CONTROL OF SENSORLESS DC DRIVES OF WELDING MACHINES

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Control circuits for reversible DC motors with speed stabilization by the electromotive force are described. Microprocessor-based transistor sensorless drive was developed, characterized by flat loading characteristics, absence of switching contacts for reversal, and possibility of precise setting of speed prior to starting the motor.

Keywords: *arc welding, DC motor, speed stabilization, sensorless drive, thyristor regulator, transistor regulator, micrprocessor, digital control*

Electric drives are an integral part of practically all the arc welding machines. This primarily is the electrode wire feed drive, drives of welding carriage displacement, transverse oscillations of welding head, welding head positioning, etc. DC motors became the most widely accepted in controlled electric drives. Compared to AC asynchronous motors they have much simpler speed control and considerably smaller overall dimensions. In addition, AC asynchronous motors are manufactured, as a rule, for 220 V and higher power voltage, which, according to safety rules [1] allows them to be used both in stationary and mobile automatic machines. Modern contactless synchronous machines feature excellent mass and size and adjustment characteristics. However, both they and their control systems are highly expensive.

The following requirements are made of electrode wire feed drives of semi-automatic welding machines: not less that 1:10 range of rotation frequency adjustment; stability of established rotation frequency irrespective of mains voltage fluctuations of +5 – +10 % and shaft load moment of 0–100 % not worse than ±10 % [2]. Drives for welding with pulsed wire feed, periodical transverse movement of the welding head, systems of automatic adjustment of nonconsumable electrode welding voltage and systems of automatic seam tracking should feature an essentially larger range of speed adjustment and limit speed.

Such characteristics can only be achieved at application of control systems with negative feedback by the motor rotation frequency. The best results were obtained in systems with the sensor of electric motor speed — DC or AC tachogenerator, pulsed optical sensor or Hall sensor. Unfortunately, speed transducers are complex, expensive and it is not always physically possible to install them. For instance, popular D90 and D25 motors of Kiev OJSC «Artyom-kontakt» do not allow connecting a speed transducer to the shaft from the motor side opposite to the reducer.

In the simplest drives tachometer bridge voltage is used as feedback signal [3, 4], its main disadvantage being its low accuracy. In reality, tachometer bridge voltage is proportional not to motor speed, but to motor power voltage and current. Such a system is equivalent to the system with negative feedback by motor supply voltage and positive feedback by load (current). The most negative characteristic of the system is the fact that current feedback is positive and its increase to improve the motor load characteristic rigidity leads to system instability. As a result, in the drives with feedback by the signal of tachometer bridge it is never possible to achieve flat drive characteristics, as in systems with speed transducers. The range of motor speed adjustment is also narrowed.

Sensorless systems with feedback by electromotive force (emf) of motor armature windings demonstrate much better results [5]. As is known, emf is equal to [6]

$$E_a = C_e n \Phi,$$

where C_e is the motor design parameter; Φ is the excitation flux; n is the motor shaft rotary speed. Thus, motor emf / characterizes motor speed not worse than machine tachometer does. The problem consists in being able to measure emf.

Value of emf can be measured, if we switch the motor into generator mode, disconnecting it from the power source. At short-time power cut-off, the motor continues rotating by inertia, and, therefore, the emf is the armature voltage. If the motor is powered from an adjustable DC source, the control system should periodically cut-off the power supply, and measure the motor voltage during the formed pause. When the motor is powered from rectified single-phase mains voltage, the motor runs in generator mode for a considerable part of mains voltage half-period. This occurs when motor emf is greater than the power source instantaneous voltage (Figure 1).

Thyristor sensorless drive. To check the principle of speed adjustment by thyristor drive motor emf a mock-up of an analog control system was made, the block diagram of which is shown in Figure 2.

The regulator was tested with DC commutator motor M of D90 type of 130 W power. The motor is powered from a controllable two-stage rectifier on optronic thyristors $VD1$, $VD2$. The rectifier is powered by step-down transformer $T1$.

