



RELIABLE LINE CURRENT RECONSTRUCTION FOR AC MOTOR DRIVES USING A DC-LINK SENSOR

Evgenije Adžić, Milan Adžić*, Vlado Porobić, Zoran Ivanović, Vladimir Katić

University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

*University of Novi Sad, College of Applied Sciences, Subotica, Serbia

Abstract: *This paper proposes a robust method for line current reconstruction in AC motor drives using a dc-link single current sensor and modified pulse-width modulation (PWM) technique. The algorithm proposes shifting the corresponding PWM pulses for a certain time interval (max. 10 μ s in this case) in order to provide the minimum sampling window needed for reliable dc-link current reading two times in a PWM period (500 μ s in this case). The average motor voltage in one PWM cycle remains unaffected by the application of the proposed algorithm. The proposed method is implemented on a TI TMS320F2812 DSP processor and verified in the hardware-in-the-loop (HIL) testing environment simulating induction motor drive in real-time (with 1 μ s simulation time step). The effectiveness of the proposed method is also confirmed in the frame of sensed indirect rotor field oriented (IFOC) control algorithm.*

Key Words: AC Motor Drives / Current Measurement / DC-link single current sensor technique / Hardware-in-the-loop / DSP

1. INTRODUCTION

In order to take advantage of power electronics in the field of motor control and to satisfy high demands from the AC drives market, reliability and control strategies must be improved. A large number of sensors, harnessing cables and signal-conditioning circuitry deteriorate system reliability, introduce the possible need for their maintenance and increase the system cost. One of the recognized directions for improving AC motor drives is the reduction or elimination of current sensors in power converter control loops and the development of a robust control of electrical machines [1].

In high-reliability AC drives the shaft sensor should be eliminated first. This can be done by using one of the shaft-sensorless methods [2-4], which all base the motor speed and position estimation on motor terminal voltage references and line currents measurements. Although this is the most efficient selection for the substitution of a shaft sensor control scheme, the usage of current sensors is not completely reliable. Further improvement can be achieved if a single current sensor that measures the dc-

link current signal only is used. In that case, an on-line reconstruction of all three motor line currents can be performed [5]. However, in order to meet high safety regulations, the application of a dc-link current sensor for motor line currents measurement can be acceptable only providing that a robust and reliable drive operation can be achieved.

In this paper, problematic issues related to motor line current reconstruction which could seriously jeopardize its application, including unobservable low modulation index operation and partially observable sector transition instances, are presented in detail. Reference **Error! Reference source not found.** proposes an immediate extension of active voltage vectors with a duration of less than a minimum width needed for dc-link current reading. The voltage command is preserved by introducing extra zero vectors or by properly correcting the active vectors in the next PWM cycle. However, these actions result in a significantly higher current ripple. Authors in [0] propose asymmetrical three-phase PWM switching patterns with shifted centers. The average voltage is now maintained within one PWM period, but the number of switching and the amount of current ripple are increased. Insertion of non-standard measurement vectors for brief intervals [0] overcomes the problem of short active voltage vectors (dc-link current sampling windows), but the demand for a non-standard PWM pattern is still its significant drawback.

After the introduction, the second section of the paper gives an overview of the HIL and the control platform used for testing and the verification of the proposed algorithm. The third section briefly presents line current reconstruction techniques using a dc-link single current sensor. In the next two sections, problematic issues related to reliable dc-link current sampling and the proposed PWM shifting method are introduced. The final section gives a comparative overview of the sensed rotor IFOC induction motor drive operation for cases when the used control feedback variables are measured line currents or reconstructed currents by the proposed method.

2. HARDWARE-IN-THE-LOOP AND THE CONTROL PLATFORM

In the early stages of control algorithm development, to further confirm the benefit of the proposed reliable current reconstruction method, a ultra-low latency (ULL) HIL platform for the testing and design of high-power electronics systems was used, replacing a real hardware setup.

The used HIL platform comprises of a programmable, application specific, processing architecture, targeted to the FPGA board with fast analog/digital input/output interfaces, and with an accompanying software tool chain performing the function of a power electronics circuit analyzer/compiler/scope [9]. This approach provided real-time execution on the order of 1 μ s emulation time step, including input/output interface latency. Therefore, from the controller's point of view, there is no distinction between real-time control of the physical power electronics system and the HIL emulator.

