Impulse Control of DC Motor with Addition of Energy

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***Abstract*—This article presents the research of a proposed method and device for pulse control of a DC motor with the addition of energy to the control powerful pulses. The method and the created principle scheme for motor control are described. A theoretical analysis of the transients in the power circuit for adding energy to powerful pulses is made. Experimental studies of the change of motor speed during control by the method of pulse width modulation (PWM) and at DC voltage supply have been made. The change of current and voltage applied to the motor anchor during control with addition of energy to the control pulses is studied.**

Keywords—pulse width modulation, duty cycle, boost converter, DC motor

I. Introduction

The method of pulse width modulation is widely used in modern electric drives for controlling DC, induction motors and stepper motors. This pulse control method allows smooth adjustment of the speed and torque of motors [1]. Characteristic of this control method is the high efficiency of the power converters, as the powerful transistors operate in switch mode. It is possible to use both pulse converters of step-down type and converters of step-up type of output voltage [2,3]. With the help of these converters, closed automatic control systems can be realized for precise regulation of the motor speed and the developed torque. When controlling a DC motor, the load for the power converter has an active-inductive character, in addition, back electromotive force is generated in the anchor winding. When the power transistors are switched on during pulse control of the motor, the current through the anchor winding increases exponentially [4]. It is known that this also changes the torque of motor, because there is a proportional relationship between the current in the anchor and the torque of motor. It is known that as the value of the DC voltage applied to a series R-L circuit increases, the rate of current increase until a predetermined maximum value is increased, and the time to reach this value decreases regardless of the time constant of the circuit. With the faster current change, the motor coil is charged faster with magnetic energy. Once the current reaches a certain value, the anchor voltage can be set to a lower value equal to the rated supply voltage for the motor. In this way, the introduction of more energy into the anchor winding of the motor at the beginning of each pulse will lead to an increase in torque and speed. The purpose of the proposed method for addition of electrical energy to each motor power pulse is to increase the torque and speed.

II. Proposed Method and Circuit for Research

The designed principle circuit for pulse control of DC motor provides powerful pulses with two voltage levels, high at the beginning of the pulse and low level equal to the rated voltage for the motor in established mode. Control pulses CP1 for the motor are generated by a pulse width modulator (PWM) from the structure of microcontroller (Fig.1). The supply voltage for the motor is provided by source V1. Transistor Q1 and driver circuit U1 control the anchor winding of the motor. A step-up pulse voltage converter has been added to the power control circuit. The control of this converter is performed with the control pulses CP2 generated by the microcontroller. These pulses have a constant duration set in advance depending on the motor parameters.

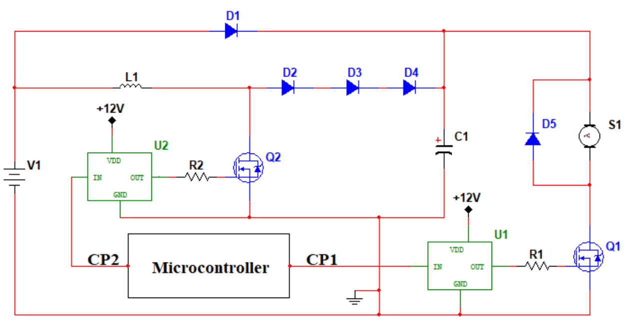

Fig. 1. Principle circuit of pulse control of the motor

Transistor Q2 and driver circuit U2 are elements of the pulse converter. When transistor Q2 is switched on, in the coil L1 magnetic energy is accumulated from the current flowing through it [5,6]. When the transistor is switched off, the magnetic energy is transformed into electrical energy and charges the capacitor C1 with a voltage higher than that of the power supply V1. Diode D1 and diodes D2, D3 and D4 connected in series do not allow discharge of the capacitor. When the transistor Q1 is switched on, a voltage higher than the supply V1 is applied to the motor armature at the initial moment until the capacitor C1 is discharged. Thus, in the anchor winding of the motor, which represents the R-L load, the transient process of current change takes place in a shorter time. The sequence of control pulses from the microcontroller for controlling the motor CP1 and for

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controlling the pulse voltage converter CP2 are shown in Fig.2.