After resistive divider $R1$, $R2$, motor armature voltage comes to repeater $DA2$, and from its output it comes to analog switch $DA4$, which is controlled by output voltage of comparator $DA3$. Voltage proportional to armature current of motor M is applied to comparator inverting input from shunt $R3$ connected into motor armature circuit. As a result, when no current flows through the motor armature, and the motor operates in generator mode, switch $DA4$ is closed and capacitor $C2$ is charged up to voltage proportional to motor emf. When the motor armature voltage is greater than emf, current flows through motor armature and switch $DA4$ is opened by a command from $DA3$. As a result, voltage on capacitor $C2$ stays proportional to motor emf all the time. After repeater $DA5$, this voltage is applied to regulator $DA1$, the output of which is connected to regulator of thyristor phase control on uni-junction transistor $VT2$. Circuit of synchronization of $VT2$ operation with the mains is assembled of transistor $VT1$ and rectifier $VD3$. Speed is assigned by potentiometer $R4$.

Testing of regulator mock-up demonstrated a high accuracy of stabilization of motor speed in a broad range of variation of mains voltage and motor shaft load. An indubitable advantage of thyristor regulator is its ultimate simplicity and reliability, it practically does not apply any limitations on motor power and supply voltage. It has the disadvantage of a low power factor, particularly at a high motor speed due to pulsed nature of motor armature current. As a result, the root-mean-square value of motor current determining its heating, is essentially higher than the average value of current determining the motor shaft moment.

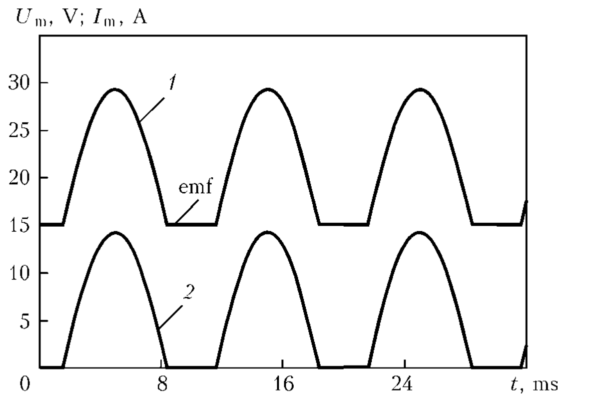

Figure 1. Oscillograms of voltage U_m (*1*) and current I_m (*2*) of the motor powered from full-wave AC voltage rectifier of 50 Hz frequency

Microprocessor-based thyristor sensorless drive. Application of microprocessors in a thyristor drive allows simplification of the device circuit, while using more perfect control algorithms. Figure 3 gives the block-diagram of microcontroller thyristor sensorless DC drive.

Application of a microcontroller allowed changing the algorithm of the motor reversal control, combining in one system, alongside the control function also the function of representation of the assigned and actual motor speed in the digital form.

Used as controller $DD1$ is this development was a single-crystal microcontroller PIC16F873 of Microchip, USA.

Potentiometer $R1$ sets motor speed v_{set}. Potentiometer output voltage is applied to one of the inputs of microcontroller analog-digital converter (ADC). Voltage from dividers $R4$ and $R5$, which are connected to armature of motor M, is applied to ADC other input. Microprocessor processing of this voltage allows extracting the value of motor emf from it.