The ULL enabled setting up a switching frequency as high as 2 kHz in the controller PWM unit, throughout all experiments in the paper. For this application, the HIL ULL property showed particularly helpful during the control algorithm design, because its time-interrupt-driven nature requires precise PWM signal shifting and fine alignment of sampling times inside the short PWM period of 500 μ s. This application in particular would show that a real-time HIL represents an irreplaceable tool for rapid and efficient design and testing of a power electronics embedded controller and its interactions with the power stage. The controller platform interfaced with the HIL system, as shown in Fig. 1, is based on a Texas Instruments DSP TMS320F2812.

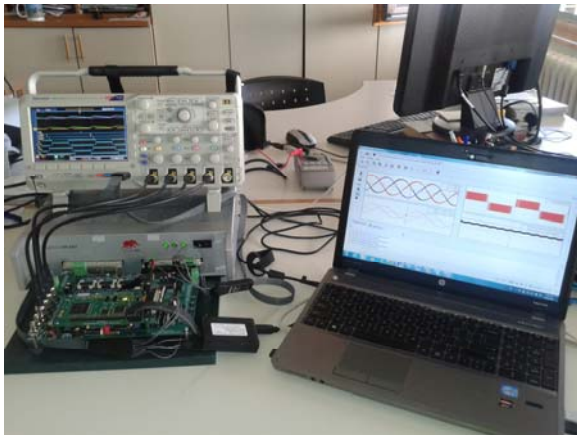


Fig. 1. The used HIL experimental setup with the controller and interface board.

3. LINE CURRENTS RECONSTRUCTION TECHNIQUE IN AC MOTOR DRIVES USING A DC-LINK SINGLE CURRENT SENSOR

The correlation between the dc-link current (i_{DC}) and the motor line-currents (i_A , i_B , i_C) depends on the state of the inverter switches. There are six switch-state combinations which yield the active voltage vectors ($V1$

$-V6$) and two which result in non-active or zero vectors ($V0$ and $V7$). During the application of non-active vectors, the DC-link current is always zero, while during the application of active vectors, it is always related to one of the line-currents [5].

A typical 3-phase PWM period contains two active voltage vectors that are on long enough for current reconstruction, as shown in Fig 2. The figure shows three PWM signals for the voltage vector in the first voltage sector, in which phase A has the highest and phase C the lowest, voltage command. During each of the two active voltage vectors, here V_1 and V_2 , one motor line-current can be sampled, here i_A and $-i_C$, respectively. Since the sum of all three line-currents flowing to the motor must be zero, measuring the two line-currents allows a determination of the remaining third motor line-current, which stays unobservable during the entire PWM period (i_B in Fig. 2).

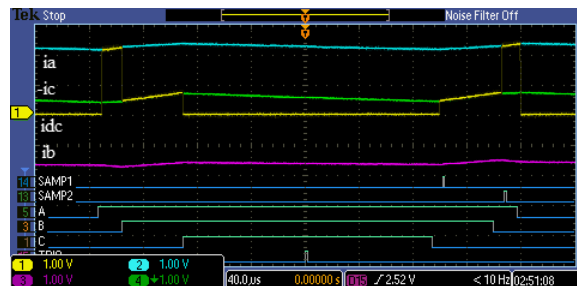


Fig. 2. Three-phase PWM pattern with two active voltage vectors and a corresponding dc-link and line currents waveforms. Sampling moments included.

For the three-phase current reconstruction principle to work, both dc-link current-sampling instants must be precisely synchronized with the PWM pulses, usually referred to the beginning or the middle of the PWM period ($TRIG$ signal in Fig. 2). According to Fig. 2, the optimal sampling instants should be calculated relative to the active vector transition moments. However, for a reliable DC-link current reading, the signal sampling must take place after an additional, pre-calculated delay, T_{delay} :

$$\begin{aligned} T_{SAMP1} &= T_{SHORT} + T_{delay} = T_{SHORT} + T_{on} + T_r + T_s \\ T_{SAMP2} &= T_{MIDDLE} + T_{delay} = T_{MIDDLE} + T_{on} + T_r + T_s \end{aligned} \quad (1)$$

