2020 IEEE KhPI Week on Advanced Technology

(KhPI Week)

CONFERENCE PROCEEDINGS

October 5 - 10, 2020

Kharkiv, Ukraine

2020 IEEE KhPI Week on Advanced Technology (KhPI Week)

IEEE Catalog Number: CFP20Z72-ART
ISBN: 978-0-7381-4236-4

Organizing Committee of 2020 IEEE KhPIWeek
Work phone: +38 (057) 707-66-34
E-mail: khpiweek@ieee.org.ua
National Technical University “Kharkiv Polytechnic Institute”
Kyrpychova Str. 2
61000, Kharkiv, Ukraine

ORGANIZERS

SPONSORS

IEEE Estonia Section PE/IE Societies Joint Chapter

IEEE Latvia Section IA/IE/PEL Societies Joint Chapter

IEEE Ukraine Section IE/PE/PEL Societies Joint Chapter

IEEE Ukraine Section PE/IE/IA Societies Joint Chapter

ORGANIZING COMMITTEE

Honorary Chairman
Prof. Yevgen Sokol, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)

Chairs
Dr. Serhii Kryvosheiev, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Roman Zaitsev, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)

Technical Program Committee Chairs
Dr. Dmytro Danylchenko, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Vadym Makarov, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)

Publication Chair
Dr. Svitlana Menshykova, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)

Financial Chair
Dr. Olena Avdeeva, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)

TECHNICAL PROGRAM COMMITTEE

Olga Kyselova, Germany
Volodymyr Klepikov
Oleksandr Lazurenko
Serhii Shevchenko
Vadym Starykov
Volodymyr Zamaruiev
Kostiantyn Makhotilo
Heorhii Melnykov
Dmytro Shokarov
Oksana Dovgaluk
Sergiy Berezka
Alekseii Pirotti
Vira Shamardina
Anron Drozdov
Olha Vodoriz
Volodymyr Ivahno
Viacheslav Kulichenko
Roman Tomashevskii
Mykhailo Shyshkin
Oleksiy Larin
Sergiy Malykhin
Yeugen Zubarev
Mykhailo Moskalets
Svitlana Rudchenko
Oleksiy Vodka
Dmytro Breslavkiy
Valeriy Uspenskiy
Andii Dashkevich
Abdelghani Chahmi, Algeria
Podnebenna Svitlana

REVIEWERS LIST

Alekseii Pirotti, Alexander Zakovorotiy, Andrey Kovalev, Bohdan Styslo, Dmitriy Kritskiy, Dmytro Danylchenko, Eduard Skukis, Gennadii Martynenko, Heorhii Melnykov, Kolisnyk Kostyantyn, Kostiantyn Makhotilo, Kseniia Minakova, Marina Chernobryvko, Mykhaylo Kirichenko, Mykhailo Shyshkin, Mykola Makhonin, Natalia Smetankina, Nataliia Zhukovska, Oksana Dovgalyuk, Oleksandr Lazurenko, Oleksandr Miroshnyk, Oleksandr Trushin, Oleksii Vodka, Oleksiy Larin, Olga Vodorez, Pavlo Krot, Roman Zaitsev, Sergey Shevchenko, Sergiy Berezka, Stanislav Dryvetskyi, Svitlana Podnebenna, Vladimir Burlaka

LOCAL ORGANIZING COMMITTEE

Chairman
Dr. Bohdan Styslo, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)

Members
Dr. Kseniia Minakova, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Stanislav Dryvetskyi, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Stanyslav Fedorchuk, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Volodymur Ivakhno, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Volodymyr Zamaruiev, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Mykhailo Shyshkin, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Mykhaylo Kirichenko, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Oleksiy Vodka, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)
Dr. Mykola Makhonin, National Technical University "Kharkiv Polytechnic Institute" (Kharkiv, Ukraine)

IEEE Conference Mentor
Ievgen Pichkalov, Chair of IEEE Ukraine Section, Ukraine

CONTENTS

Challenges of energy measurements of low-energy spark discharges

K. Korytchenko, R. Tomashevskiy, I. Varshamova
Institute of Education and Science in Power Engineering, Electronics and Electromechanics
National Technical University "KhPI"
Kharkiv, Ukraine
korytchenko_kv@ukr.net

