implementation. It was practically applied in measurement device for monitoring of quality of laser welding in supercapasitors. For this purpose the eddy-current probe was connected to the negative resistance converter (NRC) which was especially designed on the base of the LC-oscillator.

Keywords: eddy current probe, laser welding, supercapacitor, negative impedance converter.

Introduction. Currently exist the mass production of a wide range of supercapacitors for use in transport, for power backup of computer systems, for improving the stability of solar power systems and other purposes [1,2].

The main part of the supercapacitor is the charge-storing device (CSD). In cylindrical supercapacitors, it designed as roll of aluminum strips of anode and cathode electrodes, covered on one side by porous material, for example, graphene [2]. Between the electrodes in the roll is a strip of separator made of dielectric material. The longitudinal section of the roll, as well as its fragment, showing the alternation order of layers in enlarged form, are schematically shown in Fig. 1.

The edges of the positive and negative electrode strips are shaping in a certain way before laser welding with positive and negative collectors respectively. These collectors use as terminals of the CSD. The design of a typical cylindrical supercapacitor has shown in Fig 2.

Objective of the work. The high discharge currents of supercapacitors require good ohmic contact of the electrodes with its collectors, so their laser welding should be of high quality.

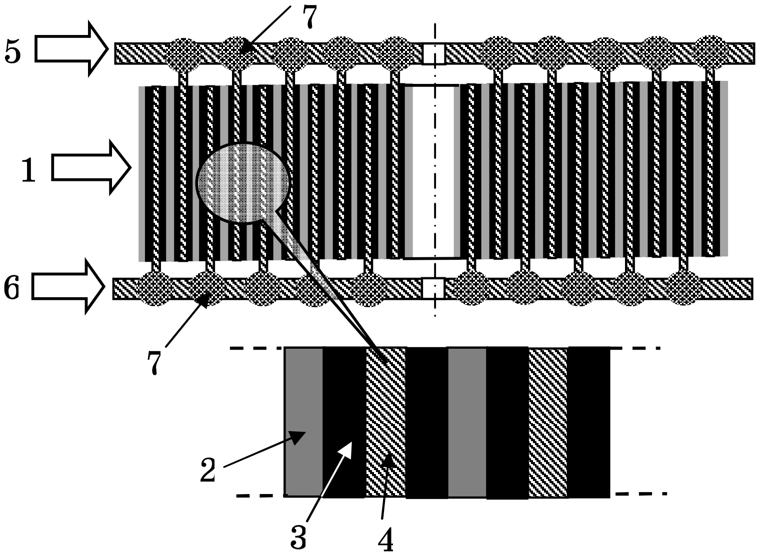


Figure 1 – Charge-storing device (CSD): 1 – roll; 2 – strip of dielectrical separator; 3 - layer of porous material; 4 - strip of aluminum foil (anode or cathode electrode); 5 - cathode collector; 6 - anode collector; 7 - welding joint (places of welding)

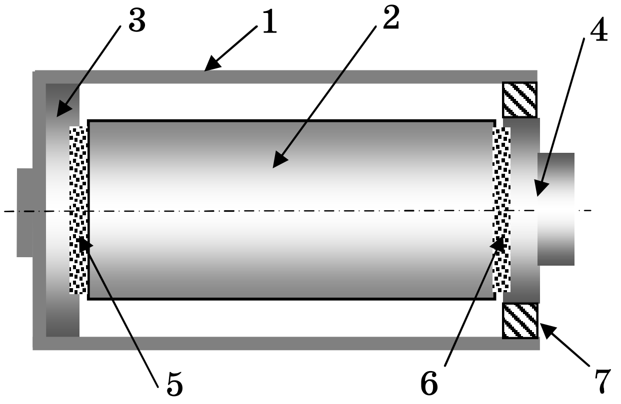


Figure 2 – The supercapacitor and its components: 1– aluminum cylindrical case; 2 – roll of the charge storing device (CSD); 3 – anode collector galvanically connected to the case; 4 – cathode collector; 5,6 – place of welding the anode and cathode collectors with electrodes of the CSD; 7 – insulating ring

Obviously, the quality of welding we can check only after the collectors already welded to the roll of CSD, so only non-destructive method we can use to evaluate this quality.

