Design of FOC Brushless DC (BLDC) Motor Controller

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***Abstract*: The paper designs a high power brushless DC motor (BLDC) closed-loop control system, mainly including design of FOC drive circuit, H bridge drive circuit, Control of rotation direction for motor and speed detection circuit. In order to improve the performance of motor running, one adopts PID algorithm, through the tuning of parameters, the control exhibits very good performance. Experiments show that both hardware and software control algorithms are reliable, stable. The running performance of the system is robust before or after adding load. It describe the principles behind field orientated control method for brushless direct current motors using an absolute position sensor and to implement a working field orientated algorithm base motor controller using a microcontroller and complementing hardware. The work consists of text, pictures and tables describing the theoretical background, implementation and system verification.**

***Keywords*: Brushless DC motor; closed-loop control system; H bridge circuit; speed detection.**

1. Introduction

Due to a number of factors price of commercially available brushless DC motors has dropped and the availability has increased. On the other hand electronics and software used to control those motors has remained relatively primitive. The motors are ran in open-loop scalar control mode without any feedback. This is understandable from the point of view where those types of motors are used: driving propellers of multirotored copters and model aeroplanes. These sorts of application do not require precise speed or position control in order for them to function. These brushless DC motors for model aircraft's are designed so that their power output per mass would be as high as possible. The reason behind this is to increase the flight time. An aspect that hasn't been considered very much is that those kinds of motors could be used in a variety of other fields like robotics and automation by using more sophisticated control methods. The benefits for using brushless DC motors in those applications are substantial: size of existing systems could be reduced, maintenance and system reliability would increase as bearings are the only part of the motor that is subject to wear. The main motivation of this thesis is to leverage the usage of low cost but high power to weight ratio motors by controlling them using field oriented control to provide precise speed control. The aim of this thesis is to create embedded solution on a microcontroller using readily available development kits to implement field oriented control for brushless DC motors with absolute encoder as feedback, in order to extend the potential usage of these kinds. The control scheme for field oriented control (FOC) differs in that the current loop occurs de-referenced from the motor's rotation. That is, independent of the motor's rotation. In the FOC approach there are two current loops, one for the Q torque and another for the D torque. The Q torque loop is driven with the user's desired torque from the servo controller. The D loop is driven with an input command of zero, so as to minimize the unwanted direct torque component. The trick to making all of this work is math-intensive transform operations that convert the vectorized phase angle to, and from, the de-referenced D and Q reference frame. Known as Park and Clarke transforms, their practical implementation in Brushless DC and AC Induction drives is now commonplace due to the availability of low-cost, high-performance DSPs and microprocessors.

Existing Motor Control/Driving Techniques: DC motor drive is fairly simple to implement when compared to an AC motor drive. DC motors can be driven directly by means of a voltage–frequency (V/F) relation; i.e., the higher the applied voltage, the higher the frequency or speed. This kind of drive is typically implemented in brushed DC motors.

For AC motor drives and some motor drives where the controller converts the applied DC into AC to drive the motor (like BLDC or PMSM), complex driving algorithms are employed to commutate the coils in a sequence to achieve desired directional rotation. The rate at which the windings are commutated is proportional to the speed with which the motor runs. A wide range of control algorithms are available.

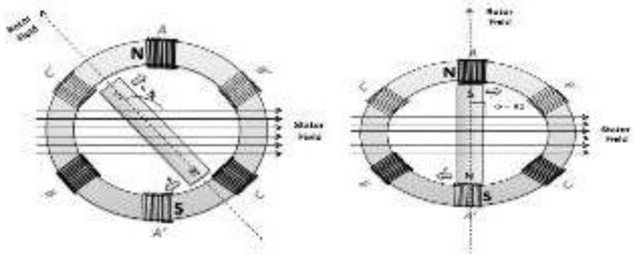
Trapezoidal control*:* Also known as 6-step control, this is the simplest algorithm .For each of the 6 commutation steps, a current path is formed between a pair of windings, leaving the third winding disconnected. This method generates high torque ripple, leading to vibration, noise, and poorer performance compared to other algorithms.

Sinusoidal control*:* Also known as voltage-over- frequency commutation, sinusoidal control overcomes many of the issues involved with trapezoidal control by supplying smoothly (sinusoidal) varying current to the 3 windings, thus reducing the torque ripple and offering a smooth rotation. However, these time-varying currents are controlled using basic PI regulators, which lead to poor performance at higher speeds.

Field Oriented Control (FOC): Also known as vector control, FOC provides better efficiency at higher speeds than sinusoidal control. It also guarantees optimized efficiency even during transient operation by perfectly maintaining the stator and rotor fluxes

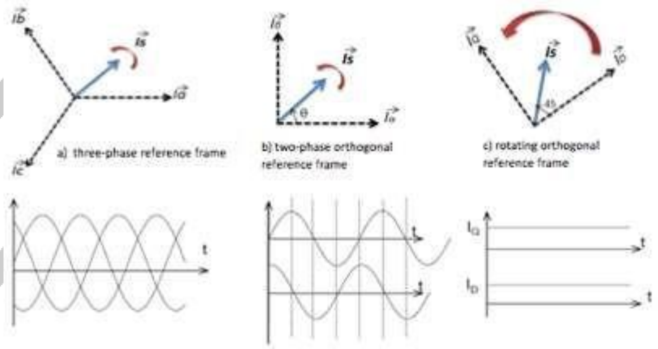
.FOC also gives better performance on dynamic load changes when compared to all other techniques.

