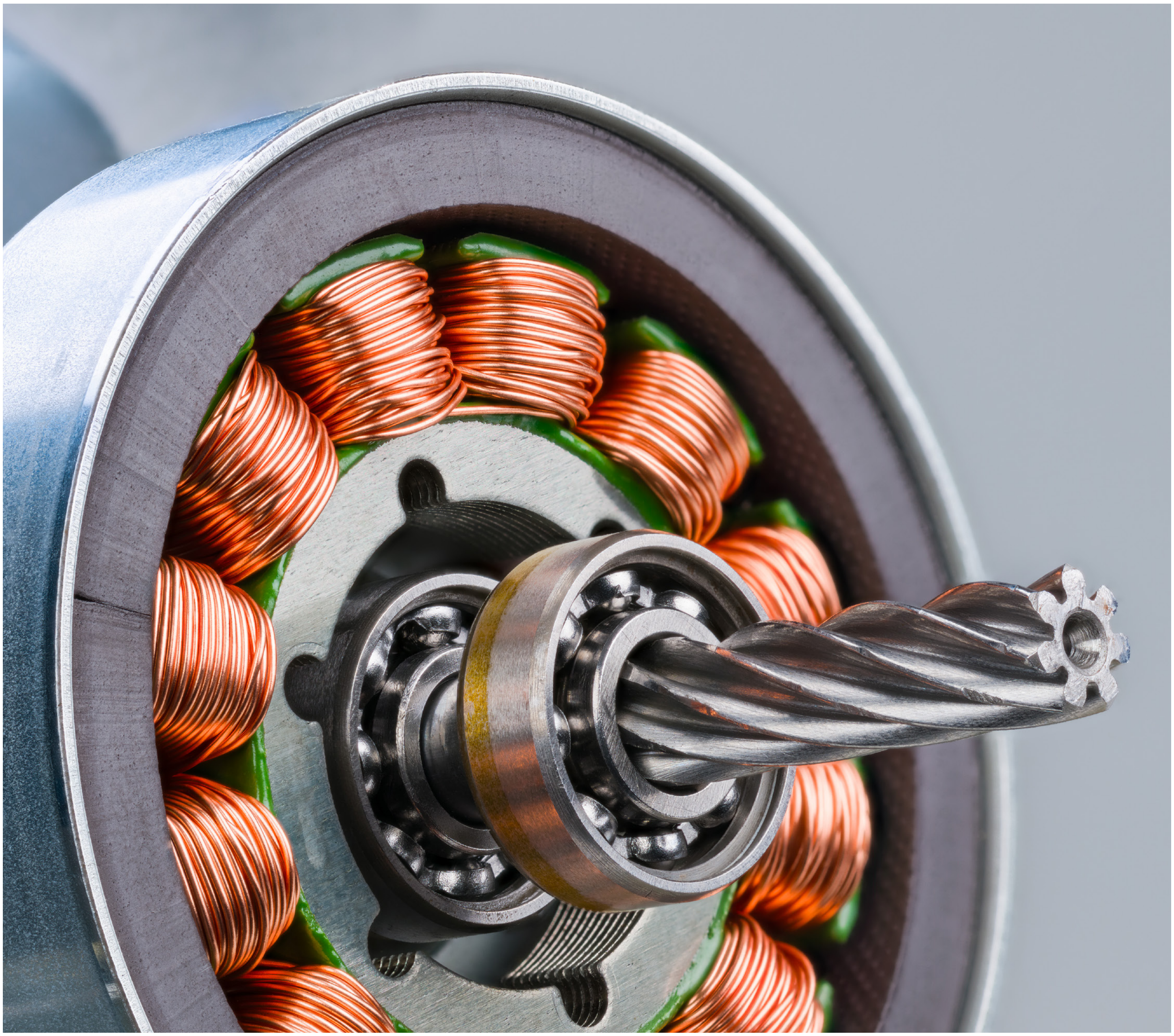
Transient Response for Sensorless Field-Oriented Control Using Integrated Current Sensing

John Emmanuel Tan, Juan Paolo Quismundo, Mark Angelo Tarvina | Power Integrations, Philippines



© 2025 Power Integrations | power.com

Abstract

Sensorless field-oriented control (FOC) for 3-phase Brushless DC (BLDC) motors and permanent magnet synchronous motors (PMSM) requires current information. Integrated current sensing is used to improve current information and reduce component count. An additional current reconstruction algorithm is required to calculate missing current information with this approach. This paper analyzes the transient response of integrated current sensing for sensorless FOC to verify its feasibility for applications with high torque and rapid speed changes for applications such as washing machines.

