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DC Motor Operation Controlled from A DC/DC Power Converter in Pulse Mode with Low Duty Cycle

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ABSTRACT

In this paper pulse mode of operation of DC motor controlled by DC/DC power converter is analyzed. DC motor operation with time intervals in which the motor operates without output load is of interest. In this mode it is possible the motor to restore energy. Also, in the paper are represented calculations for the amount of the restored energy in the pulse mode operation of the motor for different duty cyclesc

KEYWORDS DC motor, DC/DC power converter, duty cycle, pulse mode

INTRODUCTION

Often in practice DC motor is supplied by a DC voltage, obtained from unregulated rectifier or accumulator batteries. In this case, DC motor operates at rated speed, determined by the rotor voltage. In case for need speed control, the DC motor is supplied by regulated rectifier or DC/DC power converter (chopper) [1]-[4].

In Fig. 1 is shown a circuit of a DC motor controlled by DC/DC power converter which is commonly used and analyzed in [1], [2]. The output voltage $u_M(t)$ depends from the gate pulse width t_i (excitation pulse) and switching period T_s ratio. Thus, the duty cycle of the DC/DC converter is defined as $k = t_i/T_s$. By changing the width of the pulse t_i (i.e. by changing the duty cycle $k = t_i/T_s$) the average voltage of the motor $u_M(t)$ is changed .

In Fig. 2 are shown the waveforms of the input current i_{sw} of DC/DC convertor which is same with current through the transistor T (Fig. 2a), the current through the diode i_D (Fig. 2b), the current through the motor i_M (Fig. 2c), and the output voltage of the motor u_M (Fig. 2d) for duty cycle $k = 0.9375$. The waveforms are obtained with simulations of the circuit represented in Fig.1 in the software package PowerSim [5].

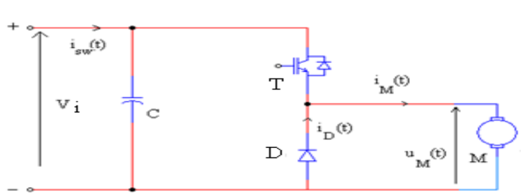


Figure1: Circuit of DC motor controlled by DC/DC power converter

Fig. 2c shows that for the topology represented in Fig. 1, the current through the DC motor is a result of the current through the transistor and the current through the diode. This is a classic case of DC motor control with DC/DC converter analyzed in [1]-[4], [6].

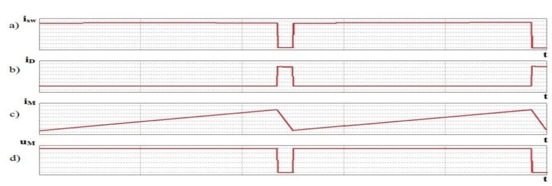


Figure 2: Waveforms of the currents and the voltage in the DC/DC converter: a) input current i_{sw}, b) current through the diode i_D, c) current through the motor i_M and d) output voltage for duty cycle $k = 0.9375$.

The operation of the DC motor that has idle time intervals and restores energy (regenerative energy) is represented in [7]. Operation of a DC motor with variable duty cycle and the amount of energy that the motor restores at different duty cycles are not in scope of this paper.

This paper emphasizes the operation of the DC motor in pulse mode and low duty cycle. Analyzes are performed when DC motor is supplied by a pulse voltage with lower amplitude and a greater duty cycle and pulse voltage with greater amplitude and lower duty cycle. In both cases analyzes are made when the motor is with and without output load. For this purpose, the topology of the DC/DC converter shown in Fig. 3 is used.

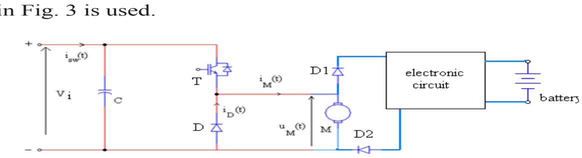


Figure 3: DC motor controlled by DC/DC power converter and integrated electronic circuit for collecting the regenerative energy from the motor

The DC/DC converter in Fig. 3 is connected with two diodes and an electronic circuit block. This circuit is turned on in time intervals when the transistor T is turned off. With this, it is possible to collect the regenerative energy which the motor has stored previously. This energy is then stored in the battery B.

