Impulse control of a DC motor with active driver circuit

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This paper describes a study and the results obtained from the implementation of pulse control over a DC motor by means of both a conventional and an active driver for controlling the powerful MOSFET. The studied active driver gives feedback on a derivative of the current in the electrical circuit of the source. The motor operates under a mode of discontinued current at change in the coefficient of the control pulses from 20 to 80%. The paper examines theoretically and experimentally the current change through the motor armature for both logical drive circuits. Based on the constructed experimental setup, involving a motor and a voltage generator for a mechanical load, the torque of the motor has been defined. For the purpose of comparing the efficiency of the engine, the consumed electric power and the developed mechanical shaft power for both control drive circuits have been determined. The change in the motor efficiency as a function of the duty cycle of the control pulses has also been studied. Comparative analysis of the obtained results has been made.

Импулсно управление на постояннотоков двигател с активна драйверна верига (Иван Танев, Светослав Иванов). *В тази статия са описани направените изследвания и получените резултати при импулсното управление на постояннотоков двигател с конвенционален и с активен драйвер за управление на мощния MOSFET транзистор. Изследвания активен драйвер е с обратна връзка по производна на тока във веригата на сорса. Двигателят работи в режим на прекъснат ток, при изменение на коефициента на управляващите импулси то 20 до 80 %. Изследвано е теоретично и експериментално изменението на тока през котвата на двигателя при управление с двете драйверни схеми. На базата на съставената опитна постановка включваща двигател и генератор на напрежение за механичен товар, е определен въртящия момент на двигателя. С цел сравнение на коефициента на полезно действие на двигателя са определени консумираната електрическа мощност и развиваната от вала механична мощност при управление с двете драйверни схеми. Направен е сравнителен анализ на получените резултати.*

1. Introduction

Power losses depend on the operating frequency of a MOSFET, as well as on the value of its input and output capacity, which affect the duration of the transitional processes.

In battery fed power trains, like in cars and lift trucks, power MOSFETs with high current ratings play a significant role. Typical applications are DC Motors or DC/DC converters. Due to the high power and low voltages of i.e. 24V in some applications high currents is the consequence. Thus there is a high demand for low voltage power MOSFETs with a low drain-source on-state resistance $R_{DS(ON)}$ and a low temperature dependence on the market to achieve lower conduction losses [1], [3].

Due to the reduction of the drain-source on-state resistance $R_{DS(ON)}$ of modern power MOSFETs and the subsequently decreasing conduction losses, the switching losses get a higher influence of the total power losses of the semiconductors. With higher switching frequencies this effect rises and can play an important role in the choice of a power MOSFET type and gate drive circuit design has an influence on the switching losses [4], [7], [8].

The modern way to reduce the switching losses or the overvoltages is the active gate control of switch on and switch off via the gate drive. With the di_D/dt feedback control, the di_D/dt of the drain current i_D is sensed and fed back to the gate control path. In this way a control of the rise of the drain current is possible [5], [6]. Characteristic of the studied motor driver circuit is that it produces a "more sloping"