where T_{SHORT} and T_{MIDDLE} are duty cycle time values of PWM pulses associated with minimum and middle phase voltage commands in a given PWM period. The sample delays include total switching-device turn-on delay-time (T_{on}), DC-link current measurement signal rise-time (T_r) and signal settling-time (T_s). The T_{on} parameter includes a dead-time that is automatically inserted by the DSP, IGBT driver response-time, PWM signal-processing time and worst-case switching-device (e.g. IGBT) on-time delay. All delay times are indicated in Fig. 3, where the case of active vector transition from $V2$ to $V1$ is shown. The first oscilloscope channel shows a dc-link current directly measured on the HIL analog output (representing an inverter dc-link current) and on

the fourth channel, the scope shows a dc-link current measured on the DSP analog input. Fig. 3 shows that in considered case introduced PWM signals dead-time equals $T_{dt}=3\ \mu\text{s}$, that dc-link current on-delay time equals $T_{on}=3\ \mu\text{s}$ and the rise and settling time around $T_{set}=2.2\ \mu\text{s}$, giving the needed sampling delay time $T_{delay}=8.2\ \mu\text{s}$. As the delay time depends on the dc-link current amplitude, the included delay time in the implementation was $T_{delay}=10\ \mu\text{s}$.

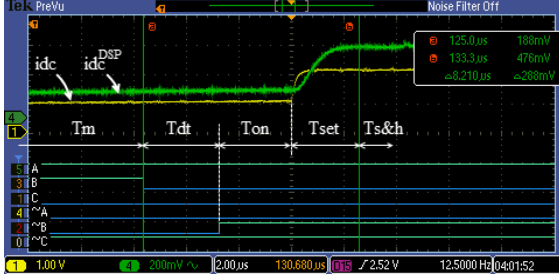


Fig. 3. Dc-link current sample delays for reliable current reading and line currents reconstruction.

4. REFERENCE VOLTAGE VECTOR SECTOR TRANSITION

Practical difficulties with DC-link current measurement can occur when a PWM period includes active vectors that are present only for a short time, which happens in two common cases. The first case occurs regardless of the modulation index, when the reference voltage vector passes near, or falls on, one of the six active vectors and produces at least one short active vector. In this situation, the method may be unable to reliably measure and calculate both motor line-currents observable in one PWM period. It can reliably measure only one line current observable in the dc-link current indicated in Fig. 4 (sampled with *SAMP2* signal), in the case when the reference voltage vector passes from sector 6 to sector 1.

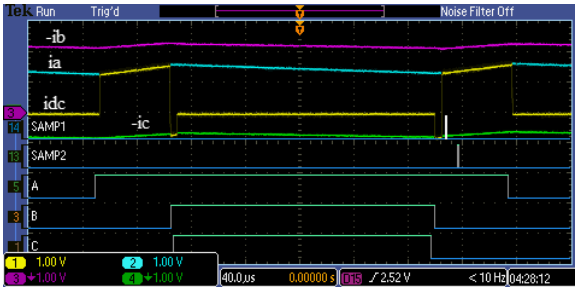


Fig. 4. The reference voltage vector passed from voltage sector 6 to sector 1. PWM B and PWM C pulses are with almost the same duty cycle, and there is not enough time for the first dc-link current sample (*SAMP1*) for reliable $-i_c$ line current reading.

Due to one short dc-link sampling window, reconstructed line currents are not adequate replacements for real line currents during voltage sector transitions. Fig. 5 proves this, illustrating recorded reconstructed currents in the DSP, i_{AREC} , i_{BREC} , and i_{CREC} , for reference

voltage with a middle modulation index 0.1 p.u. and reference speed 0.125 p.u.

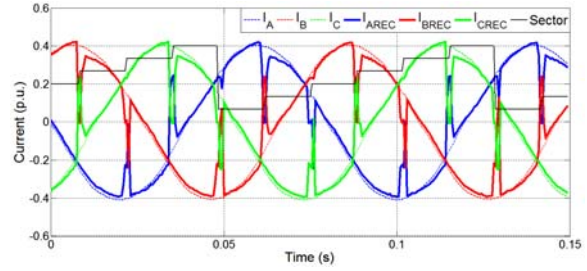


Fig. 5. Error in reconstructed line current waveforms during reference voltage vector sector transitions.