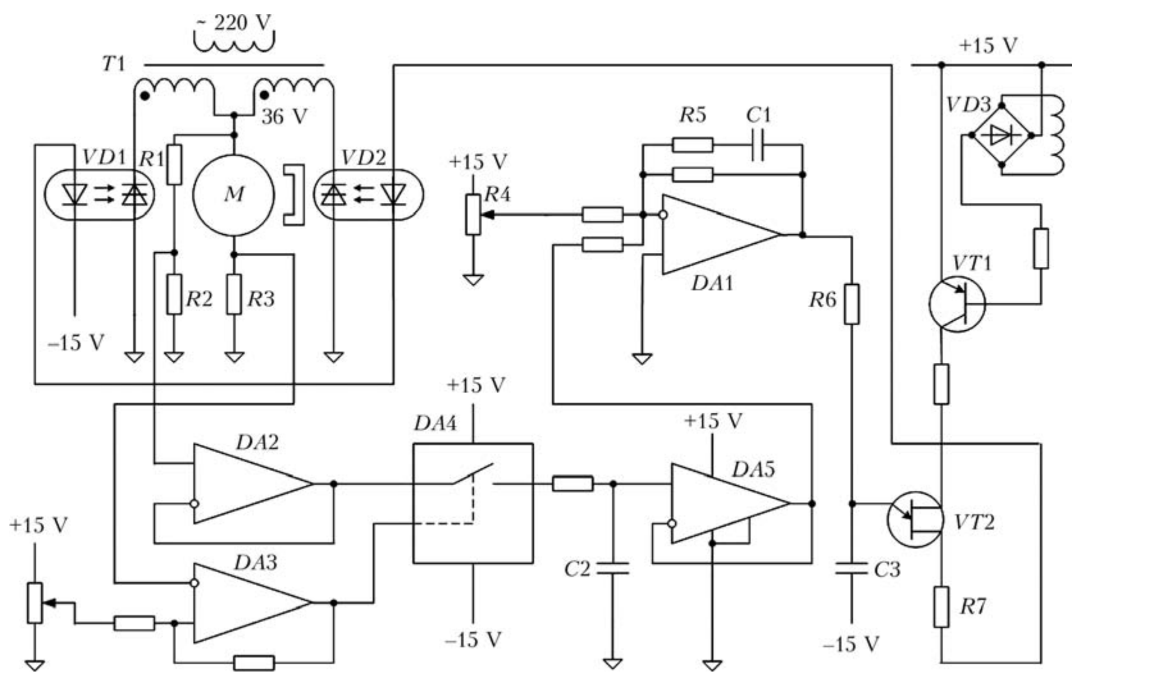

Figure 2. Block diagram of speed adjustment of non-reversible thyristor drive with negative feedback by DC motor emf