In Fig.4 are shown experimentally obtained waveforms of the voltage $u_M(t)$ (channel 1) and the current $i_M(t)$ (channel 2) of the DC motor in case when the motor is controlled by a DC/DC power converter with duty cycle $k = t_i/T_s$ and the built electronic block as in Fig. 3.

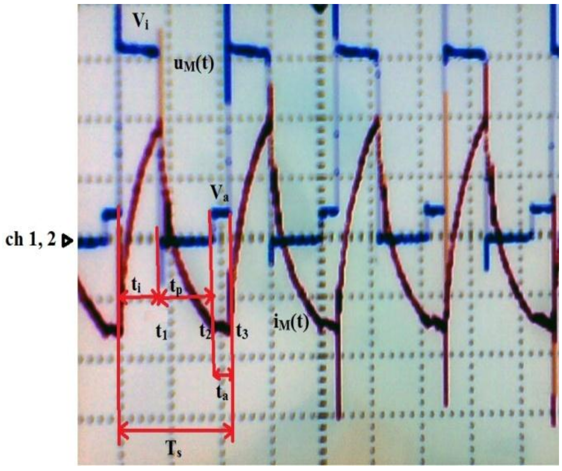


Figure 4: Waveforms of the voltage u_M(t) (channel 1) and current i_M(t) (channel 2) of the DC motor, controlled by a DC/DC power converter: with duty cycle $k = t_i/T_s$, excitation pulse with duration t_i, amplitude $V_i$and frequency f_s.

The amplitude of the excitation voltage pulse is V_i, the frequency is f_s, (the period is T_s), and the duration is t_i. The duration of the excitation pulse t_i is determined by the time in which the transistor in the DC/DC converter is turned on [4]. t_p is the pause time, and t_a is the time interval in which the motor operates in regenerative mode, i.e. restores energy, or simply the motor operates as a generator and generates a voltage with amplitude V_a.

OPERATION OF DC MOTOR IN PULSE MODE

Analyzes are performed for mode in which the motor operates without output load. The power which the DC motor receives during one period is:

$$P_M(t) = \frac{1}{T_s}\int_0^{T_s} u_M(t) i_M(t) dt \qquad (1)$$

Where $T_s = 1/f_s$ is the period of the pulse, $u_M(t)$ is the voltage of the motor and $i_M(t)$ is the current through the motor. The power that the motor receives in the time interval $t_1 = ti$ (in Fig. 4, the time in which the transistor in the DC/DC converter is turned on) is:

$$P_M(t) = \frac{1}{T_s}\int_0^{t_i} u_M(t) i_M(t) dt \qquad (2)$$

In the time interval t_i, the voltage u_M has amplitude V_i, so that (2) gets the form:

$$P_{M,i}(t) = \frac{V_i}{T_s}\int_0^{t_i} i_i(t) dt \qquad (3)$$

The waveform of the current $i_i(t)$ in the time interval t_i can be approximated with an equation of straight line, i.e.:

$$i_i(t) = \frac{t}{t_i}\left[i_i(t_i) - i_i(0)\right] + i_i(0) \quad (4)$$

In (4), $i_i(0)$ is the current of the motor at the moment $t = 0$, and $i_i(t_i)$ is the current at the finishing moment of the time interval t_i.

If (4) is substituted in (3), after solving the integral, for the power which the motor receives from the power source in the time interval (0, ti) is obtained:

$$P_{M,i}(t) = V_i \frac{t_i}{T_s}\left[\frac{i_i(t_i)}{2} + \frac{i_i(0)}{2}\right] \quad (5)$$

