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PMSM DRIVE BASED
ON STM32F4 MICROCONTROLLER

In this paper based on STM32F4 microcontroller and dedicated for permanent magnet synchronous motor (PMSM) drive is presented. Information concern structure and implementation of the program main blocks such as: modulator, speed and position calculation, communication interface are depicted. Designing process of cascade control structure with PI controllers is shown. An internal model control (IMC) was used to calculate coefficients of current controllers while the symmetric optimum criterion was applied to compute angular speed controller. Since mathematical model of the drive is non-linear, linearization and decoupling procedure as well as dead-time compensation are also included. Finally, experimental test results for PMSM with FOC control algorithm are shown.

KEYWORDS: PMSM, drive, STM32F4, VSI, FOC

1. INTRODUCTION

Permanent magnet synchronous motors are commonly used in application demand precise control of angular position, velocity and electromagnetic torque such as: robots, CNC machines, electrical vehicles [1-3]. The main requirements for the drive dedicated for PMSM concerns high performance and compact structure. The most often implemented control algorithm is field-oriented control (FOC) with cascade control structure [4]. Due to superior disturbance compensation properties, state feedback control structure can also be used [5]. Relatively short time required for accomplish of control algorithm (it is in a range from 50 μs to 100 μs for a typical switching frequency 10÷20 kHz) causes that fast computational units have to be employed. Texas Instruments (TI) or Analog Devices (AD) microprocessors dedicated for electrical drives (ex. TMS320 from TI, ADSP-21061 from AD) are commonly used in a commercial applications [6, 7]. In the proposed solution, microcontroller with ARM Cortex-M4 core (STM32F407VGT6) will be used. Due to its high computational potential, relatively large internal flash memory (up to 1MB) and low price, this

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type of microcontrollers are used in digital audio amplifiers [8], overcurrent relays [9] and data acquisition systems [10]. Thanks to fast floating point unit and peripherals similar to those in DSP, described microcontroller seems to be a good choice for electrical drive control systems.

2. HARDWARE CONFIGURATION

Structure of the STM32F4-based PMSM drive is shown in Fig. 1a, while a photo is presented in Fig. 2. The hardware is composed of a STM32F407VGT6 microcontroller, Semikron SK45GD063 power integrated module and Skyper 32 Pro gate drivers. A typical 2-level topology of voltage source inverter was used in this application. Measurements of electrical variables (i.e., phase currents, DC-link voltage) are made by using LTS 15-NP current transducer and LV 25-P voltage transducer along with interfaces that are responsible for signals conversion to the level suitable for A/D converter of microcontroller. Mechanical variables of the motor (i.e., angular position and speed) are calculated by using Hiperface® standard along with quadrature encoder inputs.
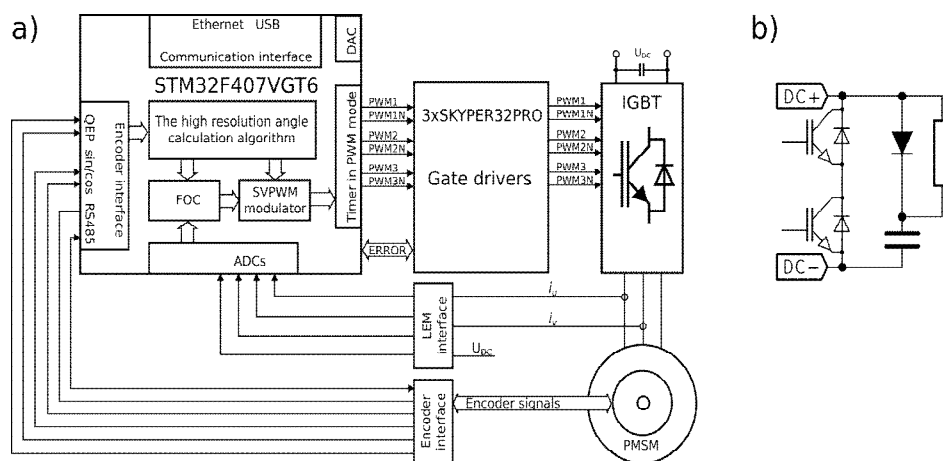

Fig. 1. a) Block diagram of the drive b) Snubber topology

STM32F407VGT6 microcontroller is based on the high-performance ARM®Cortex® 32-bit core operating at the frequency up to 168 MHz. Three separate A/D converters (12-bit), PWM outputs and fast floating point unit of microcontroller caused that it seems to be low cost, high performance alternative for DSP (ex. TMS320, ADSP-21061) that are commonly used in AC drives.