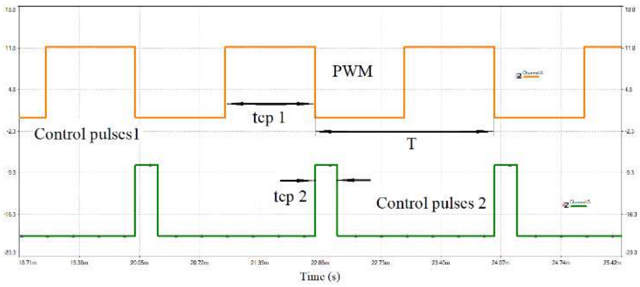

Fig. 2. Sequence of pulses CP1 and CP2 generated by the microcontroller

Each control pulse CP2 for the converter is generated immediately after switching off the transistor Q1. The duration of the control pulses tcp2 is constant and the amount of energy that will be accumulated in the coil L1 depends on it. The duration of the control pulses tcp1 determines the duty cycle of the PWM for motor control. The experiments were performed with a DC executive motor PIC 8 - 6 / 2.5 at a control pulse frequency of 500Hz. The value of the supply voltage V1 is 30V. The inductance of coil L1 is 2mH and the capacitance of capacitor C1 is 470nF. The used transistors Q1 and Q2 are IRF530 and the diodes D1 – D4 are FR604. TC4422 driver circuits are used to control the transistors.

III. Teoretical Analysis of the Transient Process for Charging the Capacitor of the Pulse Converter

The main contribution to realization of the method for addition of energy to the control pulses for the motor has the pulse voltage converter, composed of the elements: driver U2, transistor Q2, coil L1, diodes D2, D3 and D4, and capacitor C1. The transient process for charging the capacitor C1 begins with the switching on of the transistor Q2 from the control pulses CP2 from the microcontroller (Fig.1). After switching on the transistor, the current flowing through the coil L1, accumulates magnetic energy in it. The peak value of this current for the time of the control pulse t_{CP2} is determined by the equation:

$$i_{Lp} = \frac{V_1 . t_{cp2}}{L_1} \quad (1)$$

The accumulated magnetic energy in the coil L1 at the end of the pulse reaches a value equal to:

$$E_{Lp} = \frac{L_1 . i_{Lp}{}^2}{2} \quad (2)$$

After switching off the transistor Q2, the accumulated magnetic energy E_{Lp} is converted into electrical energy ΔE_{C1} and is added to the accumulated energy in the capacitor E_{C0} from the power supply V1:

$$E_{C1} = E_{C0} + \Delta E_{C1} \quad (3)$$

Where E_{C0} is determined by the equation:

$$E_{C0} = \frac{C_1 . V_1^2}{2} \quad (4)$$

When the transistor is switched off, the energy accumulated in the coil is transmitted to the capacitor, converting the magnetic energy into electrical energy. This is a phenomenon observed in a series resonant circuit [7].

$$\Delta E_{C1} = E_{Lp} \quad (5)$$

As a consequence of charging of the capacitor C1 by the pulse converter, its voltage increases by a value ΔV, determined by the equation:

$$\Delta V = \sqrt{\frac{L_1 . i_{Lp}{}^2}{C_1}} \quad (6)$$

As a result, the capacitor is charged to the maximum voltage $V_{C\max}$:

$$V_{C\max} = V_1 + \Delta V = V_1 + \sqrt{\frac{L_1 . i_{Lp}{}^2}{C_1}} \quad (7)$$

After substituting the value of the current i_{Lp} from equation (1), the dependence of the maximum value of the voltage $V_{C\max}$ of the capacitor C1 on the duration of the control pulse t_{CP2} is obtained:

$$V_{C\max} = V_1 + \frac{V_1 . t_{CP2}}{\sqrt{L_1 . C_1}} \quad (8)$$

By changing the pulse duration t_{CP2}, the maximum value of the voltage to which the capacitor C1 will be charged can be changed, and as a consequence, the rate of change of current in the anchor winding of the motor will be changed during the control pulse t_{CP1}.

Figure 3 shows graphically the dependence of the maximum value of the voltage on the capacitor C1 at the end of the control pulse tcp2.

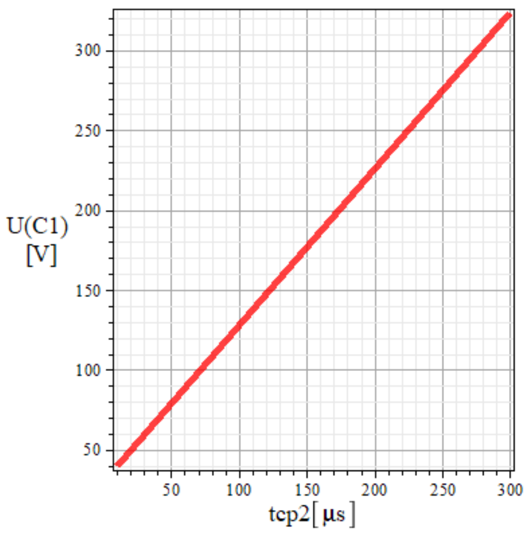

Fig. 3. Maximum value of the voltage of the capacitor C1, depending on the pulse duration tcp2

This dependence is linear which allows the control system to smoothly adjust the amount of energy that will be added to each powerful pulse for the anchor winding of the motor.