In time interval $t_a = t_3 - t_2$, the motor operates in regenerative mode, i.e. restores energy. The voltage which the motor generates in this interval is $u_a(t)$, and the current is $i_a(t)$. The power which the motor restores in this interval can be determined from the equation:

$$P_a(t) = \frac{1}{T_s}\int_{t_2}^{t_3} u_a(t) i_a(t) dt \qquad (6)$$

In time interval t_a, the voltage $u_a(t)$ has amplitude V_a as shown in Fig. 4, and the current $i_a(t)$ can be determined as the average of its values at the moments t_2 and t_3:

$$I_a = \left[\frac{i_a(t_2) + i_a(t_3)}{2}\right] \quad (7)$$

With this, (6) gets the form:

$$P_a(t) = \frac{V_a}{T_s}\left[\frac{i_a(t_2 + i_a(t_3)}{2}\right]\int_{t_2}^{t_3} dt =$$

$$= \frac{V_a}{T_s}\left[\frac{i_a(t_2 + i_a(t_3)}{2}\right](t_3 - t_2) = \frac{V_a}{T_s}\left[\frac{i_a(t_2 + i_a(t_3)}{2}\right]t_a$$

(8)

The duty cycle $k = t_i/T_s$ depends on the time interval t_i, in which the transistor in the DC/DC converter is turned on. For two values of the duty cycle k_1 и k_2 the corresponding time intervals t_i will be marked as $t_{i,1}$ and $t_{i,2}$, the time intervals t_a will be marked as $t_{a,1}$ and $t_{a,2}$, and the corresponding variables in (5) and (8) will be marked with indexes $_{i,1}$ and $_{i,2}$. So, for value of k_1, for the power that the motor receives from the power source in the time interval $t_{i,1}$, from (5) is obtained:

$$P_{M,i,1} = V_{i,1}\frac{t_{i,1}}{T_s}\left[\frac{i_{i,1}(t_{i,1})}{2} + \frac{i_{i,1}(0)}{2}\right] (9)$$

And for the value k_2, the power that the motor receives in time interval $t_{i,2}$ is obtained:

$$P_{M,i,2} = V_{i,2}\frac{t_{i,2}}{T_s}\left[\frac{i_{i,2}(t_{i,2})}{2} + \frac{i_{i,2}(0)}{2}\right] (10)$$

If (9) and (10) are divided the following equation is obtained:

$$\frac{P_{M,i,1}}{P_{M,i,2}} = \frac{V_{i,1}t_{i,1}}{V_{i,2}t_{i,2}}\frac{i_{i,1}(t_{i,1}) + i_{i,1}(0)}{i_{i,2}(t_{i,2}) + i_{i,2}(0)} (11)$$

The power that the motor receives from the power source, depends on its mechanical load, and always will be same regardless of the duty cycle k, the time interval t_i and the amplitude V_i. This means that the value of (11) is always a unit. If $k_1 < k_2$ then $(t_{i,1} = k_1T_s) < (t_{i,2} = k_2T_s)$, therefore from the equality of the received power of the motor in both cases, follows that $V_{i,1} > V_{i,2}$ and $(i_{i,1}(t_{i,1}) + i_{i,1}(0)) > (i_{i,2}(t_{i,2}) + i_{i,2}(0))$.

For the value k_1 from (8) for the power which the motor restores in the time interval ta,1 is obtained

$$P_{a,1} = \frac{V_{a,1}}{T_s}\left[\frac{i_{a,1}(t_2) + i_{a,1}(t_3)}{2}\right]t_{a,1} (12)$$

For the value k_2 from (8), for the power which the motor restores in time interval $t_{a,2}$ is obtained:

$$P_{a,2} = \frac{V_{a,2}}{T_s}\left[\frac{i_{a,2}(t_2) + i_{a,2}(t_3)}{2}\right]t_{a,2} (13)$$

If (12) and (13) are divided the following equation is obtained:

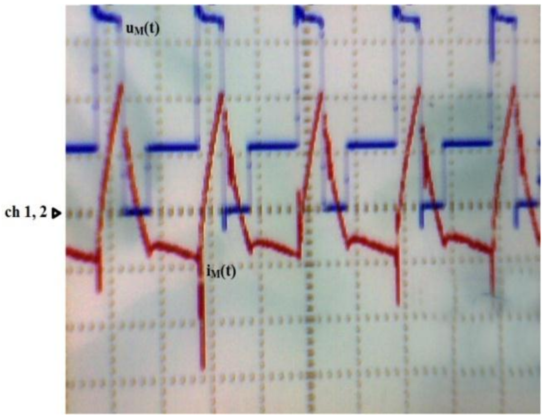
$$\frac{P_{a,1}}{P_{a,2}} = \frac{V_{a,1}t_{a,1}}{V_{a,2}t_{a,2}}\frac{i_{a,1}(t_2) + i_{a,1}(t_3)}{i_{a,2}(t_2) + i_{a,2}(t_3)} \quad (14)$$

From (14) can be determined the relation between the powers which the motor restores energy in two different time intervals $t_{a,1}$ and $t_{a,2}$ for two different duty cycles k_1 and k_2.