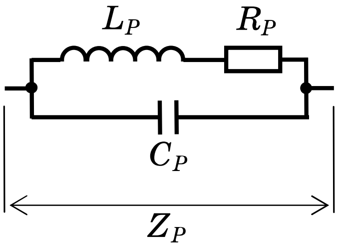
Thus, the objective of this work was to select an effective method of testing and develop corresponding means required for its implementation in the device for evaluating quality of laser welding in supercapasitors.

Testing method. Laser welding is performed in several places on the surface of collector. In our case they shape was as circular sectors (total 6 sectors on collector). It means that the welding seam is going along the perimeter of the sector. The welding quality first of all depends on number and size of defects from the side of collector witch is reverse towards to side of action the laser beam. Consequently, the welding defects must be detected not only in thickness of the collector material but mainly from its bottom side where collector is welded with foil of the electrodes. Considering that the collectors and electrodes are made of non-magnetic metal - aluminum, was selected the eddy-current method of weld testing. Its effectiveness in the context of the described here objectives is confirmed of the practical investigations and results of other authors [3-5].

Implementation method. To implement the method it is necessary that the induced eddy currents could to penetrate through the weld on the bottom of the collector towards the foil of electrodes, i.e. in a direction perpendicular to the plane of the collector. This is possible when working on the tangential component of the vortex magnetic field. To create the necessary configuration of the field in the welded joint zone, we used a parametric eddy current probe with a U-shaped ferrite core. On the core spooled a three-section coil, which consist of 300 + 300 + 300 = 900 turns of a copper wire with a diameter of 0.02 mm. Cores of the desired shape and size for the anode and cathode collectors were cut from the EPCOS ferrite cores of the EF series with $\mu \cong 1700$.

The electrical model of the eddy-current probe and its impedance Z_S are shown in Fig. 3.

Investigations of the designed probes have shown that coil's capacitance C_P has a significant influence on the impedance Z_P beginning from frequencies the order of 1 MHz and higher. In our case, to ensure a significant depth of penetration of the probe field into the collector metal (aluminum), we worked at a frequency f = 1.5 kHz. At this frequency, the influence of C_P can be ignored.



$$Z_P=Re(Z_P)+jIm(Z_P),$$
$$Re(Z)=R_P/D,$$
$$Im(Z_P)=[\omega L_P-\omega C_P R_P{}^2-\omega^3 L_P C_P{}^2]/D,$$
$$D=[1+(\omega C R_P)^2+\omega^2(\omega L_P C_P)^2-2\omega^2 L_P C_P)]$$

а

б

Figure 3 – Electrical model of the probe and its impedance Z_P. a) the electrical model. b) impedance, where: R_P and L_P - the ohmic resistance of the wire and the inductance of the coil, respectively;
C_P – capacitance of the coil

If the welded joint of the collector with the foil of roll is completely absent, the quality of welding is estimated as 0% – "DEFECT"; if the welding is fully matched to the standard, the quality of welding is estimated as 100% – "NORMAL". In general case the impedance of the probe will be:

$$Z_X=j2\pi\cdot f\cdot(L_P+L_X)+(R_P+R_X),\ \ L_X\in[L_0,L_{100}],\ \ R_X\in[R_0,R_{100}], \tag{1}$$

where L_X and R_X – is an inductance and resistance that were added to the impedance of the probe in the result of interaction the probe field with tested welding seam.

It was experimentally established that at the working frequency the introduced inductive constituent of the probe impedance practically does not change depending on the quality of the welding, i.e.:

$$(L_P+L_X)\approx L_P$$

Therefore, value of the inductive constituent is not an informative parameter of the welding quality.

On the other hand, the total ohmic resistance of the probe $R_{SUM}=R_P+R_X$ depends on the quality of the welded joint. Since the testing process is carried out at the practically constant frequency, the value of the ohmic resistance of the coil R_P can be regarded as a constant. Therefore, as informative parameter for estimation welding quality we can use only R_X.

