AN2372
Application note

Low cost sinusoidal control of BLDC motors with Hall sensors using ST7FMC

Introduction

BLDC motors are the workhorses in most light industrial applications. In some cases, Hall-effect position sensors are used to simplify control logics for controlling these motors. BLDC motors, by the nature of currents through them, are somewhat noisy and a little less efficient. These disadvantages plus the cost of sensors are an integral part of these drive systems. However, if the motor can be driven with sinusoidal currents, preferably with only one Hall-effect sensor, these drawbacks can be greatly reduced.

A 3-phase Permanent Magnet Synchronous Motor (PMSM) has permanent magnets on the rotor and current-carrying windings on the stator. There are two modes of control:

- as a BLDC motor, where, based on rotor position, only two windings carry current at any given time (reducing winding utility by 33%)
- as a three phase AC motor, where three-phase sinusoidal voltages are applied on all three windings and all three windings carry current at all times

The comparison chart below shows the advantages of controlling the PMSM motor like an AC motor instead of a BLDC motor.

AC motor	BLDC motor
Currents are sinusoidal	Currents are rectangular
Current harmonics in switching frequency range	Rectangular currents have harmonics in odd multiples of fundamental frequency (which are in audible range) plus switching frequency harmonics.
Lower audible noise	Higher audible noise
Lower core losses in motor	Higher core losses
Current peak value lesser, power circuit dimensioning can be optimized	Current peak value higher. Higher dimensioning of power circuit
Phase rms current lower	Phase rms current higher
Electric torque developed is flat	Torque has commutation ripples
Higher switching losses in inverter as all switches take PWM	Switching losses minimal because only one of the switches take PWM
Implementation is little complex	Implementation is simple

Implementation of this scheme with an ST7FMC can give additional advantages such as load angle control to help optimize the motor current, and voltage foldback current protection to help limit motor currents by reducing the applied voltage to implement current limit control.

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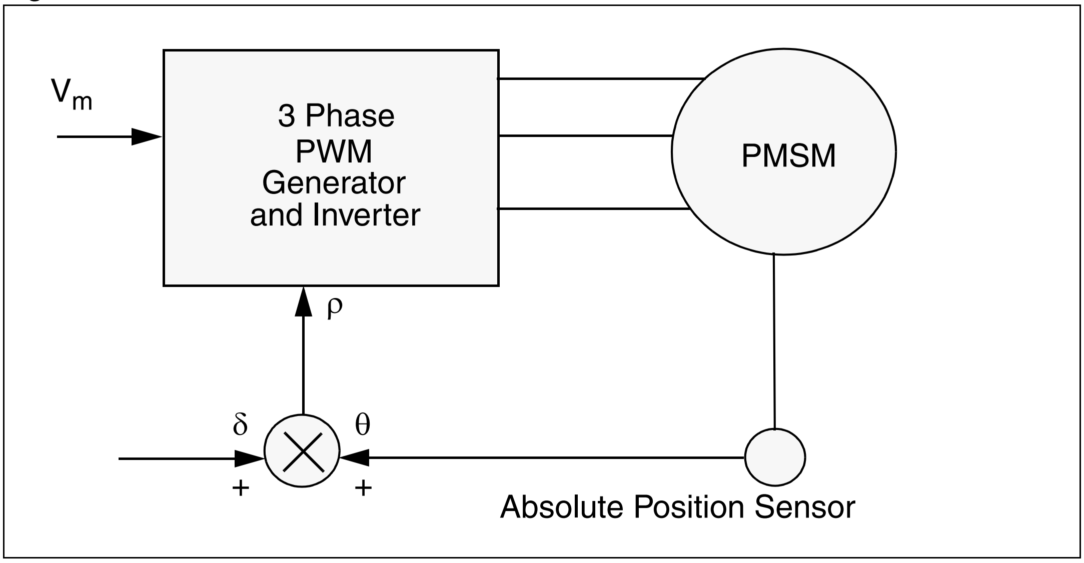
1 Theory of operation and control