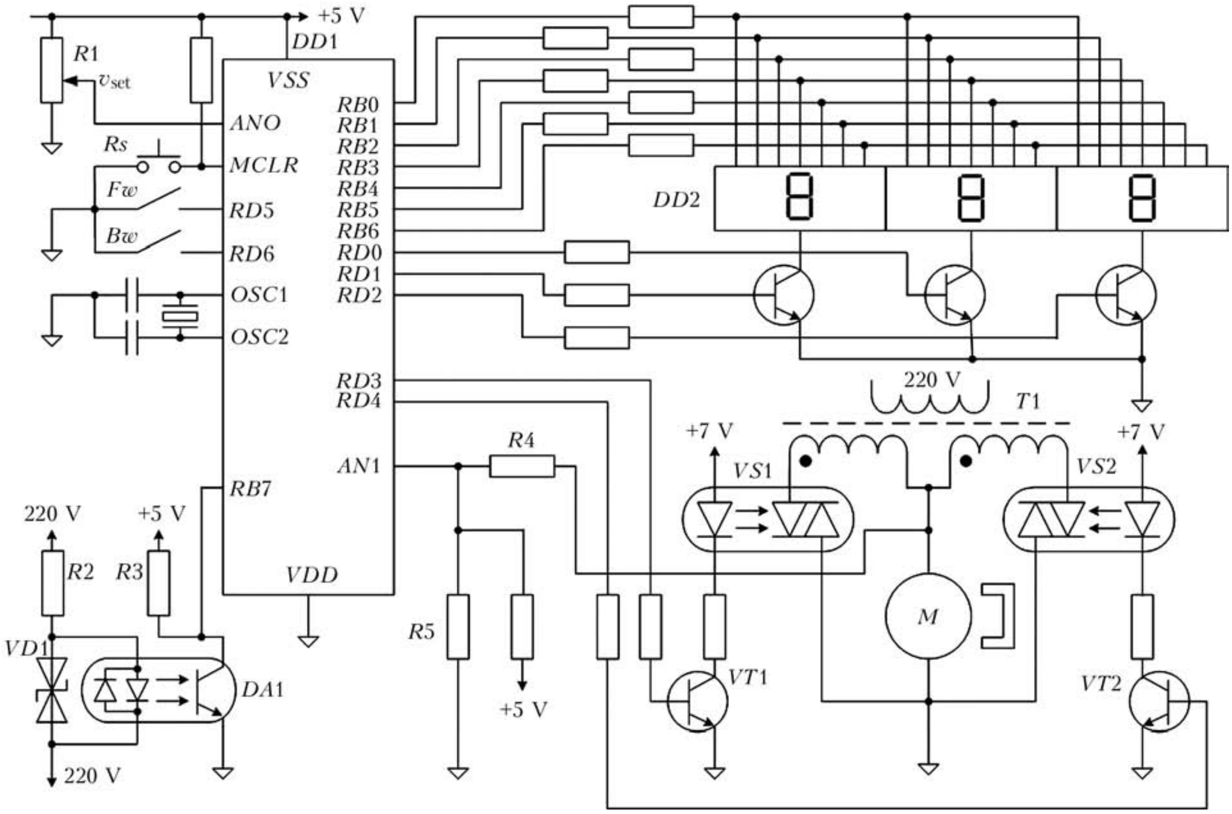

Figure 3. Block diagram of microprocessor-based reversing thyristor sensorless drive

Synchronization with mains voltage is performed by a circuit assembled of *R*2, *R*3, *VD*1, *DA*1. This results in formation at input *RB*7 of controller *DD*1 of pulses of synchronization with the mains, starting the interrupt-driven subroutine of drive control at the start of each half-period of mains voltage.

Switches *Fw* (forward) and *Bw* (backwards) generate commands for motor shaft revolution in the respective direction. *Rs* button is used for controller hand reset.

Pulses of switching on opto-triacs *VS*1 and *VS*2 are generated at controller outputs *RD*3 and *RD*4. These pulses are applied to bases of transistors *VT*1, *VT*2, to the collectors of which the opto-triac emitting diodes are connected. At switching on of transistors *VT*1, *VT*2 the respective opto-triac is switched on in the direction determined by switches *Fw* and *Bw*.

Opto-triacs are connected in single-phase circuit of full-wave reversible rectifier powered from transformer *T*1, in which the secondary winding has a center tap. The rectifier is loaded on the armature of DC commutator motor *M* with excitation from permanent magnets.

A large number of output registers of PIC16F873 microcontroller, in addition to control and adjustment devices, allows connecting to it a three-digit seven-segment LED indicator *DD*2 in the dynamic control mode. At open switches *Fw* and *Bw* the indicator shows value of set motor speed, and at switching on of motor rotation, the indicator shows the value of measured motor speed. Static error of speed adjustment is absent, due to application of discrete proportional-integral control algorithm, and motor speed is equal to the set value, thus allowing the speed value to be assigned with high accuracy before starting the motor.

Microprocessor transistor sensorless drive. For power supply to low-power low-voltage DC motors the most rational is application of transistorized pulse-width converters. A typical solution is a bridge circuit based on power field transistors with insulated gate (MOSFET). High frequency of pulse-width conversion results in low ripple of motor armature current, and transistor operation in the switching mode ensures their minimum heating, compared to operation in the linear mode. Microcontroller PIC16F684, ideally suited for such purposes, was selected for transistor control. It has built-in functions of pulse-width modulation (PWM) of transistor bridge control, current protection in each PWM period, function of protection from bridge through-currents at motor reversal, and it incorporates flash-memory, thus simplifying system debugging. The above-mentioned microcontroller is manufactured in 14-leg DIP case. A simplified schematic of microprocessor sensorless transistor reversible DC drive is given in Figure 4.