S. Essmann
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
stefan.essmann@ptb.de
D. Dubinin, K. Ostapov
National University of Civil Defence of Ukraine, Kharkiv, Ukraine

***Abstract*—The method of measuring the energy deposited into the gas-discharge gap of a low-energy discharge that is based on measuring the discharge current and voltage across the spark gap has been analyzed. A numerical model of transient in a distributed-element circuit is used to assess the connection impact. The effect of the connection distance between the high-voltage probe and the tips of discharge electrodes on the correct measurement of voltage across the gap is revealed. The difference between the discharge current flowing through the gas discharge gap and the discharge current flowing through the discharge capacitor is evaluated.**

***Keywords*—spark discharge; spark energy; voltage and current across spark gap**

I. INTRODUCTION

Determining the minimum ignition energy of flammable mixtures has practical importance for explosion protection and fire safety problems [1]. Also, a reliable ignition of the combustible mixture obtained by the minimum energy of the spark discharge provides a reduction in erosion of the discharge electrodes. It increases the lifespan of the spark plugs in internal-combustion engines. Therefore, a plurality of experimental and theoretical works has been done to measure the spark energy deposited into the gas-discharge gap [2-4].

The ignition of combustible mixtures can occur by a spark discharge when the total spark energy ($CU^2/2$) is several tens of microjoules, e.g. the minimum ignition energy of hydrogen is 17 µJ [5]. High-voltage capacitors with a capacitance equaled to several picofarads are used to accumulate such low energy. A discharge gap has a capacitance**,** too. The gap capacitance depends on the gap design and it can equal several picofarads. For example, typical spark plugs have a capacitance of about 5-10 pF. Compensated voltage dividers having an input capacitance are used to measure the voltage across elements of the discharge circuit. For example, input capacitance of the P6015A High Voltage Probe is about 3 pF when probe is properly low-frequency compensated [6]. As a result, the discharge energy is accumulated in the discharge capacitor, in the capacitor of the spark gap and in the voltage probe. Therefore, measurement of the total capacitance of an electrical circuit of low-energy spark discharge is carried out when a fully assembled discharge circuit is connected to measuring devices [3, 7].

A well-known method for measuring the energy deposited into the gas discharge gap is based on measuring the discharge current i and voltage u across the spark gap [8]. The energy Q deposited into the spark gap is calculated from the expression

$$Q = \int uidt \,. \quad (1)$$

When the method is applied it is assumed that ideal measuring tools which do not make changes in measuring signals are used. It is also assumed that the probe is connected directly to the discharge gap when voltage across the gas discharge gap is measured. Since a part of the total energy is accumulated in the high-voltage probe, the probe connection can lead to significant changes in the voltage signal because this part of energy is of the same order of magnitude as the total energy of the low-energy spark discharge. Also, due to technical limitations, as a rule, the connection points of the high-voltage probe are located far from the tips of the discharge electrodes. It should be noted that an influence of the distance of the divider connection on the quality of voltage measurements across the spark gap is mentioned in work [9]. Therefore, the influence of these factors requires research.

A difference between the experimental and calculated currents and voltages obtained in the series RLC discharge circuit is observed in studies [3,4]. This work is a continuation of previous studies and considers the effect of the distributed elements of the discharge circuit on the spark current. The effect of the remote connection of the high-voltage probe on the measurement of voltage across the spark gap is also investigated.

II. NUMERICAL STUDY OF TRANSIENTS IN A LOW ENERGY DISCHARGE CIRCUIT

A. Spark Discharge Gap Equivalent Circuits

Various equivalent circuits are used to present a spark gap as an electrical load to study transients in spark discharge circuits. For instance, in work [4] the spark gap is presented as the resistance R_{sp} of the spark channel that varies over time (Fig. 1a) to simulate the expansion of the spark channel. Moreover, the authors indicate that the spark gap also has a reactance that varies over time. However, this is reactance is negligible when compared to the resistance of the discharge circuit and does not need to be considered in numerical studies of the spark discharge development.

