

Impact of PWM Control Frequency onto Efficiency of a 1 kW Permanent Magnet Synchronous Motor

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Abstract—The paper explains how to select the best PWM control frequency for specific Permanent Magnet Synchronous Motors (PMSM) to achieve its maximum efficiency. Examinations were carried out for a PMSM unit with the power of 1 kW, rated speed of 1000 rpm and rated torque of 6 Nm. The PWM frequency ranged from 4 kHz to 20 kHz with the increment of 1 kHz. Measurements were taken for each of the foregoing frequencies, for the load torques of 2 Nm, 4 Nm and 6 Nm and for the rotation speeds of 300 rpm, 500 rpm, 750 rpm, 1000 rpm and 1200 rpm to find out efficiency of the PMSM motor. The achieved results make it possible to properly adjust the PWM control frequency for each PMSM motor to operate the motor in the most efficient way and, in consequence, save energy consumed by that motor.

Index Terms—Motor drives; permanent magnet machines; torque control; vector control; PWM.

I. INTRODUCTION

In the group of electric motors, the motors with NdFeB permanent magnets have the highest efficiency and maximum torque [1]. Electric motors with permanent magnets allow for simplifying engine design. The motor stator is generally similar to the induction motor stator, and the rotor comprises permanent magnets affixed in a suitable manner, wherein there are two basic designs: rotor magnets glued to the rotor surface and magnets glued inside rotor grooving [1]. The most common designs of brushless motors include synchronous brushless PMSM (Permanent Magnet Synchronous Motor) and a DC brushless motor BLDC (BrushLess DC electric motor) [2]–[4].

The simplified design of permanent magnet motors is their indisputable advantage. However, because they are devoid of the commutator, the weight of control is transferred substantially in the direction of electronic control of the electric motor. The magnets and the windings in PMSM are arranged so that the electromagnetic force resulting from the

rotation is a form of sinusoidal. The control system must be capable of supplying the motor sinusoidal. Generally, the Field Oriented Control (FOC) is used for this purpose. The power loss related to torque and rotary speed can be reduced, among others, by adjusting the value of d current in a dq model [5]. The methods of increasing the efficiency of a driving system with a PMSM are also described in [6]. A detailed simulation analysis of the motor's work has been performed, including the frequency of pulse width modulation. It should be stressed that the simulations in Matlab/Simulink will never reflect reality (distortions, nonlinearities, parasitic elements, *etc.*). This is the reason for performing experiments with a real motor driven by a real circuit and motivation to the research presented in this paper. The disturbances and their impact on the control unit were examined earlier and it was presented in [7]. The article presents the experimental results of the efficiency of a 1 kW PMSM motor for different frequencies and different torque loads.

II. FIELD ORIENTED CONTROL

Field Oriented Control of the PMSM motor, in great simplification, involves measuring the feedback signal (voltage and current values of the stator windings, the position angle of the rotor), the transformation of those on the two-phase system, the calculation of a new phase voltage with their transformation to the three-phase system, and appropriate control the power inverter (Fig. 1).

Feedback, important for PMSM motor control, provides current, voltage and angle of rotation through the used sensors. Then, by appropriately scaling the signals (i_a , i_b , and i_c) in the ADC, Clark transformation is performed, which enables the transition from phase to two-phase system (i_a , i_b). Then, using the information about the position of the rotor the Park transformation is performed, through which it is possible to switch to a rotating coordinate system (d, q). As a result of these calculations currents (i_{ds} , i_{qs}) are obtained. In the next step, calculated currents (i_{ds} , i_{qs}) and the currents

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(i_{ds}^*, i_{qs}^*) are served on the PI controllers that set new values of voltage (V_{qs}^*, V_{ds}^*). Values of these voltages are subjected to the inverse transform Park (using the information of the rotor position q), which produces a voltage (V_a, V_b). Based on this, in turn, voltage (V_a, V_b, V_c) are generated. Respective rectangular waveforms, for controlling the power transistors T1-T6 of the inverter are produced by PWM block. Power unit produces a voltage three-phase inverter with an appropriate amplitude and offset.

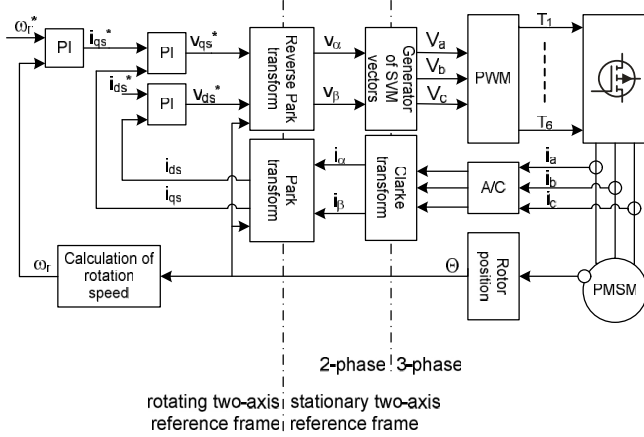


Fig. 1. Signal flowing diagram for a PMSM motor.