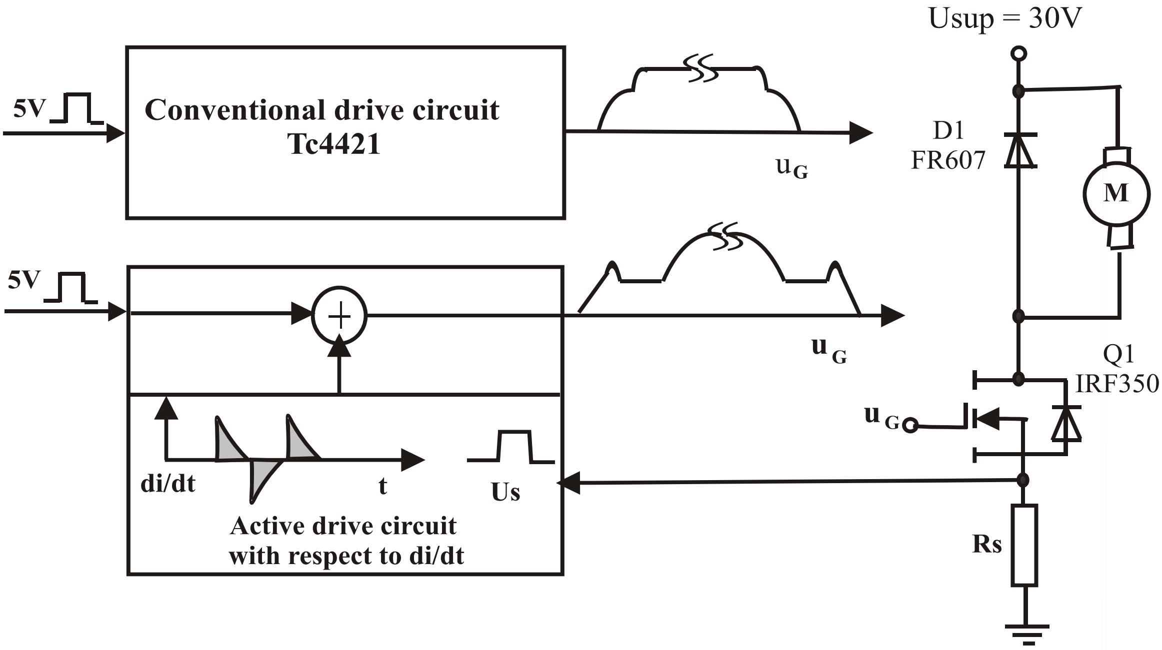

Fig. 1. Schematic of the experimental laboratory model for studying the transients in the DC motor.

control pulse with sinusoidal transitions. Figure 1 shows the shapes of the two control signals.

This paper presents the results obtained from studying an active motor driver circuit with di/dt feedback and a conventional motor driver circuit by the company Microchip, type TS4421, at impulse control of a DC motor, Figure 1. The power losses have been studied, the average value of the current, flowing through its armature coil, $i_{ave,}$ has been determined, the torque M_T has been defined, and a comparison of the efficiency η for the two cases of control has been drawn.

2. Determination of the average current through the armature coil of the DC motor

A motor with maximum operating voltage of 30V and rated torque M_T = 0,11 N.m was used for the purposes of the study. The main engine parameters required for analytical research of transients are: constant BEMF k_b = 0,01; active resistance of the armature winding R = 3,7Ω; inductance of the anchor L = 4mH. Constant torque torgue k_t = 0,0072N.m /A. Research has were made at a frequency of control pulses f = 400Hz and a period of repetition T = 2,5ms, with a duty cycle D = 50%.

During the study the motor was powered with voltage 30V. The studies were carried out under a mode of discontinued current.

2.1 Control by a conventional driver TS4421

The average value of the current flowing through the motor armature at pulse control, provided that the load is active-inductive with BEMF, is determined by the equation:

$$I_{ave} = \frac{2}{T}\int_0^{T/2} \frac{U-E}{R}(1-e^{-\frac{R}{L}t})dt = \tag{1}$$

$$= \frac{U-E}{R}(1+\frac{2L.e^{-\frac{R}{2}\frac{T}{L}}}{R.T} - \frac{2L}{R.T}) =$$

After substituting the values, involved in the equation, with the numerical values of the average current, for I_{ave} it is obtained:

$$I_{ave} = 1,541 \text{ A}.$$

2.2 Control by an active driver with feedback with respect to di/dt

The change of the drain current of the transistor in the closed system comprising the MOSFET and the driver circuit with a negative feedback on a current derivative, can be presented by the equation [2]:

$$i_{DS}(t) = \frac{\frac{U-E}{R}.(1-e^{-\frac{R}{L}t})}{1+k(\frac{U-E}{L}.e^{-\frac{R}{L}t})} \tag{2}$$

where k is the current gain of the feedback circuit with respect to a derivative of the current.