1. Introduction

FOC is an advanced motor control technique suitable for applications with fast dynamic response requirements. FOC makes use of the motor current information and the rotor position to control, directly or indirectly, the torque and flux produced by the motor. The rotor position is provided by sensors or for sensorless applications, estimated by observer-based systems [1, 2].

This paper examines the feasibility of using a low-side switch-integrated current sensing with FOC.

2. Field-Oriented Control With Integrated Current Sensing

The FOC technique controls the flux- and torque-producing components of the stator [1, 2]. FOC is normally used for PMSM and BLDC motors. The permanent magnet in the rotor provides the flux required in running the motor, so the flux-producing component of the stator current vector can be set to zero for optimization. The torque-producing component is maximized for the given stator current with this approach. Knowledge of the rotor position and the measurement of the stator current are required for this control method. The FOC block diagram is illustrated in Fig. 1.

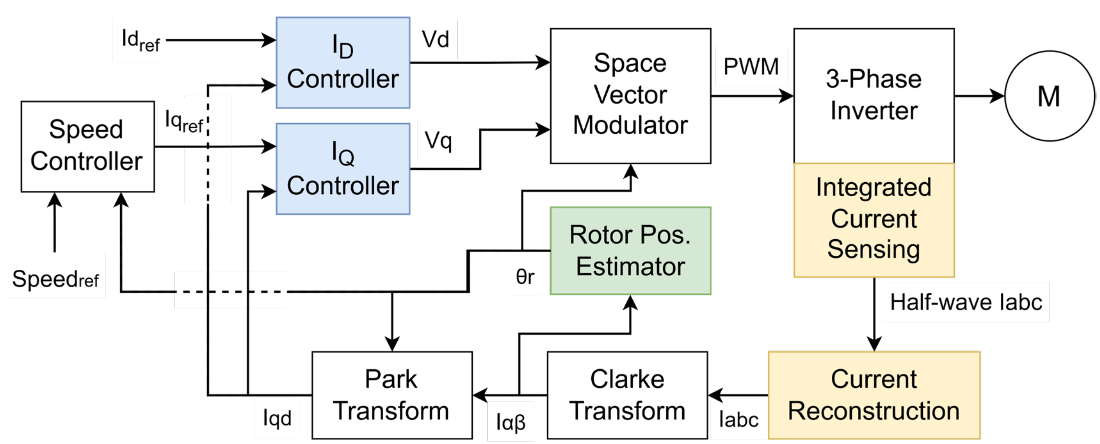


Fig. 1 Block diagram for field-oriented control with integrated current sensing

2.1 Integrated Current Sensing in the Low-side Switch

Current sensing incorporated into the power switches reduces the number of components, including a resistive sensing element or current shunt. Figure 2 shows a parallel sensing transistor used for lossless current sensing. This provides an output current proportional to the low-side switch current.

Amplification is added to the current sensing circuit. A small-signal resistor is then used to convert this sense current to a voltage signal, feeding it to the controller's analog-to-digital converter (ADC).

The sense information is provided when the low-side switch is on, which means that only half the current information is provided. The feasibility of using a current reconstruction algorithm to reproduce the missing half-wave information for FOC has been proven [3].

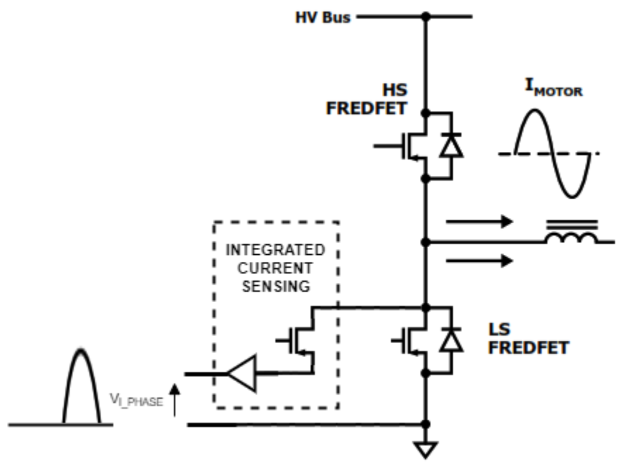


Fig. 2 Low-side switch integrated sensing

2.2 Current Reconstruction

As the current vector rotates during motor operation, the available sensed current information alternates between two available phases (highlighted sectors, Fig. 3) and one available phase (non-highlighted sectors in Fig. 3).

