# DIRECT USE OF BRIDGESWITCH™ CURRENT SENSE SIGNAL OUTPUT IN FIELD ORIENTED CONTROL OF BRUSHLESS DC MOTORS

High performance motor drives commonly use field-oriented control (FOC) since it offers smooth and efficient operation throughout the entire speed range. BridgeSwitch offers a unique function by providing a small signal output that is an instantaneous representation of the positive phase current. This function can eliminate commonly used discrete current sense resistors and associated amplifiers, thereby reducing cost and design complexity. A proposed algorithm allows using the small signal output provided by each device through directly measuring, reconstructing, and predicting the full phase current information in 3-phase motor drives utilizing FOC where the motor provides the rotor position information.

WHITEPAPER

motor drivers


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# Introduction

Applications that require smaller and more efficient motor drives with reduced audible noise commonly use Brushless DC (BLDC) motors. This type of motor allows speed and torque to be adjusted by varying the frequency and voltage applied to the motor. Various methods exist for controlling a BLDC motor. They include trapezoidal commutation, sinusoidal commutation, and field-oriented control (FOC). Each method has advantages and disadvantages. High performance motor drives usually employ FOC because it offers smooth rotation and efficient operation across the full speed range [1]. FOC uses mathematical conversions to transform the motor currents from the three-phase reference frame of the stator windings to the two-axis reference of the rotor [2].

A common method of measuring motor currents is to add shunt resistors in series with the low-side switch (MOSFET or IGBT) of each leg in a three-phase inverter. Figure 1 depicts a typical current sense implementation. Operational amplifier U1 filters and amplifies the voltage signal $V_{SHUNT}$ across $R_{SHUNT}$. It is also necessary to add a DC offset $V_{OFFSET}$ through resistor R1 to the output signal $V_{OPAMP}$, because the analog-to-digital (ADC) input to the motor control microcontroller can typically only support positive signals.

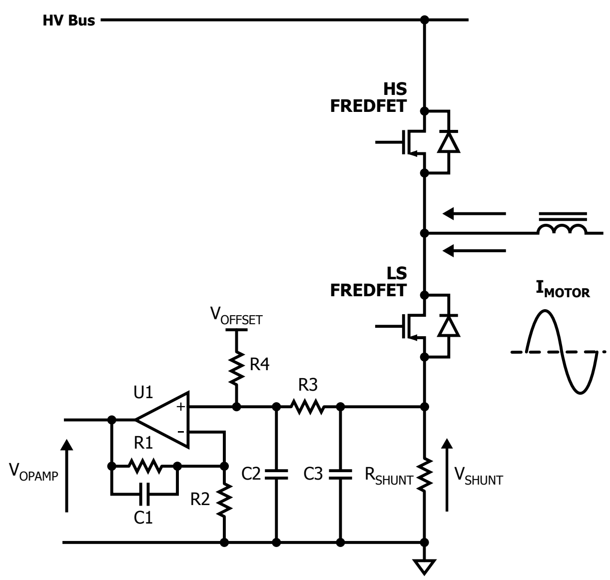


Figure 1 Motor Current Sensing with Series Shunt Resistor (PI-8996-071119)

Figure 2 depicts an example of motor winding currents and resulting op-amp output signals for all three phases. This example assumes a motor peak current of 1 A, and a frequency of 200 Hz. The shunt resistor $R_{SHUNT}$ is 0.5 Ω and R1, R2, R3, and R4 are each 1 kΩ. $V_{OFFSET}$ is 2.5 V.