Finally, the electrical model of the probe (1) can be simplified and presented as:

$$Z_X=j2\pi\cdot f\cdot L_P+(R_P+R_X)=j2\pi\cdot f\cdot L_P+R_{SUM}. \tag{2}$$

For reception of the information concerning result of welding quality estimation, we used the resonant method. The required resonant circuit is realized by parallel connection of the sensor with additional capacitors. We selected the parallel circuit because one terminal of the probe and one terminal of each additional capacitor can be grounded. It increases the noise immunity of measurement results.

Obviously that sensitivity of the sensor concerning to the welding defects depends on the ratio of the value R_P and R_X. The resistance R_P for the anode and cathode sensors is slightly different and equal to an average of 60 ohms. Experiments have shown that such an R_P value does not allow obtaining the required sensitivity. In order to increase the sensitivity, a negative resistance R_{NEG} is introduced into the resonant circuit. This reduces the R_P what increases the Q-factor of the resonant circuit. To introduce R_{NEG}, the negative resistance converter (NRC) was used.

As well known, all NRC's contain a circuit of positive feedback. Considering the features of the resonance method of measurement, the NRC using the circuit of sine wave oscillator based on Op-amp [6] was designed. It is important that In this case the NRC circuit and the resonant circuit including the probe **P** be as single unit (Fig. 4).

The main components of NRC that determine its functionality are such: a non-inverting operational amplifier (OA) **DA1**; the adjustable negative feedback (resistive divider **R1***, **R2**, **R3***); the positive feedback that consist of resistor **R4** and the resonance circuit (probe **P** and capacitors **C1***, **C2***, **C3***).

The other components perform the service functions of the buffer repeater (C5, **R5**, OA **DA2**) and the scaling amplifier (**R6**, **R7**, OA **DA3**). Schemes of NRC for anodic and cathodic probes are identical. They differ only by the capacitances of additional capacitors **C1***, **C2***, **C3***.

The behavior of the NRC is determined by the loop gain between the output of the OA **DA1** and its non-inverting input. The gain factor OA **DA1**:

$$K_A = \frac{1+(\mathbf{R1}+\alpha\mathbf{R2})}{\mathbf{R1}^* + (1-\alpha)\cdot\mathbf{R2}+\mathbf{R3}^*}, \quad 0 \le \alpha \le 1 \tag{3}$$

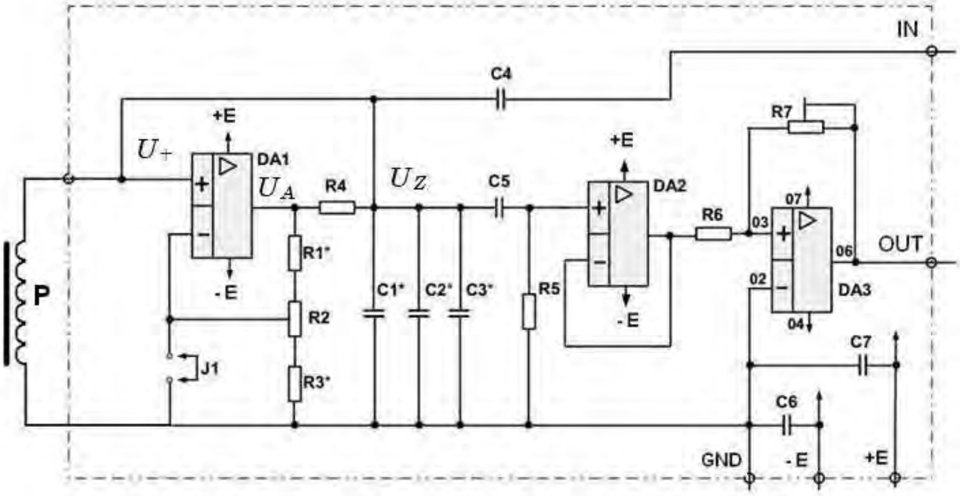


Figure 4 – Negative resistance converter

The voltage at the output of the OA **DA1** is equal to:

$$U_A = K_A \cdot U_+,$$

where: U_+ – voltage on the non-inverting input of the OA **DA1**.

