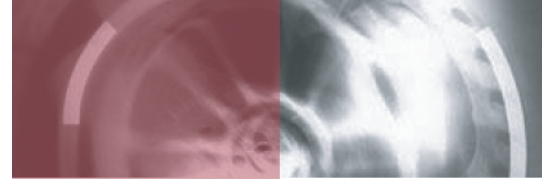




**White Paper**

**Published Article**



**Advances in Sensorless Control  
of BLDC Motors**

## ADVANCES IN SENSORLESS CONTROL OF BRUSHLESS DC MOTOR

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Brushless DC (BLDC) motors and Permanent Magnet AC (PMAC) motors have been widely used in servo and motion-control applications in the industrial marketplace since the early 1980s. Since the mid 1990s the use of Brushless DC motors has been increasing rapidly in non-servo, commercial applications such as fans, pumps, compressors, centrifuges, washer drums, automotive subsystems and disk-drive spindles. The Electronic Motor Drive (EMD) market for BLDC motors is booming and expected to grow from \$290 million in 2003 to \$1.3 billion in 2008, a compound annual growth rate of 34%.<sup>i</sup>

### Motor Technology Comparison

Feature	BLDC	Brushed DC	AC Induction
Maintenance	None	Periodic	None
Life	Longer	Shorter	Longer
Efficiency	High	Moderate	High/Moderate
Power Vs. Size	High	Moderate/Low	Moderate
Inertia	Low	High	High
Electric Noise	Low	High (Arcing)	Low
<b>Cost</b>	<b>High (Coming Down)</b>	<b>Moderate</b>	<b>Low</b>
<b>Control</b>	<b>Complex</b>	<b>Simple</b>	<b>Simple/Complex</b>
Control Requirement	Always Required	Optional	Optional

High efficiency and high power-to-size ratio are key BLDC motor advantages; the downside in the short-term is increased cost and relative control complexity. Ongoing cost reductions of magnet materials and semiconductors used in BLDC motors are narrowing the cost gap and adding momentum to BLDC motor use and attendant EMD applications. Equally important, control complexities are being alleviated by advances in modern DSP technology, which facilitates implementation of sensorless control algorithms and eliminates the need for position sensors (and associated wiring) required in conventional BLDC motor-control systems.

## BLDC Motor Operating Principle

BLDC motors are commutated in six steps every  $60^\circ$  during a full cycle of  $360^\circ$  electrical. Two of the three coils are energized at any time. Figure 1 shows the commutation sequence.

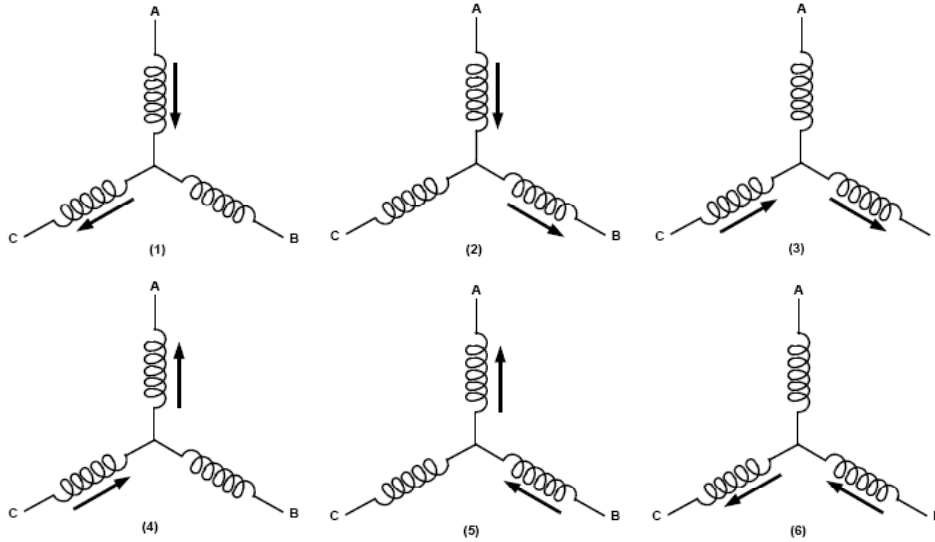


Figure 1. Six-step Commutation Sequence

This type of commutation yields maximum torque from the two energized coils in BLDC motors with trapezoidal speed induced voltage (back-EMF). In conventional drive systems the switching of the winding is controlled with feedback from three hall sensors. Figure 2 shows a typical control system with hall-sensor feedback.