When two phase currents are available (non-highlighted sector, for example: ib and ic), the third phase current (for example: ia) is calculated using the relationship described in Eq. (1). When one phase current is available (highlighted sectors, for example: ic), the other two-phase currents (for example: ia* and ib*) are calculated using the relationships described in Eqs. (2), (3), and (4) depending on which are applicable. The current vector angle, θαβ, is required for the calculation, while the current vector magnitude, imag, is implicitly used during substitution.

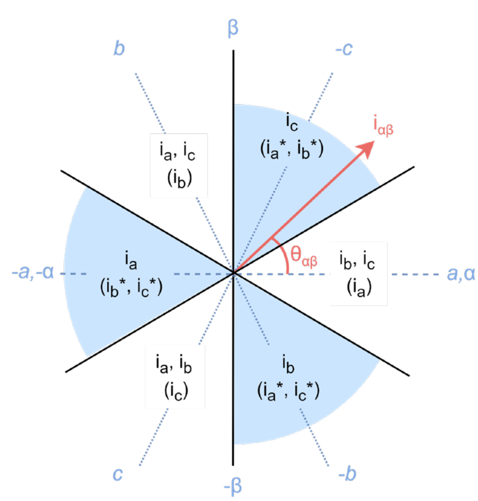


Fig. 3 Current reconstruction diagram

$$i_a + i_b + i_c = 0 \quad (1)$$

$$i_a = i_{maa} \cos \cos \theta_{\alpha\beta} \quad (2)$$

$$i_b = i_{maa} \cos \cos (\theta_{\alpha\beta} - 120°) \quad (3)$$

$$i_c = i_{maa} \cos \cos (\theta_{\alpha\beta} + 120°) \quad (4)$$

Where: ia, ib, and ic are the three phase currents, imag is the stator current vector magnitude, and θαβ is the stator current vector angle.

Figure 4 shows the integrated current sensing information (top diagram), and the reconstructed phase currents (bottom diagram) during an operation with constant stator vector magnitude.

The information sensed in the ADC input is in millivolts, and the reconstructed phase currents is in milliamperes. Amplification is determined by the integrated sensing circuit used for the conversion.

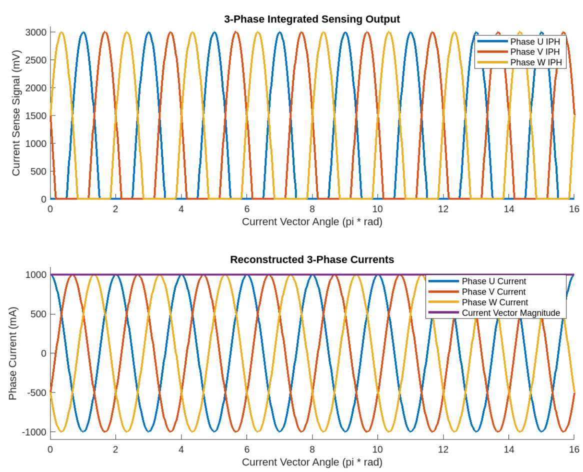


Fig. 4 Current reconstruction with constant current vector magnitude

3. Closed Loop Control

A typical use case for a motor-driven system is constant speed control. The FOC block diagram in Fig. 1 shows how both speed and current control are connected. The speed controller, running as the outer loop, determines the target quadrature current, which is proportional to the torque produced by the motor. Current controllers, running as the inner loop, determine the correct stator vector magnitude and angle for FOC operation.