This voltage is input to the positive feedback circuit, so the output voltage at ZK is equal to:

$$U_Z = U_A \cdot \frac{Z_K}{\mathbf{R4}+Z_K} = K_A \cdot U_+ \cdot \frac{Z_K}{\mathbf{R4}+Z_K} \,. \tag{4}$$

Taking into account (2) we have:

$$Z_K = \frac{-j(2j\pi L_P+R_{SUM})}{-j+4j\pi^2 f^2 C_{SUM}\; L_P+2\pi f C_{SUM} R_{SUM}}$$

– impedance of a resonant circuit; C_{SUM} = **C1*+C2*+C3***.

Since $U_Z = U_+$ (see Fig. 4), the state of the NRC is determined by the behavior of the complex transmission coefficient $\underline{\boldsymbol{K}}$:

$$\underline{\boldsymbol{K}} = \frac{K_A \cdot Z_K}{\mathbf{R4}+Z_K} \,. \tag{5}$$

In the expanded form:

$$\underline{\boldsymbol{K}} = \frac{K_A \cdot (j \cdot 2\pi \cdot f L_P + R_{SUM})}{\mathbf{R4} \cdot (1-4\pi^2 \cdot f^2\, C_{SUM} L_P + j \cdot 2\pi \cdot f C_{SUM} R_{SUM}) + j \cdot 2\pi \cdot f L_P + R_{SUM}} \,. \tag{6}$$

Herewith:

$$\boldsymbol{\Phi}(f) = \arg \underline{\boldsymbol{K}}\,(j2\pi f)$$

– phase frequency characteristic of $\underline{\boldsymbol{K}}$ (PFC) and

$$A(f) = |\,\underline{\boldsymbol{K}}\,(j2\pi f)|$$

– amplitude frequency characteristic of $\underline{\boldsymbol{K}}$ (AFC).

If at some frequency $f = F_{GEN}$

$$\boldsymbol{\Phi}(F_{GEN}) = 0 \quad \text{и} \quad A(F_{GEN}) = 1,$$

NRC goes into self-excitation mode and it generates sinusoidal oscillations with a frequency of F_{GEN}. This corresponds to a full compensation of losses in the probe: $R_{SUM}=0$, because $R_P+R_X=|R_{NEG}|$.

The working mode of NRC is the regime of partial loss compensation. In this mode, due to the negative resistance R_{NEG}, which is created by NRC, the losses R_P of the probe are reduced to the value providing the necessary sensitivity for R_X. Consequently, we can write that

$$R_{SUM} = R_P + R_X - R_{NEG}\,.$$

The control of the R_{NEG} value is achieved by adjusting the gain K_A of the amplifier **DA1**.

To determine the dependence of the absolute value of R_{NEG} from K_A, we simplify R_{SUM} from (2), for what we delete temporarily from consideration of R_X, so that $R_{SUM} = R_P$–RNEG. For clarity of definition of this dependence, we accept:

$$\mathbf{R4}= 5.1 \text{ kOhm};\ L_P=24 \text{ mH};\ C_{SUM}=0.42\ \mu\text{F}. \tag{7}$$

Assume that $R_{SUM} = 40$ Ohm. The solution of the system of equations $\{\underline{\boldsymbol{\Phi}}(f) = 0,\ \underline{A}(f) = 1\}$ with respect to f and K_A gives: $f = F_{GEN} =$ 1562.87 Hz, $K_A = 4.5699$.

Now assume that $R_{SUM} = 60$ Ohm. In this case: $f = F_{GEN} =$ 1534.47 Hz, $K_A = 6.3549$.

Therefore, increasing the gain K_A of the OA **DA1** from 4.5699 to 6.3549 and $R_{SUM} = 60$ Ohms is equivalent to reducing the R_{SUM} from 60 Ohms to 40 Ohms = 20 Ohms. On the other hand, it is equivalent to the fact that negative resistance R_{NEG} increased from 0 to 20 Ohms.