These formulas do not take into account the active energy losses in the coil L1 and in the series-connected diodes D2, D3 and D4 in the circuit of the pulse voltage converter.

IV. Experimental Results

Experimental studies of the change in the speed of rotation of the motor and the change in current through the anchor winding at different values of duty cycle of the control pulses D have been carried out. A comparative analysis of the results obtained in the control with the conventional PWM method (without adding additional energy to the control pulses for the motor) and in the control with a constant voltage equal to the average value of the rectangular pulses. The duration of the control pulse for the pulse boost converter tcp2 is equal to 250µs. This pulse duration is in accordance with the minimum pause of the control pulses for the motor tcp1. For the selected control pulse frequency 500Hz, the pulse repetition period is 2ms. At the maximum duty cycle D = 80% the pause is equal to 400µs. In this way there will be no coincidence in time of two control pulses $t_{cp}1$ and $t_{cp}2$. The results of the measurements of the motor speed in revolutions per minute with a change of the duty cycle D from 20% to 80% are shown in Table 1.

TABLE 1

		DC control method	PWM Conventional method	PWM Method with adding of energy
D [%]	V_{ave} [V]	***n*** **[rpm]**	***n*** **[rpm]**	***n*** **[rpm]**
20	6	183	140	200
30	9	633	523	733
40	12	983	873	1120
50	15	1363	1213	1403
60	18	1767	1563	1740
70	21	2153	1887	2033
80	24	2467	2263	2380

The measurements of the speed of rotation of the motor from a source of DC voltage are made for values Vave corresponding to the duty cycle of the pulses D, determined by the equation:

$$V_{ave} = V1 \,.\, D \tag{9}$$

The obtained results are shown graphically in Figure 4.

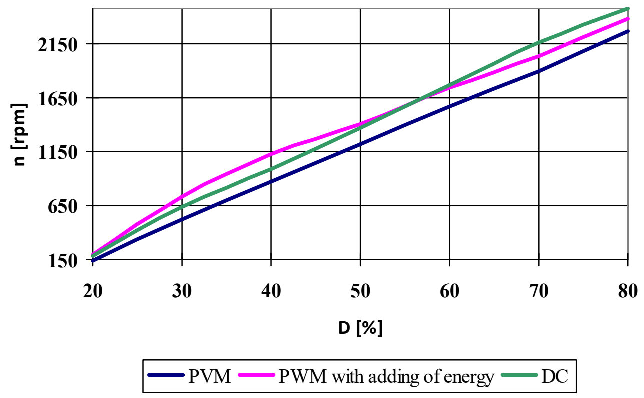

Fig. 4. Change in motor rotation speed as a function of pulse duty cycle

From the obtained results of the measurements it can be seen that the speed of rotation of the motor has the highest value when controlling with the proposed method with adding energy until reaching the pulse duty cycle D = 55%. At values of the duty cycle D from 55% to 80% the speed of rotation of the motor in the proposed method becomes lower compared to the control with DC voltage of the anchor, but remains higher than the control in the conventional method with PWM.

Figures 5 and 6 show oscillograms of applied anchor voltage of the motor and current through the anchor at the duty cycle of control pulses D=50%, respectively when controlling with both PWM methods. Figure 5 shows the change in voltage of the motor anchor when switching on the transistor Q1 during control with the addition of energy to the pulses. At the time of switching on, the anchor voltage is 100V. After about 50µs this voltage drops to the value of the supply voltage 30V. As a consequence of this voltage jump, the current through the motor anchor reaches a value of 1A for 50 µs and then increases linearly to a value of 2.92A.

The speed of rotation of motor in the method with the addition of energy is 190 rpm higher than the speed in control with the conventional method. The rotation speed is also 40 rpm higher than the 15V DC control, which corresponds to a duty cycle of D = 50%.