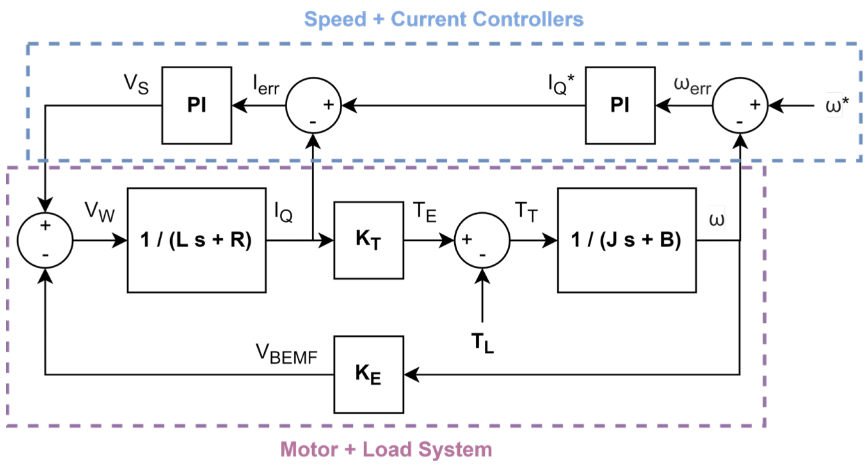


Fig. 5 System block diagram with motor system transfer functions

3.1 System Response to Changing Load

Figure 5 shows the system block diagram with the motor system transfer functions.

Consider a case with constant speed control and target speed ω*. During steady-state operation, the motor provides electrical torque (TE) to the system and runs at a certain speed (ω). When the load torque increases (TL), the total torque (TT) is reduced, and the speed (ω) and back-EMF voltage (VBEMF), in turn, decreases. The speed error (ωerr) increases, and the speed controller increases the target quadrature current (IQ*). The current error (Ierr) increases, and in response the current controller increases the applied stator voltage (VS). The higher applied winding voltage (VW) increases the quadrature current (IQ) and the electrical torque (TE). The higher total torque (TT) leads to an increased speed (ω). These adjustments will continue until the speed (ω) reaches the target speed (ω*).

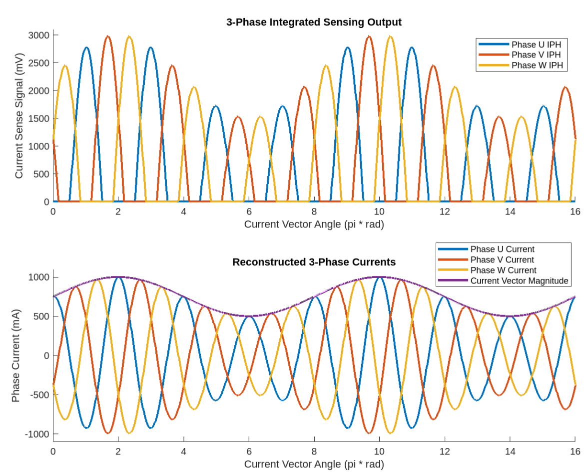


Fig. 6 Current reconstruction with varying current vector magnitude

Changes in the system load (TL) or target speed (ω*) leads to varying quadrature current (IQ) and stator current vector magnitude (Imag). Figure 6 shows the simulated current reconstruction with a sinusoidally varying stator current vector magnitude.

4. Experimental Results

For this paper, 8 kHz-sensorless FOC is used to drive a 3-phase BLDC motor with Power Integrations® reference design kit RDK-853. The inverter uses the integrated half-bridge BridgeSwitch™ BRD1265C which provides motor current information via the integrated lossless current mirror (IPH). Infineon's low-cost 32-bit Arm® Cortex®-M0 microcontroller, XMC1400, is used with Power Integrations' MotorXpert™ Suite. The suite supports sensorless 3-phase FOC with integrated current sensing.

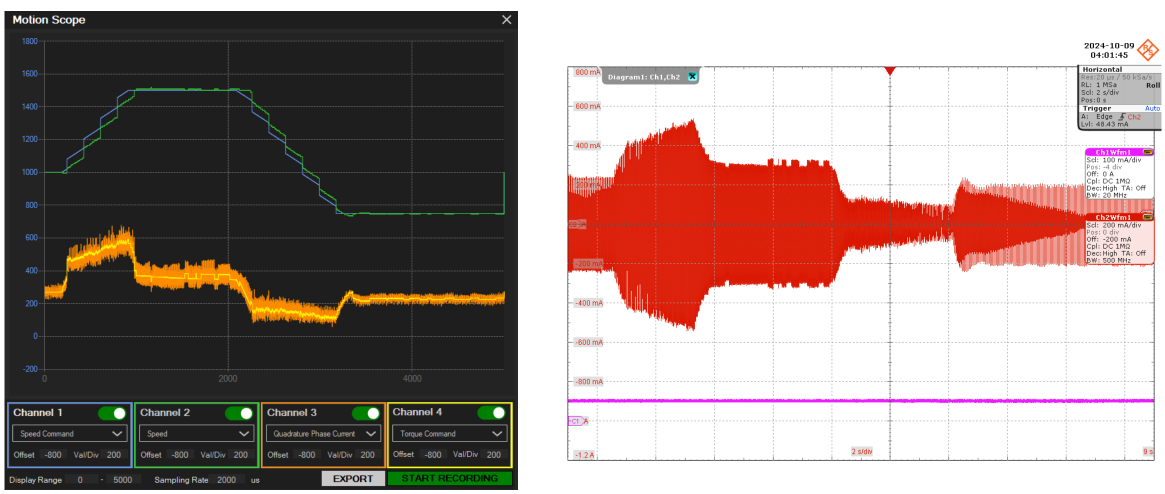
The feasibility of FOC with integrated current sensing is tested by varying the system load and the target speed.