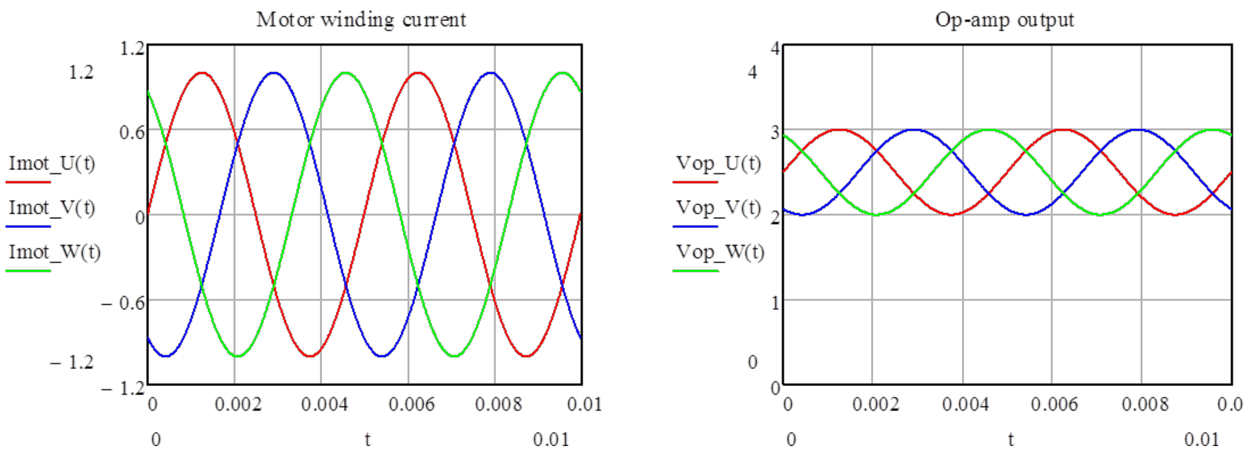


Figure 2 Three-Phase Motor Winding Currents and Shunt-Resistor Based Sensing Op-Amp-Output Signals

Using series shunt resistors for measuring motor currents significantly increases component count and overall system cost. The added resistance also reduces efficiency and can cause additional EMI challenges due to introduction of a voltage offset to the ground path.

BridgeSwitch devices overcome these disadvantages with an integrated phase current (IPH) output signal. The IPH output provides a small signal current; proportional to the instantaneous-channel-current flowing thru the low-side FREDFET (the output does not provide a signal when the diode is conducting). This eliminates the need to add a DC offset to the measured motor current. Figure 3 depicts the typical implementation of this approach. A small signal resistor $R_{IPH}$ converts the IPH output current into a voltage signal for digitization by the system microcontroller.

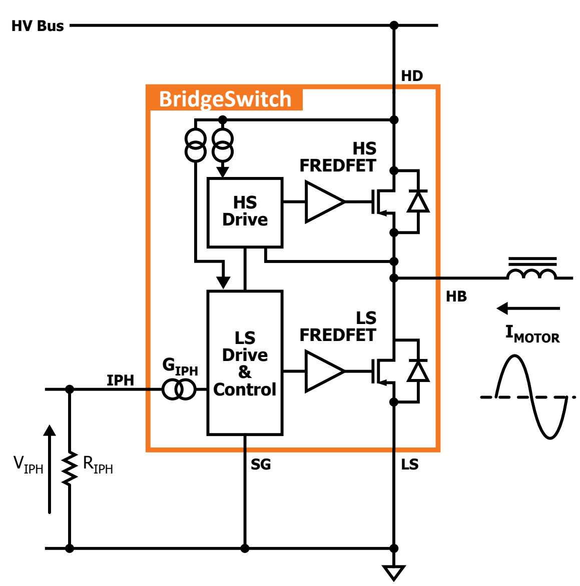


Figure 3 BridgeSwitch Phase Current Output IPH (PI-8995-071119)

FREDFET Drain current $I_{DRAIN}(t)$, phase-current output-gain $g_{IPH}$ (typ. 100 µA/A), and $R_{IPH}$ govern the voltage amplitude $V_{IPH}(t)$ provided at the IPH output for a given system:

$$V_{IPH}(t) = \begin{cases} I_{DRAIN}(t) \times g_{IPH} \times R_{IPH} & \text{for } I_{MOTOR}(t) \geq 0 \\ 0 & \text{for } I_{MOTOR}(t) < 0 \end{cases}$$

Figure 4 shows an example of the combined waveforms provided at the IPH output of the BridgeSwitch devices in a three-phase inverter. The illustration depicts the output for a motor peak current of 1 A, a frequency of 200 Hz, and an IPH-pin resistor of 30 kΩ.