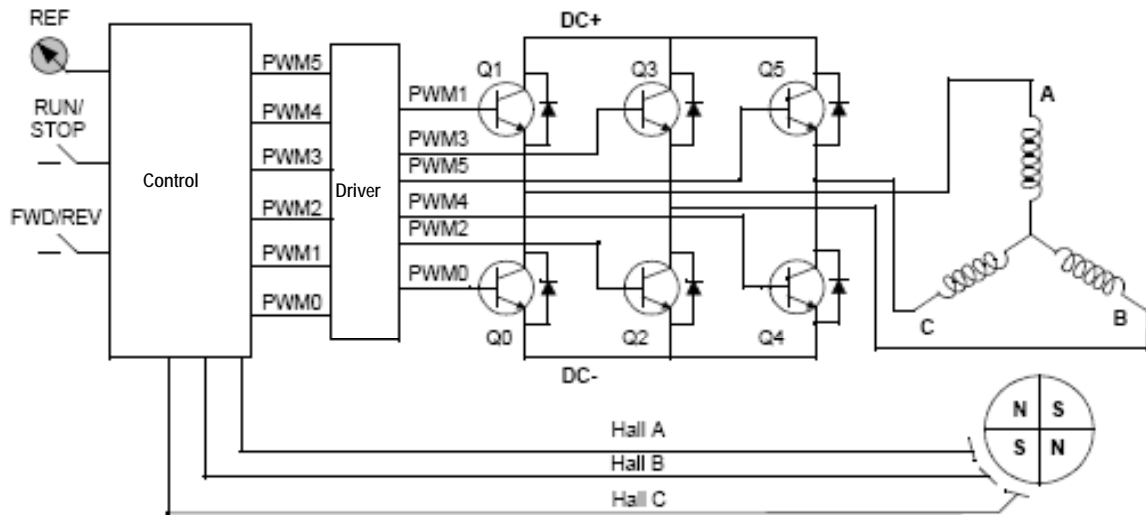


Figure 2. Hall Sensor Motor Drive

Simple control logic, robust and reliable motor start, and maximum motor torque are the main benefits of hall sensor based systems. The additional wiring for the hall sensors, potential malfunction due to contamination, and general failures of the sensors themselves are the primary disadvantages.

### Sensorless Commutation Based on Back-EMF

The BLDC motor's back-EMF can be used for motor commutation instead of hall sensor feedback. Back-EMF in the off-phase undergoes a polarity reversal during the time the phase is off. Figure 3 shows simplified time domain waveforms of phase-to-neutral back-EMF and motor current.

