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Sensored Field Oriented Control of BLDC Motor for Pico Satellite Attitude Control

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Abstract:- A Field Oriented control scheme for a BLDC (Brush Less Direct Current) motor is presented. The motor is used for attitude control of 3U sized Pico satellite by exchanging angular momentum with the rigid body. Compared to the conventional control schemes which give performance limitations, with FOC a better dynamic performance can be achieved, even the algorithm introduce more complex mathematical transformations in order to decouple the torque generation. The algorithm itself is implemented directly in the hardware and with the mathematical processing power of modern micro controllers such advanced control algorithms are easily implemented. Computer simulation is presented to verify the control strategy.

Keywords:- *BLDC, Field Oriented Control.*

I. INTRODUCTION

BLDC (Brush Less DC) motors are widely used for applications that demand long life, reliability, and high efficiency. Are lighter compared to brushed with the same torque output. In order to achieve field oriented control, the rotor position is required, which is obtained through the use of three hall sensors. For reduced cost applications the rotor position is estimated through the use of model based estimators(observers) [1]. The used permanent magnet rotor has 4 pole pairs, thus the hall sensors giving 24 tics per one mechanical revolution. Field oriented control relies on the decoupled magnetizing flux and torque, and perform separate torque control [3]. In order to a achieve high performance, the control strategy employs an inner loop for torque control which is enclosed by an outer velocity control loop. For any position of the rotor, and thus the rotor flux, there is an optimal direction of the stator flux which maximizes the generated torque. In the BLDC motor, stator flux is produced by current flowing in equally spaced three windings separated by 120^o. Each winding produce a flux vector with orientation 120^o from the other two. Current space vectors are used to model the flux produced by the windings, with direction the produced flux direction and magnitude proportional to the current flowing through the windings. The total stator flux is then the sum of the three current space vectors.

- *The outer loop of the control scheme consists of a PID (Proportional Integral Derivative)* correction of the velocity error, while the inner loop consists of two PI corrections, one for the direct component of the stator and rotor projected flux vectors, and one for the quadrature stator and rotor projected flux vectors (d and q axes). The angle between the two axes should be kept at 90^o which results in the maximum output torque, while the magnitude of the torque is regulated from the magnitude control of the quadrature axis. In Pico satellites missions, power management is important, so the controller output should not overshoot while the torque output should be kept constant in order to avoid vibrations in the overall system.

II. BLDC MOTOR

The BLDC motor used for the purpose of this paper, consists of 3 coils separated by 120^o angle. Since the FOC algorithm is implemented directly on the hardware, the electrical and mechanical model of the motor are used for simulation purposes, however, are not deemed necessary to be presented. *Figure 1* shows the motor stator with the three coil pairs along with the rotor permanent magnet and the position of the hall effect based sensors. Rotor magnet consists of 8 poles(4 pole pairs).

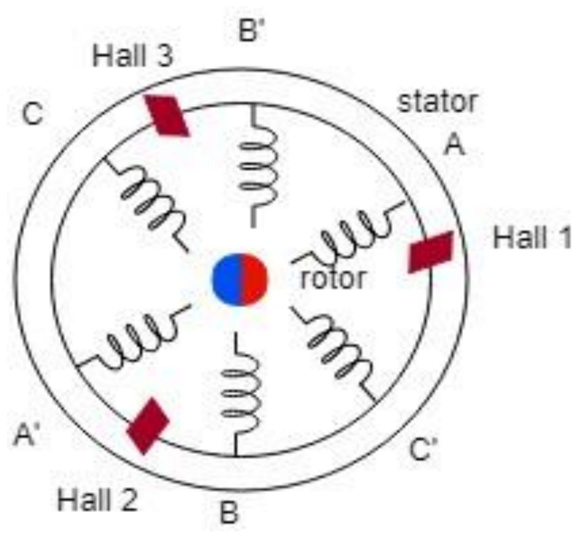

Fig 1:- BLDC stator and rotor

During the commutation, two of the three coils are energized each time. The opposite pairs energized with different polarity, giving rise to a rotating magnetic field. Rotor follows the stator magnetic field in a synchronous frequency with the supplied current. In order to achieve FOC hall effect sensors are essential providing digital signals which measure rotor position [2].