Shown in Fig. 1b snubber RCD topology has been employed in order to provide efficient damping of output voltage oscillations of inverter [11]. Such

topology has lower power dissipation on the resistor and significantly reduces it overheating.
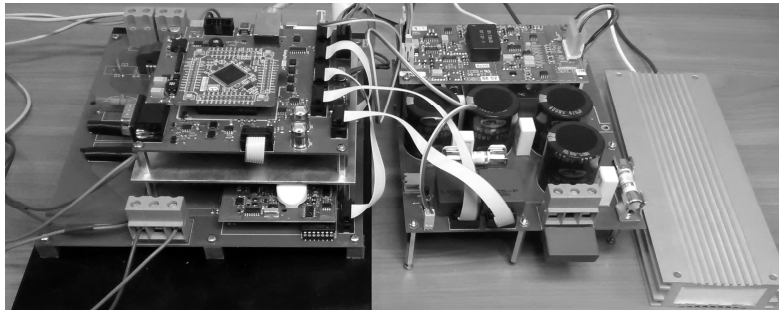

Fig. 2. Photo of the drive

3. SOFTWARE CONFIGURATION

3.1. Control algorithm

In the proposed approach, field-oriented control (FOC) has been applied to ensure high performance operation of PMSM. Cascade control structure with PI type angular speed and space vector components of currents was employed. Since model of the plant (i.e., PMSM fed by VSI) is non-linear and cross-coupled, a simple linearization method described in [6] has been used. Synthesis procedure of controllers have been made in Matlab/Simulink environment.

Firstly, current control loop was design. Schematic diagram of PMSM current control loop is presented in Fig. 3. Linearization as well as controller (IMC) were implemented in triggered subsystems in order to assure proper generation of discrete control signals. Thanks to the use of triggered measure block, electrical and mechanical variables are sensed in the midpoint of PWM. In order to design current controllers, an internal model control (IMC) method has been used [12]. A 5 ms rise time was selected for compute coefficients of PI current controllers. In order to avoid windup phenomenon, the tracking back calculation method has been employed [13]. Block diagram of discrete PI type controller with anti-windup path is shown in Fig. 4a. Depicted structure of controller have been used in a current as well as in the angular speed control loop. Simulation step response of q-axis current is presented in Fig. 4b. From Fig. 4b it can be seen, that the rise time of q-axis current is equal 5 ms, what fulfils our requirements. The main parameters of designed drive and PMSM are depicted in Table 3.1.

An angular speed control loop was design according to the symmetric-optimum criterion [14]. In order to reduce large overshoot of angular speed step

response, the low pass filter for reference value was added. Schematic diagram of FOC structure used to synthesis process of speed controller is shown in Fig. 5. Simulation step response of designed FOC for PMSM drive is presented in Fig. 6.

Table 3.1. Drive & PMSM parameters

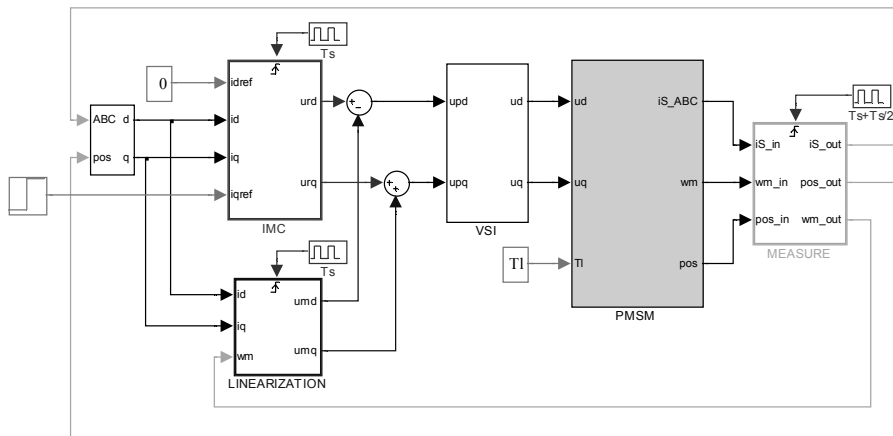| Parameter		Parameter	
VSI switching frequency	f_s = 10 kHz	PMSM no. of pole pairs	p = 3
VSI DC-link	U_{dc} = 200 V	PMSM resistance	R_s = 1.05 Ω
PMSM rated power	P_N = 2.76 kW	PMSM inductance	L_s = 9.5 mH
PMSM rated speed	Ω_{mN} = 314 rad/s	PMSM torque constant	K_t = 1.64 Nm/A
PMSM rated current	I_N = 5.8 A	PMSM friction	B_m = 1.4×10⁻³ Nms/rad
PMSM rated torque	T_{eN} = 8.8 Nm	Total moment of inertia	J_d = 2.2×10⁻² kgm²