When spark ignition systems is calculated in work [10], the spark gap was given as a parallel connection between the capacitance C_{sp} of the spark gap and the resistance R_{sp} of the gap. The corresponding equivalent circuit model is given in Fig. 1b. But the mentioned equivalent circuit of the spark gap

978-0-7381-4236-4/20/$31.00 ©2020 IEEE

was applied to simulate transients in the ignition systems before the start of the spark breakdown. Thus, the gap resistance reflects the plug leakage current [10] only.

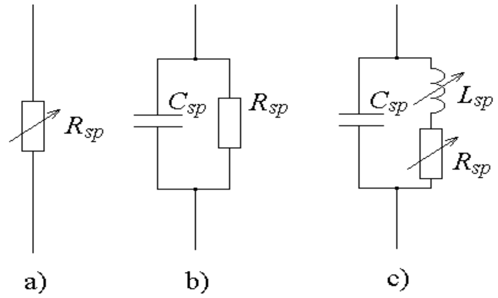

Fig 1. Spark discharge gap equivalent circuit models

In work [11], the equivalent circuit of the spark gap is given as a series connection of spark resistance and inductance, which are variable over time. In works [12, 13], the equivalent circuit of the spark gap is presented by the circuit (Fig. 1c). However, in works [12, 13] the discharge current is studied only for constant spark resistance and inductance of the discharge gap.

In this work, we consider the spark discharge gap equivalent circuit model shown in Fig. 1c where the spark resistance and inductance are variable over time.

B. Equivalent Spark Circuit and Transient Analysis

Two simulation variants are considered. It is assumed in the first simulation task that a high-voltage probe is connected directly to the tips of discharge electrodes. It is adopted in the second simulation variant that the connection points of the probe are located far from the discharge gap. It is additionally assumed that the capacitance of the probe significantly exceeds the capacitance of the gas-discharge gap in the second simulation variant. In both cases, the equivalent discharge circuit shown in Fig. 2 is used.

In both simulation tasks, the capacitance of the capacitor C_{sp} consists of the sum of the capacitances of the probe and the spark gap. In the first simulation variant, the inductance L_{sp} and resistance R_{sp} equal those of the spark channel, respectively. In the second simulation variant, the inductance L_{sp} consists of the sum of the inductance of the spark channel and the inductance of a section of the circuit connecting the probe with the tip of the electrode. Also in the second simulation variant, the resistance R_{sp} consists of the sum of the resistance of the spark channel and the resistance of a section of the circuit connecting the probe with the tip of the electrode.

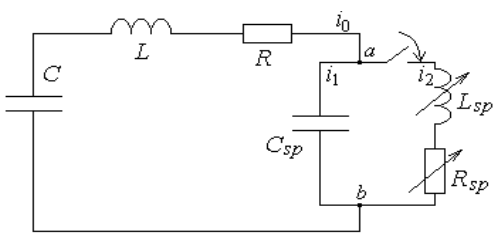

Fig 2. Spark discharge equivalent circuit

The numerical model of the spark discharge equivalent circuit is written as follows:

$$\frac{1}{C}\int i_0 dt + L\frac{di_0}{dt} + Ri_0 + \frac{1}{C_{sp}}\int i_1 dt = 0\,, \qquad (2)$$

$$-\frac{1}{C_{sp}}\int i_1 dt + L_{sp}\frac{di_2}{dt} + i_2\frac{dL_{sp}}{dt} + R_{sp}i_2 = 0\,, \qquad (3)$$

$$i_0 = i_1 + i_2\,. \qquad (4)$$

It is assumed in the initial conditions that there is no current in all branches of the circuit, and all capacitors are charged to voltage U_0.

C. Spark Inductance and Resistance

The spark resistance and inductance are variable during the expansion of the spark channel. The inductance of the spark channel is calculated by an equation of inductance of a small size conductor having a circular cross-section. The inductance equation has the following form [14]

$$L_{sp}(r) = 2l_{sp}\left[ln\left(\frac{4l_{sp}}{2r}\right) - 1 + \frac{4r}{\pi l_{sp}} - \frac{r^2}{2\cdot l_{sp}^2}\right]\cdot 10^{-7}\,[\mathrm{H}], \qquad (5)$$

where l_{sp} is the spark gap length; r is the conductor radius.