In three-phase AC motors, currents flowing in the stator windings create a magnetic field with a definite magnitude and orientation inside the motor. When a DC current passes though these windings, it produces a static magnetic field. The permanent magnets in a free spinning rotor interact with the stator flux and experience a force of attraction to fall in line with the stator flux and lock with it. If now the stator flux orientation is changed by adjusting the stator currents, the rotor that is already locked with the stator flux, also changes its orientation to take the new position of the stator flux. If the stator is now excited with sinusoidal varying currents, the stator flux inside the motor spins at the frequency of its sinusoidal currents and pulls along the rotor at this frequency.

The ability of the rotor to stay locked with the stator flux depends on the strength of the magnetic fields and the magnitude of load torque disturbances on the rotor. Once the rotor is in motion, if at any time the it falls out of alignment with the stator flux, it cannot spin anymore and comes to a halt. If the stator is still excited with sinusoidal currents, then the rotor experiences pulsating torque in either direction at the frequency of stator currents.

Figure 1. Self control of PMSM

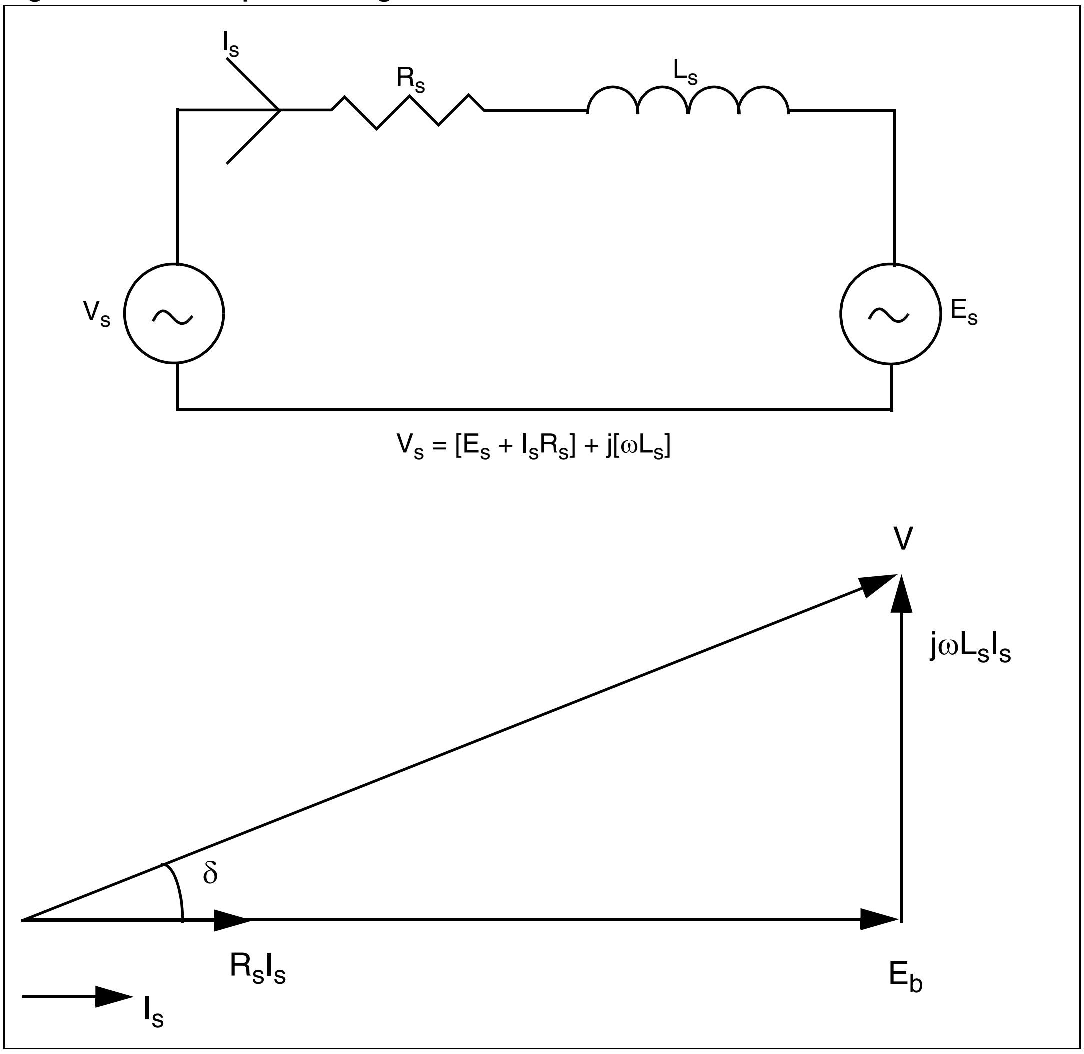


However, this situation can be overcome if we force the sinusoidal angular values of stator currents to correspond to the angular position of the rotor (plus an offset) as shown in *Figure 1*. What this means is that even if the rotor tries to fall out of alignment for any reason, since the stator current (which determines the stator flux magnitude and orientation) depends only on the angular position of the rotor, it pushes/pulls the stator flux in the direction of the rotor disturbance to maintain alignment, thereby giving improved stability and control.