Fig. 3. Block diagram of PMSM current control loop (Simulink model)
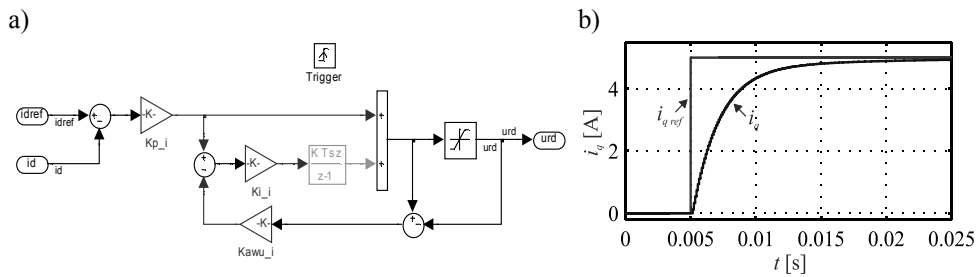
a)

b)

Fig. 4. Current control loop: a) block diagram of discrete current controllers with anti-windup path, b) simulation step response of q-axis current
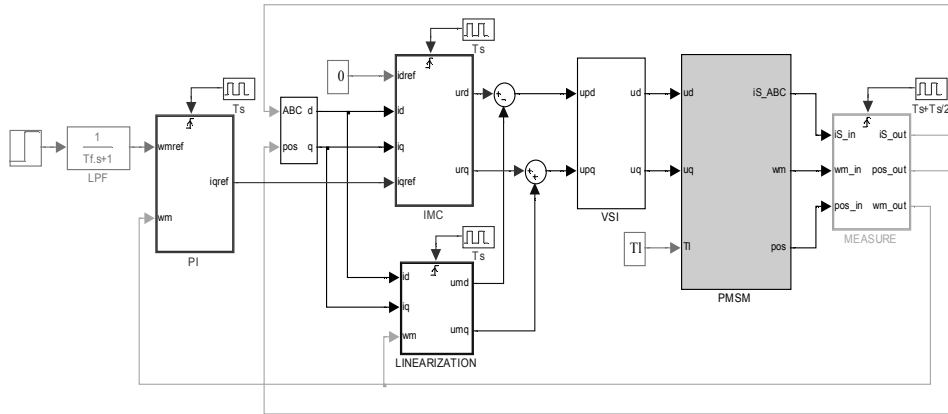
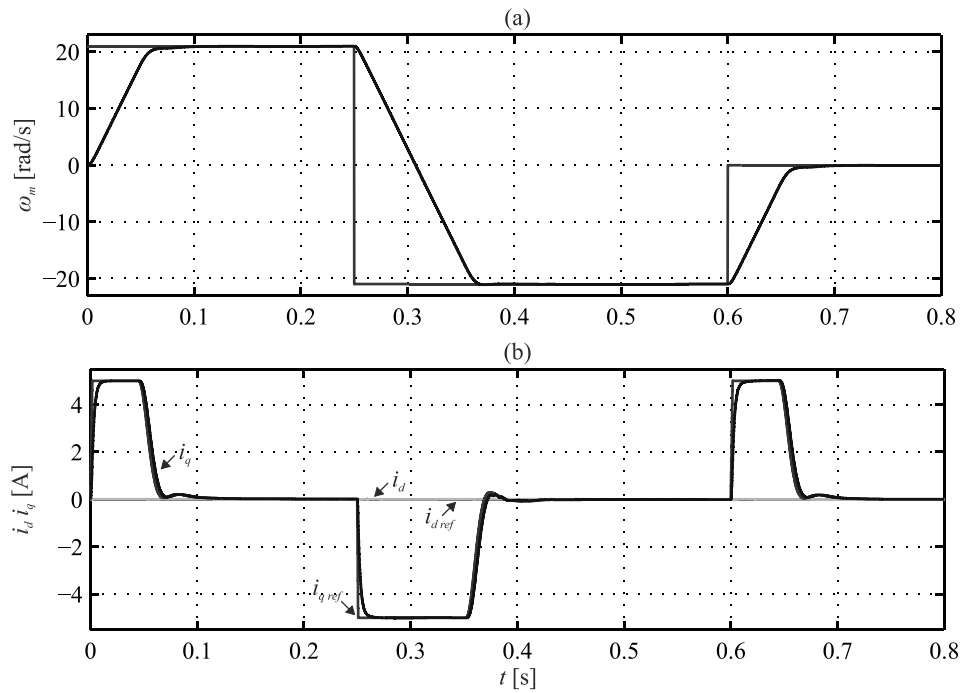Fig. 5. Block diagram of FOC structure for PMSM (Simulink model)