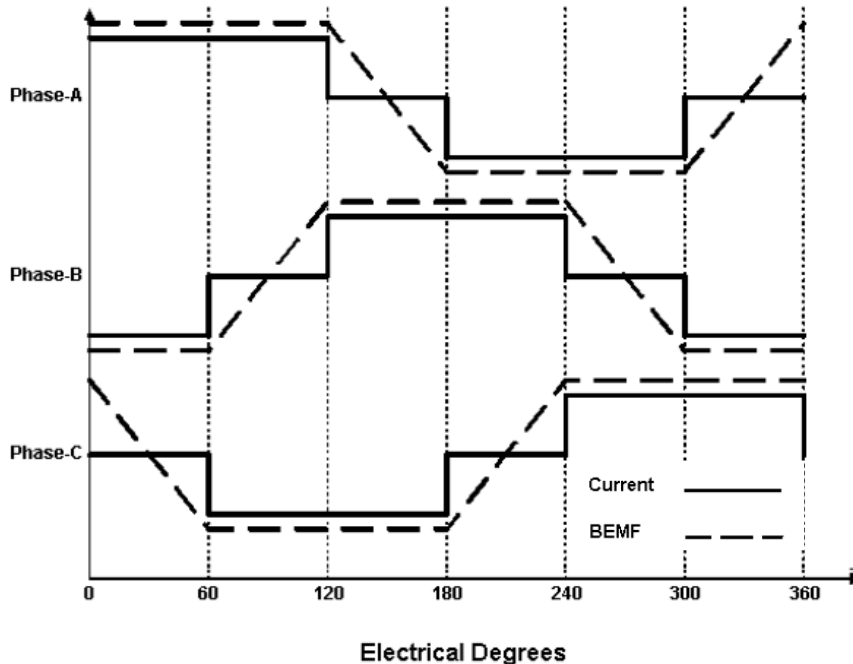


Figure 3. Motor Current and Back-EMF Waveforms

There are two ways to implement a commutation algorithm based on the back-EMF voltage.

1. The back-EMF crosses through zero 30° before the ideal commutation point. The controller commutates the motor at a time delay derived from the actual motor speed after detecting zero crossing of the back-EMF.
2. The controller integrates the back-EMF to a flux-per-pole value derived from the motor's speed constant, in order to determine the proper commutation point. This method provides more consistent sector-to-sector transition at low speeds with less torque variation. It is also more flexible, allowing the implementation of phase advance field weakening beyond 30° electrical, in order to increase the available motor speed.

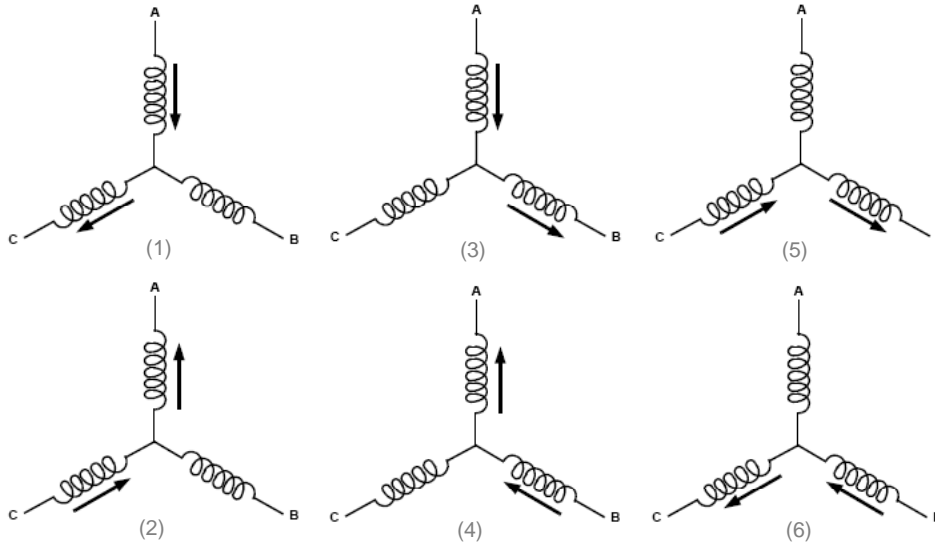
Both methods require measurement of the phase-to-neutral back-EMF voltage. It is certainly possible to have a "fourth" motor connection to make the neutral point accessible from the outside, but it is not necessary because the neutral point voltage can be estimated with sufficient accuracy from the supply voltage.

### Sensorless Startup

As the back-EMF is proportional to speed, a sensorless controller needs a way to find the initial rotor position, for starting the motor and accelerating it to sufficient speed for detection of back-EMF voltage. Startup is undoubtedly the biggest hurdle any sensorless-control algorithm must overcome. Conventional methods drive a current through the motor windings, forcing the motor rotor into a known position to ensure proper motor start. This can cause up to 180° of (2-pole) motor rotation opposite to the desired direction, adding to acceleration and startup time. The current required to orient the rotor depends on the inertial and frictional load of the motor. If the initial current to orient the motor is too high, there may be overshoot and ringing in the system. If the current is too low, the motor may not start at all. Such a system is not robust with respect to system load conditions.

