Antoni Sawicki

Selected Properties of High-Frequency Electric Arc Initiators and Stabilisation Oscillators.

Part 1. Devices with Free Electric Arc

Abstract: The article presents selected physical properties of electric arc used in welding engineering as well as discusses differences in requirements concerning ionisers used to initiate and re-initiate electric arc. In addition, the article compares properties of ioniser systems used to stabilise electric arc burning as well as discusses spark gap and semiconductor systems generating high-frequency and high-voltage impulses used to generate spark discharges. The article also discusses the effect of ioniser operation after the modification of static current-voltage characteristics, enabling the modelling of dynamic states of electric arc.

Keywords: electric spark, electric arc, arc initiator, arc stabilisation oscillator

DOI: 10.17729/ebis.2021.2/4

Introduction

Technical publications contain little information concerning the design and operating conditions of electric arc ionisers used in welding engineering. The online overview of publications in English, French and German reveals that western research centres do not particularly thoroughly investigate the above-named issues although the manufacturers of welding equipment from western countries offer industrial equipment satisfying requirements of the most demanding customers. Unlike technical publications available in western countries, publications in Russian (in original) [1–7] contain detailed information related to the design and operating conditions of ionisers. Because of the extreme operating states of such systems, their mathematical description is very difficult. In principle, the aforesaid description could refer to low and high-voltage generators characterised relatively low impulse frequency [1–3]. Presently, high-frequency generators remain beyond the possibilities of computed modelling and simulations. Reference publications sometimes present [4] analytical methods used to calculate transition states in linear inductor circuits before the occurrence of spark discharges.

Some of the most innovative works [4–7] are performed at the E.O. Paton Electric Welding Institute in Kiev. These works, based on plasma physics-related premises, involve the detailed analysis of the initiation and development of electric discharges in the electrode gap. In addition, the aforesaid works contain rational examples of design solutions of electronic arc initiators and stabilisation oscillators. This article aims to systematise reference information

---

dr hab. inż. Antoni Sawicki (PhD (DSc) Habilitated Eng.) – SEP – Association of Polish Electrical Engineers (FSNT-SEP), Częstochowa Division

useful in tests and modelling of selected welding machines.

Selected properties of electric arc used in welding engineering

Most welding machines utilise free electric arc. Free arc is generated if no measures are applied to intensively cool the plasma column. In such a situation, heat exchange between highly heated gas and its environment (usually air) takes place in a natural manner. The plasma column can develop and move within the entire working area, up to the limits determined by arc properties (and favouring discharge instability).

If the plasma column is affected by any external limitations, influencing its shape and section, arc is referred to as compressed. Limiting factors are numerous. They can be forced by intense flows of gas or liquids washing around arc in the working area (furnace plasma torches) or in narrow channels and nozzles (stream plasma torches). It is also possible to compress the plasma column using very narrow and intensively cooled walls of channels in spectrometer plasma torches. Short arc can also be compressed by massive electrodes in furnaces. Important properties of compressed arc include its higher stability. Such arc can be used in the low-current welding (0.5 A – 30 A) of thin (0.2 mm – 0.3 mm) elements.

In most technological cases, open arc is used. In such cases, there are no barriers (near arc) precluding or impeding the circulation of gas in the working area or stopping optical radiation. Arc separated from the external area is referred to as enclosed. An example of enclosed arc is welding arc under flux – its atmosphere is only composed of electrode vapours and flux. Sometimes semi-enclosed arc is used. Advantages resulting from the use of enclosed arc include high welding process stability, high weld quality, low argon consumption (10–30 times), high technological process rate, smaller residual deformations and improved work conditions.

In most technological cases, the most favourable manner of powering arc is based on direct current. Arc powered by direct current is characterised by very high stability. Changes of current constitute one of the methods enabling the control of discharge power. As regards free arc, decreased current triggers discharge instability and termination. Additional limitations affect arc compressed in plasma torches. Overly low current could change the cathode operating state from thermoemissive to autoemissive, accompanied by the increased erosion of cathode material and shortened service life of a device.

Because of relatively low investment and operating costs of welding machines, arc is frequently powered by alternating current. This fact may result from technological needs related to the welding of thin-walled elements in various positions in space or from the necessity of arc affecting metal oxides on the weld surface. If current is unipolar or bipolar and its waveform is rectangular, stability-related problems are similar to those accompanying the powering of arc using direct current. The use of bipolar current having a triangular, trapezoid or sinusoidal waveform can be accompanied by the relatively slow passing of current through the zero value. Such a situation favours the cooling and deionisation of plasma, consequently triggering the termination of arc. For this reason, the above-presented arc cannot be long and frequently requires increased supply voltage or the additional source of energy improving the ionisation of gas. In cases of sinusoidal current, it is convenient to use three-phase sources as they enable the simultaneous burning of two or three arcs. Technological applications include the use of three-phase welding machines [8] and three-phase plasma torches. In such cases, it is possible to combine three arcs into a triangle or a star located in one chamber.