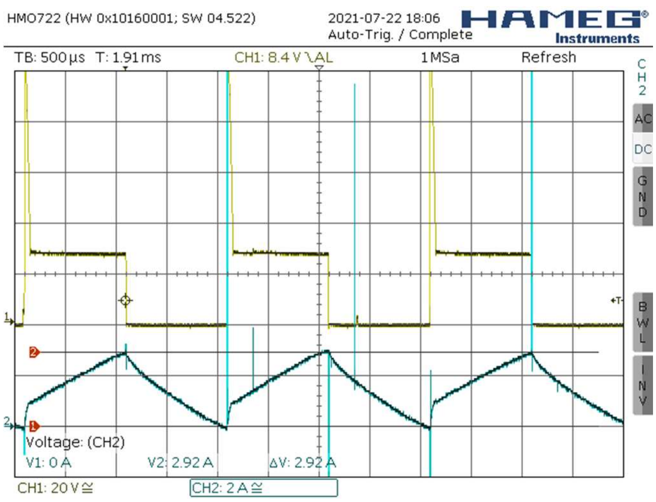

Fig. 5. Change of voltage (beam 1) and change of current (beam 2) of the motor anchor in the method with addition of energy

When controlling with the conventional PWM method (Fig.6) during the control pulse, the anchor winding is supplied with a DC voltage equal to 30V and the current through the anchor winding increases exponentially. In this case, the maximum value of the current through the armature of the motor reaches a lower value of 2.84A than that of the proposed driver. Therefore, in the method of adding energy to each pulse, the motor develops higher torque than the conventional PWM method. In the experiments performed, the applied torque of the motor shaft is constant and equal to the nominal one Mnom = 0,1 N.m.

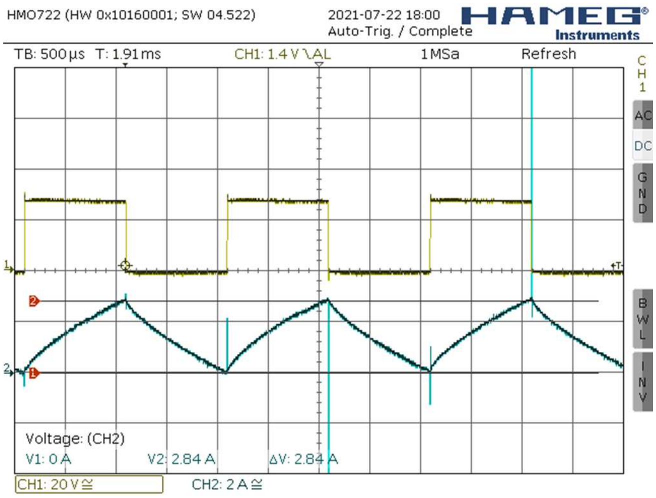

Fig. 6. Change of voltage (beam 1) and change of current (beam 2) of the motor armature in the conventional method with PWM

When controlling with pulse duty cycle D in the entire range from 20% to 80%, the motor operates in continuous current mode. The results of the measurements of the peak current values when controlled by a conventional and energy-added method are shown in Figure 7.

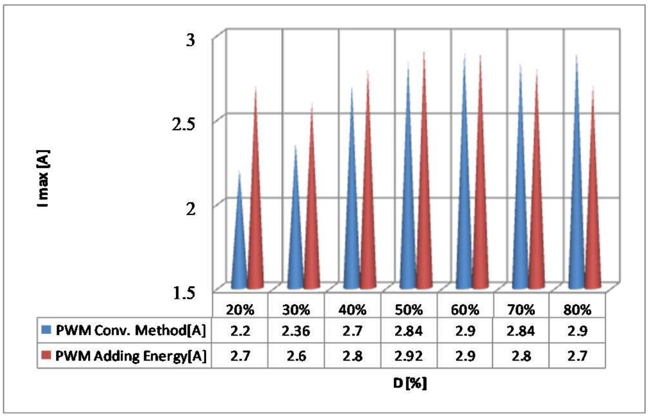

Fig. 7. Peak current values when controlled by conventional and energy-added method

At duty cycle up to 55%, the peak value of the current in the energy-added method reaches a higher value than in the conventional method. At duty cycle of 60% to 80% the peak current value in the energy-added method becomes smaller than in the conventional method, but the motor nevertheless develops a higher rotation speed.

V. CONCLUSION

The designed method and device for pulse control of DC motor with addition of energy allow to increase the speed and torque of the motor shaft at the same duty cycle of the control pulses in comparison with the conventional method for PWM. At pulse duty cycle from 20% to 55% with the proposed new method, the motor develops a higher speed compared to the power supply from a DC source. The pulse voltage converter included in the circuit allows for dosing of the added energy in each of the powerful pulses. In this paper it is made an analysis of the transient process for charging an accumulating capacitor, which provides a high level of voltage at the beginning of the pulse. The relationship between the amplitude value of the voltage of the power pulses and the duration of the control pulses for the pulse voltage converter is determined. This dependence is linear, which allows smooth regulation of the added energy in one control system. The designed impulse control circuit can be included in the structure of a closed automatic control system, as the control is entirely digital. The proposed method of pulse control can be applied in the control of DC, induction and stepper motors.

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