Fig. 6. Speed mode: simulation step response of PMSM drive: a) reference and angular speed,
b) space vector components of PMSM currents

Fig. 6 shows proper operation of PMSM drive during start-up and speed reversal. Angular speed (Fig. 6a) and space vector components of PMSM current (Fig. 6b) are controlled properly, without steady-state error.

3.2. SVPWM modulation

In order to obtain gate signals for power transistors, SVPWM algorithm has been employed. Basics of SVPWM used is shown in Fig. 7. Execution time of depicted part of algorithm was taken into account during implementation. For this reason, it was decided to use off-line calculated switching times for each sector (Tab. 3.2) instead of directly using arcus tangens function. It should be noted, that there are three similar equations (the only difference lies in the sign). Described property has been used during the code optimization.
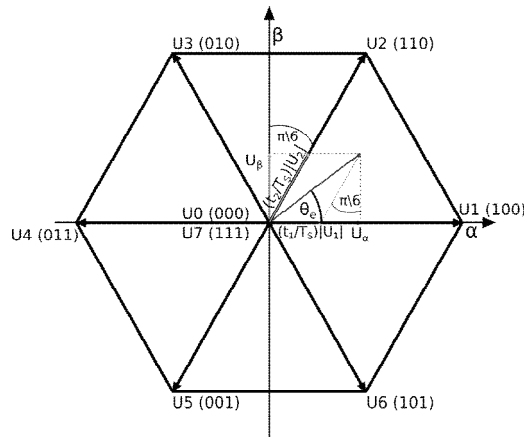
Fig. 7. SVM modulator

Table 3.2. Switching time equations for each sector

Sector	t_1	t_2
1	$\dfrac{T_S}{2U_{DC}}\left(3U_\alpha - \sqrt{3}U_\beta\right)$	$\dfrac{T_S}{U_{DC}}\sqrt{3}U_\beta$
2	$\dfrac{T_S}{2U_{DC}}\left(-3U_\alpha + \sqrt{3}U_\beta\right)$	$\dfrac{T_S}{2U_{DC}}\left(3U_\alpha + \sqrt{3}U_\beta\right)$
3	$\dfrac{T_S}{U_{DC}}\sqrt{3}U_\beta$	$\dfrac{T_S}{2U_{DC}}\left(-3U_\alpha - \sqrt{3}U_\beta\right)$
4	$\dfrac{T_S}{U_{DC}}\left(-\sqrt{3}U_\beta\right)$	$\dfrac{T_S}{2U_{DC}}\left(-3U_\alpha + \sqrt{3}U_\beta\right)$
5	$\dfrac{T_S}{2U_{DC}}\left(-3U_\alpha - \sqrt{3}U_\beta\right)$	$\dfrac{T_S}{2U_{DC}}\left(3U_\alpha - \sqrt{3}U_\beta\right)$
6	$\dfrac{T_S}{2U_{DC}}\left(3U_\alpha + \sqrt{3}U_\beta\right)$	$\dfrac{T_S}{U_{DC}}\left(-\sqrt{3}U_\beta\right)$

A simple dead-time compensation method based on solution described in [15] has been employed to reduce distortion of phase currents. This solution provides satisfactory level of VSI non-linearity compensation and low complexity.