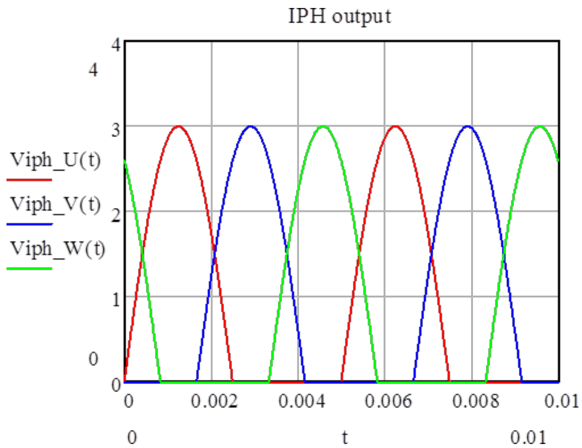


Figure 4 Three-Phase IPH Output Voltage Signals

The voltage signal on the IPH output includes amplitude, frequency and phase information for the respective motor current in a given inverter leg. This allows direct use of the IPH output signal by an FOC with a suitable motor current reconstruction and prediction algorithms in the system microcontroller.

## Motor Current Reconstruction and Prediction Algorithms

When using the IPH signal output for motor current sensing, the phase current information is available for the positive half-cycle of each phase. A reconstruction and prediction algorithm enables derivation of the negative half-cycle current information for use in the FOC.

In a balanced three-phase system, during normal operation of a wye-connected machine, the sum of the phase currents must be zero:

$$i_u + i_v + i_w = 0$$

Thus, part of the negative half-cycle current information of a given phase can be reconstructed when measurements from the two other phases are available:

$$i_u = -i_v - i_w$$

$$i_v = -i_u - i_w$$

$$i_w = -i_u - i_v$$

However in a 3-phase inverter, during two 60-degree intervals, only a single-phase current measurement is available at each IPH output. During these 60-degree intervals, the instantaneous stationary reference frame currents ($i_\alpha$ and $i_\beta$) and the reference vector angle in the stationary reference frame ($\theta_{\alpha\beta}$*) can be used to predict the missing phase currents.

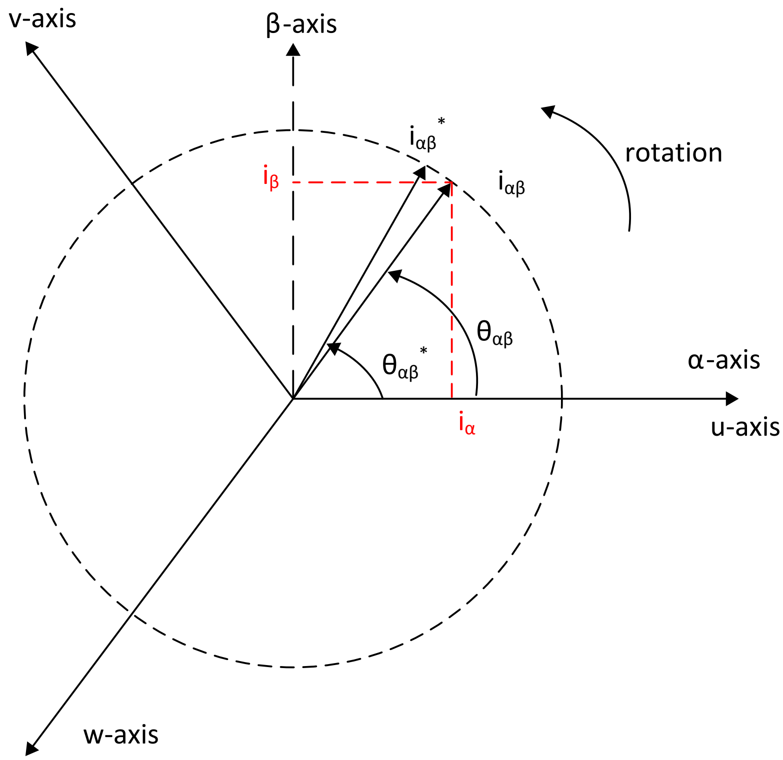


Figure 5 Instantaneous Complex Reference $i_{\alpha\beta}$* and $i_{\alpha\beta}$ Actual Current Vectors [3]

