https://doi.org/10.15407/tpwj2019.09.09

DRIVES OF MECHANISMS OF AUTOMATIC MACHINES FOR ORBITAL TIG WELDING OF METAL PIPELINE BUTT JOINTS IN NPP POWER UNITS

N.M. MAKHLIN and **V.Yu. BURYAK**
SE «SEC of Welding and Control in the Field of Nuclear Energy of Ukraine
of E.O.Paton Electric Welding Institute of the NAS of Ukraine»
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: electro@paton.kiev.ua

Electric drives are integral devices in any welding installation for arc and plasma welding. Since a number of specific requirements are made to the accuracy and reliability of the actuating mechanisms in modern automatic machines for orbital welding of position butt joints of pipelines in NPP units, these requirements are also imposed on their driving mechanisms, that required development of the latter. The schemes of unified reversible DC drives of actuating mechanisms in modern automatic machines for orbital welding of position butt joints in NPP pipelines are described. A transistor drive with feedback from an optical speed sensor, characterized by high reliability, ability to accurately preset (program) the rotation speed of the motor shaft, absence of mechanical switching contacts for starting or stopping, or for reversing, as well as a device for high-precision high-speed automatic arc voltage control was designed. The results of industrial operation of some automatic machines for orbital welding designed at the Scientific and Engineering Center of Welding and Control in the Field of Nuclear Energy (SEC WCNE), are given, which use the described reversing drives and the device for automatic arc voltage control. The aim of this, paper is to present the results of the work carried out at the SEC WCNE in the direction of designing components of automatic machines for orbital welding of position butts in thin-walled pipelines from austenitic, pearlitic and carbon steels and nonferrous metal alloys (except for aluminium and its alloys). 12 Ref., 8 Figures.

Keywords: *orbital arc welding, nonconsumable electrode, inert gases, drive, direct current electric motor, optoelectric speed sensor, transistor regulator*

Improvement of automatic machines for orbital welding (GTAW) of position butt joints of pipelines in NPP power units is directly related to increase of operating reliability of actuating mechanisms, in particular, electric drives [1, 2]. It was shown [3] that the controlled dc drives of mechanisms of such automatic machines have several advantages compared to electric drives of asynchronous ac motors. Here, it is rational to use drives with negative feedback by the rotation frequency of motor output shaft.

According to the research conducted at SEC WCNE, allowing for the features of operation of automatic machines for GTAW, in particular, when the welding head with the actuating mechanisms and control system with drive controllers can be removed to a considerable distance from each other and can be in different rooms (that is often the case in nuclear engineering), the most stable, accurate, reliable and independent on external disturbances for systems with negative feedback by rotation frequency of motor output shaft, are the incremental optoelectric sensors of rotation speed (encoders), generating a strictly constant number of output square-wave information pulses (constant pulse sequence) per one revolution of the motor shaft (Figure 1, *a*). At present both small-sized dc motors (gear motors) with two shaft outputs, and optoelectric sensors of rotation speed of motor output shaft (encoders) are widely avaliable in the market of Ukraine at a quite acceptable cost. For instance, encoder 0.5.2420.1211.0128 (0125) can be used as

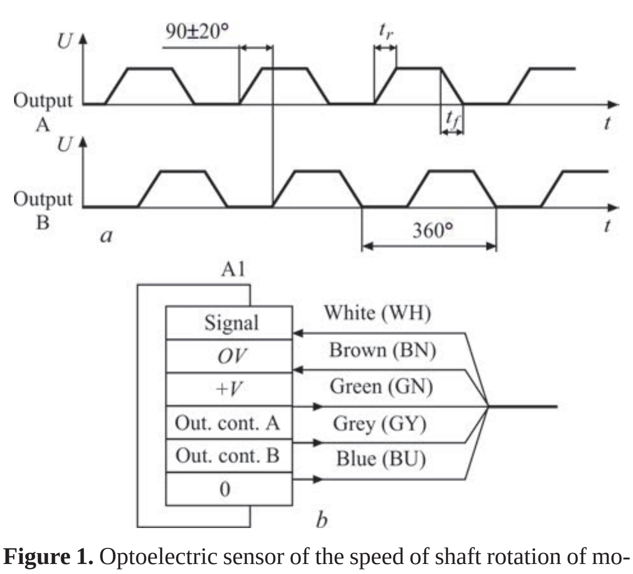

Figure 1. Optoelectric sensor of the speed of shaft rotation of motor (encoder) 05.2420.1211.0128 (0125) of «Kübler» Company: *a* — pulse sequences at information outputs A and B; *b* — connection diagram

