INNOVATION WITH PURPOSE

INNOVATIVE FOC MOTOR CONTROL: IMPROVE TIME TO MARKET BY ELIMINATING SOFTWARE DEVELOPMENT

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INTRODUCTION

In recent years, brushless DC [BLDC] motor control has been gaining traction in markets where improvements in battery life are required, such as cordless power tools. This is largely being driven by demand for increased efficiency, lower noise, and higher reliability. Just a short time ago, BLDC motors used in high performance systems also required software-based microcontrollers to create efficient and quiet commutation. Newer solutions offer options with embedded commutation, offering low noise and efficient drive with no microcontroller or custom software. Sensorless sinusoidal BLDC motor drivers meet these characteristics in simple, single-package solutions that can be up to 70% smaller compared to microcontroller solutions.

Even though the fundamentals of BLDC motor control remain constant, BLDC motor characteristics vary widely across applications. Addressing differing requirements may be the biggest challenge when it comes to developing motion control algorithms. Creating specific software-housed algorithms for each application not only increases R&D expenditures, but also adversely affects time to market.

By embedding the motor commutation algorithm in hardware, engineers give customers the ability to select parameters for start-up and running conditions with simple-to-use graphical user interfaces (GUIs). These parameters are stored in the on-chip EEPROM and are used by the hardware-based algorithm, with no programming required. In this way, multiple motors for different applications can share the same hardware with one device, avoiding pitfalls of older BLDC methods.

This paper will focus on the basics of the sensorless control algorithm, the advantages of different sensing techniques, and how the GUI can drive a full-featured sensorless sinusoidal BLDC motor with no software programming required.

BASICS OF SENSORLESS BLDC CONTROL

To drive a BLDC motor, the rotor position must be known. This is often accomplished with Hall sensors or encoders; however, these circuits can become very complex and expensive. Designers can reduce complexity and cost by enabling sensorless technology. When operating without physical sensors, the rotor position is determined by a circuit called the "position observer" which looks at a different property of the motor called back electromotive force, or BEMF.

When the BLDC motor spins, the relative motion between the windings (stator) and the magnetic field (rotor) produces BEMF, which is the same property that allows a motor to act as a generator. There are two methodologies for measuring BEMF: windowed (BEMF observed) and windowless (BEMF calculated). With this information, the user can estimate the rotor position to control motor rotation.

Windowed Versus Windowless Position Observer

The three-phase BLDC motor has three windings, or phases. In a trapezoidal drive, for example, the controller drives current into two of the three phases, while the third has no current flow through the phase. The undriven phase is also called floating phase. BEMF will be induced on the floating phase, which will imply the rotor position information.

By measuring the BEMF voltage on the floating phase using an analog-to-digital converter (ADC) or voltage comparator, the phase can be used as a "sensor" to measure the rotor position. This is the "direct" or observed way of measuring BEMF. During this process, the floating phase is required to measure the BEMF voltage. The process can be seen in Figure 1.

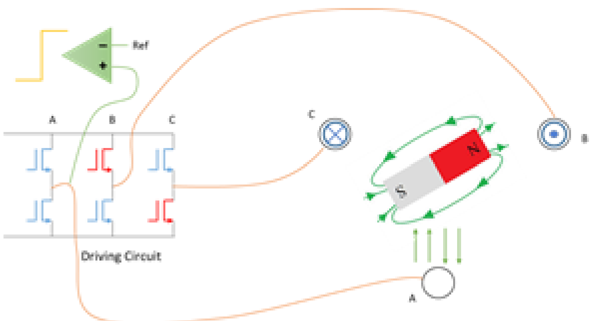

Figure 1: Floating Phase

In three-phase sinusoidal drive, current flows in all three windings, which makes BEMF measurement difficult. One method for observing BEMF in sinusoidal drive is to have an electrical observation "window" while driving the motor, enabling direct BEMF measurement.