Two electric arcs characterised by the same dissipated power are not necessarily equivalent in terms of technology or energy. Arc energy has various forms (heat, light, gas flow, noise, etc.) and is discharged through several channels. The process is affected by the waveform of current, the type and the pressure of gas, the material, shape and the dimension of electrodes and the distance between them as well as by external factors affecting the plasma column, electrodes, etc. Depending on needs, various mathematical models of arc are created. The idealisation degree of each model depends on adopted reduction assumptions.

Not every electric discharge in gas or liquid can be referred to as arc. Types of discharges depend on many external factors, particularly on working gas pressure. Discharges differ in properties, technological applications and, consequently, their mathematical descriptions. Some of the most complex types of discharges are spark discharges, particularly those characterised by high frequency. It is impossible to model such discharges using simple engineering methods [5].

When calculating processes in DC circuits or in low-frequency AC circuits it is usually possible to use the same simple channel models of arc. The selection of a given model depends on the range of current changes and ranges of changes of external factors affecting the plasma column. The aforesaid changes are responsible, among other things, for changes in shapes of static and dynamic current-voltage characteristics. The problem of model selection can be simplified by using a universal model, e.g. the Pentegov-Sidorec model [9] or the Mayr-Pentegov model [10]. Publication [5] contains detailed characteristics concerning results following the use of AC arc in welding processes.

The advantages of AC current-based welding processes are the following:

- lack of magnetic blow-out,
- possibility of obtaining the more fine-grained structure of the weld metal and of the heat affected zone,
- simpler design and, consequently, lower price and higher reliability of the power supply source.

The disadvantages of AC current-based welding processes are the following:

- low arc burning stability,
- higher arc voltage,
- (sometimes) necessity of using additional systems initiating and stabilising arc discharge.

Alternating current arc has found technological applications in the following welding processes:

- MMA welding,
- TIG welding,
- plasma welding.

In industrial practice, methods improving the stability of AC arc burning are the following [5]:

- metallurgical – characterised by limited potential, consisting in:
  - ◦ providing the arc area with chemical elements characterised by low ionisation potential (coating, electrode wire, shielding gas),
  - ◦ providing a covered electrode or an electrode wire with a chemical element characterised by low electronic work function,
- electric – characterised by significant potential because of:
  - ◦ significant upslope of current passing through the zero value,
  - ◦ increased voltage of the no-load state of the power supply source (90–130 V),
  - ◦ use of pilot arc,
  - ◦ use of high-voltage impulse generator (400–1000 V).

Electric arc ignition

Electric field intensity needed to break gas under atmospheric pressure (approximately 10^5 Pa), restricted within the range of $1{\cdot}10^4$ V/cm to $1{\cdot}10^5$ V/cm, is by 2–3 orders of magnitude lower than electric field intensity triggering autoemisison from electrodes. A decrease in breakdown voltage can be obtained through gas ionisation, requiring additional energy and achievable using one of the methods presented below [11]:

- static electric field (unipolar and (at the same time) growing voltage 10^2–10^3 V/s),

- high-frequency electric field (slowly growing amplitude of high-frequency voltage),
- high-voltage impulses,
- intense optical radiation,
- radioactive radiation,
- heating with pilot arc (thermal ionisation).

The initiation of welding arc can be facilitated by:

- initial sharpening of the non-consumable electrode,
- preventing the formation of a large metal drop during GMA welding by:
  - magnetic field superimposition,
  - electrode reverse movement.

Ionisation can be facilitated by the evaporation of metallic elements. The disadvantages of the arc ignition contact method are the following:

- instability and long stabilisation of the welding process,
- losses of welding materials and electric energy,
- low quality of the initial weld fragment,
- lack of universal methods when using electrodes having various diameters.

The ignition of arc after the direct contact between the electrode and the detail may last excessively long, resulting in the generation of unfavourable short circuit current. In such a situation, the thin wire can be molten and ejected, which, in turn, could result in the termination of initiated arc. The general formula for the voltage of the breakdown U_b of the electrode gap is the following:

$$U_b = U_0 + Ed$$

where U_0 – voltage constant component, d – electrode gap length and E – electric field intensity.

The generation of an impulse of breakdown voltage on the electrode gap is followed by a delay depending on the concentration of gas particles in the gap area and on the predominance of impulse voltage over breakdown voltage in the static state. With a 50% probability of gas breakdown, the characteristic of $U_b(t_i)$ has the following form [5]:

$$U_b = \left(1 + \sqrt[3]{\frac{a}{t_i p d}}\right) U_{bs}$$

where a – constant parameter depending on the type of gas, t_i – voltage impulse duration, U_{bs} – breakdown voltage in the homogenous static field.

Value t_i does not exceed several microseconds. The condition of arc formation is the following:

$$R_{cs} < R_{th}$$

where R_{cs} – resistance of the conducting channel formed by spark discharge, R_{th} – threshold resistance depending on the power supply rate of the power supply source and on an increase in the value of source voltage.

The minimum value of impulse energy depends on the type of gas (the lowest in the case of argon, whereas the highest in the case of air and CO_2). The above-named condition can be satisfied if alternating current, the frequency of which is restricted within the range of 50 Hz to 200 Hz, is used. In cases of sinusoidal current, the impulse initiating arc should start near the amplitude of voltage, i.e. be shifted by approximately 75–80 electric degrees in relation to the passage of voltage through the zero value, and increase quickly. The foregoing also depends on the types of materials of both electrodes and momentary polarity.