Under this condition, the PMSM motor acts like a DC motor where commutation is performed by inverter switches and the speed is determined by the magnitude of applied voltage. The frequency of applied sinusoidal voltage varies directly with speed and automatically tracks itself to a value such that it matches with the V/f ratio for the motor. For precise speed maneuvers, load angle tuning can be brought into play. For operations in field weakening mode, applied voltage magnitude can remain at the maximum level and the load angle should be increased appropriately.

Even though it acts like a DC motor, it still follows the basic theory of AC synchronous motor control. A single-phase equivalent circuit of the motor and a phasor diagram of motor voltages and current are shown in *Figure 2*. By adjusting the phase angle between back-emf and applied voltage, and/or the magnitude of applied voltage, the power factor of the machine can be set to unity. This helps to maximize the power output for a given value of phase current and to minimize the inverter rating.

Figure 2. PMSM phasor diagram at UPF



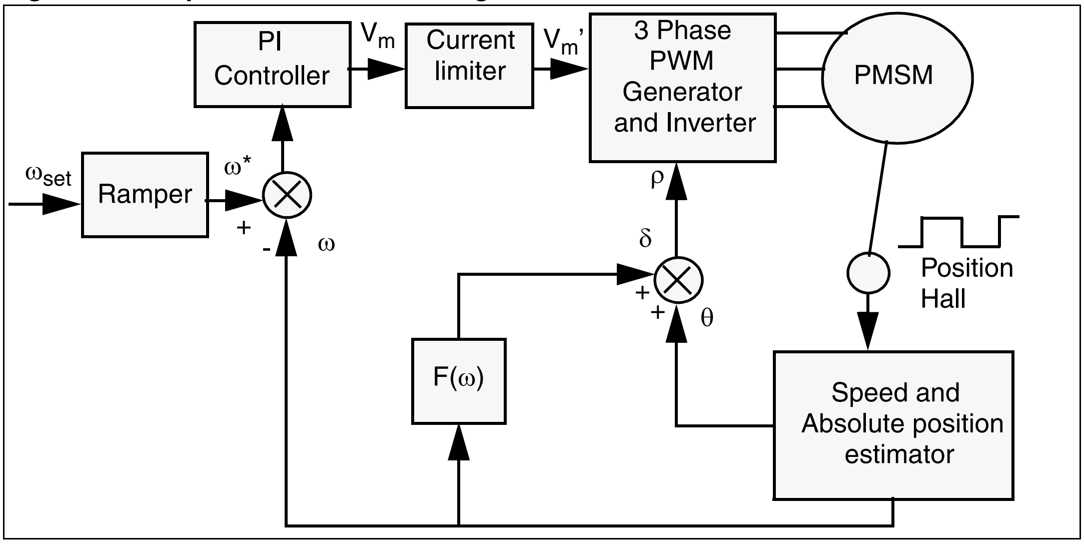
To implement this control, knowledge of rotor position is necessary. An absolute position encoder may give incredibly accurate resolution and precision, but its cost is very prohibitive. On the other hand, Hall sensors mounted in BLDC motors give a very course resolution of close to 60° to 180° depending on the number of sensors, but they are inexpensive. They generate rising/falling edges at these positions to indicate the angular value at that point. However, to get intermediate angular positions of the rotor between these edges, additional intelligence is needed by the controller for estimation.