Equations for Clarke and Park transformations are presented in (1) and (2) respectively [2]–[4], [8]:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \quad (1)$$

$$\begin{bmatrix} u_q \\ u_d \\ u_0 \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin(\theta) & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}, \quad (2)$$

where θ is the position angle of the rotor.

Measurements related to impact of the PWM control frequency onto efficiency of Permanent Magnet Synchronous Motors (PMSM) were carried out within the first zone of the motor control due to operation of the motor with the load torques up to 6 Nm.

III. EXPERIMENTS

A. Laboratory Setup

In order to conduct the research, the laboratory, whose scheme is shown in Fig. 2 is used. The digital signal processor TMS320F2812 is used as a control system. This processor is a dedicated system for controlling 3-phase motors [9]. The processor includes a multi-channel ADC, PWM module with the ability to programmatically set the dead time.

One of the problems is the electromagnetic interference coming from the PM synchronous motor. Figure 3 shows the waveform of one rotation of the motor phases. The method of reduction the impact of these disturbances on the system is shown in [7]. Parameters of the motor are summarized in Table I.

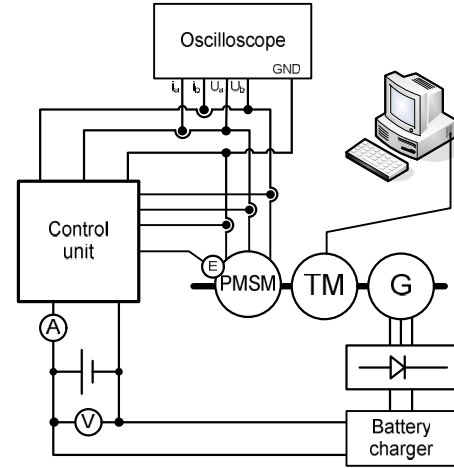


Fig. 2. The laboratory set with PMSM motor.

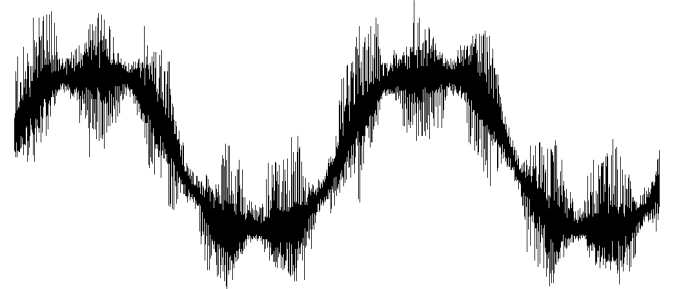


Fig. 3. The back-EMF of the PMSM motor operated in the generator mode.

TABLE I. PMSM MOTOR NAMEPLATE.

Number of poles	3
Rated current	25 A
Rated voltage	48 V
Torque	6 Nm
Rated speed	1000 rpm
Maximal current	35 A
Rated power	1 kW

One of the most important components in the Field Oriented Control system analysed in this paper is the encoder and sensors meant to measure winding currents (Fig. 2).

The MAB28 by Megatron [10] is used as the encoder transducer. The main advantage of MAB28 is the lack of impact of its work on electromagnetic interference generated by the engine. In order to measure the phase currents, the CASR 25-NP current transducers have been used [11].

The PM50RLA060 bridge produced by Mitsubishi has been selected as a power bridge of the inverter [12]. This bridge consists of IGBTs with a maximum current of $I_C = 50$ A and a maximum voltage $U_{CE} = 600$ V, which allows one to control engines with high operating voltages and large

currents as ratings.

The laboratory setup as seen in Fig. 2 includes a 4-channel oscilloscope, torque meter TM and engine G that work as a generator. The voltage of the generator is rectified and used to charge the batteries that supply power inverter. The tested PMSM motor with an output of 1kW is connected on one shaft together with TM (DATAFLEX 22/20 [13]) and the generator G.

The torque meter at its output provides a voltage signal proportional to the load torque. Due to the shift of the 0 point of this meter, the PMSM motor has been tested in both directions. Then the average load torque is determined.

Another problem is to measure the efficiency of the engine. For this purpose, an Aron connection circuit can be used as shown in Fig. 4. In the case of motor PMSM the 4-channel digital oscilloscope, two current probes and two voltage probes are used.