High-voltage impulses should be characterised by the following parameters [5]:

- energy restricted within the range of 0.01 J to 0.50 J,
- amplitude restricted within the range of 3.0 kV to 10.0 kV,
- duration (amounting to 0.05 of the amplitude value) restricted within the range of 3 µs to 20 µs.

The probability of plasma arc ignition is expressed by the following formula [12]:

$$P_r = \frac{n_{ig}}{n_{ds}} 100\%$$

where n_{ig} – number of obtained arc ignitions, n_{ds} – number of device start-ups.

The above-named probability depends on energy balance in the near-electrode area:

$$P_r = \frac{E_{de} - E_{di}}{E_{de}} 100\%$$

where E_{de} – energy supplied by the power supply source to the channel of electric discharge, E_{di} – energy dissipated in the surrounding area. After appropriate transformations [12], the formula can be expressed in the following form:

$$P_r = \frac{ui - L\frac{di}{dt}i - 2rh\vartheta_1 q}{ui} 100\%$$

where r – spark channel radius, h – spark channel length, q – energy needed to heat up the unit of gas volume from the temperature of surrounding gas to the temperature of arc surface (approximately 6500 K), v_1 – gas velocity (flow rate).

The above-presented formula revealed that in order to increase the probability of arc ignition it is necessary to:

- reduce inductivity in the power-carrying circuit of the power supply source,
- reduce the length of the spark discharge channel by decreasing the distance between the electrodes,
- reduce the flow rate of gas washing around the spark channel.

Issues of electric arc re-ignition

The passage of current through the zero value is accompanied by the reduction of:

- gas temperature,
- gas ionisation degree,
- gas conductance,
- temperature of electrode spots,
- thermionic emission of electrons from the electrode.

The methods of increasing the stability of electric arc burring are the following [1]:

- metallurgical (easily ionising additives from the electrode, electrode coating or shielding gas),
- electric (fast increase in voltage and current during changes of electrode polarity, increase in the no-load state voltage of the power supply source, use of generators of low-voltage (up to 1000 V) impulse generators and of an up-slope time of (1–10)·10^{-4} s, the use of additional high-voltage and high-frequency generators,
- thermal (use of constantly burring pilot arc).

In comparison with the first gas breakdown voltage, the second breakdown is additionally affected by the electrophysical properties of electrodes [5]. As a result, the second breakdown depends on the momentary breakdown of electrode polarity:

$$U_b(C\_elW) < U_b(A\_elW)$$

where C_elW – cathode is a tungsten electrode, A_elW – anode is a tungsten electrode.

Time for plasma deionisation should be as short as possible as in such a case the second breakdown voltage is the lowest. The second breakdown voltage is affected by the following factors:

- low potential of gas ionisation,
- easily ionising electrode coating additives (Ca, Na),
- sharp current up-slope.

The condition of arc re-ignition is the following:

$$U_2 > U_{bb}$$

where U_2 – voltage between the electrode and the detail during the passage of current through the zero value, U_{bb} – arc re-ignition voltage.

During the change of current polarity, dead time depends on the following factors:

- chemical composition of gas and its ionisation potential,
- rate of current changes ($di_A/dt > 10$ kA/s).

Dead time can be identified (with sufficient (in terms of practice) accuracy) using the following formula [6]:

$$\frac{di_A}{dt} \approx \frac{\Delta i_A}{dt} = I_{A0}\omega$$

where I_{A0} – value of arc current amplitude, ω – current pulsation.

The most common methods making it possible to increase arc stability are the following [6]:

- increasing the amplitude of output voltage impulses from the power supply source after changing arc current polarity,
- use of additional inverters utilising energy accumulated in inductive-capacitive,
- use of rectangular current,
- simultaneous combination of several methods.

The impulse stabilisation of arc burning stability can sometimes be achieved using welding circuit energy, without the necessity of connecting additional charging systems of capacitor accumulators. To this end, it is possible to use self-induction electromotive force, generated during the breaking of the circuit by means of a fast commutator. The direction of the aforesaid voltage overlaps with the direction of power supply source voltage. Such a solution, ensuring reliable ignition and maintaining arc burning voltage, has been used in DC plasma torch power supply systems and welding transformers having an operating frequency of 50 Hz [13]. The latter case involves the use of a controlled key closing and opening the circuit of the transformer secondary winding at appropriate moments. Systems provided with the capacitive accumulator of energy are more reliable than electromagnetic accumulators. In addition, they enable the obtainment of high spark discharge energy more easily.

If the frequency of the regulator is relatively low (restricted within the range of 0 kHz to 20 kHz), the amplitude of the voltage of spark-over between electrodes does not depend on frequency and overlaps with DC source-triggered spark-over voltage. If frequency is higher, spark-over voltage decreases initially and obtains a minimum on the abscissa having a frequency of approximately 5 MHz. An increase in frequency is accompanied by an increase in spark-over voltage (reaching a value being 1.5 times higher than voltage obtained using a DC power supply (Fig. 1)).