The calculated "windowless" method has become possible as digital densities have increased and processing techniques have advanced. Much research [1][2] has been done to explain the "windowless" control algorithm, with some focusing on the control accuracy and robustness to motor parameter drifts, some focusing on dynamic response and wide range of applications, and some focusing on simplifying the calculation and easy implementation. Regardless of focus, all these attributes are based on the same fundamental principle and equation—the BEMF equation—as seen below in Equation 1.

$$\begin{bmatrix} u_{UN} \\ u_{VN} \\ u_{WN} \end{bmatrix} = \begin{bmatrix} R_S & 0 & 0 \\ 0 & R_S & 0 \\ 0 & 0 & R_S \end{bmatrix} \begin{bmatrix} i_U \\ i_V \\ i_W \end{bmatrix} + \begin{bmatrix} L_{UU} & L_{VU} & L_{WU} \\ L_{UV} & L_{VV} & L_{WV} \\ L_{UW} & L_{VW} & L_{WW} \end{bmatrix} p \begin{bmatrix} i_U \\ i_V \\ i_W \end{bmatrix} + \begin{bmatrix} e_U \\ e_V \\ e_W \end{bmatrix}$$

Equation 1: BEMF Equation

The windowed method, as shown in Figure 2, is simpler than the windowless method. This method requires fewer hardwired resources as no ADC is used, as well as fewer calculations. The windowed method is also immune to motor parameter drifts. It's important to note, however, that this method operates at lower motor speeds.

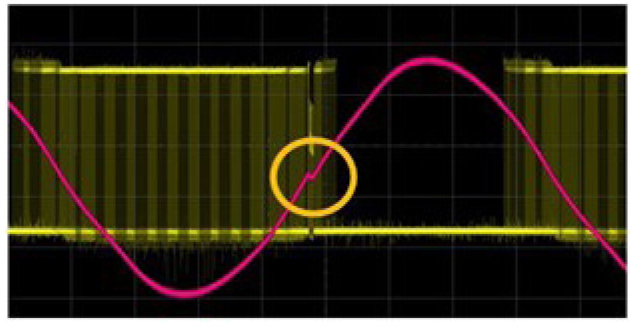

Figure 2: Windowed Method

The windowless method removes the "observation window" and reduces acoustic noise by maintaining continuous current in all windings, as shown in Figure 3.

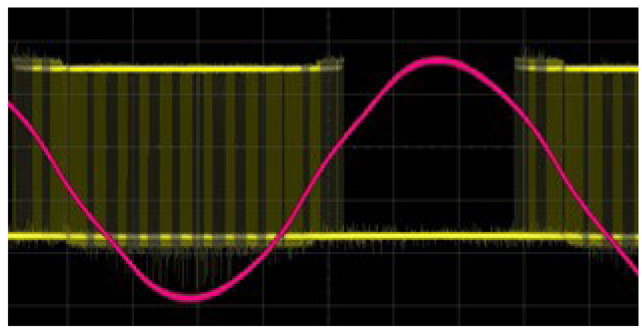

Figure 3: Windowless Method

Improve Efficiency With Phase Advance

It's necessary to have a simplified frame of reference in order to understand the concept of phase advance. By using the direct-quadrature-zero transform, or dq transform, it's possible to use the rotating reference frame of a three-element vector to produce three DC signals, which are easier to use to perform calculations.

The motor variables of voltage, current, and magnetic flux are transferred to the dq coordinate during the transform. D-axis is the direction when magnetic flux reaches its maximum, while q-axis is 90 degrees from the d-axis. The axes are shown in Figure 4.

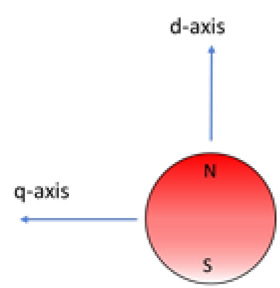

Figure 4: DQ Axes

The motor current, as a vector, contains both d-axis and q-axis elements. The d-axis current (id) produces the inductive flux in the d-axis direction. The q-axis current (iq) produces the inductive flux in the q-axis direction. Currents are viewable in Figure 5.

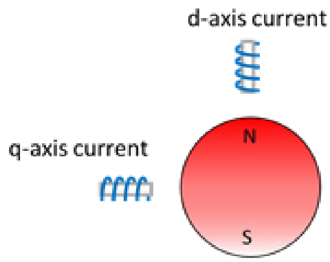

Figure 5: Axis Currents

The q-axis current generates q-axis inductive flux, which interacts with the permanent magnetic flux (centered in d-axis) to generate torque on the rotor. This generated torque causes the rotor to spin.