Therefore, it is desirable to use the proposed method, which achieves an effective dc-link current measurement by shifting the three-phase PWM voltage pulses sufficiently, if longer active vectors are needed. Fig. 6 shows the applied solution with a recorded example, where the first active voltage vector on the lagging side of the PWM period is less than the predetermined shortest active vector time, or minimal dc current sampling-window (same as the Fig. 4 case):

$$T_{\min} = T_{on} + T_r + T_s + T_{S\&H} \quad (2)$$

where $T_{S\&H}$ is the minimum time during which the dc-link current signal has to be present at the DSP analog inputs after the sampling has been initiated. In the proposed solution, the PWM signal associated with the middle voltage command phase (here, *PWM B*) is shifted to the right in order to form a sufficiently long first sampling window on the lagging side of the PWM period. Similarly, when there is not enough time for the second dc-link current sample, the PWM signal associated with the highest voltage command phase (here, *PWMA*) is also shifted to the right in order to form a second sampling window. After modifying the PWM (Fig. 6), a DC-link current measurement can be reliably taken at the first possible instant (here, $-i_c$ with sampling signal *SAMP1*).

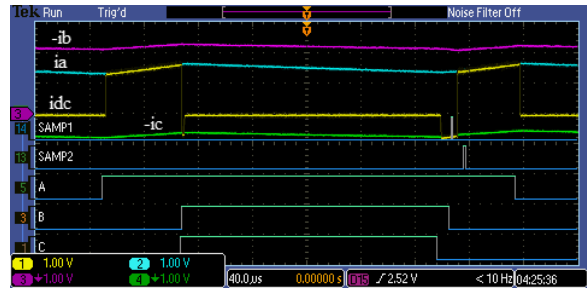


Fig. 6. Reference voltage vector passed from voltage sector 6 to sector 1. PWM B pulse is shifted to the right in order to provide enough time for first dc-link current sample (*SAMP1*) and a reliable $-i_c$ line current reading.

For the same voltage vector reference used for recording Fig. 5, reconstructed line currents with proposed PWM modification are given in Fig. 7. Reconstructed line currents are much less distorted and

large abrupt changes in current values are completely eliminated.

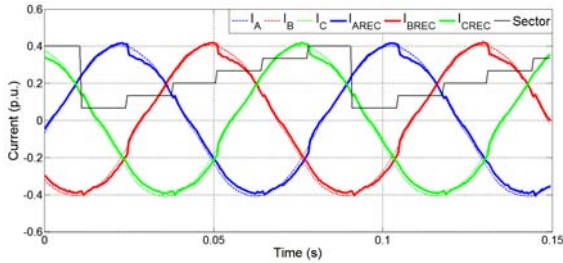


Fig. 7. Reconstructed line currents waveforms when the proposed PWM shifting method during reference voltage vector sector transitions is used.

5. REFERENCE VOLTAGE VECTOR WITH A LOW MODULATION INDEX

The second case of interest is for the reference voltage vector with a low modulation index, when both active vectors are present for a short time.

Fig. 8 illustrates the case when the reference voltage vector was with a low modulation index of 0.02 p.u. and when there is not enough time for reliably reading both line currents observable in the dc-link current.

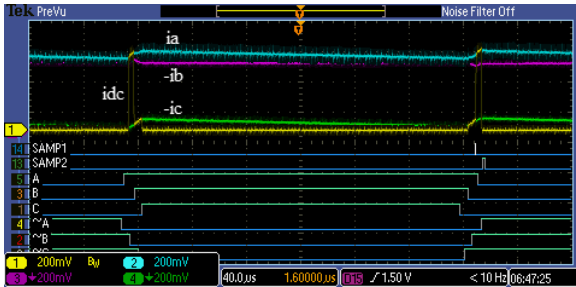


Fig. 8. The reference voltage vector with a low modulation index in the first voltage sector. All PWM pulses are with almost the same duty cycle of 50%, and there is not enough time for both dc-link current samples (SAMP1, SAMP2).

The reconstructed line currents for that case are shown in Fig. 9, indicating that they are not usable for providing reliable current feedback for the motor control algorithm.

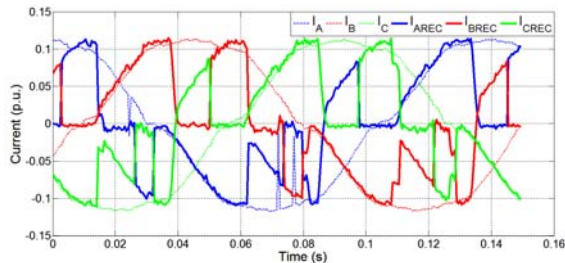


Fig. 9. Error in the reconstructed line current waveforms for the reference voltage vector with a low modulation index.