The drive power components are based on powerful complementary field-effect transistors *VT*2–*VT*5. Transistors *VT*3, *VT*5 have logic level control inputs, and are directly controlled by microcontroller. Transistors *VT*2, *VT*4, live with high voltage, are connected to microcontroller control outputs through

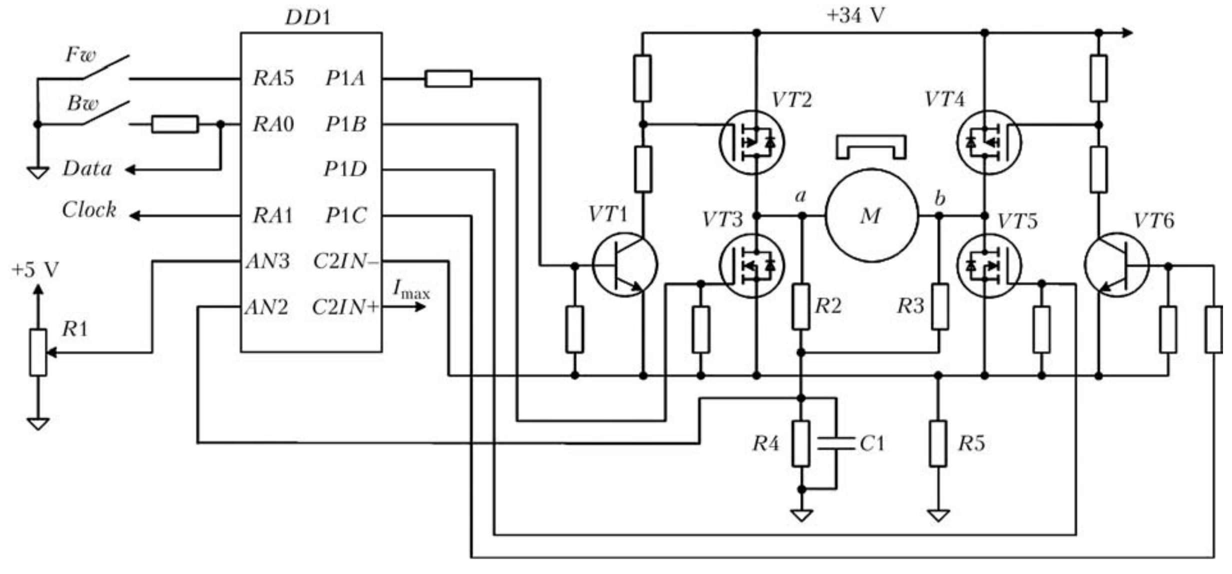

Figure 4. Simplified block diagram of microprocessor-based sensorless reversible transistor drive

low-power matching transistors *VT*1, *VT*6. Direction of motor rotation is assigned by *Fw* and *Bw* switches.

PWM control is used for adjustment of motor revolutions, in which the mean value of voltage applied to the motor, determines its revolutions, while changing according to the power pulse ratio. A signal from *Fw* switch switches on transistors *VT*1 and *VT*2, and PWM signal is applied to the gate of transistor *VT*5. As a result, the motor rotates in the working direction at the set speed. At reversal transistors *VT*3, *VT*4, *VT*6 switch on.

As was noted above emf of motor armature winding can be measured at the moment, when no power is applied to the armature, and the motor rotating by inertia runs in generator mode. Power switching off is performed in each PWM period, and, therefore, theoretically, emf can be measured with PWM frequency. In reality it is only possible at comparatively low PWM frequency, as the electric circuit of motor armature has a quite considerable inductance. At switching off of the supply voltage the armature current starts decreasing, thus causing self-induced emf, which is subtracted from armature winding emf. If during the supply voltage pause, armature current drops to zero, armature emf can be observed in the winding after that. Thus, measurement of motor emf values with maximum frequency, i.e. in each PWM period, requires its relatively low frequency, ensuring an intermittent current of motor armature. In addition, the maximum range of relative duration of PWM pulse should be limited so that the duration of mandatory PWM pause were sufficient for emf measurement. In this connection, a method of periodical short-term interruption of motor power supply at high PWM frequency was applied.