Field Oriented Control is one of the methods used in variable frequency drives or variable speed drives to control the torque (and thus the speed) of three-phase AC electric motors by controlling the current .With FOC, the torque and the flux can be controlled independently.FOC provides faster dynamic response than is required for applications like washing machines. There is no torque ripple and smoother, accurate motor control can be achieved at low and high speeds using FOC. The torque of an induction motor is at a maximum when the stator and the rotor magnetic fields are orthogonal to each other. In FOC, the stator currents are measured and adjusted so that the angle between the rotor and stator flux is 90 degrees to achieve the maximum torque (as shown in the following figures)



FOC operates on the resultant vector of the three phase currents rather than controlling each phase independently. The control variables of an AC induction motor are made stationary (DC) using mathematical transformations. In a way, FOC tries to control an induction motor by imitating DC motor operation as it deals with stationary parameters

There are two methods used in FOC .Using Direct FOC, the rotor flux angle is directly computed from flux estimations or measurements .With Indirect FOC, the rotor flux angle is indirectly computed from available speed and slip computations.



The steps involved in sensored FOC are as follows:

Step 1: Two of the three stator phase currents are measured and the third current is determined using Kirchoff''s current relation, Ia + Ib + Ic = 0 Where Ia, Ib, and Ic are phase currents,

step 2: The three phase currents are converted into a 2-axis coordinate system from the 3-axis system of the stator, using a Clarke transformation,

$$(I_a, I_b, I_c) \Rightarrow (I_\alpha, I_\beta)$$

Where Ia and ß are the stator currents transformed to the 2- axis coordinate system.

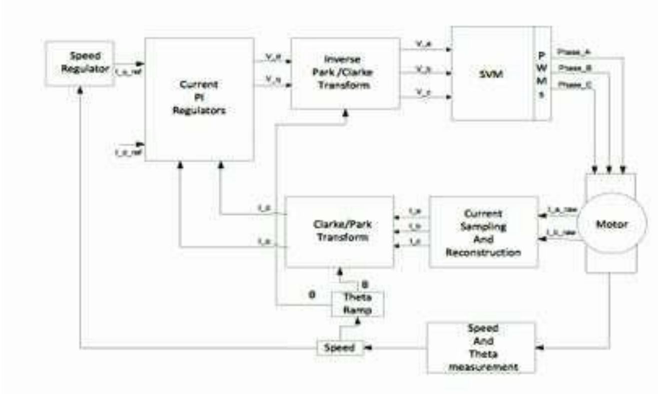
Step 3: The components along the 2-axis of the stator currents are time varying in nature and to track them using traditional PIs is complex. Rather, the stationary reference is rotated based on the rotor position (which is determined with the help of sensors or from back EMF) to a rotary reference where the components along the axis remain constant and traditional PI controllers can be used to counter any error. This rotation is done using a Park transformation,

$$(I_\alpha, I_\beta) \Rightarrow (I_d, I_q)$$

Where Id and Iq are the in-phase and quadrature phase stator currents from the rotor perspective

Step 4: Once the vectors have become time invariant, we can compare the corresponding axis vectors with the reference and use a PI controller (see equation below) for each axis to determine the error correction signal. The Id reference controls the rotor magnetizing flux. The Iq reference controls the torque output of the motor.

$$Out = K_p * (In - In_{ref}) + K_i \int (In - In_{ref}).dt$$



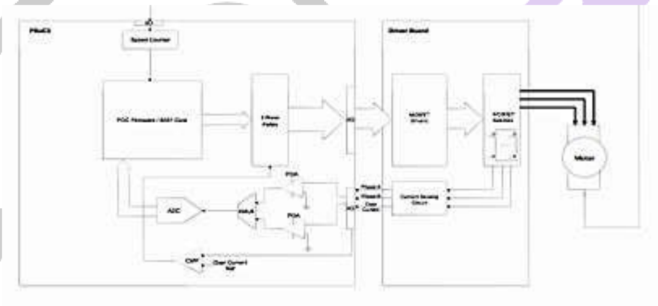
Step 5: The corresponding outputs of the PI controllers are then passed through an inverse Park and Clarke transformation to convert them back to the 3-phase stator reference.

Step 6: With the 3-phase reference signals generated, the PWM is modulated using Space Vector Modulation (SVM).

Why FOC?

The scalar control or the six-step commutation process, which was traditionally used for controlling BLDC motors based on the hall sensor inputs (or also sensorless), has a dynamic response. It energizes a pair of windings only when the motor reaches the next position, and the commutation is moved to the next step. In the case of a sensored implementation, hall sensors are used to determine the rotor position and the motor is commutated accordingly. The advantage of scalar control is that it is very easy to implement. Some advanced scalar control methods use the back EMF generated from the motor to determine the rotor position. However, this kind of dynamic response is not suitable in applications where the load changes dynamically within a cycle. Only advanced algorithms such as FOC can handle these dynamic load changes.