The d-axis current does not generate rotational torque. As the inductive flux generated by the current is parallel to the magnetic flux, it can produce zero force. As a result, d-axis current is realized as heat generated from i×R2 losses; this results in direct loss of efficiency. To optimize the efficiency, the current vector would ideally be controlled such that id is equal to zero. With current in the d-axis equal to zero, all the current resides in the q-axis. The result is a vector most suited to generate inductive flux, and therefore generate mechanical torque.

The technique to bring the d-axis current to zero is called phase advance. The phase voltage will lead the phase current because motor winding is an inductive circuit. To maintain maximum efficiency, phase advance is used to align the phase current to the BEMF. Alignment is accomplished by advancing the phase voltage by angle ∂, as the calculation in Figure 6 shows. Allegro MicroSystems motor drivers use an integrated phase advance algorithm to dynamically change the lead angle, maximizing efficiency across all operating conditions.

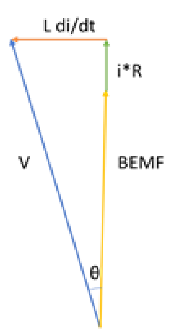

Figure 6: Phase Advance Calculation

Note: The concept of id equal to zero is only true for an ideal motor model. In the real world there are second-order effects caused by interaction of the permanent magnet and the iron in the motor, which generates detent torque. To negate the detent force, there should be some small amount of current in the d-axis which relates to the lead angle. Allegro's phase advance algorithm considers the total effects in the system and adjusts the lead angle to provide the highest operating efficiency.

A FLEXIBLE SOLUTION WITHOUT SOFTWARE

Increases in customer requirements over time have led to a shift towards motion control designs that favor flexibility and improved time to market. To meet more demanding customer requirements, Allegro has developed a solution to ease the burden placed on engineers who must work across multiple systems. Allegro's hardware-based algorithm is what can be called a "plug-in and spin" solution, both eliminating the cycle of software development and debug and significantly reducing time to market, all while improving flexibility by implementing an easy-to-use graphical user interface (GUI). Now, high performance and full-featured sensorless control is just a few mouse clicks away. Many functions included in the GUI that simplify sensorless control are shown below in Figure 7.

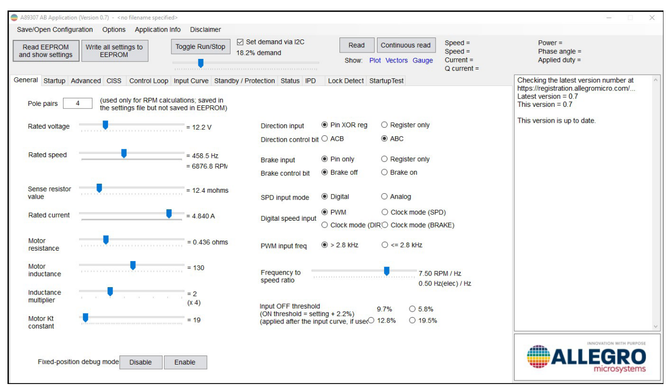

Figure 7: Allegro GUI Software A5932

Selection of Parameters

The most challenging time for sensorless BLDC control is at start-up, as BEMF is proportional to the motor speed. Allegro's software addresses this challenge for all motor types by providing configurability for key parameters that govern how the motor starts up.

At start-up, when motor speed is at zero or low RPM, the BEMF is minimal and hidden by measurement noise. One way to generate BEMF is to control the motor in open loop until the speed can generate enough BEMF for detection to occur. However, when an open loop start-up method is used, the alignment of the rotor to the stator can cause the rotor to move slightly in either forward or reverse direction, and the rotor can oscillate slightly before it comes to rest due to the inertia of the load.

Initial position detection (IPD) is one way to prevent this movement issue. Allegro's intelligent algorithm can detect initial motor position by injecting high-frequency pulses before the rotor spins. This is useful for fan-type motors, which have exposed blades. Even though IPD does not cause the rotor to move initially, the process of high-frequency injection can cause acoustic noise in some motor designs. Therefore, for applications that require extremely quiet operation, the user may want to disable the IPD. This is a configurable option in Allegro's GUI, as seen in Figure 8.