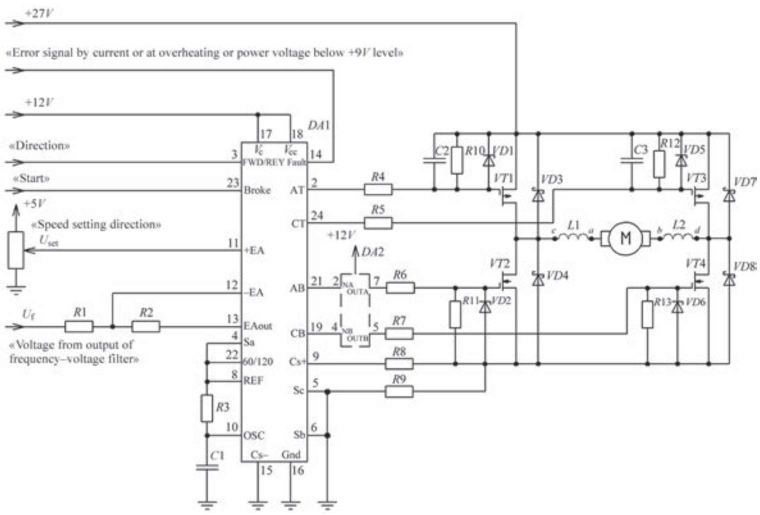

Figure 2. Simplified block-diagram of a unified drive of the mechanisms in automatic machines for GTAW of position butts of cylindrical metal pipelines

such an optoelectric sensor, the connection diagram of which is given in Figure 1, *b*. It is developed and manufactured by Kübler Company [4].

One of the features of this encoder is availability of two output channels in it — channel A and channel B, in which the pulse sequences are similar by amplitude, load capacity and repetition frequency, but are shifted by phase by (90 ± 20)° (Figure 1, *a*) that significantly widens the area of this encoder application and simplifies the repairability of the drives, in which such encoders are used. All the communications with the encoder are carried out through a coaxial or axial cable from multicolored insulated cores.

Analysis of various published sources, in particular [5–7], and accumulated experience of designing the electric drives, as well as the conclusions following from work [3], give every reason to believe that it is the most rational to apply for construction of electric drives of actuating mechanisms in automatic machines for GTAW the transistorized pulse-width modulators (as in the case of sensorless drives of welding machines), where the basic circuit solution is the bridge circuit with powerful field transistors with an insulated gate (MOSFET). The main feature of the proposed engineering solution consists in that variation of the type and selection of the respective electric characteristics of the bridge transistors allows, if required, achieving maximum values of electric drive power (right up to 500 W), practically without changing either the structure, or, mainly, the nominal values of its components, that enables unification of the drives designed for various-purpose automatic machines for GTAW.

Figure 2 gives a simplified diagram of a unified drive of the mechanisms of GTAW automatic machines.

The power part of the drive is an H-bridge formed by powerful field transistors with an insulated gate MOSFET *VT*1–*VT*4. In the basic variant of the drive MOSFET with P-type channel IRF4905 are used as «upper» transistors *VT*1 and *VT*3, operating in the mode of transistor switches, and MOSFET with N-type channel IRF3205Z are used as «lower» transistors *VT*2 and *VT*4, functioning in the mode of pulse-width modulation (PWM). In the case, if the motor armature inductance is low (that is characteristic for low power dc motors), inductances (with an infinite or large magnetic gap) can be connected in series with the armature: *L*1 between points *c* and *a* and *L*2 — between points *d* and *b*. If it is necessary to ensure functioning of higher power drive, then in order to control «lower» transistors *VT*2 and *VT*4, operating in PWM mode, a two-channel driver *DA*2 can be added to the drive scheme, for instance, of IXDN604SIA type, developed and manufactured by IXYS Company.