In the calculations, the length of the spark gap is l_{sp} = 1 mm. It is assumed that the conductor radius is equal to the radius of the spark channel. The time history of the radius of the conductive channel is taken from [4] and had the following form (Fig. 3).

Numerical data of the spark channel radius are processed by a method of least squares to obtain an approximation curve. As a result, the dependence of the spark channel radius on the time is expressed by

$$r(t) = -76.329t + 0.269\sqrt{t} - 1.044\cdot 10^{-5}\,[\mathrm{m}]. \qquad (6)$$

It is assumed that the expansion of the spark channel begins in 10 ns after the spark breakdown. Therefore, the channel radius is fixed and corresponded to the radius at the time of 10 ns during the discharge period of 0-10 ns. It is also assumed that the expansion of the studied spark channel practically ceases in 300 ns after the spark breakdown that corresponds to the experimental data [4].

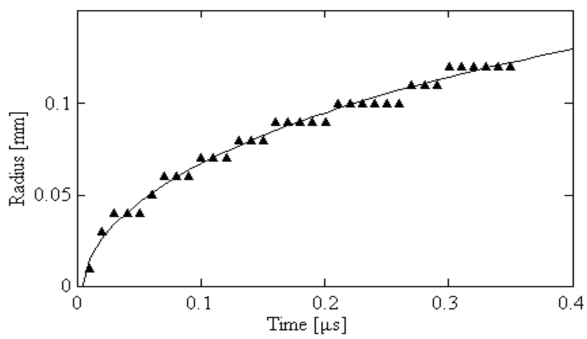

Fig 3. Spark channel radius as a function of time [4]

Using these conditions, and substituting the dependence (6) into the equation (5), we obtained the dependence of the spark channel inductance on the time that has the form shown in Fig. 4.

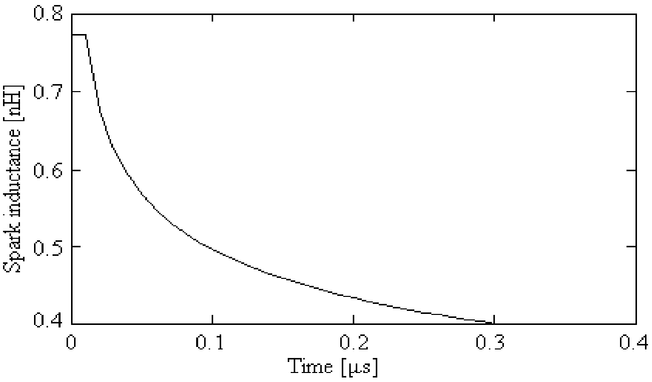

Fig 4. Time history of spark inductance L_{sp}

The numerical data on the change in the resistance of the spark channel over time are taken from the results of studies of [4].Time history of spark resistance is shown in Fig. 5.

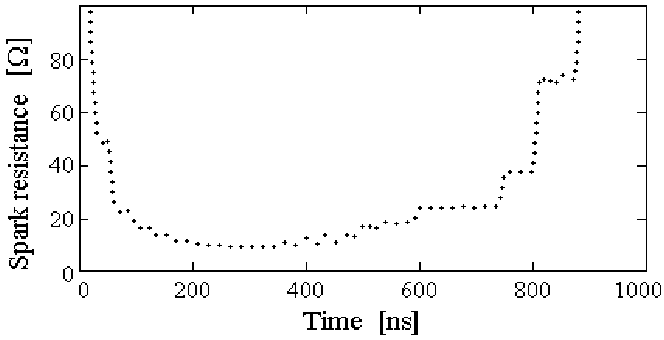

Fig 5. Time history of spark resistance R_{sp} [4]

It should be noted that the time histories of the spark resistance and the spark channel radius depends on the spark current. Thus, a change of the spark discharge circuit can lead to a change in the spark current, too. But it is considered the discharge circuits where the total spark energy and spark duration are similar. Therefore, these data on the resistance and the radius can be used to provide estimation of the other circuits.