Instantaneous motor currents $i_u$, $i_v$, and $i_w$ determine the stationary reference-frame currents:

$$i_\alpha = \frac{2}{3} i_u$$

$$i_\beta = \frac{1}{\sqrt{3}} i_v - \frac{1}{\sqrt{3}} i_w$$

The angle of current reference vector $i_{\alpha\beta}^*$ in the rotor reference frame ($\theta_{dq}^*$) and the electrical rotor position ($\theta_\lambda$) determine $\theta_{\alpha\beta}^*$ as shown in Figure 6.

$$\theta^*_{\alpha\beta} = \theta_\lambda + \theta^*_{dq}$$

The mechanical rotor position $\theta_m$ obtained from a quadrature encoder and the number of pole pairs determine the electrical rotor position $\theta_\lambda$:

$$\theta_\lambda = \text{PolePair} \times \theta_m$$

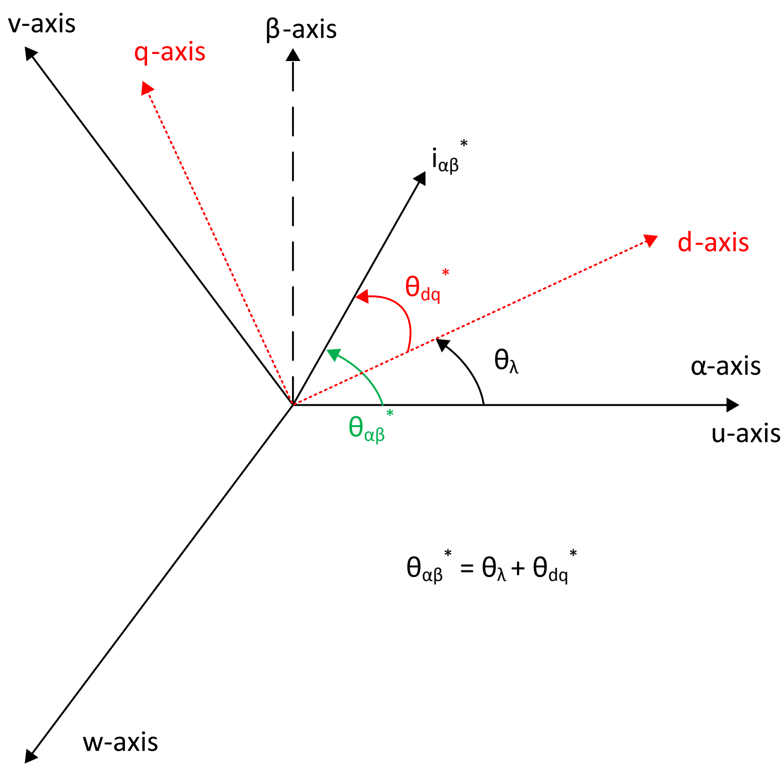


Figure 6 Relationship Between Stationary and Rotor Reference Frame

Assuming that $i_{\alpha\beta}$ exactly matches the current vector reference ($i_{\alpha\beta}$*) (i.e. $\theta_{\alpha\beta} = \theta_{\alpha\beta}$*) [3] and that $\theta_{\alpha\beta} = \theta_{\alpha\beta}$*, the relationship between motor current and the magnitude of the stationary reference frame current vector ($|i_{\alpha\beta}|$) at any instance of time is given by:

$$i_u = |\, i_{\alpha\beta} \,| \times \cos(\theta_{\alpha\beta}{}^*),$$

$$i_v = |\, i_{\alpha\beta} \,| \times \cos\left(\theta_{\alpha\beta}{}^* - 2 \times \frac{\pi}{3}\right),$$

$$i_w = |\, i_{\alpha\beta} \,| \times \cos\left(\theta_{\alpha\beta}{}^* + 2 \times \frac{\pi}{3}\right)$$