In this case, for determining the average value of the current, flowing through the motor armature, it is necessary to take into account the impact of the negative feedback on the derivative of the current. The average current value can be determined from the equation:

$$I_{ave} = \frac{2}{T}\int_{0}^{T/2} \frac{\frac{U-E}{R}(1-e^{-\frac{R}{L}t})}{1+k(\frac{U-E}{L}.e^{-\frac{R}{L}t})}dt \tag{3}$$

After introducing the new variables, the following equation is obtained:

$$\frac{U-E}{R} = A,\ k\frac{U-E}{L} = B,\ -\frac{R}{L} = \lambda \tag{4}$$

The limits of variation of the time t are in the interval from 0 - T/2. The change of parameter k is in the interval: $1 \div e^{\frac{\lambda.T}{2}}$.

$$I = \frac{2A}{T}\frac{1-e}{1+B.e}dt \tag{5}$$

After putting the following expressions, it is obtained

$$\begin{aligned} & e = x \rightarrow \lambda t = \ln x \rightarrow t = \frac{1}{\lambda}\ln x \\ & dt = \frac{1}{\lambda x}dx \end{aligned} \tag{6}$$

$$I_{ave} = \frac{2A}{T.\lambda}\int_{1}^{e^{\frac{\lambda T}{2}}} \frac{1-x}{(1+B.x)x}dx = \tag{7}$$

$$= \frac{(A_2 + A_1.B)x + A_1}{x(1+B.x)} \tag{8}$$

$$\begin{aligned} & A_2 + A_1.B = -1 \\ & \rightarrow A_1 = 1,\ A_2 = -1-B \end{aligned} \tag{9}$$

$$I_{ave} = \frac{2A}{T.\lambda}\int_{1}^{e^{\frac{\lambda T}{2}}} (\frac{1}{X} - (1+B)\frac{1}{1+B.x})\,dx \tag{10}$$

The solution of the integral is as it follows:

$$\begin{aligned} I_{ave} = & \frac{U-E}{R} + \frac{2L(L+k(U-E))}{R^2.T.k} \times \\ & \ln\frac{L+k(U-E).e^{-\frac{R}{2}.\frac{T}{L}}}{L+k(U-E)} \end{aligned} \tag{11}$$

After substituting with the numerical values, at a value of the feedback coefficient k = 0.0001 (a parameter of the studied driver), for the average current value I_{ave} it is obtained:

I_{ave} = 1,314 A

From the calculations it can be seen that when control with an active driver circuit is implemented, the average value of the current, flowing through the armature of the motor, is smaller.

3. Determination of the torque M_T at impulse control of a DC motor

The studies of the mechanical characteristics were made by means of an experimental model, comprising a motor, mechanically connected to a DC generator. The rotational speed of the motor is measured by a DC tachometer. The block diagram of the experimental model is shown in Figure 2. The basic electrical and mechanical parameters describing the operation of the studied system are presented as well. At pulse control with a duty cycle - 75%, different torque values are obtained for the cases of control, realized by means of the two different drivers.