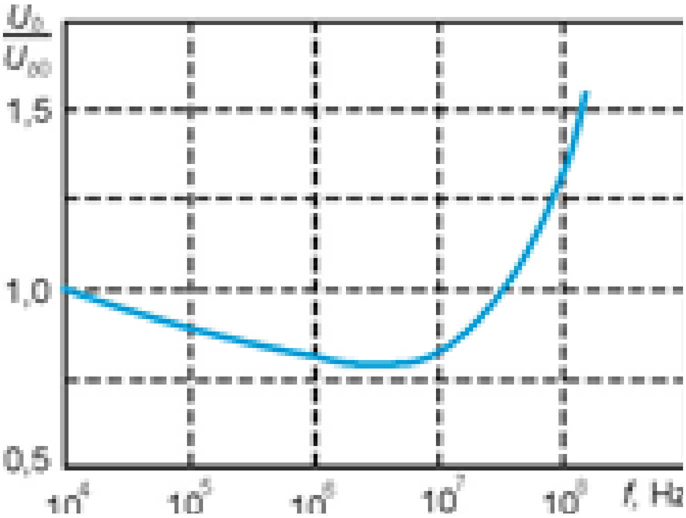

Fig. 1. Proportion of breakdown voltage U_b having preset vibration frequency to breakdown voltage U_{b0} generated by the DC source in relation to the frequency of electric impulses in the air

Mechanisms occurring during the re-breakdown of the gas gap during TIG welding are the following [5]:

- diffusive glow discharge on surface Al,
- subnormal glow discharge,
- normal glow discharge,
- abnormal glow discharge,
- arc discharge.

The energy of impulses ensuring arc re-ignition depends on the following factors:

- type of material being welded,
- welding technology (MAG, MMA, TIG),
- chemical composition of gas or electrode coating material.

Requirements concerning the reduction of electromagnetic interference in relation to arc inductors are less restrictive than those concerning regulators. The reason lies in the shorter operation time of inductor generators. The selection of the type and the operation mode of the ignition system is decisive for the minimum value of voltage applied on electrodes, between which a spontaneous discharge may take place.

Proper AC arc ignitions affect the following:

- quality of beads (particularly of their initial fragment),
- use of welding consumables,
- consumption of electric energy.

Properties of systems improving the stability of electric arc burning

Welding power source no-load state voltage can reach up to 80 V. In cases of AC welding power sources, the value of amplitude could reach approximately 113 V. Welding processes can be improved by using welding oscillators, generating impulses having frequency restricted within the range of 100 kHz to 500 kHz and voltage restricted within the range of 2000 V to 6000 V (sometimes up to 10 kV).

High-voltage impulse generators are divided into:

- initiating arc (first) ignition,
- initiating arc ignition and re-ignitions.

The most important parameters characterising oscillators used for triggering spark discharges are the following:

- output voltage,
- impulse energy,
- arc current.

Inductors are produced in the following versions:

- portable inductors connected externally,
- inductors embedded in welding machines,
- universal inductors.

Technological applications of oscillators are the following:

- AC TIG welding of thin details,
- AC welding of details using electrodes provided with coatings characterised by low ionising potential.

The high-frequency generator should be located on the side of high-voltage of the transformer powering the ioniser. The reasons for such a location are the following:

- use of the generator on the low-voltage side would require the transformation of high-frequency low voltage into high-amplitude voltage. In such a case, the initial resistance of the inductor would be determined by the internal resistance of the transformer, the winding of which would require containing many turns. The resistance of circuits shunting the arc segment cannot be high.
- use of the generator on the high-voltage side would enable the use of the transformer, the ratio of which would be close to 1. In such a case, the initial resistance of the inductor is low as the primary and secondary windings of the transformer can have small numbers of turns.

Mechanisms of gas gap breakdown are the following [5]:

- streamer mechanism – thick plasma channel from the anode to the cathode,
- spark mechanism – spontaneous, instable and high level of gas ionisation; high temperature of plasma electrons,
- transitional mechanism from spark to arc,
- stationary arc discharge.

Investigation on welding arc by G.I. Leskov and V.P. Lugin revealed that:

- gas flow rate does not affect breakdown voltage,
- change of voltage impulse frequency within the range of 100 Hz to 3000 Hz does not affect breakdown voltage.

Breakdown voltage is affected by the following factors:

- chemical composition of gas,
- electrode gap length,
- electric field inhomogeneity.

The description contained in publication [5] leads to the conclusion that operating conditions of AC arc ignition initiators and arc stabilisation oscillators differ in terms of:

- initiation,
- duration,
- supplied energy,
- voltage.

The frequency of stabilising impulse repetition can be equal to:

- supply voltage frequency,
- double supply voltage frequency.

High-voltage impulses should be characterised by the following parameters [5]:

- energy restricted within the range of 0.2 J to 1.0 J,
- amplitude of voltage restricted within the range of 400 V to 950 V,

- duration (amounting to 0.05 of amplitude value) restricted within the range of 50 μs to 100 μs (with the consumable electrode in CO_2 shielding for a time restricted within the range of 0.2 μs to 1.0 μs).

The arc stabilisation oscillator can be connected to the welding power source [5] using either the parallel or the series connection. The type of connection affects the operation of welding machines.