For control of power transistor H-bridge, we propose the available in Ukraine specialized microcircuit MC33035DWG developed and manufactured by ON Semiconductor Company as the main element in the considered drive. It is a multichannel microcontroller to control the dc motors, which is designed for surface mounting, allowing performance of PWM and ensuring protection of the controlled H-bridge from current overloads, or its overheating, or protection from inadmissible lowering of the level of power supply to the microcircuit proper. Here, the speed of motor shaft rotation is determined by average values of voltage applied to it, and regulation of the number of motor shaft revolutions and stabilization of this number per a unit of time are achieved by changing the duty cycle of power pulses of the drains of the respective «lower» transistors of H-bridge.

Arrival of START signal (low logic level «log. 0») to microcontroller BRAKE input (pin 23 of microcircuit *DA*1), results in switching on of power transistor *VT*1 in open transistor switch mode and of power transistor *VT* 4 — in PWM mode. As a result, the motor shaft rotates with the set speed and in the set working direction. At reversal «high» logic level («unit» level) arrives to input 3 of microcircuit *DA*1 that leads to switching off power transistors *VT*1 and *VT*4 and switching on power transistor *VT*3 in open transistor switch mode and of power transistor *VT*2 – in PWM mode.

Stop realization at manual or automatic feeding of «Stop» signal is performed at arrival of «high» logic level («unit» level) to «Brake» input of the microcontroller (pin 23 of microcircuit *DA*1), resulting in automatic switching off of power transistors *VT*1 and *VT*3 and practically simultaneous switching on of power transistors *VT*2 and *VT*4, which in this case will automatically go from PWM mode into the mode of permanently open transistor switches, that ensures effective dynamic braking of the motor.

Figure 3 shows an oscillogram, illustrating «acceleration» (i.e. rising of voltage and current of the drive in time) of fully loaded drives of actuating mechanisms in automatic machines for GTAW; and Figure 4 gives an oscillogram illustrating «braking» of these drives. The given oscillograms show that the longest «acceleration» time (allowing for the inertia of the mechanisms of automatic machines for GTAW) of approximately 80 % of the largest working value of voltage at the motor armature (largest working value of armature current) does not exceed 20 ms, and the longest time of «braking» under the same conditions is not more than 25 ms.

The preset (programmed) signal (voltage) of setting the speed is adjustable in the range from 0 up to +5 *V DC*. It is formed outside the drive main part, being subjected to filtration of the high-frequency components, and comes to the inverting input of microcontroller error amplifier (pin 11 of microcircuit *DA*1). A signal (voltage), the average value of which is directly proportional to the frequency of pulse sequence at the output of one of the encoder channels, is applied to the inverting input of this error amplifier (pin 12 of microcircuit *DA*1) via resistor *R*1. This signal is formed using «frequency/voltage» integrated converter and 2nd order filter. Output voltage of error amplifier affects the duty cycle of PWM pulses, the frequency of which is determined by time-setting chain *R*3*C*1. In the proposed drive PWM frequency is equal to approximately 25 kHz and, thus, on the one hand, it goes beyond the audible sound range, and causes slight ripple of motor armature current, and on the other hand, it ensures an acceptable level of dynamic losses in power transistors of H-bridge.

Operating in the mode of permanently open transistor switch «upper» power transistor *VT*1 (here the «upper» power transistor *VT*3 is switched off) is switched on by applying to the gate of this power transistor via resistor *R*6 the voltage from AT output of microcontroller *DA*1 (pin 2 of microcircuit *DA*1), and operating in the mode of permanently open transistor switch «upper» power transistor *VT*3 (here «upper» power transistor *VT*1 is switched off and is in the condition of permanently closed transistor switch) is switched on by applying the voltage from CT output of microcontroller *DA*1 (pin 24 of microcircuit *DA*1) to the gate of this power transistor via resistor *R*6. The gates of power transistors *VT*1 and *VT*3 are protected by *RCD*-chains: the gate of power transistor *VT*1 — by chain *R*10*C*2*VD*1, and gate of power transistor *VT*3 — by chain *R*12*C*3*VD*5. During the entire cycle of operation of «upper» power transistor *VT*1 the «lower» power transistor *VT*4 operates «in pair» with