D. Results of the Numerical Study

Similar to the research conditions of work [4], it is applied that $C + C_{sp} = 15.4$ pF, $U_0 = 4840$ V, $L = 8$ µH, $R = 30$ Ω. In the first simulation variant, it is assumed that $C_{sp} = 3.4$ pF and $C = 12$ pF. In this case, the capacity C_{sp} consists of the sum of the probe capacitance (3 pF) and the spark gap capacitance (0.4 pF). So, the capacitor C_{sp} accumulates more than 20% of the total energy.

Simulated discharge currents in different branches of the electric circuit are presented in Fig. 6. It is observed that after 10-20 ns from the beginning of the discharge development, the current i_2 flowing through the spark gap begins to coincide with the current i_0 flowing through capacitor C. Also the current i_1 flowing through capacitor C_{sp} almost disappears after this period of time. The spark duration is one order of magnitude larger than 20 ns in the investigated variant. Thus, we can assume that when the voltage probe is connected to the tips of discharge electrodes, the influence of the current difference on the energy deposition can be neglected.

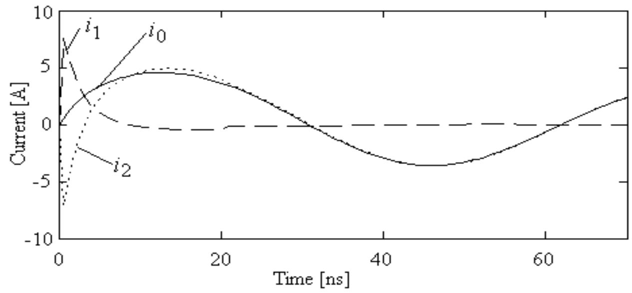

Fig 6. Discharge currents in the branches of the circuit in the first simulation variant

For example, the simulated voltage u_{ab} across nodes a and b marked in the circuit diagram (Fig. 2) is presented in Fig. 7.

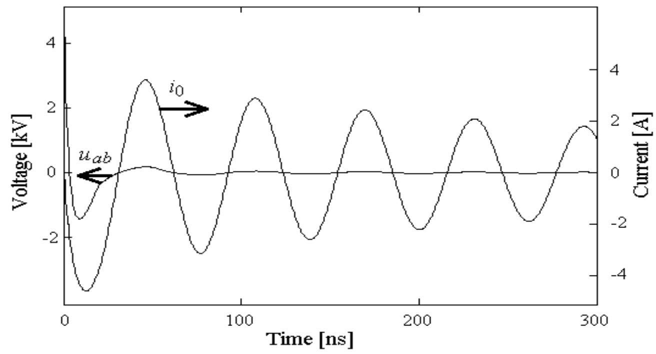

Fig 7. Voltage u_{ab} drop across simulated spark gap and the discharge current i_0 in the first simulation variant

It is observed that the voltage u_{ab} and the discharge current change synchronously after 20-30 ns. This confirms the earlier assumption about the influence of the connection points of the high-voltage probe.

In the second simulation variant, it is assumed that C_{sp} = 3.4 pF and $C = 12$ pF. A condition when the connection points of the voltage divider are removed from the discharge gap on a certain distance is considered. As a result, additional inductance L_{ad} and resistance R_{ad} appear between the voltage divider and the discharge gap. Therefore, in the calculated variant it is assumed that inductance L_{sp} equals $L_{sp} = L_{sp}(r) + L_{ad}$, where $L_{ad} = 2.5$ µH. Inductance L of 5.5 µH is applied. Thus, the total inductance does not change. It is similarly assumed that resistance R_{sp} equals $R_{sp} = R_{sp}(t) + R_{ad}$, where $R_{ad} = 9$ Ω. Further, the resistance R is reduced to 21 Ω.

Results of the current i_0 in the second simulation variant and experimentally measured current are presented in Fig. 8.