III. FIELD ORIENTED CONTROL

The three phase currents can be represented as complex space vectors. These complex vectors are projected from a speed and three phase time depended system into two time invariant coordinate system[3]. The three phase diagram can be seen in the *figure 2* along with the stator current i_p space vector which is a combination of the instantaneous coil currents. The stator phase diagram represents the three phase sinusoidal system.

In order to simplify the analysis of the three phase system, Clarke and Park transform is employed, which will be discussed next.

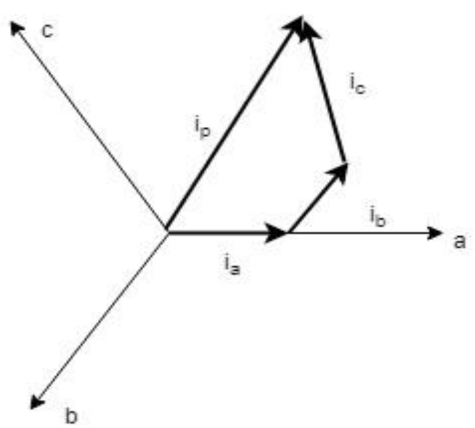

Fig 2:- Stator phase diagram

A. Forward Clarke transform

The three phase system *(a,b,c)*, is transformed into *(α,β)*, two coordinate time variant and orthogonal projection. The transformation is made using the components, on the vertical and horizontal direction, of the three phase complex vectors. The mathematical expressions used to modify the three phase into two are as[3]:

$$i_\alpha = \sqrt{\frac{2}{3}}[i_a - \sin(30)i_c - \sin(30)i_b] \quad (1)$$

$$i_\beta = \sqrt{\frac{2}{3}}[\cos(30)i_c - \cos(30)i_b] \quad (2)$$

Were $i_a = i_m \sin(\omega t)$, $i_b = i_m \sin(\omega t + 240)$, $i_c = i_m \sin(\omega t + 120)$ are the sifted phase currents with ω been the angular velocity in [*rad/sec*] and i_m been the amplitude of the waveform. *Equation* 1 and 2 represents the projection into *(α,β)* coordinate system, assuming that axis α and a are in the same direction. Clarke transform can be seen in the *figure 3*

B. Forward Park transform

As it has been discussed the stator currents have been projected into an orthogonal two axes system (α,β). Further analysis requires the projection from (α,β) to (d,q), rotating with current space vector, time invariant axes. In order to achieve this projection the Park transform is employed which requires the information of the electrical angle given in radians $\theta_{el} = n_p \times \theta_{mech}$, were θ_{mech} is the mechanical angle of the rotor and is derived from the hall sensors and n_p are the pole pairs of the rotor. Park transform can be expressed as[3]

$$i_d = \cos(\theta_{el})i_\alpha + \sin(\theta_{el})i_\beta \quad (3)$$

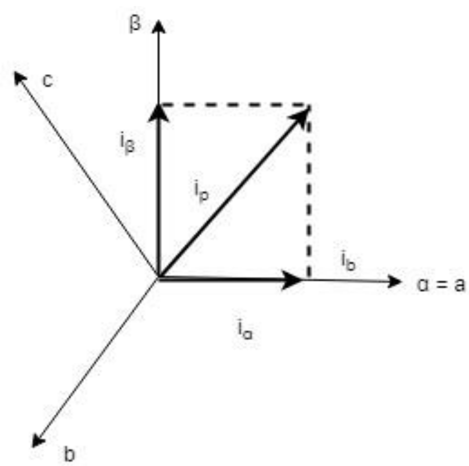

Fig 3:- Clarke transform, (a,b,c)—— > (α,β)

$$i_q = -\sin(\theta_{el})i_\alpha + \cos(\theta_{el})i_\beta \quad (4)$$

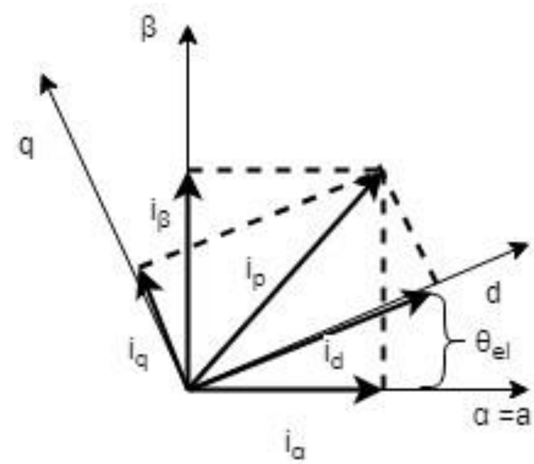

Fig 4:- Park transform, (α,β) —— > (d,q)