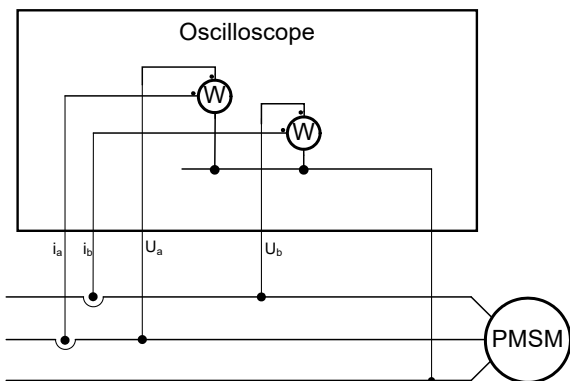


Fig. 4. The Aron circuit for measurements of active power with use of an oscilloscope.

B. Experimental Results

Measurements were taken in the following way:

- Setting of the PWM control frequency for the motor (4kHz-20kHz with the increment of 1kHz),

- Setting of the constant rotation frequency for the motor (300 rpm, 750 rpm, 1000 rpm, 1200 rpm),
- Setting of the constant load torque for the motor (2 Nm, 4 Nm, 6 Nm),
- For the given motor, speed (rpm) and load torques measurements were taken to find out power consumed by the motor (by means of the oscilloscope) and power delivered to the output shaft (by means of a torque meter).

Hence, one can say that the measurements were taken for each initially preset rotation speed of the PMSM motor (300 rpm, 750 rpm, 1000 rpm and 1200 rpm), for each frequency of supplying voltage and current (4 kHz–20 kHz with the increment of 1 kHz) and for constant load torques of 2 Nm, 4 Nm and 6 Nm, so they cover the full range of the motor operation. Consequently, the collected information makes it possible to establish how the efficiency of the PMSM motor changes in pace with variations of the motor rpm, load torque and control frequency.

Table II summarizes results acquired from measurements of the PMSM motor efficiency for PWM frequencies ranging from 4 kHz to 20 kHz with the increment of 1 kHz, for the speed values of 300 rpm, 500 rpm, 750 rpm, 1000 rpm and 1200 rpm for the constant torque of 2 Nm.

The graph for efficiency of the PMSM motor plotted for variations of the PWM control frequency and for the constant load torque of 2 Nm is shown in Fig. 5.

Table III summarizes results collected from measurements of the PMSM motor efficiency for PWM frequencies ranging from 4 kHz to 20 kHz with the increment of 1 kHz, for the speed values of 300 rpm, 500 rpm, 750 rpm, 1000 rpm and 1200 rpm for the constant load torque of 4 Nm.

The graph for efficiency of the PMSM motor plotted for variations of the PWM control frequency and for the constant load torque of 4 Nm is shown in Fig. 6.

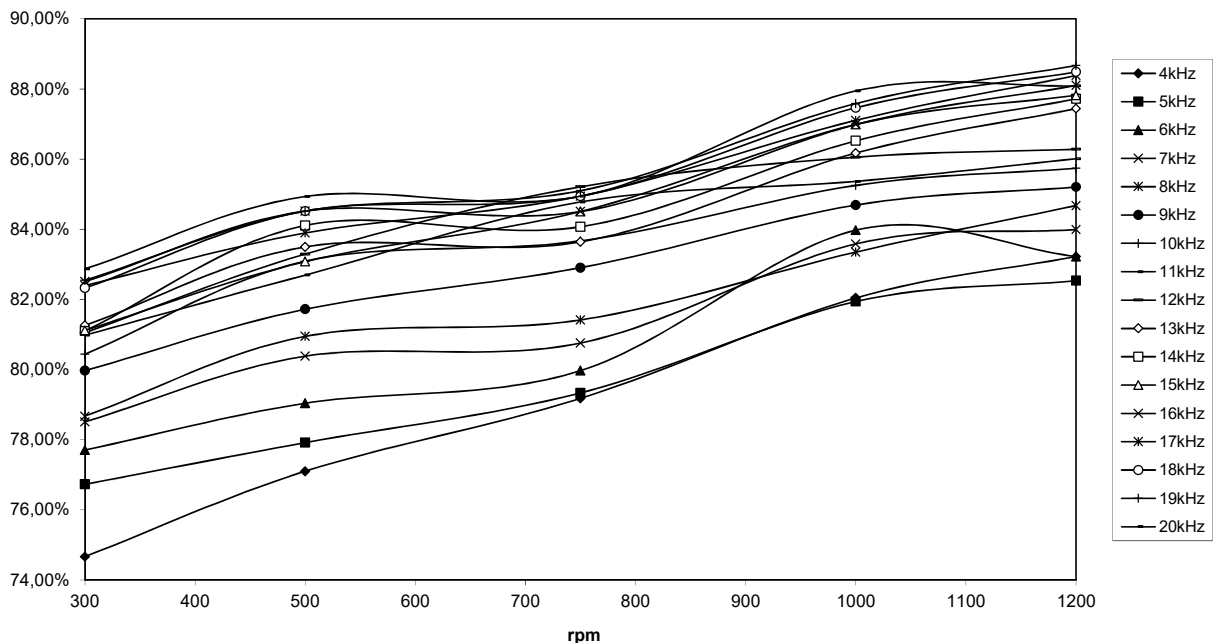


Fig. 5. Efficiency of the PMSM motor for various PWM control frequencies and for the load torque of 2 Nm.