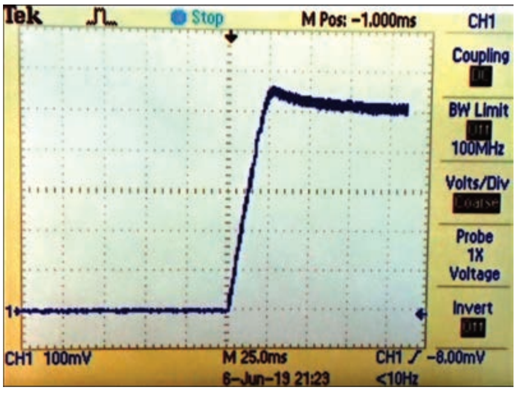

Figure 3. Oscillogram of «acceleration» of the drive of mechanisms of nonconsumable electrode rotation and oscillation in automatic machines for GTAW of position butt joints of metal pipelines

it in PWM mode, which is controlled via resistor *R*7 by pulsed voltage from CB output of microcontroller *DA*1 (pin 19 of microcircuit *DA*1). When «upper» power transistor *VT*3 is in the switched-on condition, «lower» power transistor *VT*2 operates «in pair» with it in PWM mode, which is controlled via resistor *R*6 by pulsed voltage from AB output of microcontroller *DA*1 (pin 21 of microcircuit *DA*1). The gates of power transistors *VT*2 and *VT*4 are protected by *RD*-chains: gate of power transistor *VT*2 — by chain *R*11*VD*2, gate of power transistor *VT*4 — by chain *R*13*VD*6.

During functioning of the proposed drive, current limitation is ensured by voltage on divider *R*8, *R*9, the signal from which (via resistor *R*8) comes to input Cs^+ of the microcontroller (pin 9 of microcircuit *DA*1).

The described reversing drive was used as a unified assembly in automatic machines ADTs 627 U3.1, ADTs 625 U3.1, ADTs 626 U3.1, ADTs 628 UKhL4, ADTs 629 UKhL4 and ADTs 630 UKhL4 for GTAW of position butt joints of metal pipelines [8, 9]. In automatic machines ADTs 627 U3.1, ADTs 625 U3.1 and ADTs 626 U3.1 for GTAW, designed predominantly for welding by the methods of autopressing or sequential penetration, this drive was applied to ensure functioning of the mechanism of rotation (ro-

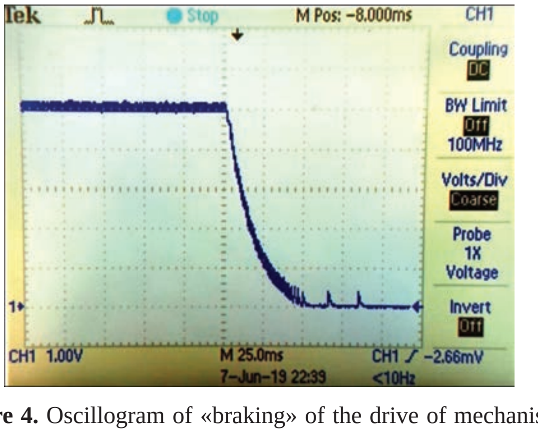

Figure 4. Oscillogram of «braking» of the drive of mechanisms of nonconsumable electrode rotation and oscillation in automatic machines for GTAW of position butt joints in metal pipelines