3.3. Communication interface

Because of its universality and capacity, an Ethernet interface has been used to allow communication between PMSM drive and host PC. Selected solution gives the opportunity to send large packet of data in the short time. The code for Ethernet communication is based on LWIP stack which is open source library. In order to reduce execution time, UDP protocol is applied to transmit data. Those are sending into two separate ports: first is used in two way communication mode to transmit control command such start, stop, etc., and the second is used to send data from the drive to PC. This type of data may include electrical and mechanical variables measured in the drive as well as calculated variables. Measured and calculated data are sending in a one millisecond period. High speed of Ethernet interface and potential to transmit large packet of data (1400 bytes in this case) gives the possibility to send data from each PWM cycle. For base PWM frequency equal to 10 kHz, only slight data buffering into 10 elements table during sending cycle is required.

3.4. Host software

In order to control and diagnose designed PMSM drive, a PC software has been designed (Fig. 8).
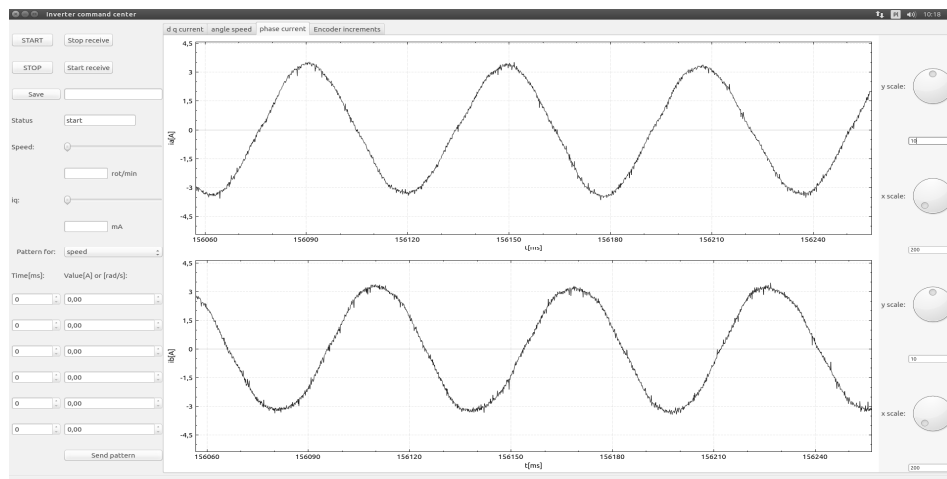

Fig. 8. The main window of designed PC software

The main tasks are as follows:
- start and stop of the drive,
- determination mode of drive operation (ex. torque mode, speed mode),
- managing status of drive with respect to gate drivers and chopper errors,
- data acquisition and visualization,
- construct and send reference value,

The entire PC software was written in C++ using Qt environment. It gives the possibility to compile source code for many platforms (Windows, Linux, etc.) and makes programming process relatively simple and non-time consuming. By using designed host software, each measured or calculated in the drive value can be acquired and visualized. In such a case the diagnosis of control algorithm is facilitated.

4. EXPERIMENTAL RESULTS

After successful implementation of control algorithm components, execution times have been measured for 150 MHz core clock. The measurements were made by using an internal timer of microprocessor. The overall time required to execute control algorithm is 9.2 µs. Execution times obtained for main components of control algorithm are summarized in Table 4.1. It should be noted, that thanks to code optimization, the overall execution time is relatively short and the proposed microprocessor can be used in electrical drives that requires higher switching frequency or more complex control algorithm.

Table 4.1. Individual execution time

Control algorithm component	Execution time
Calculation and processing of speed, position, DC-link voltage and phase currents	4.83 µs
Clarke & Park transforms	0.35 µs
FOC with decoupling	1.76 µs
Dead-time compensation	0.93 µs
Inverse Park transform & SVPWM	1.28 µs

Firstly, proper operation of the drive with 2.7 kW PMSM and with additional moment of inertia was examined in a torque mode. Fig. 9 shows step responses of q-axis current. As it can be seen, q-axis current is controlled properly, without steady-state error and overshoot. Its rise time is c.a. 5 ms, what satisfies assumptions. Since zero d-axis control strategy has been employed, value of direct current is equal to zero.