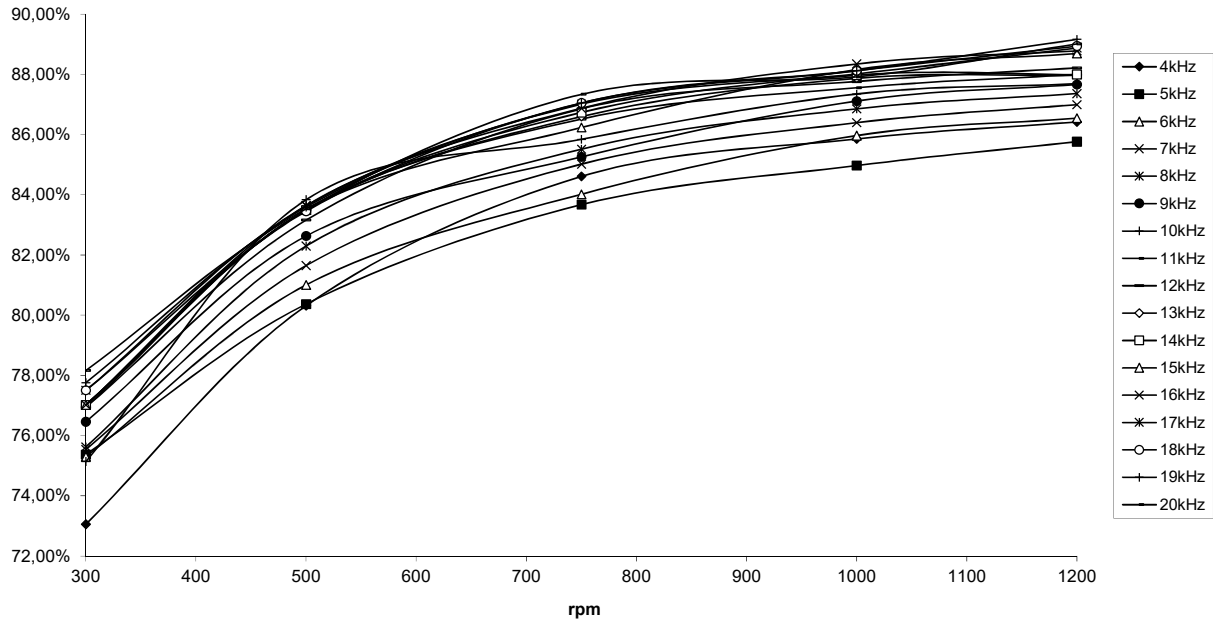


Fig. 6. Efficiency of the PMSM motor for various PWM control frequencies and for the load torque of 4 Nm.

TABLE II. EFFICIENCY OF THE PMSM MOTOR FOR THE LOAD TORQUE OF 2 NM.

f[kHz]	rpm				
	300	500	750	1000	1200
4 kHz	74.66 %	77.10 %	79.18 %	82.04 %	83.22 %
5 kHz	76.73 %	77.92 %	79.33 %	81.94 %	82.53 %
6 kHz	77.70 %	79.04 %	79.97 %	83.97 %	83.22 %
7 kHz	78.51 %	80.38 %	80.76 %	83.58 %	83.99 %
8 kHz	78.67 %	80.95 %	81.41 %	83.35 %	84.68 %
9 kHz	79.97 %	81.72 %	82.90 %	84.69 %	85.20 %
10 kHz	80.44 %	83.09 %	83.67 %	85.25 %	85.74 %
11 kHz	80.98 %	82.69 %	84.78 %	85.37 %	86.01 %
12 kHz	81.05 %	83.29 %	85.21 %	86.05 %	86.28 %
13 kHz	81.26 %	83.50 %	83.64 %	86.17 %	87.44 %
14 kHz	81.10 %	84.11 %	84.07 %	86.52 %	87.72 %
15 kHz	81.12 %	83.08 %	84.50 %	86.99 %	87.82 %
16 kHz	82.50 %	84.52 %	84.50 %	86.99 %	88.10 %
17 kHz	82.40 %	83.89 %	84.94 %	87.11 %	88.38 %
18 kHz	82.32 %	84.52 %	84.94 %	87.46 %	88.49 %
19 kHz	82.54 %	84.52 %	85.10 %	87.58 %	88.67 %
20 kHz	82.87 %	84.93 %	84.94 %	87.95 %	88.09 %

