*International Journal of Engineering Science Invention*
*ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726*
*www.ijesi.org Volume 2 Issue 4 ǁ April. 2013 ǁ PP.57-60*

# Methods of Commutation and Current Control Mechanism For Brushless Motors

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**ABSTRACT:** *Unlike brushed DC motors, every brushless motor requires a "drive" to supply commutated current to the motor windings synchronized to the rotor position. Due to the increasing demand for compact and reliable motors and the evolution of low-cost power semiconductor switches and permanent magnet (PM) materials, brushless motors became popular in every application from home appliance to aerospace industry.In this paper, various different schemes of electronic commutation and current control will be discussed. Starting from a simple 6-step drive without current control, discussion will include bus current control, sinusoidal commutation, phase current control, and synchronous regulator. Relative advantages of various commutation techniques and current control schemes with respect to dynamic performance and steady-state torque output are discussed*

**Keywords:** *brushless motors, rotor position, sinusoidal commutation, dynamic performance, synchronous regulator.*

## I. INTRODUCTION

For brushless motor drives, current control is often used to improve performanceand reliability. This tutorial paper analyses and compares various different schemes of electronic commutation and current control.In other words, some kind of feedback positionsensors is necessary to commutate brushless motors. Some drives are just commutating whileothers may include voltage control with or without current-loop. Fig. 1 shows a block diagramof a typical brushless motor drive system.

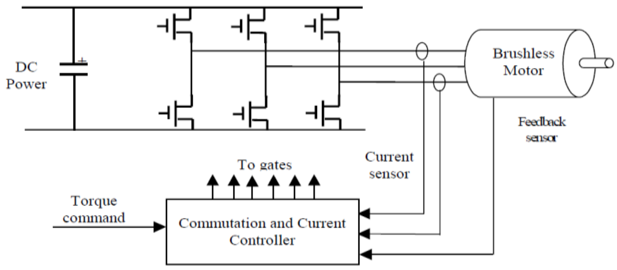


**Fig. 1. Block Diagram of a Brushless Motor Drive System**

The ac machines,like induction motors, and brushless permanent magnet motors do not have brushes, and their rotors are robust because commutator and/or rings do not exist. That means very low maintenance. This also increases the power-toweightratio and the efficiency. For induction motors, flux control has been developed, which offers a high dynamic performance for electric traction applications. However, this control type is complex and sophisticated.

In this case, power semiconductor switches of Fig. 1 are used not only to commutate but also tocontrol the motor terminal (drive output) voltage via the PWM (pulse width modulation) technique. The technique generates a fixed frequency (usually 2 kHz - 30 kHz) voltage pulse whose on-time duration is controlled. Since the brushless motor is highly inductive, the motor current produced from this switched voltage would be almost identical to that from the fixed voltage whose magnitude is the average of the switched voltage waveform. Although PWM control is now very popular in drives, variable bus voltage control is still used in some applications where dynamic performance is not important.

## II. 6-STEP COMMUTATION AND CURRENT CONTROL METHODS

One of the simplest methods of commutating 3 phasebrushless motor, commonly known as the "6-step drive" will be discussed in this section. In this method, each phase voltage is energized for 120 deg. (electrical) interval according to its rotor electrical angle as shown in Fig 2(b).

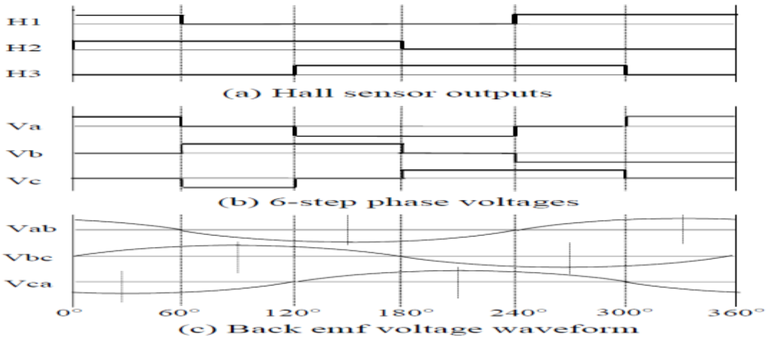


**Fig. 2. 120° Conduction Commutation**

This may be realized by the switch configuration of Fig. 2 Each phase voltage is positive (negative) when the top switch is on (off) and the bottom switch is off (on). No voltage is injected when both switches are off, in which case the actual terminal voltage is governed by the back emf voltage of the motor. In other words, each phase voltage at a time takes one of three states - positive, negative, or float. At every sector, only one phase is energized as positive and one of the other phases is energized as negative in order to maintain current path. In order to commutate properly, the controller needs to know the sector (60 degree interval) position of the shaft angle.