Fig. 10 shows proper operation of PMSM drive during start-up and speed reversal. Angular speed (Fig. 10a) and space vector components of PMSM current (Fig. 10b) are controlled properly, without steady-state error.
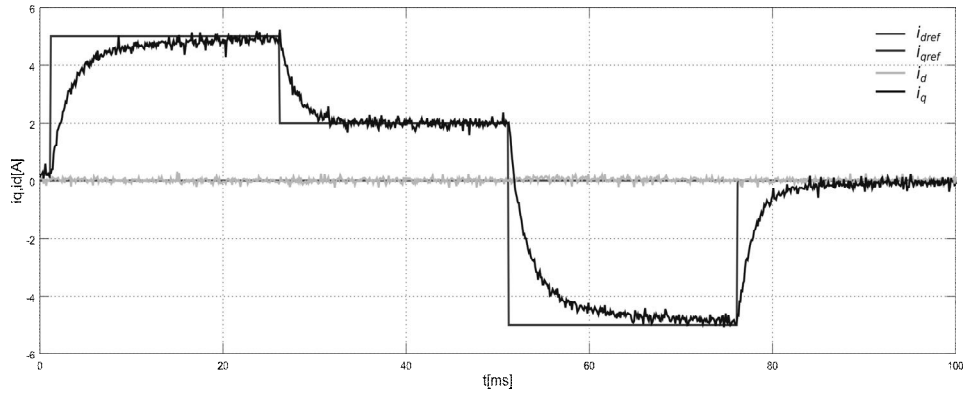
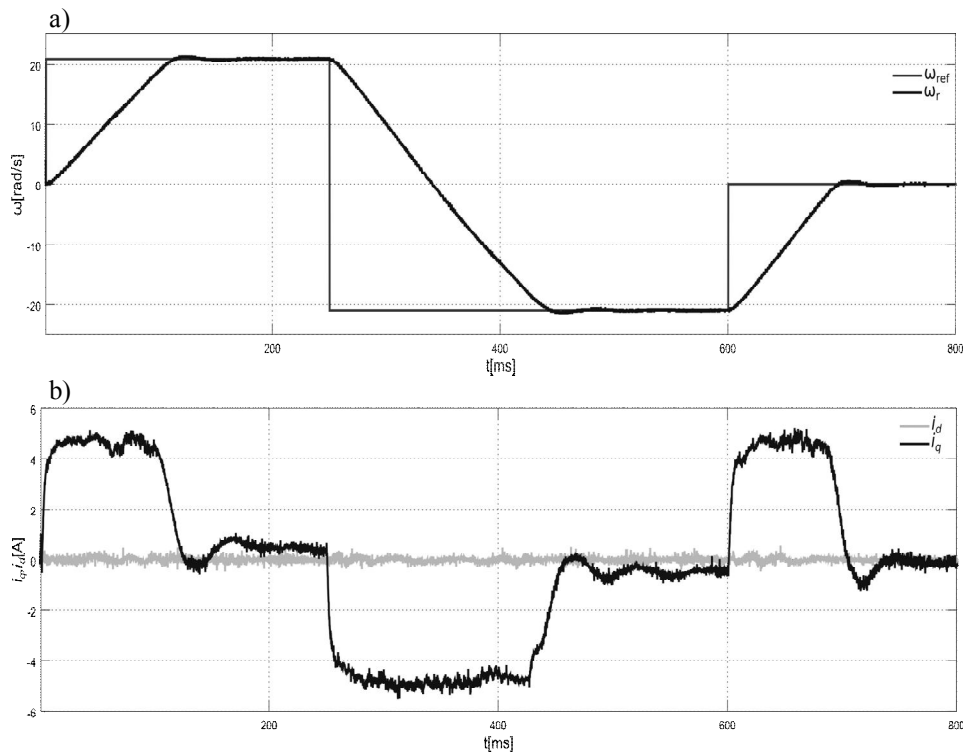Fig. 9. Torque mode: experimental step responses of q-axis current

Fig. 10. Speed mode: experimental step response of PMSM drive: a) reference and angular speed,
b) space vector components of PMSM currents

5. CONCLUSION

It was found that STM32F4 microcontroller can be successfully applied to design high performance AC drive dedicated for PMSM. Simulation as well as experimental test results proves proper operation of the drive in torque and speed mode. Thanks to designed host software, the diagnosis of control algorithm is facilitated. It is planned to implement and examine more complex control algorithms such as state feedback and adaptive control.

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