2 Experimental implementation using ST7FMC

The power of ST7MC to control BLDC motors with trapezoidal flux distribution, in 6 step mode, is well known. In addition to this, ST7MC is also capable of delivering three phase sinusoidal complementary PWMs with programmable dead time insertion to control a two-level three-phase inverter that can drive any three-phase loads. It has a speed feedback block that can either count the number of encoder pulses in a given time frame (in encoder mode) or identify the time lapsed between two consecutive tacho edges (in tacho mode). In the experiment performed using ST7MC on a three-phase PMSM, three-phase PWM generation and speed feedback in tacho mode are used.

The control block diagram is shown in *Figure 3*. A speed command from the user is passed through a ramper that sets the acceleration and deceleration rates and generates a speed command for closed loop control. This is compared with a speed feedback estimate and the error is passed through a PI controller that generates the magnitude reference for a 3 phase sine voltage to be applied on the motor. Usually speed loops set the current reference for an inner current loop for current controlled ramp up and ramp down. But this is handled in a simplified manner and is described in *Section 2.2*. Speed feedback is estimated as described in *Section 2.1*.

Figure 3. Implementation block diagram



θ represents the estimated angular position of phase back emf A at any given instant. δ represents the angle enforced between the back emf and applied stator voltages. By controlling this value, the motor can be made to operate in unity power factor. In this experiment, the load is assumed to be a friction load. This means that the load torque increases linearly with speed. To obtain close to unity power factor at all speeds, the load angle is varied linearly with speed. Provision is given on this test setup to exclude load angle compensation to study the difference in performance. The effect of load angle compensation is predominantly visible at higher loads and speeds. With load angle compensation, the phase currents and DC link currents are appreciably lower than without it under same load conditions and the waveforms are shown in *Figure 4*.

Figure 4. Experimental waveforms with and without load angle compensation

2.1 Speed and absolute position estimation

The control scheme requires instantaneous position of back emf A to generate sinusoidal PWM pulses for motor control. However, with only a Hall sensor feedback, that generates only two edges within a 360° electrical cycle (corresponding to say 0° and 180°), instantaneous position information is not available. To obtain the intermediate values, an estimation of rotor speed is required, so that an integration of rotor speed at the pwm update period gives the rotor position at these instants.

The basic estimation scheme is as follows:

θ is the estimated angle

θ_H is the actual rotor angle at instant of a given Hall edge

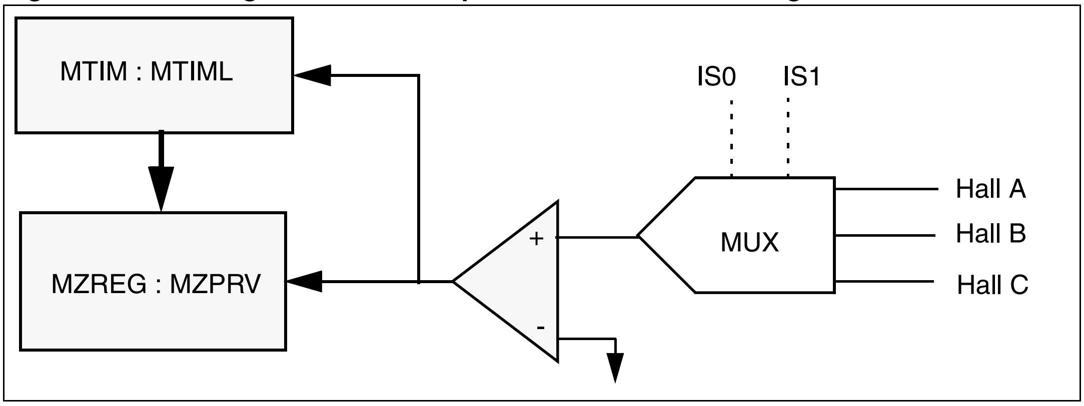
ω is the rotor speed

At the instant of a Hall edge, $\theta = \theta_H$

For intermediate positions, for use in pwm update routines,

$\theta \Leftarrow \omega . T_{pwmupdate} + \theta$

Figure 5. Hall edge detection and period measurement using ST7FMC



However, there are two different methods to estimate the rotor speed:

1. division method
2. PLL method

There are some commonalities between these methods. *Figure 5* shows a simplified diagram of Hall feedback connection to ST7FMC. IS1 and IS0 bits are used to connect one of the Hall inputs to the comparator that will next change its output state after the current one. When the comparator detects a state change, the contents of a free running timer (MTIMH:MTIML) are captured into (MZREG:MZPRV) and the timer is reset to zero, and an interrupt (C) is generated. Inside the C ISR, the Hall sensor states are read, θ_H is identified and $\theta = \theta_H$ is implemented.

In the division method, rotor speed is calculated on the basis of time difference between two consecutive edges. With 1 or 3 Hall sensors feedback, consecutive edges correspond to 180° or 60° respectively. The existing motor has 3 sensors and hence captured period corresponds to 60 electrical degrees.

Electrical speed $\omega = 2\pi /(T_{360})$

Or,

$\omega = 2\pi /(6.\ T_{60})$

If only one Hall sensor is present, the captured period corresponds to 180°, and hence