When operated by the 2-quadrant switching, a positive ecurrent is detected during pwm on period and can be used to limit the current by turning pwm off as soon as current limit is detected. For 4-quadrant switching, a positive current is detected during pwm on period, while negative of one of the phase current is detected during pwm off period. Therefore, an absolute value circuit is normally necessary to limit or regulate the current in this case. An alternative method is to capture the current only during pwm on time on digital drives with A/D converters. In general, 6-step drive produces high torque ripple, especially during transition of commutation, and the overall system efficiency is poor. In addition, audible noise might be animportant concern for high power motors. Nevertheless, they are very popular in small size applications where high dynamic performance or accurate speed regulation is not required.

## III. SINUSOIDAL COMMUTATION AND CURRENT CONTROL

Instead of conventional phase current regulator, the “synchronous regulator” [3] based onrotating reference frame may be employed. In this case, measured 3 phase currents are first transformed to d-axis (rotor magnetic axis) and q-axis (axis in quadrature to d-axis) current components based on the rotor angle and then current-loops are closed in order to produce desired d- and q-axis voltage commands. These voltage commands may be inverse transformed back to phase voltage commands for conventional PWM circuits or Space Vector PWM [1].Block diagram of a synchronous regulator is introduced in Fig. 3 In synchronous regulators both d- and q-axis current commands are constant values in steady-state without sinusoidal modulation, much like a separately excited DC motor. When synchronous regulators are used instead of phase current regulators, the bandwidth requirement for commutation vanishes if the current compensators incorporate integral control due to its inherent zero steady-state error tracking capability to step inputs. Nevertheless, a reasonably high bandwidth, with a fast sampling rate for digital systems, is still required for smooth current regulation. Note that the concept of synchronous regulator assumes sinusoidal steady-state current and is limited to motors driven by sinusoidal drives.On the above cross-coupled multi-variable system model, Vq and Vd are inputs and Id and Iq are outputs while the dominant system time constants are Ld / RsandLq / Rs for d-axis and q-axis, respectively. With the synchronous regulator, the induced EMF (back EMF) term of $\omega\lambda m$ on q-axisis a slowly varying disturbance proportional to the speed and can simply be compensated by injecting an offset voltage. With back EMF compensation, the magnitude of current error can be kept at a small value and actual current tracks commanded current faster.

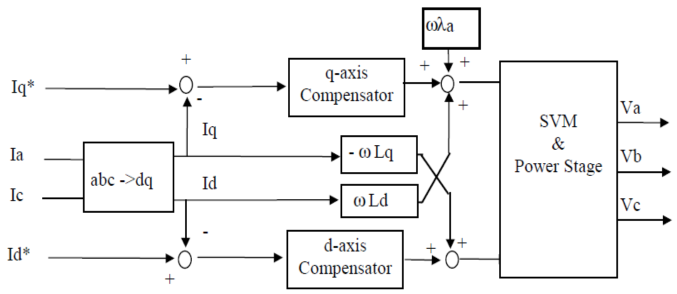


**Fig. 3(a). Synchronous Regulator with Decoupling Control**

For better dynamic performance, crosscouplingterms ($\omega L_d I_d$ and $\omega LqIq$) may also be compensated as in Fig. 3(a)When traditional phase current regulators are used, generated back EMF of AC motors when the motor is rotating acts as a sinusoidal voltage disturbance and is difficult to compensate unless an accurate dynamic model of the motor is incorporated. A similar statement can be applicable to the de-coupling compensation. Whether back EMF compensation is employed or not, back EMF effectively reduces available DC bus voltage, resulting in lower effective gain and a low dynamic current regulator performance at high speed. When a motor is operated with flux-weakening, current regulation must be performed well under low available bus voltage. In general, drives for fieldweakeningoperation should be designed for higher current-loop bandwidth. With practical motor drives using IGBT switches and PWM frequencies less than 25 kHz, 1 - 3 kHz bandwidth may be achieved with careful design efforts.

Consider the dynamic model of the plant for which current regulators will be designed. For both phase current regulators and synchronous regulators, the current control circuit is composed of a compensator, a PWM amplifier connected with a motor, and a current measurement circuit. Block diagram of a current-regulator with a PI compensator is shown in Fig. 3(b)The time delay block is applicable to a digital current control system where data conversion time and computation time delays are not negligible. When a continuous model isused, the time delay should include a sample and hold delay of one half of the sampling period. An open-loop transfer function from input command Ic(s) to the measured current Ifb(s) can be modeled as a second order plus time delay (Td) system as

$$\frac{I_{fb}(s)}{I_c(s)} = (K/L)\,\frac{1}{(s+\omega_e)(s/\omega_f+1)}\,\exp(-\,sT_d)$$

where open-loop gain K is proportional to the available bus voltage and L is the motorinductance. For synchronous regulators, L is either Lq or Ld, while for phase current control the inductance may swing between maximum (Lq) and minimum (Ld) value as rotor turns.