When the phase current information is only available for a single phase (e.g. $i_v$), $|i_{\alpha\beta}|$ can be derived as:

$$|\, i_{\alpha\beta} \,| = \frac{i_V}{\cos\left(\theta_{\alpha\beta}{}^* - 2 \times \frac{\pi}{3}\right)}$$

During steady-state operation, $|i_{\alpha\beta}|$ is constant. Thus, the phase current information for the u-axis and w-axis can be predicted as:

$$i_u = |\, i_{\alpha\beta} \,| \times \cos(\theta_{\alpha\beta}{}^*),$$

$$i_w = |\, i_{\alpha\beta} \,| \times \cos\left(\theta_{\alpha\beta}{}^* + 2 \times \frac{\pi}{3}\right)$$

In conclusion, a reconstruction and prediction algorithm can be used to obtain phase-current information across an entire 360-degree rotation using:

1. IPH output signal measurements of the phase when available
2. Reconstruction of the phase current when two other phase current information are available
3. Prediction of all three phase currents when information on only one other phase current is available by using the IPH output signal, the electrical rotor position, and the reference currents in the rotor reference frame.

Figure 7 depicts the flowchart for the reconstruction and prediction algorithm.

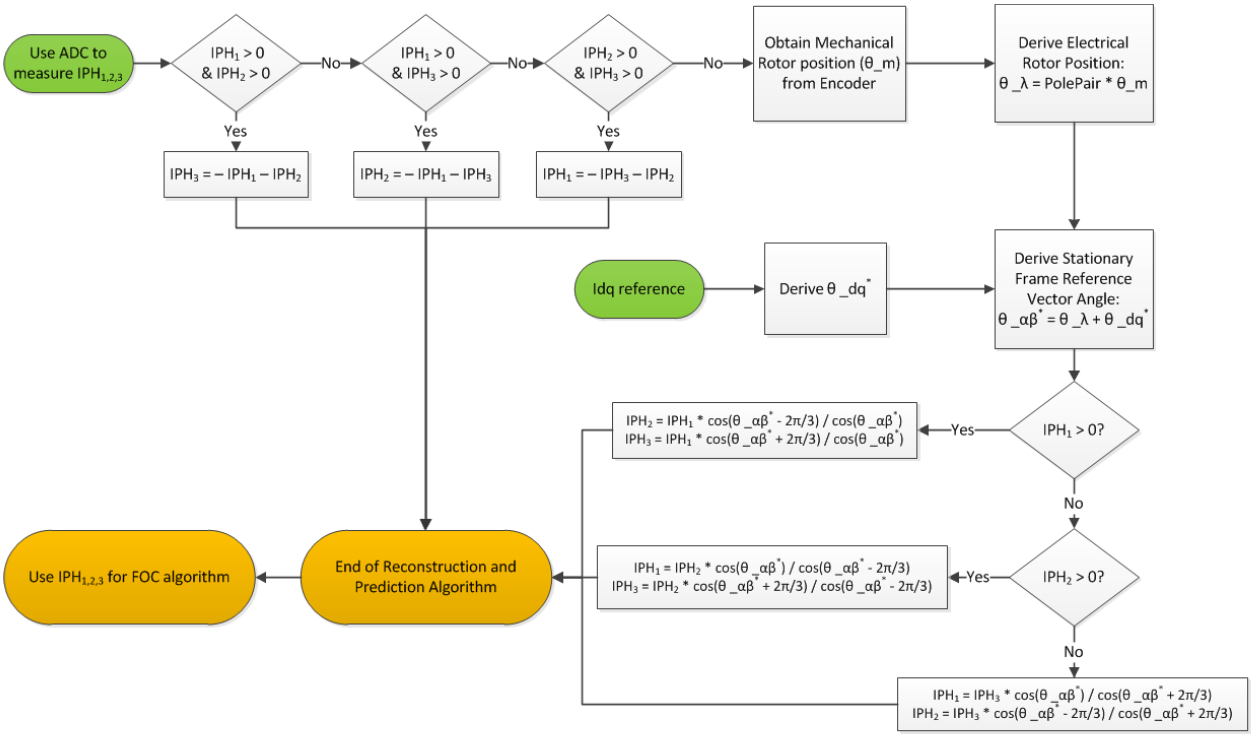


Figure 7 Phase Current Reconstruction and Prediction Algorithm

## System Simulation

Figure 9 shows simulated motor currents reconstructed for a closed loop BLDC motor-drive model implemented with PLECS. Figure 8 shows the top-level schematic of the 3-phase inverter.