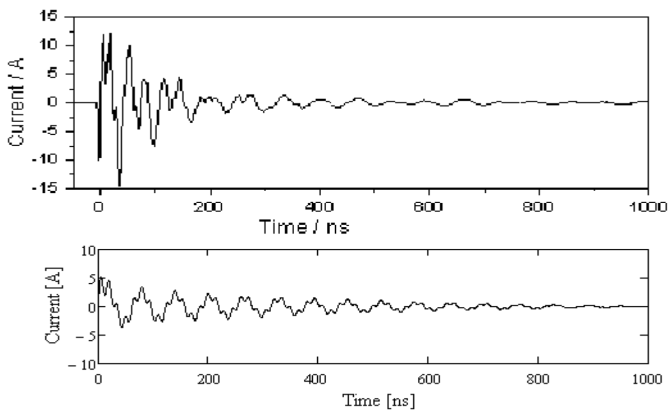

Fig 8. Comparison of experimental (top) and calculated (bottom) discharge currents

The presented comparison of the currents shows that the use of an electrical equivalent circuit with distributed parameters allows to clarify the untypical current curve obtained experimentally in series *RLC*-circuit. The reason for the untypical current curve is the connection of the high-voltage probe at an appreciable distance from the tip of the discharge electrodes.

In the second simulation variant, the simulated voltage u_{ab} across nodes *a* and *b* marked in the circuit diagram (Fig. 2) is presented in Fig. 9. High-frequency oscillations are present in the simulated voltage signal u_{ab}. The oscillation frequency is about 55 MHz. The P6015A high-voltage probe, which is used in the experiment [3], allows measurements at a signal frequency of up to 75 MHz under certain measurement conditions. If such conditions are not satisfied, we can observe signal averaging, as shown in Fig. 8. In this case, we have a qualitative agreement with the results of experimental measurements.

A comparison of the currents i_0 and i_2, arising in the second simulation variant, is presented in Fig. 10. Additionally, a discharge current i_{RLC} in series *RLC*-circuit with the similar concentrated circuit parameters is given in Fig. 10. We observe a difference in the discharge current i_2, flowing through the spark gap, and discharge current i_0, flowing in the branch of the discharge capacitor *C*. These differences should be taken into account in the numerical study of the spark discharge.

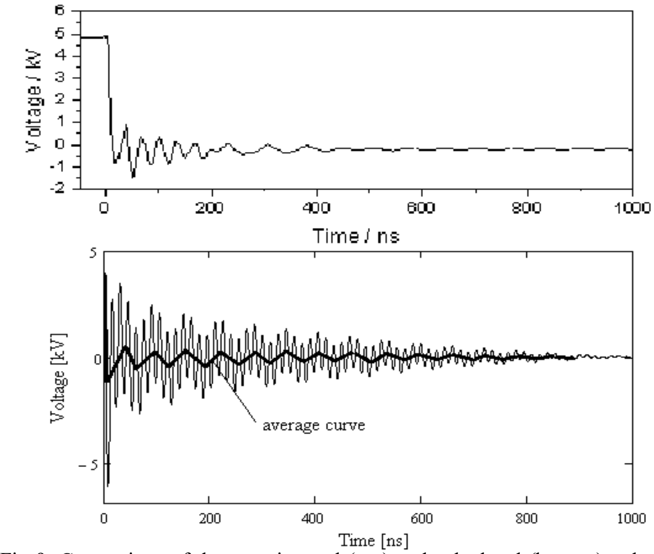

Fig 9. Comparison of the experimental (top) and calculated (bottom) voltage across the voltage divider in the second simulation variant

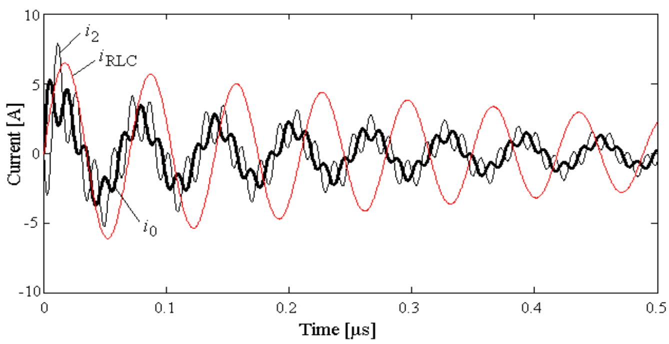

Fig 10. Current comparison of i_0 and i_2, arising in the second simulation variant and current i_{RLC}, arising in a *RLC*-circuit with lumped circuit parameters

Thus, the method of measuring the spark energy based on expression (1) allows correctly studying the energy deposited into the low-energy spark discharge only if the high-voltage probe is connected closely to the spark gap.