TABLE III. EFFICIENCY OF THE PMSM MOTOR FOR THE LOAD TORQUE OF 4 NM.

f[kHz]	rpm				
	300	500	750	1000	1200
4 kHz	73.05 %	80.31 %	84.61 %	85.85 %	86.42 %
5 kHz	75.37 %	80.37 %	83.67 %	84.97 %	85.76 %
6 kHz	75.30 %	81.00 %	84.02 %	85.96 %	86.54 %
7 kHz	75.54 %	81.65 %	85.02 %	86.39 %	86.99 %
8 kHz	75.62 %	82.30 %	85.52 %	86.85 %	87.36 %
9 kHz	76.46 %	82.63 %	85.26 %	87.11 %	87.66 %
10 kHz	75.14 %	83.83 %	85.84 %	87.35 %	87.69 %
11 kHz	76.94 %	83.49 %	86.51 %	87.55 %	87.99 %
12 kHz	76.94 %	83.16 %	86.85 %	87.76 %	88.21 %
13 kHz	77.02 %	83.49 %	86.60 %	87.87 %	87.97 %
14 kHz	77.02 %	83.49 %	86.73 %	87.97 %	87.99 %
15 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
16 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
17 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
18 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
19 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
20 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %

f[kHz]	rpm				
	300	500	750	1000	1200
4 kHz	73.05 %	80.31 %	84.61 %	85.85 %	86.42 %
5 kHz	75.37 %	80.37 %	83.67 %	84.97 %	85.76 %
6 kHz	75.30 %	81.00 %	84.02 %	85.96 %	86.54 %
7 kHz	75.54 %	81.65 %	85.02 %	86.39 %	86.99 %
8 kHz	75.62 %	82.30 %	85.52 %	86.85 %	87.36 %
9 kHz	76.46 %	82.63 %	85.26 %	87.11 %	87.66 %
10 kHz	75.14 %	83.83 %	85.84 %	87.35 %	87.69 %
11 kHz	76.94 %	83.49 %	86.51 %	87.55 %	87.99 %
12 kHz	76.94 %	83.16 %	86.85 %	87.76 %	88.21 %
13 kHz	77.02 %	83.49 %	86.60 %	87.87 %	87.97 %
14 kHz	77.02 %	83.49 %	86.73 %	87.97 %	87.99 %
15 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
16 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
17 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
18 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
19 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %
20 kHz	77.02 %	83.49 %	86.23 %	88.16 %	88.69 %

Table IV summarizes results collected from measurements of the PMSM motor efficiency for PWM frequencies ranging from 4 kHz to 20 kHz with the increment of 1 kHz, for the speed values of 300 rpm, 500 rpm, 750 rpm, and 1000 rpm for the constant load torque of 6 Nm.

Since rotational speed of 1200 rpm entails transition of the motor to the second zone of control, measurements of the motor efficiency for that rotation speed were given up.

TABLE IV. EFFICIENCY OF THE PMSM MOTOR FOR THE LOAD TORQUE OF 6 NM.

f[kHz]	rpm			
	300	500	750	1000
4 kHz	70.60 %	76.99 %	83.85 %	85.63 %
5 kHz	70.59 %	78.13 %	83.67 %	85.07 %
6 kHz	71.98 %	78.65 %	84.32 %	85.62 %
7 kHz	71.86 %	78.94 %	84.39 %	85.98 %
8 kHz	72.13 %	79.30 %	84.61 %	86.22 %
9 kHz	72.28 %	79.50 %	84.40 %	86.46 %
10 kHz	72.86 %	79.70 %	84.48 %	86.34 %
11 kHz	72.92 %	79.80 %	85.07 %	86.70 %
12 kHz	73.17 %	79.90 %	85.14 %	86.61 %
13 kHz	72.92 %	80.00 %	85.23 %	86.73 %
14 kHz	72.92 %	80.30 %	85.38 %	86.78 %
15 kHz	75.95 %	80.19 %	85.45 %	86.90 %
16 kHz	73.06 %	80.40 %	85.46 %	86.97 %
17 kHz	73.06 %	80.60 %	85.73 %	87.03 %
18 kHz	73.42 %	80.60 %	85.66 %	87.03 %
19 kHz	73.19 %	80.60 %	85.66 %	87.08 %
20 kHz	72.93 %	80.50 %	86.02 %	86.99 %