Figures 7(a), 8(a), and 9(a) show the control system variables using MotorXpert Suite's Motion Scope. CH1 (blue) shows the Speed Command (ω*), CH2 (green) shows the Speed (ω), CH3 (orange) shows the Quadrature Phase Current (IQ), and CH4 (yellow) shows the Torque Command or Target Quadrature Phase Current (IQ*).

Figures 7(b), 8(b), and 9(b) show system currents captured by an oscilloscope. CH1 (purple) shows the control current input to the brake load, which is proportional to the system load, and CH2 (red) shows the motor phase current.

4.1 Speed Change With Constant Load

Figure 7 shows the operation with constant load where the target speed is changed from 750 RPM to 1500 RPM and back again to 750 RPM.



(a)

(b)

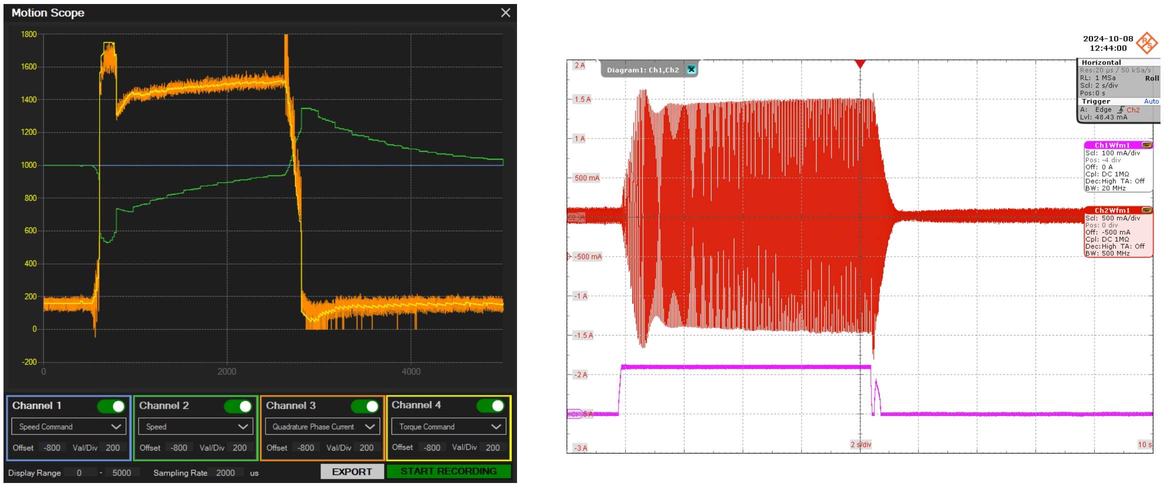
Fig. 7 Operation with constant load and target speed step changes: (a) control system variables, (b) motor phase current and brake load control current

In Figs. 7(a) and 7(b), the quadrature current and the motor phase current is increased by the system when the speed is less than the target speed and is reduced by the system when the speed is greater than the target speed.

4.2 Load Change With Constant Speed

Figure 8 shows the operation with a constant target speed of 1000 RPM, where the system load control is changed from 0 mA to 120 mA and back to 0 mA.

In Figs. 8(a) and 8(b), the speed falls when the system load is increased, triggering an increase in the quadrature and motor phase currents while the current speed is less than the target speed. When the system load is removed, the speed rises, triggering a decrease in the quadrature and motor phase currents while the current speed is more than the target speed.