The calculated dependence of the negative resistance R_{NEG} on the gain K_A for the same values of the quantities (7) for R_{SUM} from 1 to 60 Ohm, we show in Table 1 and in Fig. 5.

Table 1

Dependence of R_{NEG} and R_{SUM} on the gain factor K_A

F_{GEN} [Hz]	K_A	R_{NEG} [Ohm]	R_{SUM} [Ohm]
1534.47	6.3550	0.00	60.00
1550.16	5.4625	10.00	50.00
1562.87	4.5700	20.00	40.00
1572.69	3.6775	30.00	30.00
1579.66	2.7850	40.00	20.00
1582.10	2.3388	45.00	15.00
1583.83	1.8925	50.00	10.00
1584.44	1.6694	52.50	7.50
1584.87	1.4462	55.00	5.00
1585.13	1.2231	57.50	2.50
1585.21	1.0892	59.00	1.00

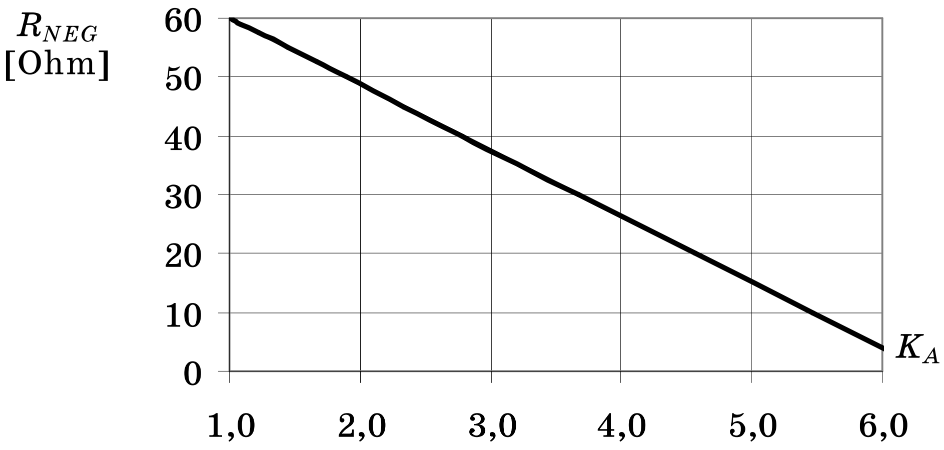


Figure 5 – Dependence of the negative resistance R_{NEG} on the gain K_A. R_{NEG} = 71,204–11,204·K_A

The dependence of R_{NEG} (K_A) was obtained under the following simplifying assumptions:

- OA **DA1** is an ideal operational amplifier;
- The influence of the connecting circuit **C5**, **R5** on the impedance Z_K of the resonant circuit is not taken into account (in the practical scheme **R5** = 2.2 MOhm).

In view of the above, the Q-factor of the probe Q_{PX}, whose field interacts with the welding joint, also depends on R_{NEG}. Taking into account the model (2) and R_{NEG}, the Q-factor of the probe Q_{PX} is defined as:

$$Q_{PX} = \frac{2\pi \cdot f \cdot L_P}{R_P - R_{NEG} + R_X}\,. \tag{8}$$

Since the value of L_P is practically independent from the quality of the welded seam, a numerical estimate of the informative parameter R_X can be obtained by measuring the quality factor Q_{PX}. For this purpose, the input **IN** of the NRC circuit is connected to a sinusoidal voltage source with a linearly varying frequency. In order to determine the numerical value of Q_{PX}, we used the usual method of three points of the resonant curve $A(f)$.

Conclusions. Partial compensation of active losses in parametric probes for eddy current testing is a promising method of increasing its sensitivity to defects of laser welding of supercapacitor collectors and electrodes. The developed NRC scheme has provided good sensitivity and stability at increasing Q-factor of the probes from $Q_{PX} \approx 3$ to $Q_{PX} \approx 80$.

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