$\omega = \pi / T_{180}$

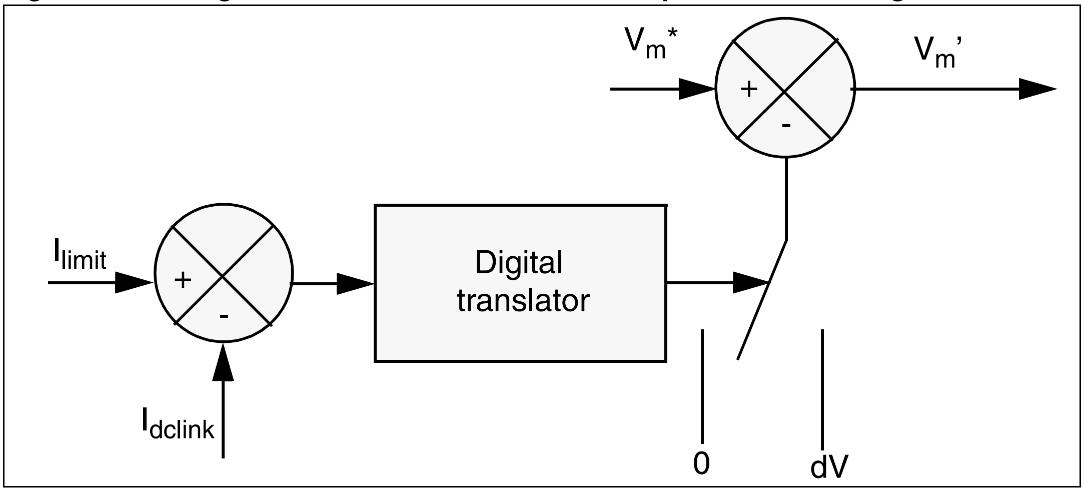
In the PLL method,

$\omega = k.\Sigma(\theta_H - \theta)$

2.2 Current control

A conventional speed control loop sets current reference for an inner current loop. Though it is very relevant for the overall control structure, it poses a few challenges. Since the phase currents are sinusoidal, extracting a DC equivalent torque current requires at least two phase currents and Park Clark transformations in the control loop. This needs two current sensors and a high MIPS computing engine. Attempting to extract all three phase current-related information from the DC link current requires additional timer hardware/logics and CPU MIPS. These requirements are obviously complicated and expensive.

Figure 6. Voltage foldback current limit control implementation using ST7FMC



Hence a cost effective voltage foldback current limit control is implemented that fits very well with the ST7FMC architecture. The control block diagram is shown in *Figure 6*. ST7FMC has an on-chip opamp and a comparator. This opamp promotes the use of a low value shunt resistor whose weak output can be amplified, thereby minimizing its power dissipation. The current signal from the opamp can be connected to the comparator whose output is tied to an interrupt generator. If the applied motor voltage is high leading to heavy currents in the DC link, such that the comparator detects over current condition, it generates an interrupt where, in its interrupt subroutine, the applied voltage is decremented marginally by dV. If this condition is continuously identified during succeeding PWM cycles, the applied voltage is constantly decremented in each interrupt, until the peak current flowing through the DC link is below the reference value. At this point, the motor operates at a voltage and speed corresponding to current limit. Since the voltage magnitude is reduced instead of clipping the on times of inverter switches, the motor currents continue to be sinusoidal. From a control standpoint, current loop implementation is highly simplified and the PMSM motor is controlled like a DC motor.

3 Conclusion

A control implementation on a PMSM motor as described in this document was implemented using ST7FMC and the performance was found to be satisfactory. Noise was drastically lower. At high speeds, power consumption of a sinusoidal drive was marginally lower than with traditional style control as with a BLDC motor. A fair comparison between the efficiencies of these schemes is not trivial as it involves various factors such as inverter switching frequency, inverter voltage drop, transient behavior of power switches in the inverter, motor currents and its winding resistance.

Appendix A Phase current comparison between 6 step BLDC drive and sine BLDC drive for same power output

For same power output, average DC link current is same

6 Step BLDC motor phase currents:

$I_{av} = 2.\ I_d /3$

$I_{rms(BLDC)} = \text{sqrt}(2/3).I_d$

$= 0.8165\ .\ I_d$

Sine-drive motor phase currents:

$I_{av} = 2.\ I_m / \pi$

Where,

$I_m = (\pi/3).\ I_d \rightarrow$ under same power delivery

$I_{rms(SINE)} = [\pi / (3.\text{sqrt}(2))]\ .\ I_d$

$= 0.74\ .\ I_d$

$I_{rms(SINE)} / I_{rms(BLDC)} = 0.906$

This shows that with a sine-drive BLDC approach, the phase rms current is lower by nearly 10% compared to a 6 step drive.

Appendix B Test procedure

The software attached with this application note can be downloaded and tested on the ST7FMC starter kit. The test procedure is as follows:

1. Configure the jumpers for sensored BLDC mode.
2. Set W12 to FIXED
3. POT1 sets the current reference. Set it to a middle position
4. RV1 sets magnitude reference for sine output. Set to zero (CCW)
5. RV2 sets load angle. Set to mid position (0°). Turning CW increases the load angle and CCW takes it negative (max / min is +/-90°)
6. Yellow button SW1 is the ON/OFF switch. Press it to turn ON.
7. Turn RV1 CW and motor starts running
8. Change POT1, RV1 and RV2 for experimenting with current limit, sine magnitude and load angle
9. Pressing SW1 again turns off the motor.

4 Revision history

Table 1. Document revision history

Date	Revision	Changes
11-Jul-2006	1	Initial release.