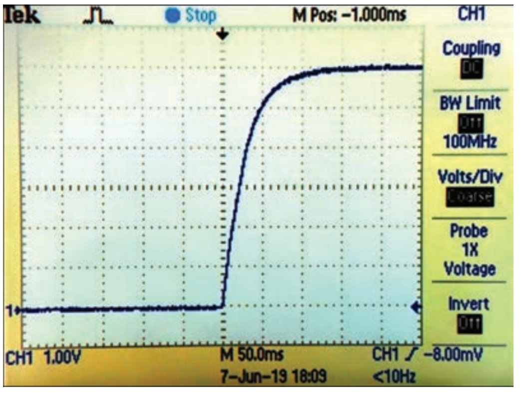

Figure 5. Oscillogram of «acceleration» of the drive of filler wire feed mechanism in automatic machines for GTAW of position butt joints of metal pipelines

tator) of the welding head faceplate around the pipes being welded. In automatic machines ADTs 628 UKhL4, ADTs 629 UKhL4 and ADTs 630 UKhL4 the described reversing drive is designed for driving the faceplate rotator, nonconsumable electrode oscillator and filler wire feed mechanism. In all the models of the above-mentioned automatic machines, the available in Ukraine gear motors 2657 W 024 CR 30/1 of Faull Haber Company and encoders 05.2420.1211.0128 (0125) of Kübler Company are used in faceplate rotators, and nonconsumable electrode oscillators of their welding heads. The filler wire feed mechanism of automatic machines ADTs 628 UKhL4, ADTs 629 UKhL4 and ADTs 630 UKhL4 for GTAW is fitted with the available in Ukraine dc motor DCM 502070-1000 of higher power (P_{max} = = 120 kW) with built-in optoelectric sensor of shaft rotation speed (encoder), at the information output of which a pulse sequence with pulse repetition rate of 1000 p/rev is formed. This device is developed and manufactured by Leadshine Technology Co., Ltd. The nominal voltage of this motor is equal to 30.3 V, nominal value of armature current is 3.94 A, nominal frequency of shaft rotation is 2900 rpm. Proceeding from the specification of motor DCM 502070-1000,

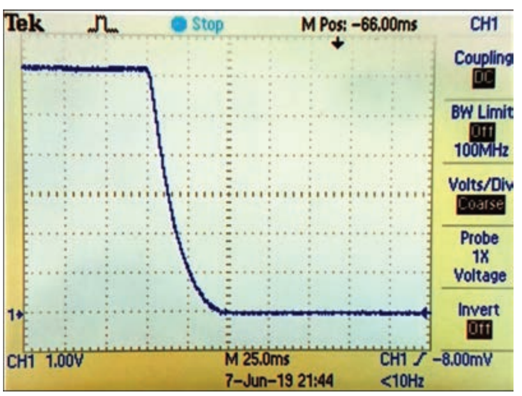

Figure 6. Oscillogram of «braking» of the drive of filler wire feed mechanism in automatic machines for GTAW of position butt joints of metal pipelines

the circuit of the above drive was taken as a base, but with slight modification: supply voltage of H-bridge was selected equal to +34 *V DC*, and driver DA2 was added to the circuit of control of «lower» power transistors of H-bridge, nominals of the components of 2nd order filter, to which the output of «frequency/voltage» converter is loaded, were corrected, as well as nominals of resistors *R*8, *R*9 (Figure 2).

Figures 5 and 6 give oscillograms illustrating the «acceleration» and «braking», respectively, at fully loaded drive of filler wire feed mechanism of automatic machines ADTs 628 UKhL4, ADTs 629 UKhL4 and ADTs 630 UKhL4 for GTAW. The given oscillograms are indicative of the fact that the time of «acceleration» of this drive (allowing for the inertia of the filler wire feed mechanism) does not exceed 45 ms, and the «braking» time — 50 ms.

During orbital welding of butt joints of pipelines in NPP power units, one of the most important characteristics of welded joint quality is the admissible irregularity of weld penetration depth, depending on spatial position of the nonconsumable electrode at the set welding speed [2, 10]. It is known that in order to achieve the required quality of the welded joint in these cases, it is necessary to simultaneously stabilize also the welding speed (speed of movement of welding head with the torch along the position butt trajectory) and welding current and voltage (arc length). And while the welding speed stabilization is ensured using the described drive, and welding current stabilization is due to «vertical» («bayonet») output volt-ampere characteristics of welding current source, arc voltage stabilization is performed either using mechanical devices for arc length stabilization (ALS), or using devices for automatic regulation of arc voltage (ARAV). The operating algorithm of ALS and ARAV devices, their design principles and technical requirements to them are described in detail in works [2, 5, 10, 11]. Mechanical device for ALS is used in automatic machine ADTs 627.U3.1 for GTAW of position butt joints of metal pipelines with nominal outer diameter from 7 up to 24 mm. In all the other above-mentioned models of automatic machines for GTAW of position butt joints of metal pipelines (with nominal outer diameter from 18 up to 219 mm) a unified ARAV device is used, the simplified scheme of which is given in Figure 7.