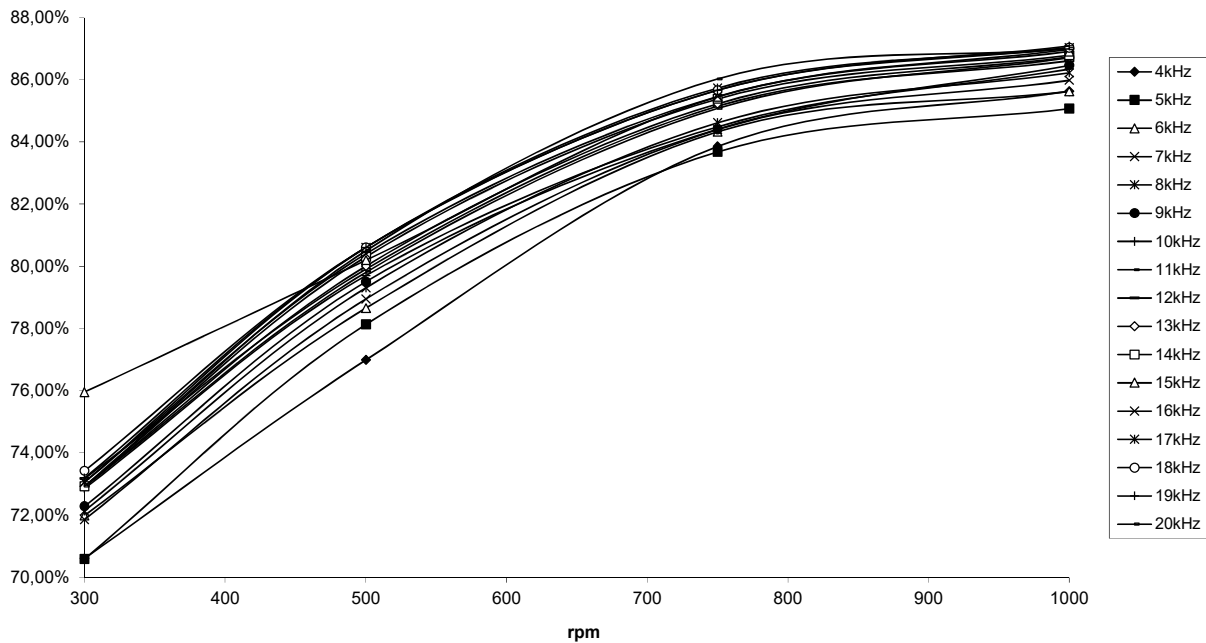


Fig. 7. Efficiency of the PMSM motor for various PWM control frequencies and for the load torque of 6 Nm.

The graph for efficiency of the PMSM motor plotted for variations of the PWM control frequency and for the constant load torque of 6 Nm is shown in Fig. 7.

As one can easily see from the foregoing graphs, efficiency of PMSM machines grows in pace with the increase of the PWM frequency. Similarly, the motor efficiency is better at higher rpm of motors.

It is also reasonable to investigate how variations of the PWM control frequency affect efficiency of PMSM motors running with various load torques.

Figure 8 presents a graph plotted for efficiency of the PMSM motor when the load torque adopts constant values of 2 Nm, 4 Nm and 6 Nm, the PWM control frequency ranges from 4 kHz to 20 kHz and the rotation speed is 300 rpm.

Figure 9 presents a graph plotted for efficiency of the PMSM motor under tests when the load torque adopts the same three constant values as above, the PWM control frequency ranges from 4 kHz to 20 kHz and the rotation

speed is 500 rpm. Similarly, relationship between the motor efficiency and the PWM control frequency was also investigated for the rotation speeds of 750 rpm and 1000 rpm, which is presented in respective graphs Fig. 10 and Fig. 11.

Figure 8 to Fig. 11 serve as a proof that rates of efficiency growth for PMSM motors in pace with increase of the PWM frequency are higher for lower load torques (2 Nm), whilst the efficiency improvement for high load torque (6 Nm) is insignificant. Thus, the conclusion can be made that the optimum frequency of the PWM control for PMSM motors should exceed 10 kHz. When that frequency is exceeded, rates for growth of the motor efficiency are quite low and for frequencies above 16 kHz the motor efficiency improvement is as low as virtually negligible.

The next issue that is worth of further investigations is the impact of the control frequency onto IGBT transistors incorporated into the output power module.