(a)

(b)

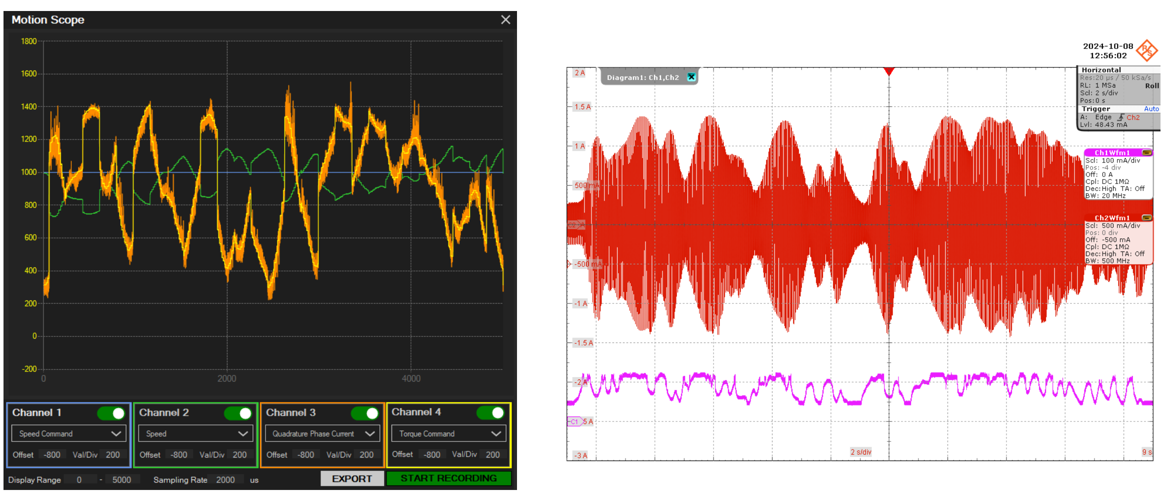
Fig. 8 Operation with constant speed and target load step changes: (a) control system variables, (b) motor phase current and brake load control current

4.3 Random Load Change With Constant Speed

Figure 9 shows the operation with a constant target speed of 1000 RPM, where the system load control is randomly changed between 50 mA and 120 mA.

In Figs. 9(a) and 9(b), the speed falls when the system load is increased, triggering an increase in the quadrature and motor phase currents while the current speed is less than the target speed. When the system load is removed, the speed rises, triggering a decrease in the quadrature and motor phase currents while the current speed is more than the target speed.

The random changes in the system load control current introduced manually using an input potentiometer, simulating a randomly loaded system.



(a)

(b)

Fig. 9 Operation with constant speed and random target load changes: (a) control system variables, (b) motor phase current and brake load control current

5. Conclusion

In this paper, the feasibility of using Field-Oriented Control (FOC) with integrated current sensing was explored for transient loading and target speed conditions.

In a practical system, the motor must continue running properly with varying target speed and system load. The transient conditions explored are a) applying ramp changes to the target speed with constant load, b) applying step changes to the load with constant target speed, and c) applying random changes to the load with constant target speed. The motor was able to continue running properly which means that FOC with integrated current sensing and the additional current reconstruction algorithm can handle transient conditions.

Additional work is required to examine actual use cases where an actual target speed and load profile needs to be determined and an examination made of meeting the requirements, for speed rise, fall, and settling times.

References

[1] Shen J, Hao H, Wang C, Jin M. 2013. Sensorless control of IPMSM using rotor flux observer. COMPEL - The international journal for computation and mathematics in electrical and electronic engineering. Vol. 32 No. 1, pp. 166-181.

[2] Sreepriya R, Rajagopal R. Sensorless control of three phase BLDC motor drive with improved flux observer. 2013 International Conference on Control Communication and Computing (ICCC). India, 2013. pp. 292-297.

[3] J. E. Tan, J. P. Quismundo and J. M. Calderon, “Performance Comparison of Using Shunt-Based and Integrated Current Sensing for Sensorless Field-Oriented Control,” PCIM Europe 2024; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nürnberg, Germany, 2024, pp. 150-160.

For more information,
visit **power.com**™

© 2025 Power Integrations | Power Integrations, the Power Integrations logo, power.com, PowiGaN, and InnoSwitch are trademarks or registered trademarks of Power Integrations, Inc., in the U.S. and/or other countries.

050525