In the proposed solution, the PWM signal associated with the middle voltage command phase (here, *PWM B*)

is shifted to the right in order to form a sufficiently long first sampling window on the lagging side of the PWM period. Then, the new duration of the succeeding voltage vector is calculated and the PWM signal associated with the highest voltage command phase (here, *PWM A*) is also shifted to the right in order to form a second sampling window.

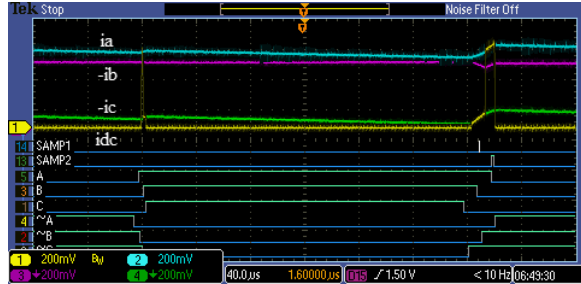


Fig. 10. The reference voltage vector with a low modulation index in the first voltage sector. *PWM B* and *PWM A* pulses are successively shifted to the right in order to provide enough time for both dc-link current samples (SAMP1 and SAMP2) and reliable $-i_C$ and i_A line current reading.

Reconstructed line currents with the proposed PWM modification are given in Fig. 11, for the same voltage vector reference used for recording results given in Fig. 9. The reconstructed line currents, i_{AREC} , i_{BREC} , and i_{CREC} , are much less distorted and almost matched with measured inverter/motor line currents, i_A , i_B and i_C .

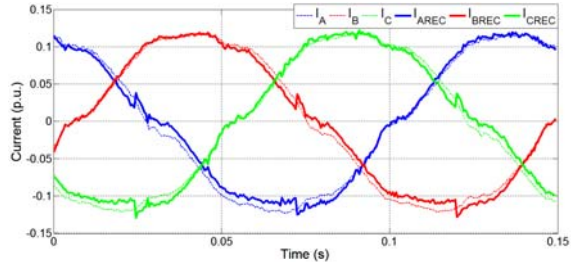


Fig. 11. The reconstructed line current waveforms when the proposed PWM shifting method, for a reference voltage vector with a low modulation index, is used.

6. IFOC INDUCTION MOTOR DRIVE USING LINE CURRENT RECONSTRUCTION

The effectiveness of a proposed PWM shifting method for reliable dc-link current reading and line current reconstruction was verified in the frame of an indirect rotor field oriented control algorithm and an induction motor drive. Speed and current response will be given and compared for cases when reconstructed and measured line currents are used as control feedback.

The recorded speed and current response for the up-down speed reference 0.1 p.u. – 0.4 p.u. (85% of nominal value) and motor load torque of 3.72 Nm (50% of nominal value), and measured line current control feedback, is given in Fig. 12. In terms of rotating reference frame d-q current variables, the response recorded in the DSP was as shown in Fig. 13.

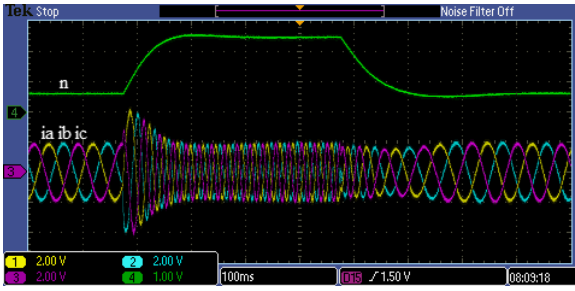


Fig. 12. HIL results: speed, n , and line current, i_A , i_B and i_C , response in an IFOC IM drive when measured terminal currents are used as control feedback.

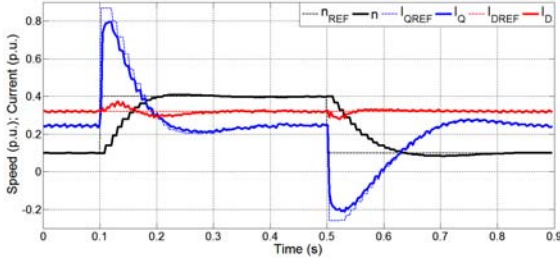


Fig. 13. DSP results: speed, n , and d-q current, i_D and i_Q , response in an IFOC IM drive when measured terminal currents are used as control feedback.