The advantages of the parallel connection are the following:

- possibility of using with any value of welding current,
- easy fixing and disconnecting of the stabilisation oscillator (having the form of a separate unit).

The disadvantages of the parallel connection are the following:

- necessity of using a transformer in the power supply system of the stabilisation oscillator (for galvanic decoupling with the supply network),
- possibility of insulation breakdown in the welding power source,
- possible transfer of high-frequency interference to the network via the welding power source,
- shunting effect of the output impedance of the welding power source or of the high-frequency protective filter is responsible for the emission of the significant amount of energy in low and high-frequency filters, thus decreasing generator efficiency and necessitating increasing the power of the oscillator.

The advantages of the series connection are the following:

- after breakdown, nearly the entire energy accumulated in the oscillating circuit is emitted in the arc gap,
- use of high-frequency is not necessary as the use of protective capacitor is sufficient,
- better electromagnetic compatibility with the network.

The disadvantages of the series connection are the following:

- limited permissible value of welding current through the cross-section of the oscillator output winding,
- problematic fixing and disconnecting of the stabilisation oscillator (having the form of a separate unit).

Some stabilisation oscillators are made as universal:

- if welding current does not exceed a permissible value, oscillators should be connected in series,
- if welding current exceeds a permissible value, oscillators should be connected in parallel.

Type of high-voltage impulse generators

Older type of welding machines were often equipped with spark generators [1, 4], characterised by a simple design and a low investment cost. Spark generators can be connected to the welding power source either in series or in parallel. The connection variants are presented in Figure 2.

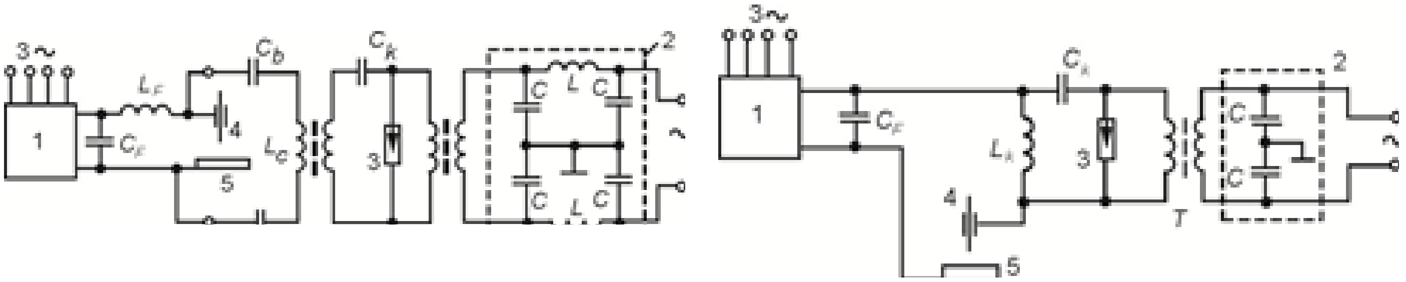

Fig. 2. Schematic diagram of the spark-gap oscillator connected to the welding power source: a) in parallel and b) in series (1 – welding power source, 2 – interference eliminator, 3 – spark gap, 4 – electrode and 5 – element subjected to welding)

Spark-gap arc generators are characterised by many disadvantages:

- difficult control over the moment of initiation,
- fast high-frequency vibration damping because of energy losses in the spark gap,
- necessary periodic spark gap adjustments,
- generation of very high levels of interference, impeding the obtainment of electromagnetic compatibility between the welding system and the power supply network,
- high level of electromagnetic interference in the machine operating area.

Interference has a frequency spectrum with numerous discharges, possibly resulting from additional resonant phenomena occurring in the system. It is advised that spark-gap arc generators should be used in separated areas away from other electronic equipment and registered in local authorities in charges of radio-telecommunications supervision.

In modern welding machines, spark-gap generators are replaced with semiconductor generators. Electronic devices can be made as universal and be used both for the initial (initiating) and repeated (stabilising) initiation of arc. Depending on needs, semiconductor generators can generate high-voltage or elevated voltage impulses. Data contained in Table 1 indicate that for this purpose it is necessary to use two independent circuits with elements *L* and *C*, forming impulses of pre-set parameters. Table 1 indicates the transformer, the secondary winding of which is connected in series to the high-current circuit.

Publication [6] presents the improvement of arc initiators and stabilisation oscillators by providing the power-carrying circuit with an additional sub-circuit containing at least one semiconductor switch and, connected in series, a separate capacitive accumulator as well as the additional primary winding of the pulse increasing transformer. The operation of the system is controlled by means of feedbacks in relation to arc current and voltage. Despite the replacement of spark-gap generators with electronic systems characterised by more stable frequency, spark discharges still need to take place in the electrode gap, which causes interference [4].

In semiconductor generators, the capacitor is charged using the voltage multiplier or resonant pumping. Many available reference publications contain information about such systems [1, 4], which can be divided into two groups where:

- capacitor is charged from welding power source terminals,
- capacitor is charged from the external source.