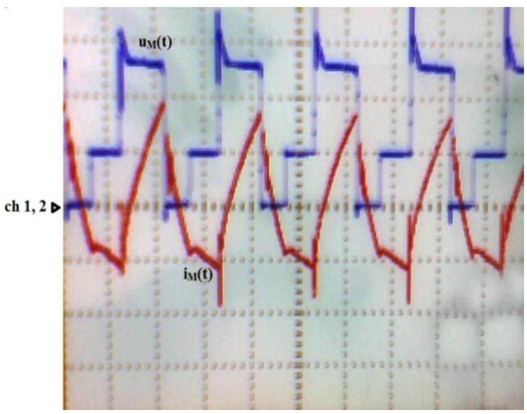
In Fig. 5 are shown experimentally obtained waveforms for the voltage $u_M(t)$ (channel 1) and the current $i_M(t)$ (channel 2) of the DC motor. The DC motor is controlled by an IGBT DC/DC power converter, for two values of the duty cycle k_1 and $k_2 > k_1$. For collecting the restored power from the motor for the time interval t_a, an electronic circuit is built which operates only in this time interval as in Fig. 3.

From the waveforms shown in Fig. 5 can be concluded that the amplitude of the excitation pulse V_i, the amplitude of the generated voltage $V_{a,i}$ and the time interval $t_{a,i}$ (in which the motor restores energy), are greater in case when the duty cycle is lower (waveforms shown in Fig. 5a); And also, the time interval t_i is short in the case when the duty cycle is lower (waveforms shown in Fig. 5a).

From (12) - (14) and from the waveforms in Fig. 5, can be concluded that when $k_1 < k_2$, $t_{i,1} < t_{i,2}$: 1) For lower duty cycles (the case with waveforms for k_1 in Fig. 5a), the voltage which the motor generates $V_{a,1}$, the average value of the current $i_{a,1}$ in the time interval $t_{a,1}$, are greater than the voltage $V_{a,2}$, the average value of current $i_{a,2}$ in the time interval $t_{a,2}$ (the case with waveforms for k_2 in Fig. 5b). The power $P_{a,1}$ which the motor restores in the time interval $t_{a,1}$ is greater than the power $P_{a,2}$ which the motor restores in the time interval $t_{a,2}$.



a)



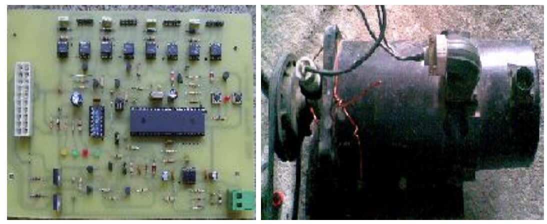
b)

Figure 5: Waveforms of the voltage u_M(t) (channel 1: H-250 µS /div, V −50V/div) and current i_M(t) (channel 2: H-250 µS/div, V −4A/div) of DC motor, controlled from an IGBT DC/DC power converter: a) for duty cycle k_1, b) for duty cycle $k_2 > k_1$.

From this can be concluded that when the DC motor operates in pulse mode and a lower duty cycle, the amount of the restored energy in the time interval $t_{a,i}$ is greater.

EXPERIMENTAL RESULTS

In the measurement phase and testing IGBT DC/DC power converter is used with switching frequency $f_s = 1.972$ kHz (period $T_s = 1/f_s = 507.10$ µs) and electronic circuit with 4-bit resolution [8], [9]. This provides that the excitation pulses of the IGBT transistor gate (which is in the time interval t_i) is in the range of $T_s/16$ = (507.10/16) µs = 31.70 µs to 16$\cdot$ $Ts/16$ = 507.10 µs. In the experimental test DC motor with permanent magnet is used with the following features: rotor voltage V_M = 100 V, rotor current i_M = 30 A, power P_M = 3 kW and n_M = 1600 rpm. In Fig. 6 are shown the control electronic circuit of the DC/DC converter and the DC motor which is used in the experimental measurements.



a) b)

Figure 6: a) Control electronic circuit of the DC/DC converter and b) DC motor used in the experimental measurements.