III. Conclusion

To study transients in an electric circuit occurring in a low-energy spark discharge, equivalent electrical discharge circuits with distributed parameters of the circuit elements should be used. According to the results of numerical studies, an increase in the deviation of the current flowing through the discharge capacitor from the current flowing through the discharge gap is revealed in the case of an increase in the distance between the connection points of the high-voltage probe and the tips of the discharge electrodes. It is revealed that the deviation of the discharge current of a real electrical circuit from the damped harmonic oscillations of an ideal series RLC circuit is caused by the connection of a high-voltage probe on a distance from the gas-discharge gap. Therefore, the correct measurement of the spark energy requires the connection of a high-voltage probe directly to the tip of discharge electrodes.

References

[1] S. Hosseinzadeh, F.Norman, F. Verplaetsen, J. Berghmans, and E.Van den Bulck, “Minimum ignition energy of mixtures of combustible dusts,” J. of Loss Prevention in the Process Industries, vol. 36, pp. 92-97, July 2015.

[2] E. K.Addai, D. Gabel, M. Kamal, and U. Krause, “Minimum ignition energy of hybrid mixtures of combustible dusts and gases,” Process Safety and Environmental Protection, vol. 102, pp. 503-512, July 2016.

[3] S. Essmann, D. Markus, and U. Maas, “Investigation of the spark channel of electrical discharges near the minimum ignition energy,” Plasma Phys. Technol., vol. 3, pp. 116-121, 2016.

[4] K. Korytchenko, S. Essmann, D. Markus, U. Maas, and E. Poklonskii, “Numerical and Experimental Investigation of the Channel Expansion of a Low-Energy Spark in the Air,” Combustion Science and Technology, vol. 191, pp. 2136-2161, 2019.

[5] E. Brandes and W. Möller, Safety Characteristic Data: Volume 1: Flammable liquids and gases. (Deutsch) Taschenbuch – 1. September 2008.

[6] P6015A 1000X High Voltage Probe. Instruction Manual. Tektronix, Inc. 14200 SW Karl Braun Drive, P.O. Box 500, Beaverton, OR 97077, USA.

[7] ASTM E582-07(2013)e1: Standard test method for minimum ignition energy and quenching distance in gaseous mixtures. 2013.

[8] B. Sforzo, J. Kim, A. Lambert, J. Jagoda, S. Menon, and J. Seitzman, “High energy spark kernel evolution: Measurements and modeling,” 8th US National Combustion Meeting, University of Utah, May 19-22, 2013, Paper 070IC-0272.

[9] N.M. Gegechkori, “Experimental Studies of Spark Discharge Channel,” J. of Exp. and Theor. Physics, vol. 21, pp. 493-506, 1951.

[10] S. Różowicz, “Use of the mathematical model of the ignition system to analyze the spark discharge, including the destruction of spark plug electrodes,” Open Phys., vol. 16, pp. 57–62, 2018.

[11] M. Istenič, I. Smithξ and B. Novac, “Dynamic resistance calculation of nanosecond spark-gaps,” 2005 IEEE Pulsed Power Conference, 13-15 June, INSPEC Accession Number: 10236068, 2005.

[12] O. Frolov, K. Kolacek, J. Schmidt, J. Straus, and V. Prukner, “Multi-channel laser-triggered spark gap,” 28th ICPIG, Prague, Czech Republic, July 15-20, pp. 1282-1283, 2007.

[13] F. Yinsheng, B. Jicheng, L. Qiang, L. Chaojiang, C. Yan, and L. Zhengkai, “Research on maintaining voltage of spark discharge in EDM,” Procedia CIRP, vol. 42, pp. 28 – 33, 2016.

[14] P. L. Kalantarov and L. A. Tseitlin, Inductance Calculations (in Russian), the Atomic Energy Press, 1986.