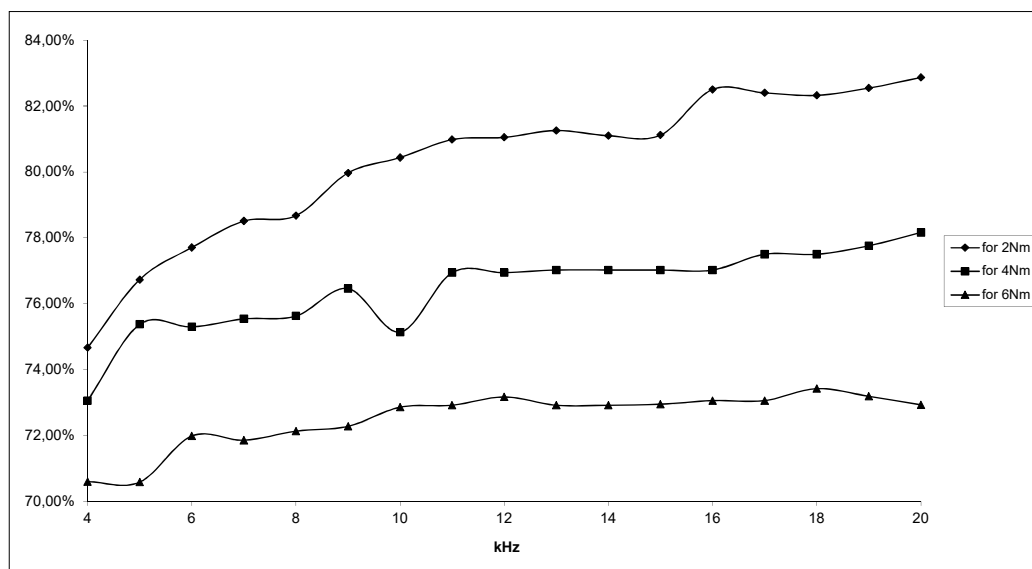


Fig. 8. Efficiency of the PMSM motor for variable frequency of PWM control and rpm = 300.

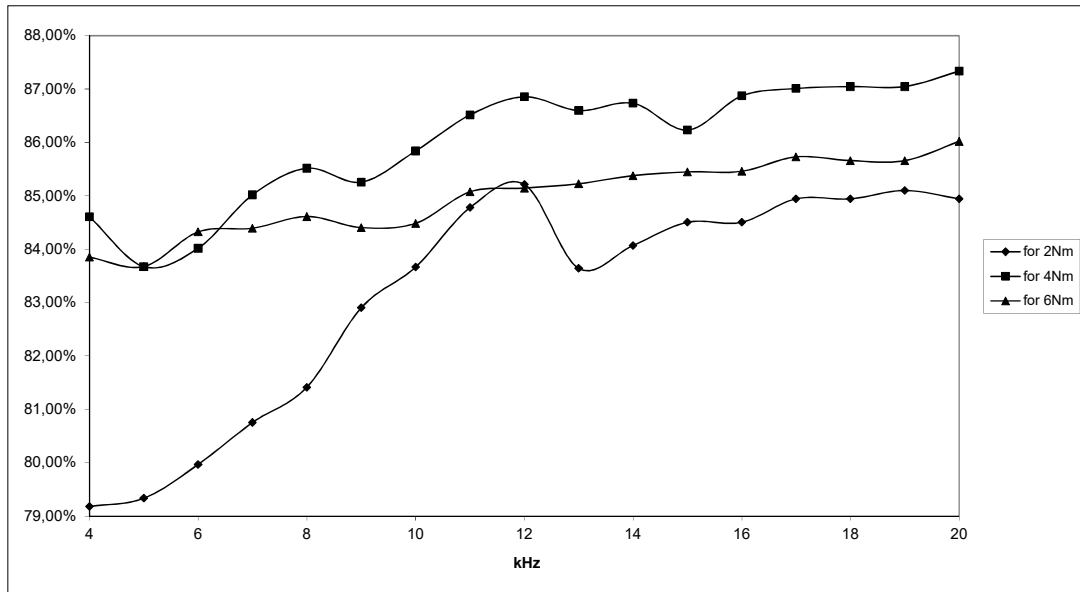


Fig. 9. Efficiency of the PMSM motor for variable frequency of PWM control and rpm = 500.