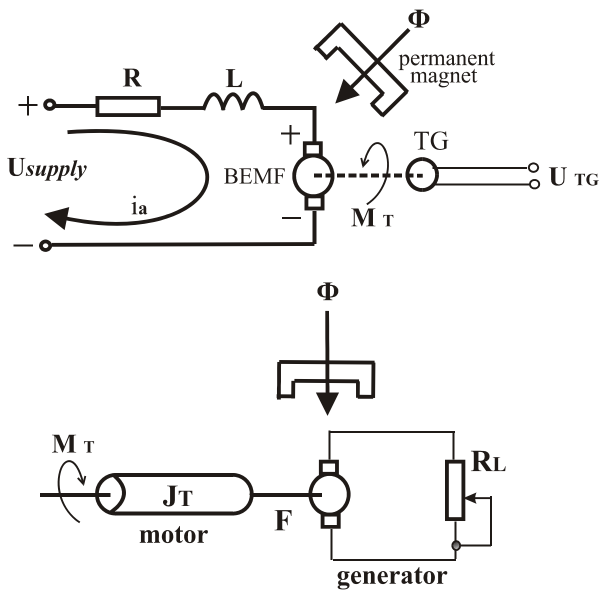

Fig. 2 Block diagram of the experimental model.

The symbols in Figure 2 denote:

Φ - magnetic flux; L - induction of windings; R- resistance of windings; J_T – inertia of motor and load; M_T – torque; TG - tachogenerator; F - rotary friction of motor and generator; Rv – potentiometer: BEMF- Back electromotive force.

The maximum torque reached by the motor armature at the end of the control pulse can be determined by the equations:

(12) $$M_{T\max} = C_e.\Phi.I_{\max} = k_T.I_{\max},$$

where I_{max} is the amplitude current value at the end of the control pulse, Figure 3.

In case of control with a conventional driver, the maximum torque reaches a value, equal to:

(13) $$M = 0,072\,.\,1,25 = 0,09N.m$$

When the control is realized by means of an active driver, the maximum torque has the value:

(14) $$M_{T\max} = 0,072\,.\,1,38 = 0,1N.m$$

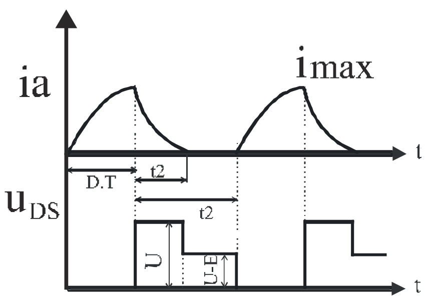

Fig. 3. Graphs, representing the voltage change on the transistor and the current change through the motor armature.

The current value is measured as the voltage on the resistor in series included the armature coil. From the obtained values of the torque it can be seen that in case of control by means of an active driver circuit, it reaches a higher value.

4. Comparison of the influence of the driver circuits on the motor efficiency

Based on the study of the amplitude value of the current, flowing through the motor armature, and the developed maximum torque, a comparative analysis of the efficiency of control with both types of drivers was made.

The mechanical power, developed by the motor shaft, has a value, determined by the equation:

(15) $$P_{mech} = M_T\,.\,\omega$$

The consumed electric power can be determined by the equation:

(16) $$P_{el} = P_{mech} + P_{loss} = P_{mech} + I^2_{ave}.r_a,$$

where r_a is active resistance of the armature winding.

When driving a DC motor with a duty cycle of the control pulses (75%), these types of power have the following values:

- In case of an active driver:

  $P = 19,6\,W$; $P_{el} = 30.1\,W$

- In case of a conventional driver:

  $P_{mech} = 18,6\,W$; $P = 33.63\,W$.

The efficiency under the control by an active driver reaches a value of 65%, while when a conventional driver is used, it has a value of 55%, provided that the attached moment of resistance M_T is the same.

Figure 4 shows the results from the experimental study of the dependence of the developed speed of the motor shaft on the duty cycle of the control impulses for the powerful transistor.