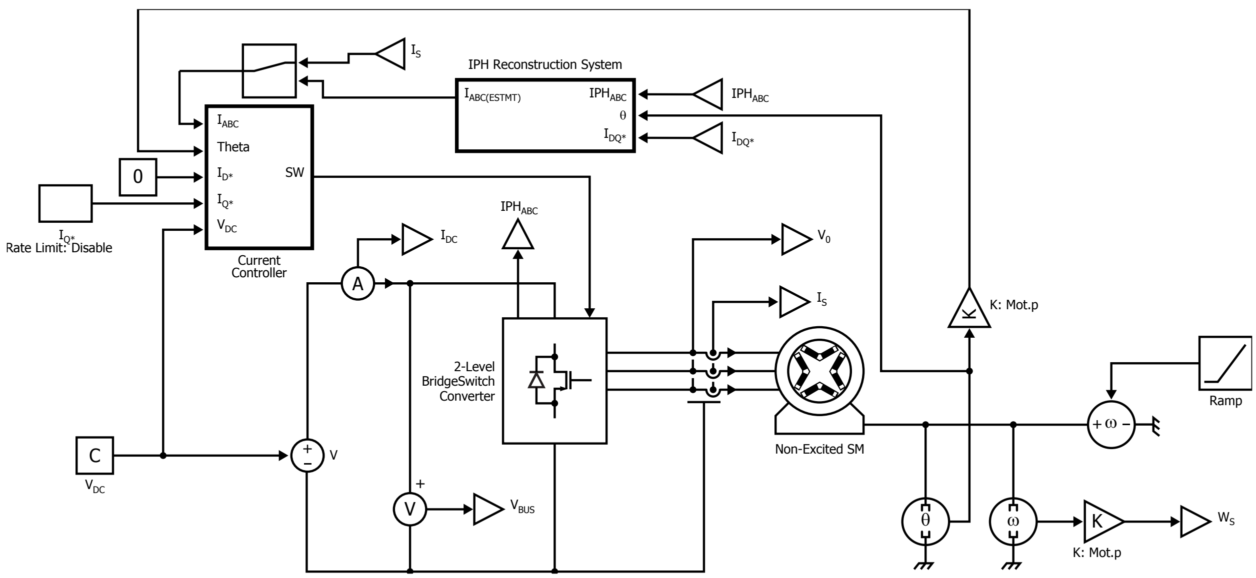


Figure 8 3-phase BLDC Motor Drive Simulation Model (PI-8997-071119)

Initially the motor was increased from stationary to a full speed over 160 ms. At 500 ms the electrical torque requirement was increased to 50%. The models assumed the use of a quadrature encoder to obtain the rotor position ($\theta_\lambda$). Transformations to-and-from the rotor reference-frame requires this information for FOC. Also required are the instantaneous values of all three phase currents.

The results compared the performance of a closed-loop current control of a BLDC system for two different methods of measuring the three phase currents:

1. Positive-half cycle current sensing using the IPH output signals with reconstruction and prediction algorithms
2. Conventional three-phase current sensing (e.g. using series shunt resistors and amplification circuits) using an ideal circuit