And can be seen in the figure 4 were i_d and i_q, flux component(direct axis) and torque component(quadrature axis) separately. As discussed two PI controllers have been de-

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signed to control separately i_d and i_q and correspond to the inner loop of the overall structure while a PID control algorithm has been set for the outer loop and speed control.

C. Inverse Park and Clarke transform

Once the controllers output correction has been calculated, the two coordinate system has to be transformed back to the original three phase system. This is obtained through inverse Park and Clarke transformations. The correction voltage outputs from the inner PI controllers are V_{dref} for the d axis and V_{qref} for the q axis. The references for the Clarke transformation block are given as

$$V_{\alpha ref} = V_{dref}\cos(\theta_{el}) - V_{qref}\sin(\theta_{el}) \quad (5)$$

$$V_{\beta ref} = V_{dref}\sin(\theta_{el}) + V_{qref}\cos(\theta_{el}) \quad (6)$$

Which performs a clockwise rotation back to α and β axes. The reference vector $\begin{pmatrix} V_{\alpha ref} \\ V_{\beta ref} \end{pmatrix}$ is the voltage space vector to be applied to the motor phases. The mapping to the three phase commands are given as

$$V_{a_{com}} = \frac{1}{\sqrt{3}} V_{\alpha ref} \quad (7)$$

$$V_{b_{com}} = \frac{1}{\sqrt{3}} (V_{\beta ref}\cos(30) - V_{\alpha ref}\sin(30)) \quad (8)$$

$$V_{c_{com}} = \frac{1}{\sqrt{3}} (-V_{\beta ref}\cos(30) - V_{\alpha ref}\sin(30)) \quad (9)$$

➢ *Space Vector Modulation*

Space vector modulation algorithm is used for the control of pulse width modulation and the creation of the alternating current waveforms, and gives more capable usage of the supply voltage. A three phase inverter converts a DC supply via a series of switches (MOSFET) into alternating current. In order to avoid shorting the DC supply,the switches must be controlled so that at any time both switches at the same leg are not *ON*. Figure 5 shows the three phase inverter which produce smooth sinusoidal curve on the motor by fast switching between the states or dynamic vectors and the figure 6 demonstrates the dynamic vectors V1-V6[4]. The binary representation shows which of the upper switches are *ON* = 1 or *OFF* = 0 at any time, implying that the pair switches in the same leg will *OFF* or *ON* at the same time. Space Vector Pulse Width Modulation(SVPWM)[5] is

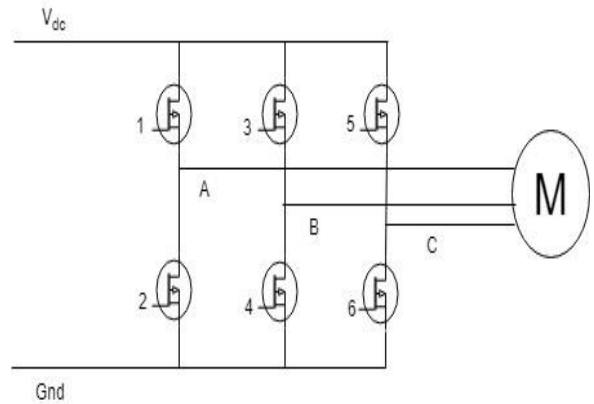

Fig 5:- Three phase inverter

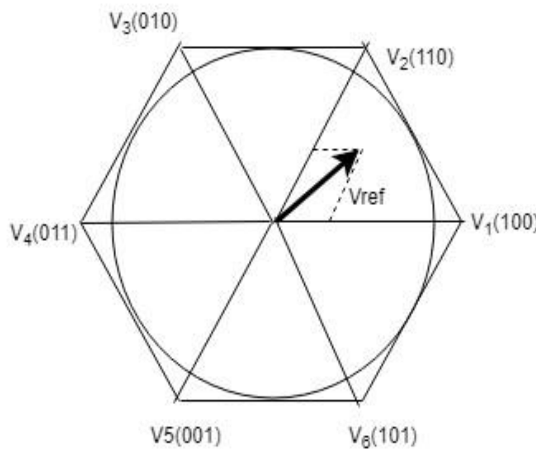

Fig 6:- Space vector modulation

Used to arrange the sequence from one state to the other. The components of the V_{ref} are calculated as