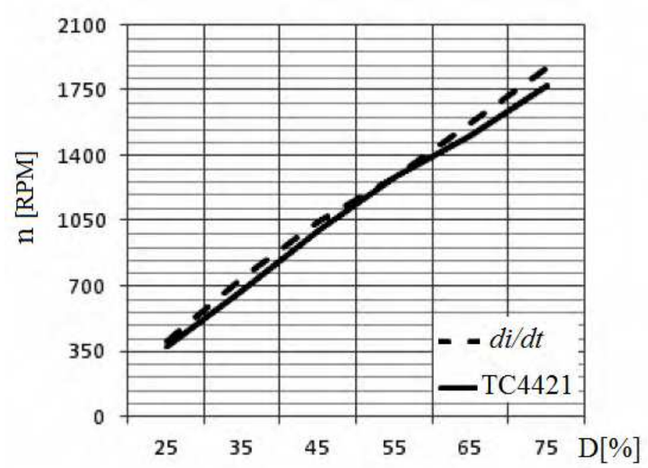

Fig. 4. Graphs of the change of speed as a function of the duty cycle pulse in case of control by means of both drivers.

The studies have been conducted in the range of variation of the duty cycle D from 25% to 75%. The graph shows that in case of control with an active driver, the DC motor reaches higher speeds while equality in the speed of rotation is obtained at D = 50%.

From the conducted analytical and experimental studies it can be seen that under the control of an active driver, the efficiency of the motor is increased by up to 10%.

5. Conclusion

It has been established by the conducted studies that the active driver reduces the speed of change of the current, flowing through the motor armature at the beginning and the end of the transition process at turning the powerful transistor on. In the studies, carried out with a duty cycle D50%, the average speed of rotation of the motor shaft was the same for both driver circuits. During the experimental study the same moment of resistance was attached to the motor shaft and, in result, the same mechanical power was reached by it for both cases of control. From the theoretical studies of the average electric power consumption it was found that under control with an active motor driver circuit the consumption has a smaller value. As a consequence, the motor efficiency under control with an active motor driver circuit was bigger by up to 10%.

The average current value under control with an active control circuit is smaller. From the harmonic analysis of the current change during the transient processes of switching the motor on and off it was found that the amplitude values of the individual harmonic currents have higher amplitude values in case of control with an active motor driver circuit. As a consequence, under the control of an active driver, the amplitude value of the current through the motor armature has a greater value and the engine reaches a higher torque.

The experimental study established that the rotational speed of the engine under the control of an active driver increased in comparison with the case of control with a conventional driver at changes in the duty cycle of pulses from 25 to 50% and from 55% to 80% (Fig. 4). In result, the efficiency of the motor increased, receiving values, reaching up to 10%.

References

[1] Bausire, Idir.R, Franchaud, J. Active gate voltage control of turn-on di/dt and turn-off dv/dt in IGBT. IEEE, vol.21, no.4, pp. 849-855, 2006.

[2] Ivanov, S., Tanev, I. Control of DC Motors with Active Driver Circuit. Techsys 2013, Vol.19, pages 243-246.

[3] Musumeci, S.; Raciti, A.; Testa, A.; Galluzo, A.; Melito, M. Switching Behaviour Improvement of Insulated Gate Controlled Devices; IEEE Transactions on Power Electronics, Vol. 12, No. 4, 1997, pp. 645-653.

[4] Neacsu, D. Active Gate Drivers for motor control applications. IEEE PESC 2001, Vancouver, CANADA, June, 17-21, 2001.

[5] Shimizu, T., K. Wada. A gate drives circuit of power Mosfets and IGBTs for low switching losses. Deagu, Korea: 7th International Conference on Power Electronics, ICPE, 2007.

[6] Weis, B., M. Bruckmann. A new gate driver circuit for improved turn-off characteristics of high current IGBT modules. St. Louis: IEEE Industry Applications Conference, 1998.

[7] Eberle, W., Zhiliang Zhang, Yan-Fei Liu, P.C. Sen. A Simple Analytical Switching Loss Model for Buck Voltage Regulators. Applied Power Electronics Conference and Exposition (APEC), 2008.

[8] Wittig, B., F. Fuchs. Analysis and Improvement of the Switching Behaviour of Low Voltage Power MOSFETs with High Current Ratings under Hard Switching Conditions. IEEE, Vol.2, 2010, pp. 644-649.

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