The main element of ARAV device is a powerful operational amplifier *DA*2, the output of which is connected to ARAV motor armature via limiting resistor *R*. This motor rotates, depending on the error signal, between the set and actual instantaneous values of arc voltage. In the differential amplifier of error, included into the structure of microcircuit *DA*2, its output voltage is directly proportional to the difference of arc voltages at direct (pin 1 of microcircuit *DA*2) and inverting (pin 2 of microcircuit *DA*2) inputs. Operating points of drain characteristics of output power transistors of microcircuit *DA*2 are determined by the value and sign of output voltage of the above amplifier. Activation of microcircuit *DA*2 is performed by logical levels using digital microcircuit *DD*1 and optotransistor *VT*1. Here, if phototransistor of optocouple *VT*1 is open, microcircuit *DA*2 is «dormant». Transition (activation) of microcircuit *DA*2 from «dormant» into working (active) state can take place only in the case, when phototransistor of optocouple *VT*1 is completely closed. Current limitation through output power transistors of microcircuit *DA*2 is determined by nominal resistance of resistor *R*10. At the moment, when voltage levels at error amplifier inputs (pins 1 and 2 of microcircuit *DA*2) become equal to each other, the voltage at this amplifier output and at the output of power transistors of microcircuit *DA*2 will become practically equal to zero and motor M will stop its rotation.

Signal for setting arc voltage $U_{a.set}$ comes from the outside through two-sided analog switch (interconnected pins 6 and 10 of microcircuit *DA*1) is filtered by T-shaped filter *R*5, *R*8, *C*1 and applied to direct input of differential amplifier of error of microcircuit *DA*2.

The signal proportional to actual current value of arc voltage U_a, is formed with the accuracy not worse than 1 % at the output of voltage sensor B1 developed at SEC WCNE (type DN — 100C) [12], from where it is fed to the inverting input of differential amplifier of error of microcircuit *DA*2 via another bilateral analog switch (interconnected pins 14 and 15 of microcircuit *DA*1) and resistor *R*6.

As the possibility of ADJUSTMENT operation, when the welding current and arc voltage are absent, is envisaged in automatic machines ADTs 627 U3.1, ADTs 625 U3.1, ADTs 626 U3.1, ADTs 628 UKhL4, ADTs 629 UKhL4 and ADTs 630 UKhL4 for GTAW of position butts joints of metal pipelines, the proposed ARAV device contains resistive dividers *R*1, *R*2 and *R*3, *R*4. Signals from these dividers are used for simulation of arc voltage, and they come to inverting input of differential amplifier of error of microcircuit *DA*2 via the respective bilateral analog switches (interconnected pins 11 and 7, 3 and 2, respectively, of microcircuit *DA*1) and resistor *R*6.

In ARAV device, readily available in Ukraine microcircuit OPA547T, developed and produced by «Texas Instruments» Company, can be applied as a powerful specialized microcircuit with bipolar power supply *DA*2, and, for instance, microcircuit DG-411DY, developed and produced by VISHAY Company, can be used as bilateral analog switches *DA*1,