Motor power supply interruption was performed during a time interval equal approximately to units of milliseconds, which is sufficient for measurement and processing of emf values by the controller. Measured emf value is read from points *a* and *b* of the bridge (see Figure 4) and applied to input AN2 (ADC) of microcontroller through dividers R2–R4. Figure 5 shows oscillograms of emf of electric motor of D90 type during its power supply interruption periods. This voltage is reduced to the range of input voltage values of microcontroller ADC (0–5 V).

Motor speed is assigned by potentiometer *R*1, its output voltage being applied to microcontroller *AN*3 input (ADC).

Microcontroller operation cycle is 10 ms. In this case control signal is applied to bridge transistors for 7.5 ms, and for 2.5 ms bridge transistors are switched off, and the motor, rotating by inertia, runs in generator mode. During this time controller takes several

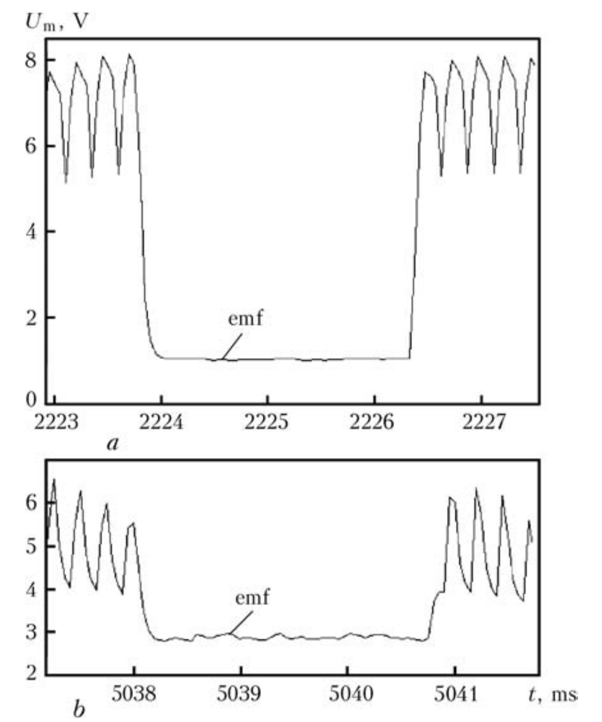

Figure 5. Oscillograms of electric motor armature voltage at low (*a*) and high (*b*) rotary speed