The following example shows how to implement an FOC control algorithm.For this example, the PSoC 3 from Cypress is used.The subsystem is split into several major modules:



The various modules of a Field Oriented Control control algorithm (as implemented using the PSoC 3 from Cypress).

Current reconstruction module

A two-shunt method is used to reconstruct the currents. With this method, the current from two legs are measured and the third current is reconstructed using Kirchhoff's current law. The PWMs are designed to be centre-aligned, and the two current samples are captured at the centre of the PWM period, every FOC cycle. Once the samples are taken, the FOC begins the ADC conversion of these samples, and the currents are reconstructed.

1. **Clarke and Park transformations**

The reconstructed currents are then transformed to 2-phase stator reference and then to 2-phase rotor references using Clarke and Park transforms respectively. Once the transformations are completed, the current in the rotor reference is ready to be regulated for the desired speed and torque.

Clarke transformation

Inputs : I_a, I_b, I_c

Outputs : I_α, I_β

Transformation:
$$I_\alpha = I_a$$
$$I_\beta = (I_a + 2 \cdot I_b)/\sqrt{3}$$

Park transformation

Inputs : I_α, I_β

Outputs : I_d, I_q

Transformation:
$$I_d = I_\alpha \cos\theta + I_\beta \sin\theta$$
$$I_q = I_\alpha \sin\theta + I_\beta \cos\theta$$

1. PI regulators

Generic PI controllers with adjustable gain and min-max saturation were implemented to regulate the 2-phase rotor reference current and the speed of the motor.

1. Inverse Park and Clarke transforms

The regulated output is then converted to the 3-phase reference (PWM duty cycle) again, to adjust the speed of the motor, by passing it through Inverse Park and Clarke transforms.

Inverse Park Transformation

Inputs : V_d, V_q

Outputs : V_α, V_β

Transformation:
$$V_\alpha = V_d \cos\theta + V_q \sin\theta$$
$$V_\beta = V_d \sin\theta + V_q \cos\theta$$

Inverse Clarke transformation

Inputs : V_α, V_β

Outputs : V_a, V_b, V_c

Transformation:
$$V_a = V_\alpha$$
$$V_b = 1/2 \cdot V_\alpha + 2/\sqrt{3} \cdot V_\beta$$
$$V_c = 1/2 \cdot V_\alpha - 2/\sqrt{3} \cdot V_\beta$$

By accumulating this electrical speed value over every FOC cycle, the position 'Θ' is computed. In this example, the FOC cycle is **200µS.** We use the relationship

$$\Theta = \omega t$$

Θ → angular distance in "t" seconds

ω → angular velocity

t → time interval for Θ calculation

1. SVM (Space Vector Modulation)

The space vector modulation technique is used to generate a sine wave to be fed to the stator coils. Based on the 3-phase reference generated by the inverse Clarke transform, the SVM generates the PWM compare values, which are phase shifted 120 degrees.

$$t_c = \frac{PWM_{Period} - 2 * (T_1 + T_2)}{2}$$

$$t_b = t_c + 2 * T_1$$
$$t_a = t_b + 2 * T_1$$

Where,

t_c, t_b, t_a → PWM compare register values, *table 4.2.*
T_1 and T_2 → Refer *Table 1.*
PWM_{period} →PWM period count.

Table1. Look up Table to find T1 and T2

Sector	T_1	T_2
1	$-V_b$	$-V_c$
2	$-V_c$	$-V_a$
3	V_b	V_a
4	$-V_a$	$-V_b$
5	V_a	V_c
6	V_c	V_b

Where,
Va, Vb and Vc → Inverse Clarke transform outputs.

Sectors are decided on the following criteria:
If $V_a > 0$, then Sector_bit_0 = 1, else 0.
If $V_b > 0$, then Sector_bit_1 = 1, else 0.
If $V_c > 0$, then Sector_bit_2 = 1, else 0.

Table 2: Look up Table to assign PWM duty cycle

Sector	1	2	3	4	5	6
PWM_A	t_b	t_a	t_a	t_c	t_c	t_b
PWM_B	t_a	t_c	t_b	t_b	t_a	t_c
PWM_C	t_c	t_b	t_c	t_a	t_b	t_a

Speed and Position sensing

First, the speed is measured by measuring the period between two rising or falling edges of one of the Hall sensor inputs. The period measured is nothing but one electrical period, which is the inverse of the electrical frequency or speed.
By accumulating this electrical speed value over every FOC cycle, the position 'T' is computed. In this example, the FOC cycle is **200µS.** We use the relationship The position T can also be calculated using the encoder inputs in place of hall sensor. Instead of accumulating speed, we get the position information directly.

With the kind of efficiency FOC brings enables, significant energy and dollar savings can be made by implementing this control technique to drive the motors which drive the world. And, with the flexibility, resources, and compact architecture provided SoCs such as the PSoC 3, the entire control algorithm inclusive of hardware (other than the driver board) can be implemented in a single chip.

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