$$V_{min} = \mathbf{min(min(}V_{acom}, V_{bcom}\mathbf{)}, V_{ccom}\mathbf{)} \quad (10)$$

$$V_{acom} = V_{acom} - V_{min} \quad (11)$$

$$V_{bcom} = V_{bcom} - V_{min} \quad (12)$$

$$V_{ccom} = V_{ccom} - V_{min} \quad (13)$$

D. Basic structure of the FOC

The two motor phase currents are measured and through Kirchoff's law the third is determined (i_a+i_b+i_c = 0). These currents are transformed through Clarke and Park blocks into a two rotating coordinate frame and are the inputs which are compared with the references i_{dref} and i_{qref}. The reference for i_{dref} is set to zero since determines the maximum torque output with 90^o angle, while the reference for i_{qref} is the output of the outer PID controller which compensates for angular speed. The block diagram of the overall structure can be seen in the *figure 7*[2] the controller's gains are

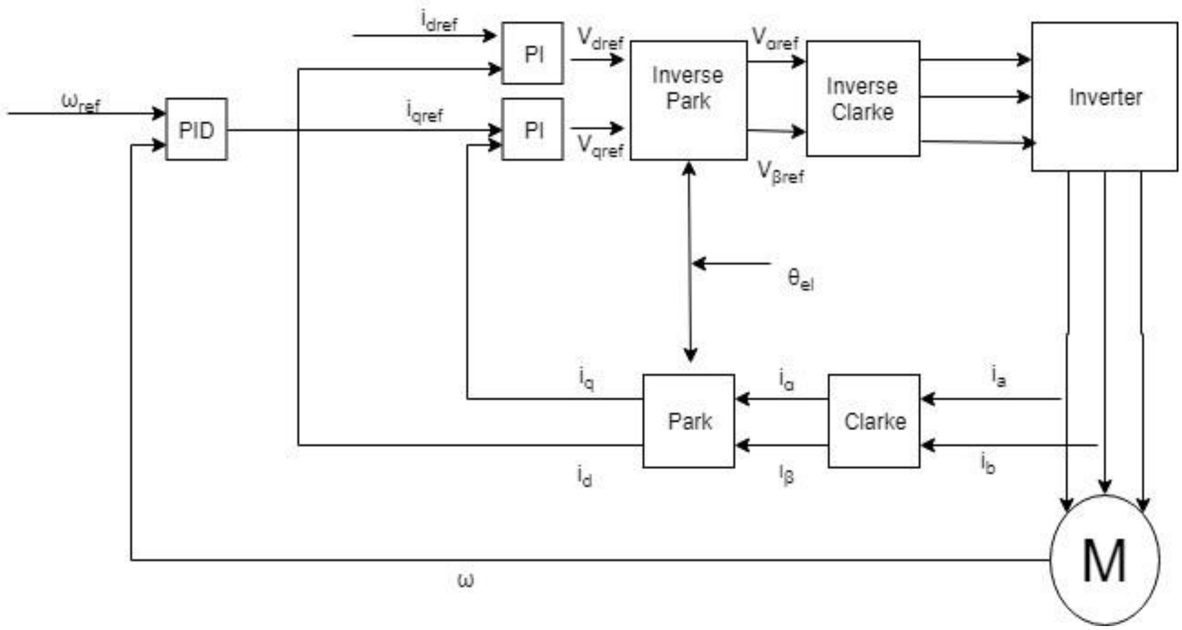

Fig 7:- FOC block diagram

Derived through trial and error in order to give no overshoot in the output response, thus more energy efficient system. The voltages from the inverse Park transform are used for the space vector pulse width modulation[4] in order to produce the duty cycles for the three phase inverter which purpose is the change direct into alternating current.