Figure 3 presents systems of initiators connected in parallel and in series to the primary circuit used for arc welding. In terms of robotic welding systems, MAG welding devices tend to dominate on the market (approximately 90%) [15]. The popularisation of TIG technologies is impeded, among others, because of the following reasons:

- low welding rate,
- complicated and laborious welding head operation,

Table 1. Comparison of selected parameters of MIG/MAG arc initiators and stabilisation oscillators (in accordance with [6])

Parameters	**Initial arc initiation**	**Arc stabilisation oscillators**
Impulse energy, J	W_{av} = 0.2–0.5 J	W_{as} = 0.6–1.0 J
Impulse amplitude, kV	3–7	0.4–0.95
Duration of impulse of $0.05U_{miw}$, μs	5–20	100–1000
Capacity of energy capacitor, F	Ck1	$C_{ks} \geq (W_{as}/W_{av})\ C_{k1}$
Pulse transformer ratio	1	1
Highest current amplitude, A	80–445	50–170

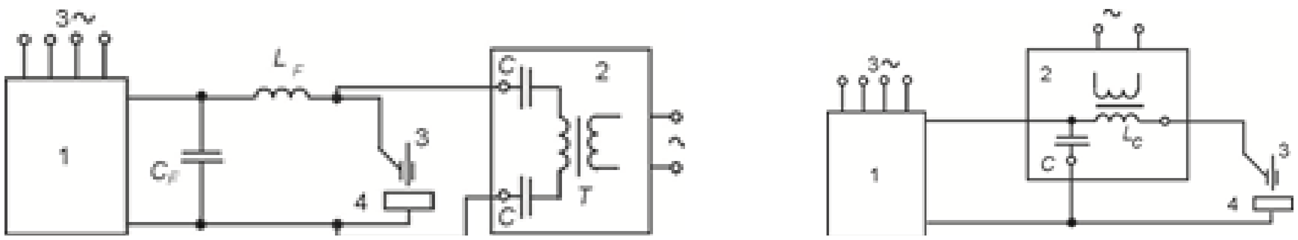

Fig. 3. Schematic diagrams of systems connecting the welding power source with the semiconductor ioniser: a) parallel connection and b) series connection (1 – welding power source, 2 – ioniser, 3 – electrode and 4 – element subjected to welding)

- complicated screening of interference resulting from the use of systems for the high-frequency and high-voltage initiation and stabilisation of arc.

Interference accompanying arc initiation could be eliminated through the application of contact-based automated ignition. In comparison with manual ignition, such a solution can be more reliable and safer even as regards thin non-consumable electrodes.

Ioniser operation effect and the modelling of electric arc

A theory explaining high-frequency spark discharge has not been formulated until today. As a result, there are no grounds for explaining the entire set of phenomena accompanying the breakdown of the electrode gap and the generation of spark discharge. Consequently, there are no simple expressions defining breakdown voltage which could be easily used in engineering calculations [4]. For this reason, the design of related equipment requires the use of experimental data or the performance of analytical and numerical calculations concerning states preceding and following the initiation of electric arc.

The primary working “element” of most welding machines is high-current electric arc. If the pressure of surrounding gas is not low (above 10^3 Pa) and the frequency of flowing current is not high (does not exceed 1 kHz), the arc column is formed of equilibrium plasma having a two-layer structure [15]. The above-presented arc is described using mathematical models [9–11, 16]. The aforesaid models can be used to calculate dynamic states in welding circuits after the initiation of arc discharge and maintaining the condition of the quasi-stationarity of processes in plasma [15]. The operation of initiators and high-frequency stabilisation oscillators results in the reduction of arc first ignition and re-ignition voltage, which can be easily represented by means of mathematical models of arc using static current-voltage characteristics (e.g. Pentegov-Sidorec or Mayra-Pentegov). The foregoing requires the modification of functions used to approximate dependence $U(I)$.

Table 2 presents two examples of generalised current-voltage characteristics of the plasma column with unspecified and defined arc ignition voltage. On the characteristic, the coordinates of the extreme (ignition) point are I_M and U_b. As can be seen in the Table, the correlation between the coordinates is similar to inverse proportionality. The formulas presented in Table 2 are sufficient to calculate dynamic states in the circuit with electric arc using the Pentegov-Sidorec model. To use the Mayr-Pentegov model, it is necessary to additionally determine values of conductance derivatives in relation to squared current. On the basis of [16] and in a manner analogous to that presented in Table 2 it is possible to create formulas useful in the calculation of conductance derivative in relation to ignition voltage.

When determining the voltage of arc ignition in welding machines it is necessary to remember about (usually varying) near-electrode voltage drops. In the near-cathode area, voltage drop is

Table 2. Functions enabling the approximation of the static current-voltage characteristics of the electric arc plasma column

No.	Characteristic of arc *U*(*I*) with unspecified ignition voltage	No.	Characteristic of arc *U*(*I*) with ignition voltage determined by current I_M	Ignition voltage U_b	Characteristic of arc *U*(*I*) with defined ignition voltage U_b
1a	$\frac{P_M}{I}+U_C$	1b	$\frac{P_M I}{I^2+I_M^2}+U_C$	$\frac{P_M}{2I_M}+U_C$	$\frac{P_M I}{I^2+\left(\frac{P_M}{2(U_b-U_C)}\right)^2}+U_C$
2a	$U_0\left(\frac{I_0}{I}\right)^n+U_C$	2b	$U_0\left(\frac{I_0 I}{I^2+I_M^2}\right)^n+U_C$	$U_0\left(\frac{I_0}{2I_M}\right)^n+U_C$	$U_0\left(\frac{I_0 I}{I^2+\frac{1}{4}\left(\frac{U_0 I_0^n}{U_b-U_C}\right)^{\frac{2}{n}}}\right)^n+U_C$