Figure 8: IPD Enable

Motor start-up acceleration rate must be adjustable to optimize for different loads. Based on Newton's second law, $F = ma$, or $T = J \times \beta$ in the rotational system (where T is the driving torque, J is the load inertia, and β is the acceleration rate), there is a maximum to ensure a successful start-up, which is $\beta_{MAX} = T_{MAX} / J$. Without the adjustable acceleration parameter, the start-up either takes too long, or has the risk of failure. Adjustment controls in the GUI are shown in Figure 9.

Figure 9: Motor Start-up Acceleration Adjustment

The start-up current parameter determines the maximum torque. Higher start-up current can potentially improve start-up time, but also causes start-up acoustic noise. See start-up current selection shown in Figure 10.

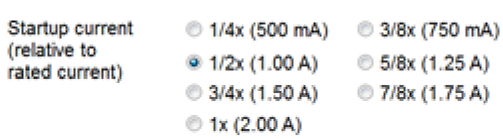

Figure 10: Start-up Current Parameter Selection

After pulling the motor to a certain speed, either the BEMF measurement or estimation method will occur. The system will then go to closed-loop condition. The threshold must be set as low as possible so that the motor will run quickly under an efficient closed-loop condition. However, it's not reliable to go to closed loop if the motor BEMF is low—the transition will fail, and the motor will be stuck. Therefore, the open-to-closed loop threshold parameter must be set. Typically, one tenth of the full speed is recommended, depending on motor parameters. See adjustment in Figure 11.

Figure 11: Loop Speed Adjustment

Integrated Closed Loop Speed Control

Applications require different speed control methods, so it's important to have a flexible GUI that allows for speed control configuration. Speed control options are seen in Figure 12.

The first speed control option in Allegro's GUI is speed open loop or speed closed loop. Speed open loop can be thought of as similar to a car's accelerator pedal—it controls the speed but doesn't directly relate the speed to the depth of pedal pressure. Driving up a hill or under a heavy load will slow down the car, even when a consistent amount of pedal pressure is applied. The closed loop mode is similar to cruise control mode—speed will be locked to a reference, and the power is adjusted based on road conditions.

Figure 12: Speed Control Options

The next configurable option is speed input mode. Typically, analog mode, PWM mode, or CLOCK mode are available, as shown in Figure 13. For PWM mode, PWM duty determines the speed demand. For analog mode, the speed demand is analog voltage. Finally, for CLOCK mode, the frequency of the input signal determines the speed.

Figure 13: Speed Input Mode

As seen in figure 14, speed curves are provided to meet different application requirements.

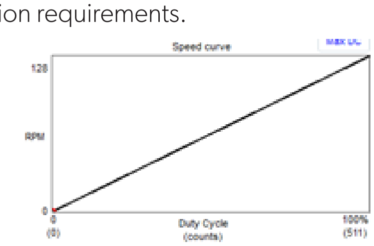

Figure 14: Speed Curve

CONCLUSION

As time has progressed, the market for motor control has begun to shift from traditional stepper and DC motor control to BLDC motors. Simultaneously, BLDC drive hass become increasingly complex regarding the development and delivery of solutions that meet customer and/or application requirements. Removing the complexity from BLDC drive allows all system designers to develop solutions that are easy to set up and validate, while providing all the benefits of sensorless sinusoidal BLDC control. Allegro MicroSystems accomplishes this with sensorless BLDC drive solutions that are unique in the market, providing industry-leading noise performance in a small, efficient footprint with no customer software programming required.

SOURCES

[1] James P. Johnson M. Ehsani Yilcan Giizelgiinler, “Review of Sensorless Methods for Brushless DC”, Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Fourth IAS Annual Meeting (Cat. No.99CH36370) Year: 1999, Volume: 1 Pages: 143 – 150

[2] N. Matsui, “Sensorless PM Brushless DC Motor Drives,” IEEE Trans. on Industrial Electronics, vol. 43, no. 2, pp. 300-308, 1996

Revision History

Number	Date	Description	Responsibility
–	March 7, 2022	Initial release	Tyler Hendrigan

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