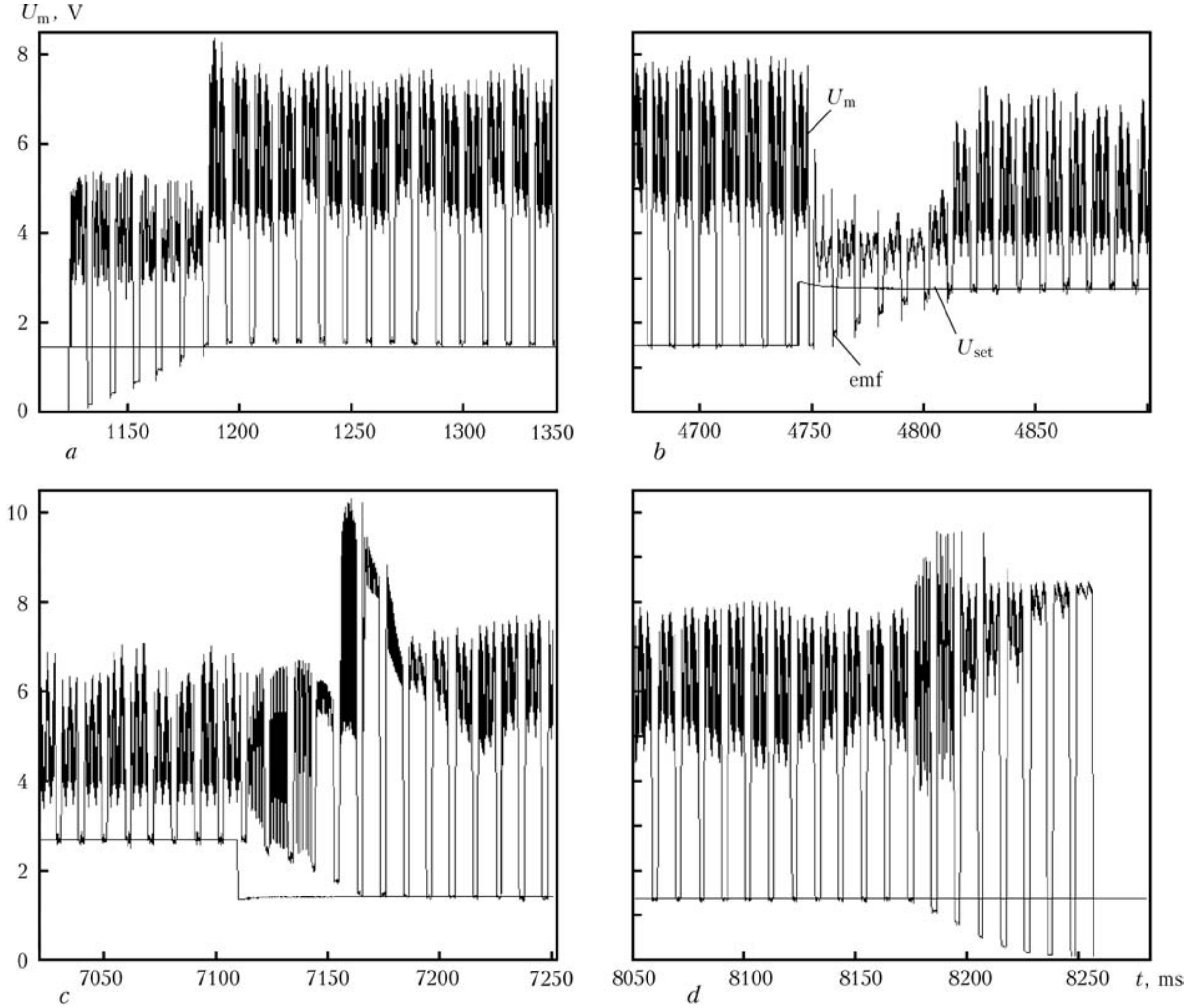

Figure 6. Transient processes in the closed adjustment system at starting (*a*), step-like increase (*b*) and decrease (*c*) of motor speed setting, as well as its stopping (*d*)

emf, measurements, averages them and calculates the control actions, namely PWM pulse duration. PWM frequencies are equal to 4 kHz.

Recurrent discrete law of proportional-integral (PI) control was used for stabilization of motor speed [6]. In order to reduce the time of executing the programmed speed lowering, the negative value of control action is implemented by reversal of motor supply voltage through appropriate control of bridge thyristors.

Figure 6 shows the transient processes with a closed feedback by motor armature emf at step-like change of assigned revolutions. As is seen from the Figure, the drive executes 30 % changes of assigned speed in 50–60 ms. Without feedback, the acceleration time is equal to 300 ms, and that of deceleration is 750 ms.

Due to application of PI-regulator, static error of speed adjustment is zero, at variation of both motor load, and mains voltage fluctuations. As a result, adjustment range is equal to not less than 1:50, which is more than enough for welding equipment.

Voltage, proportional to armature current, is read from shunt *R*5, and is applied to inverting input $C2IN^-$ of microcontroller built-in comparator. Voltage proportional to the assigned maximum armature current I_{max} is applied to non-inverting input. If motor current is higher than I_{max}, motor power is cut-off till the next PWM period. This way instant protection of bridge transistors by current is achieved practically without any additional equipment or programming costs. It results in effective limiting of armature current during transient processes at motor starting, reversal and abrupt load change, etc.