U_C = 20V. In turn, in the near-anode area, voltage drop is U_A = 5–10 V [1]. Resultant arc voltage $u_a(i)$ is the sum of voltage drops on the plasma column *u* and in very thin near-electrode areas. The sum of near-cathode voltage drop U_C and near-anode voltage drop U_A is usually designated as U_{AC}. Voltage drops do not depend on the type of power supply current (AC or DC). In the latter case, depending on electrode properties, the sum of voltage drops can be symmetric or asymmetric. The form of the symmetric sum of voltage drops is the following:

$$u_a(i)=u(i)+U_{AC}\,\mathrm{sgn}(i)$$

whereas the asymmetric sum of voltage drops is the following:

$$u_a(i)=u(i)+\begin{cases}-U_{AC1}, & \text{if } i<0\\ U_{AC2}, & \text{if } i\geq 0\end{cases}$$

Formula (7) also shows that breakdown voltage depends on electrode polarity. For this reason, also breakdown voltage can be asymmetric. Usually, near-electrode voltage drops are treated separately, creating (on their basis) an additional element connected in series with the column [16]. To properly represent the properties of arc it is necessary to increase value U_b (presented in Table 2) by near-electrode voltage drops. In the symmetric case, resultant breakdown voltage is as follows:

$$U_{ab}=U_b+U_{AC}$$

whereas in the asymmetric case:

$$U_{ab}(i)=\begin{cases}-U_{b1}-U_{AC1}, & \text{if } i<0\\ U_{b2}+U_{AC2}, & \text{if } i\geq 0\end{cases}$$

When considering the asymmetry of near-electrode voltage values is it usually necessary to take into account material-related differences and electrode thermal states. In terms of the asymmetry of breakdown voltage (U_{b1}, U_{b2}), also the shapes and dimensions of electrodes are important.

Figure 4 presents diagrams of static current-voltage characteristics with unspecified and determined ignition voltage; it does not present shifts of diagrams resulting from near-electrode voltage drops. The cases with unspecified (very high) voltage correspond to the lack of operation of arc discharge stabilisation oscillators. In dynamic states, extreme values of arc voltage are also affected by the damping function value.

Waveforms of current exciting arc in welding machines can be identified on the basis of the operation of two sources, i.e. the primary source and the secondary source (stabilisation oscillator) [6]. However, the duration of additional impulses is relatively short and, as a result, the operation of the stabilisation oscillator