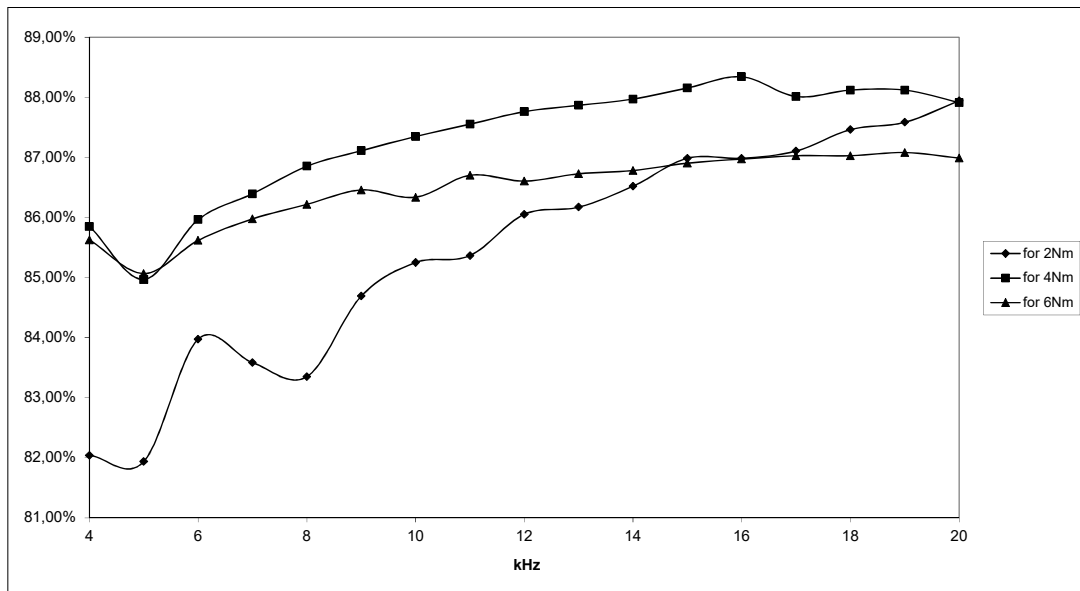


Fig. 10. Efficiency of the PMSM motor for variable frequency of PWM control and rpm = 750.

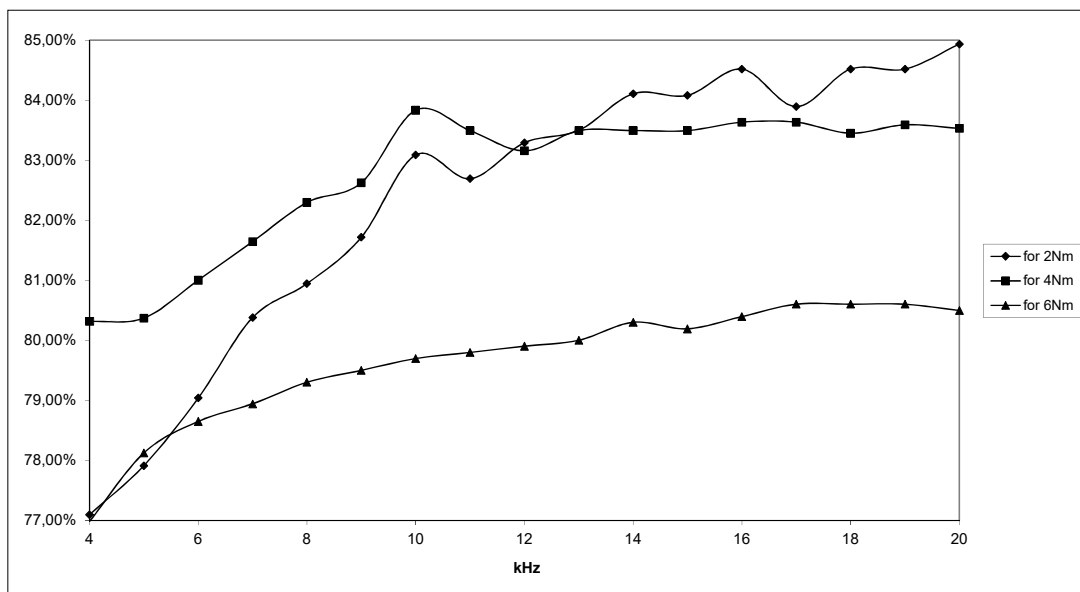


Fig. 11. Efficiency of the PMSM motor for variable frequency of PWM control and rpm = 1000.

IV. CONCLUSIONS

The paper describes how the most appropriate frequency of PWM control for a PMSM motor was selected in experimental way to achieve the maximum possible efficiency of the motor operation. The investigations were carried out for the PMSM motor with the power of 1 kW, rated speed of 1000 rpm and the rated torque of 6 Nm. The PWM frequency varied within the range from 4 kHz to 20 kHz with the increment of 1 kHz. The measurements aimed at determination of the PMSM motor efficiency were taken for the foregoing series of frequencies with the load torques of 2 Nm, 4 Nm and 6 Nm as well as rotation speeds of 300 rpm, 500 rpm, 750 rpm, 1000rpm and 1200rpm. The key benefit from operation of motors with maximum achievable efficiency is the opportunity of savings on energy consumption by the PMSM motor. Experimental studies made it possible to reveal that PMSM motors should be preferably controlled from PWM generators running at the frequency range from 10 kHz to 16 kHz. Operation of motors at low frequency below 10 kHz worsens its efficiency even by several percents, which is significant at times when savings on energy consumption are considered as key objectives. Growth of the PWM frequency above 16 kHz enables merely insignificant improvement of the motor efficiency, thus it is no sense to pursue that idea. The reason for this is the loss in the magnetic circuit of the motor. It has to do with the materials used to build the magnetic circuit.

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