## “Ping” Method

More advanced methods determine motor rotor position based on the motor-phase saturation inductance change. The controller generates 6 short, opposing current pulses that drive the motor phases into saturation. Figure 4 shows the current pulse sequence used to determine the change in saturation inductance. The controller calculates the motor rotor position based on the saturation inductance change in each phase. We refer to this procedure as the “ping” method.

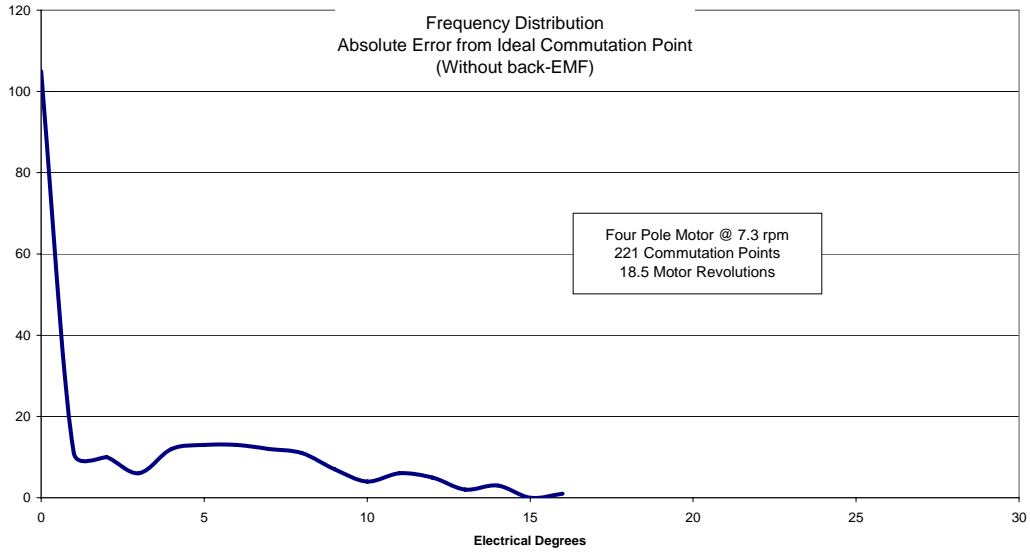


**Figure 4. Current Pulse Sequence - "Ping" Method**

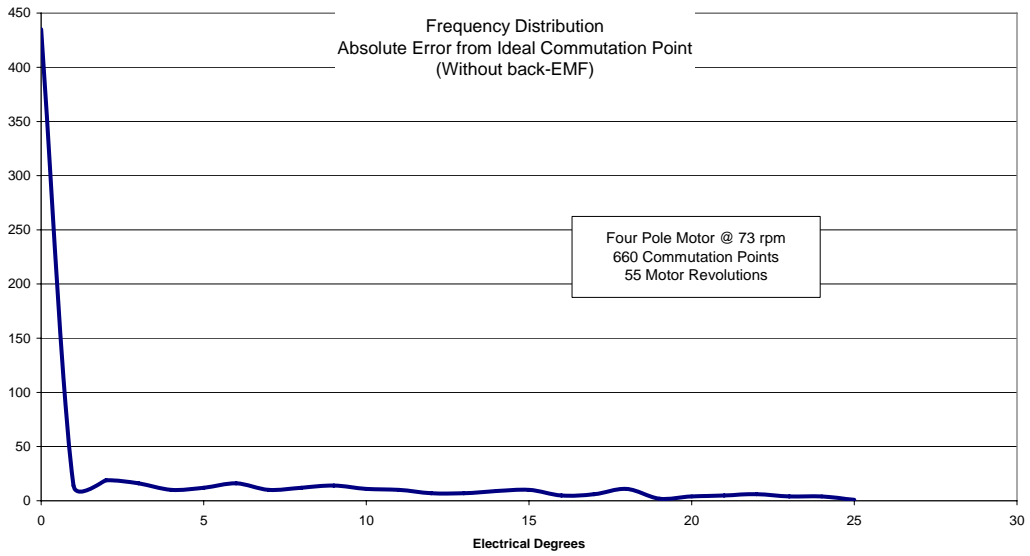
The motor rotor remains stationary during the initial “ping” period, because the current pulses are short and in opposing sequence. In most cases, the motor reaches sufficient speed for back-EMF commutation to take control before the next commutation-sector change. Rarely, (usually if the motor’s load is extremely heavy) the ping process repeats while the motor rotates at low speeds below the back-EMF commutation threshold. This is possible because the “ping” period time is negligible with respect to the time between sector transitions at low motor speeds. The “ping” method guarantees unidirectional motor start, which is independent of motor loading conditions. The system is robust with respect to system load conditions.