Connection to speed/setter digital indicator is performed through series interface I^2C by transfer of *Data* and *Clock* signals through microcontroller outputs *RA*0 and *RA*1. Indicator data is updated with 0.32 s interval. In the stopping mode the indicator displays the set speed, and in the rotation mode it shows the measured speed value averaged over data updating interval.

Thus, DC motors became the most widely accepted for drives of non-stationary welding machines. Application of negative feedback by motor speed greatly improves drive stability, its static and dynamic characteristics. Application of motor armature emf as signal of negative feedback by speed provides an essential cost reduction and improvement of the reliability of motor automatic control system. The developed microprocessor transistor sensorless drive features flat load characteristics, absence of switch contacts for reversal, high reliability, small overall dimensions and low cost, and ability of precise setting of motor speed before its starting.

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PRODUCTION OF POWDER OF THE Ni–Cr–Al–Y SYSTEM ALLOY DOPED WITH SILICON BY THE POWDER METALLURGY METHOD

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The influence of solid-phase interaction of Ni–Cr–Al–Y alloy with silicon at up to 1100 °C temperature was studied. It was established that to produce the Ni–Cr–Al–Y + Si alloy it is expedient to use nickel mechanically doped with silicon as one of the initial intermetallic components of the alloy, this preventing presence of free silicon in the alloy and ensuring uniform distribution of silicon through the powder volume.

Keywords: *detonation spraying, powders, heat-resistant alloy Ni–Cr–Al–Y, mechanical doping with silicon, solid-phase interaction, phase composition, distribution of doping elements*

Heat-resistant nickel-base alloys are widely applied to manufacture parts operating under extreme conditions of high temperatures and aggressive environments [1]. Development of new materials for protective coatings by adding doping elements to compositions of standard alloys in order to improve their service characteristics, such as heat and corrosion resistance, is of high current importance.

According to the diagram of dependence of heat and corrosion resistance of coatings upon the content of chromium in them [2], the chosen alloy for the investigations (composition, wt.%: 79 Ni, 15 Cr, 5.8 Al, 0.2 Y) is classed with the most heat-resistant ones, and doping with active additions is one of the ways of increasing its functional characteristics of heat and corrosion resistance. Silicon is not often referred to as belonging to the doping elements (boron, magnesium, zirconium, hafnium, etc.), although it should play an important role as a coating element that forms a strong and dense self-passivating oxide film during oxidation. Some researchers studied the effect of silicon on resistance of alloys at increased temperatures [3, 4]. However, these studies are of a contradictory character and contain no generalisations on the protection mechanism of the coatings to be used as a basis to select certain amounts of doping additions or compounds containing the required elements and set the method for adding them to an alloy.

The purpose of this study was to investigate solid-phase interaction of initial components of the Ni–Cr–Al–Y alloys with silicon within a service temperature range (up to 1100 °C). The alloys were produced by the powder metallurgy method. Several methods are available for adding doping impurities [5]. Silicon can be added to the initial mixture of nickel, chromium and aluminium powders, followed by powder metallurgy operations (mixing, crushing or mechanical activation, heat treatment, etc.), or it is possible to first produce a silicon compound with one or several initial components and then mix it with other components of the alloy. The doping method is determined by technological peculiarities of subsequent processes. This study considered several methods for adding silicon.

One of methods for adding a silicon impurity to a complex nickel-base alloy is adding it together with yttrium oxide during the process of production of a standard alloy powder. Yttrium oxide and silicon (up to 4 wt.%) are added at a stage of mixing to a mixture of Ni_3Al and Cr(Ni) powders preliminarily produced by solid-phase synthesis in vacuum. Then, following the flow diagram of the process developed by the authors, the diffusion processes of interaction of silicon with main phases of the alloy, i.e. Ni_3Al and Cr(Ni), should take place during vacuum heat treatment.

The interaction products after vacuum heat treatment at a temperature of 1000 °C for 2 h were investigated by X-ray analysis and scanning electron mi-