There are two major factors limiting high closed-loop bandwidth on a current-loop. Oneis multiple pulsing phenomenon on analog current control and the other is current-loopresonance. Multiple pulsing occurs when the closed-loop system command response is fasterthan the slew rate of the triangle waveform in analog PWM method. In this case, the actual PWM rate would be higher than the designed PWM frequency, and could possibly causeoverheating of the motor and drive and may result in unexpected drive failure. For a digitalcurrent regulator multiple pulsing does not occur due to the fact that current is sampled only onceper cycle. It is not too difficult to verify that multiple pulsing frequency (fp) is about 60% of thePWM frequency when there is no appreciable filtering (cut off frequency lower than PWMfrequency) present in the circuit.

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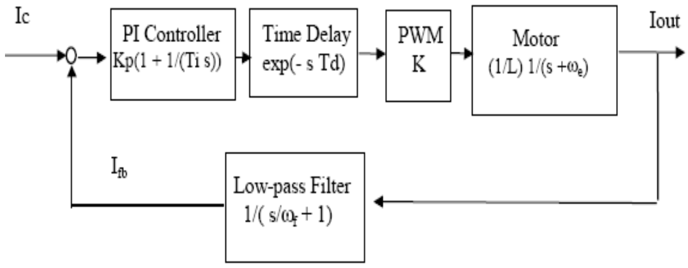


**Fig. 3(b) Block Diagram of a Current-loop**

Most practical closed-loop systems tend to resonate when controller gain is increased. Incurrent-loops, resonance occurs when unity gain occurs at a particular frequency whose phasedelay is -180°. When analog current-loop is designed with minimal phase lag in the currentmeasurement circuit, resonance frequency can be designed even higher than the multiple pulsingfrequency. On the other hand, digital current control adds signal processing delay (dataconversion delay and computational delay) and inherent sample and hold delay into the currentloop, forcing the resonance frequency (fr) considerably lower than that of the analog PWMcircuit. Often, sampling frequency is selected to twice the PWM frequency (double sampling) inorder to achieve high bandwidth. The achievable bandwidth with small overshoot is typically lessthan 1/2 of fr, as indicted by a closed-loop PID tuning method known as Ziegler-Nicholsontuning rule [5].

This can be easily corrected if a PDFF [8]controller is used, which is a first order pole-assignment structure with a feed-forward term. It isalso called as a PID controller with set point weighing [9]. Next, the PI controller lacks phaseleading capability that gives additional damping in the response. Since digital current regulatorhas significant time delay, a derivative term can improve system response. High ordercompensators may be used either to increased bandwidth or to decrease sensitivity to parametervariations. Most practical analog and digital current regulators use the popular PI controller due to itsimplicity and fast calculation time. Higher order control algorithms such as pole-zeroplacement control based on state-space concept has been reported [6,7].

## IV. RESULT AND COMPRATIVE STUDY

Complex controlalgorithms may be used with digital control but a compromise should be made between theamount of phase lead achieved and additional computation time required to process. Whensignal processing time is considerably shorter than sampling period, a higher order compensatormay improve dynamics. Note that in digital designs, higher sampling frequencies couldsometimes be much more effective in obtaining higher bandwidth than using a higher ordercompensator. The PI controller has major limitations in digital current control. One is aninherent controller zero that causes overshoot.

## V. CONCLUSION

Although asimple 6-step 2-quadrant drive without current control may be sufficient for some application,varying degrees of sophistication on commutation and current control are required to achieveperformance requirement governed by application needs.Sinusoidal control offers smoother torque, quieter operation and higher efficiency comparedto 6-step commutation. It requires higher resolution feedback device such as resolver orincremental encoders.Bus current control method does not compensate for the inherent phase lag of the linecurrents, while phase current regulator with sinusoidal commutation reduces the phase lag,resulting in higher torque at high speeds. Required current-loop bandwidth of the servo system comes from two performanceobjectives. First, it should be at least 6-8 times higher than desired velocity loop bandwidth.Second, it should be at least 5 times the maximum excitation frequency in order to amplifycurrent wave-form without too much attenuation.Further compensation of phase lag may either be achieved by phase advance technique, or byuse of synchronous regulator.

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