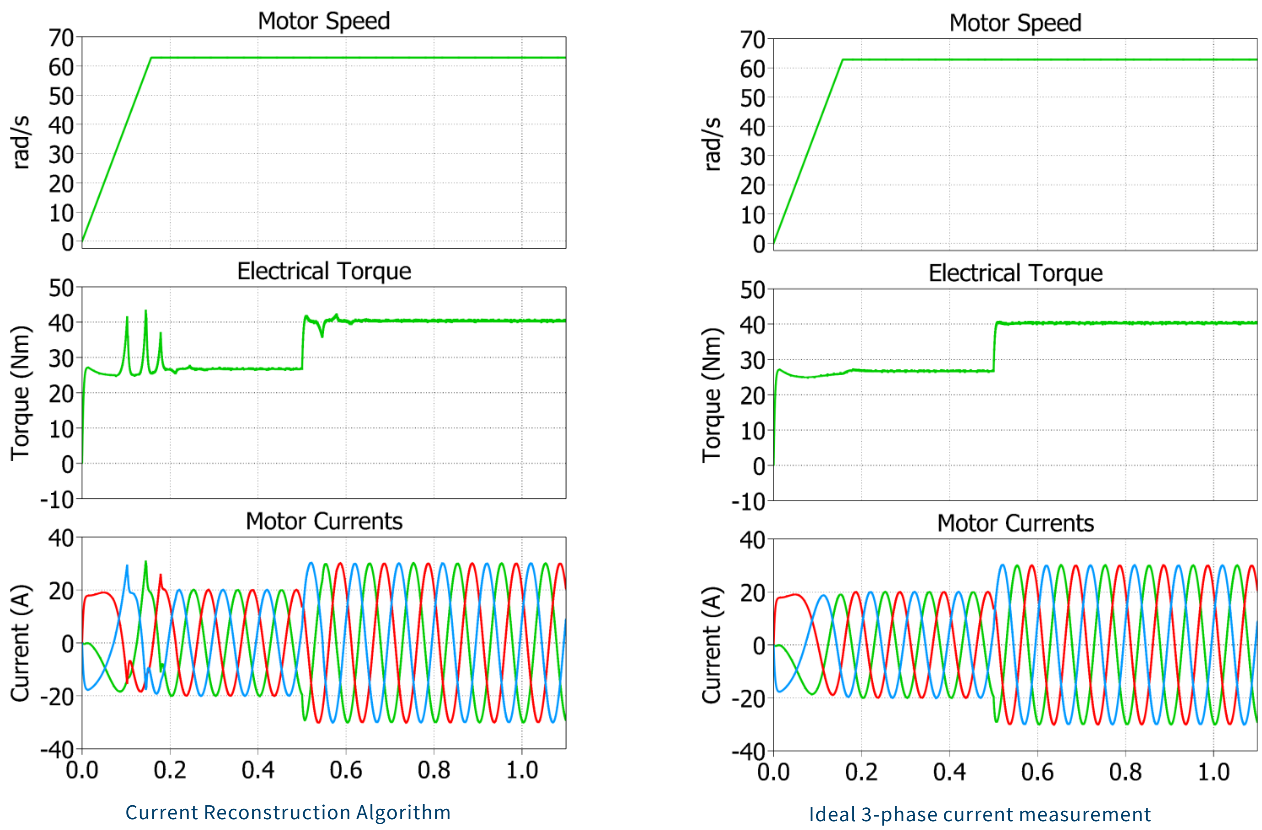


Figure 9 Simulation Results

## Conclusion

The simulation results show that directly using the IPH information provided by BridgeSwitch for BLDC motor drives using FOC is feasible. Further study will focus on the use of the reconstruction and prediction algorithms in other field oriented motor control schemes, which use mathematical models for determining the instantaneous rotor position (sensorless rotor position determination).

## References

[1] “What is ‘Field Oriented Control’ and what good is it?”, Copley Controls Corp., 2002

[2] M.V. Ramesh, J. Amarnath, S. Kamakshaiah, and M. Balakrishna, “Field Oriented Control for Space Vector Modulation based Brushless DC Motor drive”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Vol. 2, Issue 9, Sept. 2013

[3] S. Chakrabarti, T. M. Jahns, and R. D. Lorenz, “A current reconstruction algorithm for three-phase inverters using integrated current sensor as low side switches,” in Conf. Rec. IEEE-IAS Annual Meeting, Salt Lake City, UT, Oct. 2003, pp. 925–932.

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