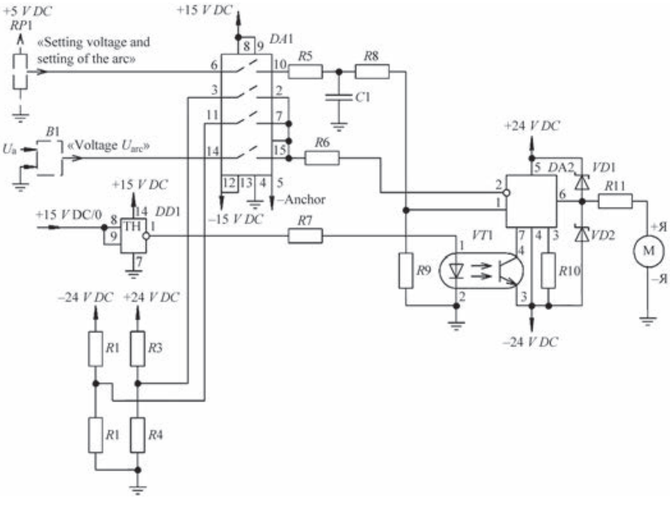

Figure 7. Simplified block-diagram of a unified ARAV device in automatic machines for GTAW of position butt joints of metal pipelines

microcircuit HEF4093BT, developed and produced by NXP Company can be applied as digital microcircuit *DD*1, and, for instance, gear motor 1524 T 024 SR 16/7 3.71:1, developed and produced by the same Faull Haber Company can be used as low-power dc motor. Figure 8 shows the voltage oscillogram at the inputs of differential amplifier of error (for the case, when the difference between voltage at direct input and voltage at inverting input of this amplifier does not exceed ±0.15 V), according to which the total time of «acceleration» of ARAV mechanism does not exceed 25 ms, and total «braking» time — 60 ms.

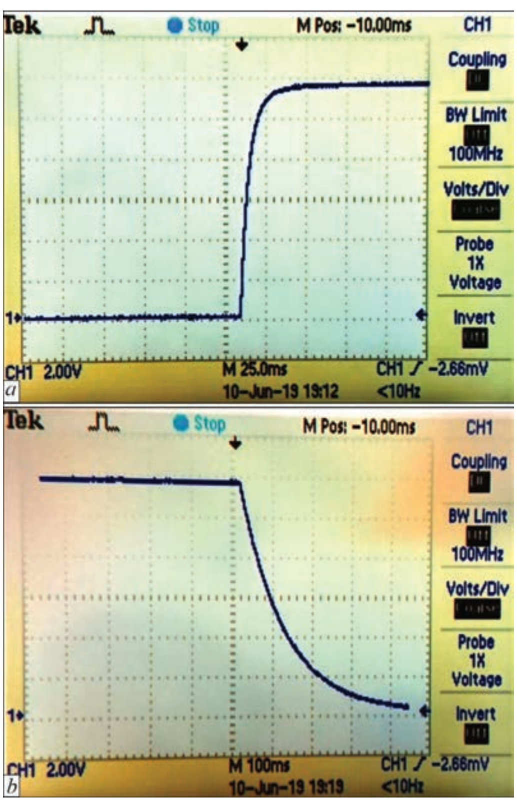

Figure 8. Oscillogram of «acceleration» (*a*) and «braking» (*b*) of ARAV device mechanism in automatic machines for GTAW of position butt joints of metal pipelines

Automatic machines ADTs 627 U3,1, ADTs 625 U3.1, ADTs 626 U3.1 for GTAW of position butt joints of metal pipelines, fitted with the above drives, not only successfully passed comprehensive technological and operational tests at PWI and SEC WCNE, but also pilot production trials at SD «Atomenergomash», SD «DB «Atomprylad» of SC «NNEGC «Energoatom», as well as TISER Ltd. Test samples of automatic machines ADTs 627 U3.1 with welding heads ADTs 627.03.00.000 and ADTs 627.03.00.000-01 have been in operation since 2010, and up to now. Results of pilot production trials are positive. At present SEC WCNE is finishing technological comprehensive and operational tests of automatic machines ADTs 628 UKhL4, ADTs 629 UKhL4 and ADTs 630 UKhL4 for GTAW of position butt joints of metal pipelines with nonconsumable electrode oscillations and mechanized filler wire feed.

Conclusions

1. Application of negative feedback by the speed of dc motor shaft rotation organized using the respective sensor (optoelectric encoder), significantly improves the static and dynamic characteristics of the drives of actuating mechanisms in automatic machines for GTAW of position butt joints of cylindrical metal pipelines (compared to sensorless drives), significantly widens the range of drive adjustment (not less than two times), improves the stability of their operation and provides the required accuracy of setting the speed of rotation of actuating mechanisms motor shafts in the above-mentioned automatic machines for GTAW.