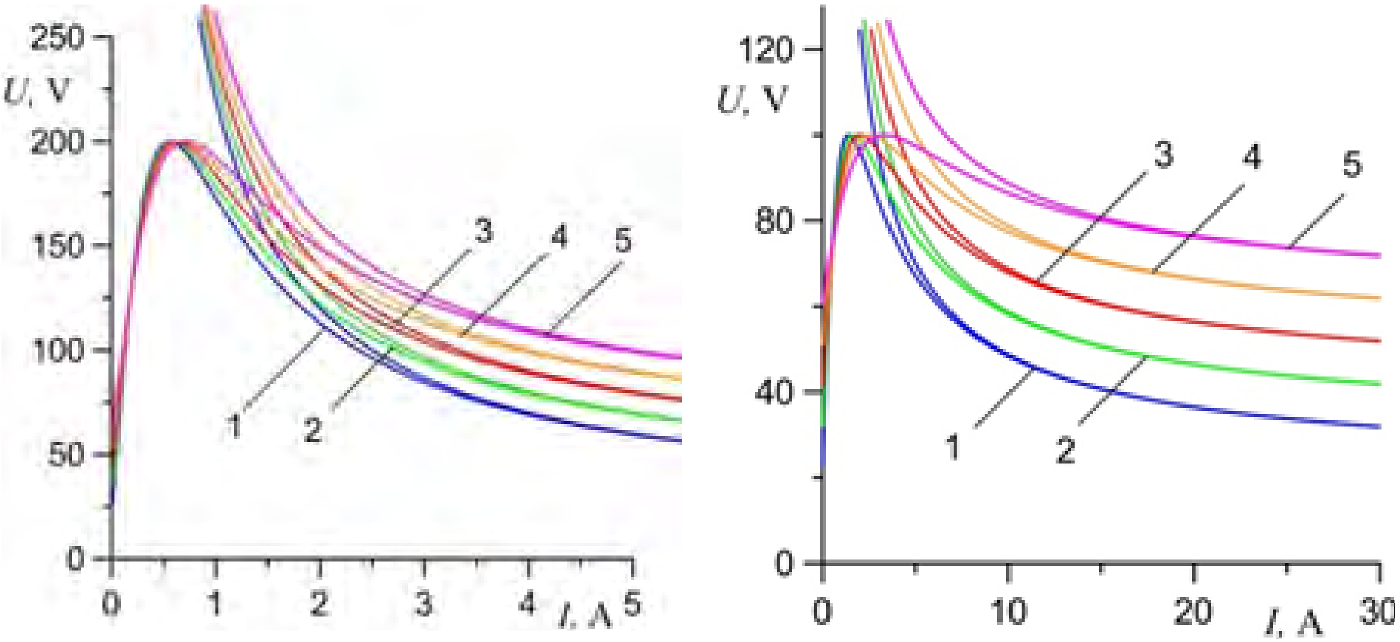

Fig. 4. Fragments of families of the static current-voltage characteristics of arc voltage with unspecified and determined ignition voltage (1 – $U_c = 20$ V, 2 – $U_c = 30$ V, 3 – $U_c = 40$ V, 4 – $U_c = 50$ V, 5 – $U_c = 60$ V): a) determined using rational functions (1a) and (1b) ($P_M = 200$ W, $U_b = 200$ V) and b) determined using power functions (2a) and (2b) ($U_0 = 50$ V, $I_0 = 5$ A, $n = 0.8$, $U_b = 100$ V)

does not significantly affect the energy balance of welding processes.

Conclusions

1. Difficulties accompanying the mathematical description of spark discharges triggered by the operation of high-frequency and high-voltage generators impede the modelling and simulation of electric arc initiators and stabilisation oscillators in selected welding machines.
2. It is possible to perform numerical calculations of transition states in non-linear circuits of inductors before the occurrence of spark discharges.
3. When modelling electric arc generated by welding machines it is possible to take into account the operation of discharge stabilisation oscillators by modifying static current-voltage characteristics.

References

[1] Paton B.E., Zaruba I.I., Dymenko V.V., Šatan A.F.: Svaročnye istočniki pitaniâ s impul'snoj stabilizaciej goreniâ dugi. Ekotehnologiâ, Kiev,2007.

[2] Pentegov I.V., Rymar S.V., Latanskij V.P.: Optymalizacja parametrów spawalniczych źródeł energii wyposażonych w kondensatorowy powielacz napięcia. Biuletyn Instytutu Spawalnictwa 1997, no. 3, pp.37–39.

[3] Andrianov A.A., Sidorec V.N.: Optimizaciâ režimov stabilizacii svaročnoj dugi peremennogo toka. Elektrotehnìka ì Elektromehanìka, 2009, no. 2, pp. 5–8.

[4] Makhlin N.M., Korotynsky A.E.: Analysis and procedure of calculation of series connection electronic devices for contactless arc excitation. The Paton Welding Journal, 2014, no. 1, pp. 30–40.

[5] Makhlin N.M.: Peculiarities of contactless ignitions of alternating current arc. The Paton Welding Journal, 2015, no. 10, pp. 29–35.

[6] Makhlin N.M.: Improvement of power supply sources in order to increase burning stability of alternating current arc. The Paton Welding Journal, 2016, no. 8, pp. 40–48.

[7] Mahlin N.M.: Soveršenstvovanie èlektronnyh ustrojstv dlâ pervonačal'nogo i povtornyh vozbuždenij dugi peremennogo toka. Avtomatičeskaâ Svarka, 2016, vol. 752, no. 4, pp. 47–51.

[8] Mihajlovg.P.: Svarka trehfaznoj dugoj. MAŠGIZ, Moskva, 1956.

[9] Pentegov I.V. and V.N. Sydorets: Comparative analysis of models of dynamic welding arc. The Paton Welding Journal, 2015, no. 12, pp. 45–48.

[10] Sawicki A.: The universal Mayr-Pentegov model of the electric arc. Przegląd Elektrotechniczny (Electrical Review) 2019, vol. 94, no. 12, pp. 208–211. (doi:10.15199/48.2019.12.47)

[11] Vakulenko V.M., Ivanov L.P.: Istočniki pitaniâ lazerov. Sov. radio 1980.

[12] Kydyraliev S.: Teoriâ stabil'nogo zažiganiâ plazmennoj dugi.Tabigyj matematika žana tehnikalyk ilimder, ŽAMUNUN Žarčysy, 2015, 1, pp. 36–43

[13] Zaruba I.I., Andreev V.V., Šatan A.F., Moskovičg.N., Halikov V.A.: Novyj tip impul' snogo stabilizatora goreniâ svaročnoj dugi peremennogo toka. Avtomat. Svarka, 2012, no. 2, pp. 51–53.

[14] Starodumov Û.I.: Principy postroeniâ ustrojstvpodžiga gazovogo razrâda. Istočniki èlektropitaniâ so special'nymi harakteristikami. Naukova dumka, Kiev, 1979.

[15] Thomas A., Nowak M., Wiśniewski D.: Zrobotyzowany system TAWERS do spawania metodami SP-MAG i TIG. Przegląd Spawalnictwa 2007, no. 8, pp. 64–67.

[16] Sawicki A.: Modele Mayra-Pentegova łuku elektrycznego z wybranymi charakterystykami napięciowo-prądowymi statycznymi. Biuletyn Instytutu Spawalnictwa 2020, no. 3, pp. 44–50.