### “Ping” Method Robustness: Test and Results

The test setup: a 4-pole BLDC motor with hall-sensor feedback. The motor is connected to a BLDC motor controller. The controller’s back-EMF commutation function is disabled and only the “ping” algorithm controls the motor commutation. The test records the difference or error between the sector transitions generated by the “ping” algorithm and the actual sector transitions of the motor obtained from the hall-sensor feedback. The data is recorded at 7 rpm and 73 rpm. Figures 5 and 6 show the frequency distribution of the absolute sector-transition error at 7 rpm and at 73 rpm.



**Figure 5. Sector Transition Error at 7 rpm**



## Figure 6. Sector Transition Error at 73 rpm

In either case the sector transitions are right on target. About 90% of all sector transitions fall within 10° electrical with only a few outliers. Maximum error increases from 16° electrical to 25° electrical as the motor speed increases from 7 rpm to 73 rpm. The accuracy at higher speeds is of lesser importance here because commutation based on back-EMF takes over at the higher motor speeds. The respective sector-transition errors of 16° and 25° electrical seem large at first, but examining motor-torque reduction associated with those errors provides a proper perspective. Torque in a BLDC motor is a function of the motor current and the angle between the flux vector of the permanent magnets in the motor and the motor current vector. The equation below ideally applies to sinusoidal systems.

$$T = \Phi \cdot I \cdot \sin(\angle(\Phi, I))$$

$\Phi$	:	Magnetic flux
$T$	:	Motor shaft torque
$I$	:	Motor phase current
$\angle(\Phi, I)$ :		Angle between phase current and magnetic flux

For the purpose of this analysis, the error resulting from applying the above equation to a BLDC motor with trapezoidal back-EMF is negligible. In addition, with a 16° sector-transition error at 7 rpm the angle between flux and current  $\angle(\Phi, I)$  is 74° (90° - 16°), which results in 96% of maximum available motor torque. At 73 rpm, a sector-transition error of 25° an angle  $\angle(\Phi, I)$  of 65° results in 91% of maximum available motor torque. Thus the torque loss is minimal and it occurs only at the infrequent outliers.

### Summary

State-of-the-art sensorless BLDC motor control technology provides performance on par with conventional hall sensor commutated drives in non-servo applications. Cost reductions of motor materials and electronic components, along with the reduced wiring and hardware simplicity of “Ping Method” sensorless controls, are making BLDC motors and drives a superior choice in commercial applications where energy efficiency or motor-frame size are of primary importance.

<sup>1</sup> North American Market Outlook, Non-servo Electronic Permanent-Magnet Synchronous Motor Drives – Drives Research – April 2004

Agile Systems is a world leader in the design, development and manufacturer of advanced motion control technology including motor control and power conversion. With expertise in integrating power electronics, digital control and network communications in small, cost effective packages, Agile Systems has established customers in a broad range of industries including semiconductor, life science, robotics, automation equipment, automotive, industrial machinery and alternative energy. Agile Systems is based in Waterloo, Ontario.

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