2. It is experimentally established that the time up to complete acceleration and braking of gear motors of such mechanisms is not more than 20 and 25 ms (for the drive of filler wire feed mechanism it is 45 and 50 ms, respectively), that enables functioning of GTAW automatic machines in the modes of step-pulse welding (at not more than 2 Hz frequency) and modulated current welding with the ratio of I_{pul}/I_p = = 4/1 (where I_{pul} is the largest value of welding current in the pulse, and I_p is the largest value of welding current in the pause) and up to 4 Hz frequency.

3. The described unified reversible drive and ARAV device do not have any electromechanical switching elements, that improves the reliability of this drive and device and enables controlling switching on/off of this drive and device using logic signals in all the possible operating modes of GTAW automatic machines.

4. The ARAV device presented in this work is also unified, designed by a relatively simple electric circuit, is characterized by high reliability and ensures maintaining a stable set value of arc voltage with the accuracy not worse than that of the best foreign samples of ARAV devices.

5. The developed and described reversible drive and ARAV device can be effectively used in any other units (in particular, in automatic machines and complexes) for nonconsumable electrode welding in inert gases or their mixtures, if motors or gear motors with two shaft outputs (for instance such a capability is envisaged for dc motors of DPR series) are applied in the drives of mechanisms of these units. Here, not only optoelectric sensors, but also those of other types can be used as sensors of the speed of motor shaft rotation, for instance tachogenerators or induction sensors, based on Hall effect.

In conclusion, the authors express their sincere gratitude to engineers D.S. Olianenko and V.E. Vodolazskiy for valuable assistance in fulfillment, documenting and preparing this work for publication.

1. Poloskov, S.I., Bukarov, V.A., Ishchenko, Yu.S. (2000) Influence of variations of parameters of argon-arc welding of pipe position butt joints on quality of welded joints. In: *Proc. of All-Russian Sci.-Techn. Conf. on Welding and Related Technologies. MPEI*, 22–25 [in Russian].
2. (1986) Equipment for arc welding: Refer. book. Ed. by V.V. Smirnov. Leningrad, Energoatomizdat [in Russian].
3. Lankin, Yu.N., Semikin, V.F., Sushy, L.F. (2010) Control of sensorless DC drives of welding machines. *The Paton Welding J.*, **3**, 24–29.
4. (2019) *Product list by «Kübler»*. URL: http:www.kuebler.com.
5. Gladkov, E.A. (2006) *Control of processes and equipment in welding: Manual for students of higher education institutions*. Moscow, Akademiya [in Russian].
6. Maniktala, S. (2008) *Pulse power sources from A to Z*. Kiev, MK-Press; St.- Petersburg, KORONA-VEK [in Russian].
7. Gotlib, I.M. (2002) *Power sources. Inverters, converters, linear and pulse stabilizers*. Moscow, Postmarket [in Russian].
8. Makhlin, N.M., Korotynsky, A.E., Bogdanovsky, V.A. et al. (2011) Single- and multioperator systems for automatic welding of position butt joints of nuclear power plant piping. *The Paton Welding J.*, **11**, 28–36.
9. Makhlin, N.M., Korotynsky, A.E., Svyrydenko, A.O. (2013) Hardware-software complexes for automatic welding of position butt joints of nuclear power plants piping. *Nauka ta Innovatsii*, 9(**6**), 31–45 [in Ukrainian].
10. Bukarov, V.A. (2002) Technology of automatic shielded-gas arc welding. In: *Welding in nuclear industry and power engineering: Transact. of NIKIMT*. Moscow, Izdat. AT2002, 1, 149–210 [in Russian].
11. (1986) *Automation of welding processes*. Ed. by V.K. Lebedev, V.P. Chernysh. Kiev, Vyshcha Shkola [in Russian].
12. Korotynsky, A.E., Makhlin, N.M., Buryak, V.G., Kunkin, D.D. (2005) Universal sensor of electric parameters of welding. *The Paton Welding J.*, **3**, 49–50.

Received 14.06.2019