E. PID controller

In the *figure 7* it can be seen that the outer loop consists of a Proportional Integral Derivative controller and the inner loop of PI structure, were the derivative term is set to 0. The PID algorithm is

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \qquad (14)$$

where K_p, K_i, K_d are the proportional,integral and derivative gains respectively and $e(t)$ is the error signal.

F. Simulation results

The proposed FOC scheme has been simulated in Python. For the simulation it has been chosen as reference signal to be 65 percent of the maximum torque the motor can provide. The gains of the controllers have been derived through trial and error in order to provide high efficiency torque output with smooth response. In the figure 8 it can be seen the compensation for the direct(d) and quadrature(q) axes respectively as well as the FOC torque reference. The error at the d axis is very high at the origin, however, the torque output of the FOC is as expected. Figure 9 shows the three

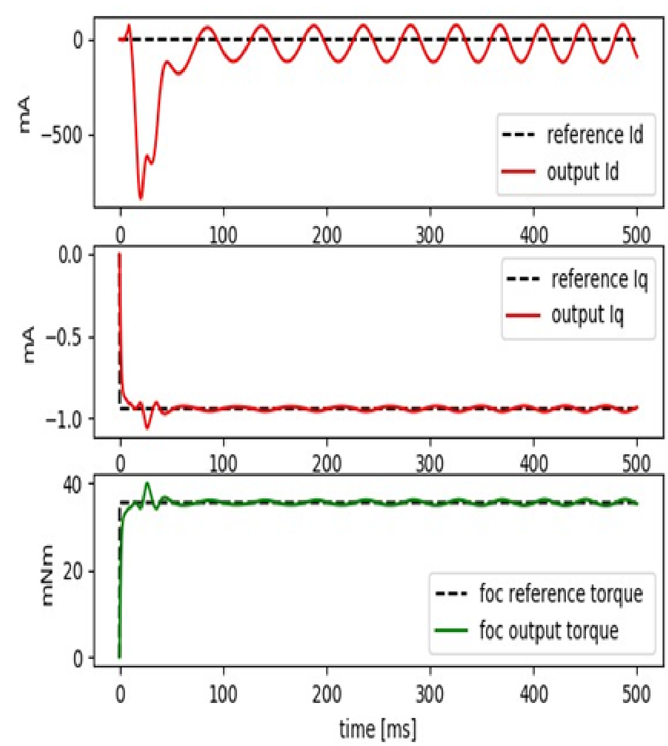

Fig 8:- Torque compensation

Phase currents as well as the velocity and the rotor position.

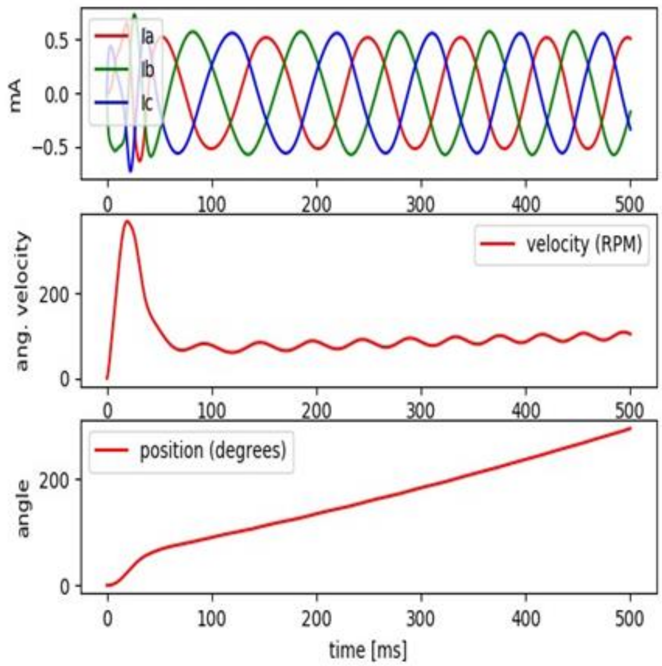

Fig 9:-Three phase currents, velocity and position of the rotor

IV. CONCLUSION

In this paper, a simple and efficient control method of a Brush less DC motor is proposed. This control method,Field Oriented Control(FOC), allows better dynamic performance while introducing complex mathematical transformations in order to decouple the torque generation. The proposed control method is built by using C embedded programming language while for simulation purposes Python programming language has been used.

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