First, motor with connected output mechanical loads is analyzed for two values of the duty cycle $k_1 = 0.25$ and $k_2 = 0.44$ The average values of the input DC voltage are determined and thus the power which the motor receives for both duty cycles is the same.

Therefore, a DC voltage source with regulated rectifier connected to the input of the DC/DC converter is used. For duty cycle k_1 = 0.25 the measured input power is P_{in} = 385 W, the average value of the input voltage in the DC/DC converter is V_{in} = 172 V, and the motor shaft speed is n = 780 rpm. For duty cycle k_2 = 0.44, it is measured P_{in} = 385 W, V_{in} = 132 V and n = 780 rpm.

The waveforms of the voltage $u_M(t)$ and the current $i_M(t)$ of the DC motor, controlled by an IGBT DC/DC power converter for duty cycle $k_1 = t_i/T_s = (4T_s/16)/T_s = 0.25$ are shown in Fig. 5a and the waveforms for duty cycle $k_2 = (7T_s/16)/T_s = 0.44$ are shown Fig. 5b.

Based on the waveforms shown in the Fig. 5a and 5b, as and in (9) - (14), in Table I and Table II the values of t_i, t_a, t_p, V_i, V_a, $i_i(0)$, $i_i(t_i)$, $i_a(t_2)$, $i_a(t_3)$, $P_{M,i}$, $P_{a,i}$, $P_{M,1}/P_{M,2}$, $P_{a,1}/P_{a,2}$ and n are given.

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From the data presented in Table 1 and Table 2 can be concluded that the power which the motor receives during the time interval t_i is almost the same for both duty cycles k_1 and k_2; and that the power which the motor restores in time interval t_a is greater when the duty cycle is lower.

TABLE– 1
THE VALUES OF t_i, t_p, t_a, V_i, V_a, $i_i(0)$, $i_i(t_1)$, $i_i(t_2)$, $i_i(t_3)$

k	t_i(µs)	t_p (µs)	t_a (µs)	V_i (V)	V_a (V)	$i_i(0)$ (A)	$i_i(t_1)$ (A)	$i_i(t_2)$ (A)	$i_i(t_3)$ (A)
0.25	126.8	120.4	260	172	58	-1.2	8.4	3	3.6
0.44	221.9	140.2	145	132	49	-1.6	7	3.3	4

TABLE – 2
THE VALUES OF $P_{M,i}$, $P_{a,i}$, $P_{M,1}$ / $P_{M,2}$, $P_{a,1}$ / $P_{a,2}$ and n

k	$P_{M,i}$ (W)	$P_{a,i}$ (W)	$P_{M,1}$ / $P_{M,2}$	$P_{a,1}$ / $P_{a,2}$	n (rpm)
0.25	154.8	98.1	≈1	1.92	1200
0.44	156	51.1			1200

CONCLUSIONS

In this paper, theoretical analysis of DC motor operation in pulse mode and low duty cycle is represented. With this theoretical analysis and from experimentally obtained waveforms of the DC motor voltage and current, controlled by a DC/DC converter for different duty cycles is determined the power which the motor receives from the power source, and also the power which it restores in time interval without excitation pulse. The results of the theoretical analysis are supported by the results from experimental measurements.

The results of the theoretical analysis and experimental measurements show that when the DC motor operates in pulse mode, the greater amplitude of the excitation pulse and lower duty cycle, the amount of the restored motor energy is greater.

Increasing the amount of the restore motor energy and restoring it to the circuit back, contributes to improve the efficiency of the system DC/DC converter – DC motor.

The results presented in the paper are applicable for DC motors modes that has periods in which the motor operates without load. This is a good basis for future research in the applications of DC motors in industrial machinery with fans and pumps.

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