The speed and current response was recorded when reconstructed line currents were used as control feedback for the same motor speed and load torque references. Recorded results given in Figs. 14 and 15 prove that the proposed PWM shifting method enables a closed loop operation using reconstructed line currents, but also indicates that d-q variable filtering could be applied for a better current steady-state response.

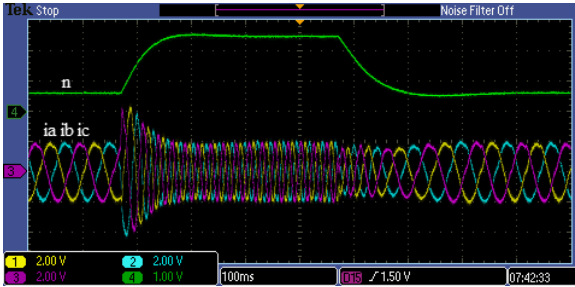


Fig. 14. HIL results: speed, n , and line current, i_A , i_B , and i_C , response in an IFOC IM drive when reconstructed currents are used as control feedback.

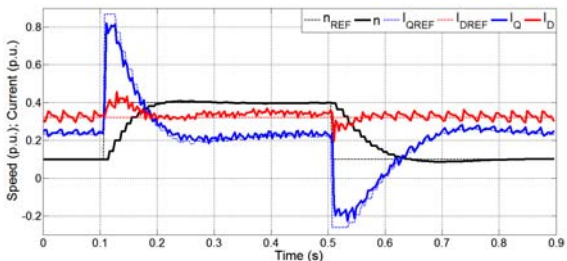


Fig. 15. DSP results: speed, n , and d-q current, i_D and i_Q , response in an IFOC IM drive when reconstructed currents are used as control feedback.

7. CONCLUSION

This paper proposes a simple and reliable PWM switching pattern for motor line-current reconstruction technique, and proves its effectiveness within the framework of developed control software for a sensed IFOC induction motor drive. Thanks to the $1\mu\text{s}$ real-time resolution of the HIL testing platform used during the course of this work, it was possible to study all the fine details of the interaction between the DSP control algorithm and the drive hardware in all operating conditions, with great ease and confidence, as they occur in real time.

8. ACKNOWLEDGEMENT

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9. REFERENCES

- [1] A. Emadi, Y.J. Lee, K. Rajashekara, "Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles," IEEE Trans. Ind. Electron., vol. 55, no. 6, pp. 2237-2245, June 2008.
- [2] J. Holtz, "Sensorless Control of Induction Machines —With or Without Signal Injection?," IEEE Trans. Ind. Electron., vol. 53, no. 1, pp. 7–30, Feb. 2006.
- [3] C. Lascu, I. Boldea, F. Blaabjerg, "A Class of speed-sensorless sliding-mode observers for high-performance induction motor drives," IEEE Trans. Ind. Electron., vol. 56, no.9, pp. 3394-3403, Sep. 2009.
- [4] J. Rodriguez, et al, "High-Performance Control Strategies for Electrical Drives: An Experimental Assessment," IEEE Trans. Ind. Electron., vol. 59, no. 2, pp. 812-820, Feb. 2012.
- [5] T.C. Green, B.W. Williams, "Derivation of Motor Line-current Waveforms from the DC-link Current of an Inverter," IEE Proceedings B, vol. 136, no. 4, pp. 196-204, July 1989.
- [6] F. Blaabjerg, J. K. Pedersen, "A New Low-Cost, Fully Fault-Protected PWM-VSI Inverter with True Phase-Current Information", IEEE Trans. Power Electron., vol. 12, no. 1, pp. 187-197, Jan. 1997.
- [7] W. C. Lee, et al, "Comparison of Single-Sensor Current Control in the DC-Link for Three-Phase Voltage-Source PWM Converters", IEEE Trans. Ind. Electron., vol. 48, no. 3, pp. 491-505, Jun 2001.
- [8] H. Kim, T. M. Jahns, "Phase Current Reconstruction for AC Motor Drives Using a DC Link Single Current Sensor and Measurement Voltage Vectors", IEEE Trans. Power Electron., vol. 21, no. 5, pp. 1413-1419, Sept. 2006.
- [9] D. Majstorović, et al, "Ultra-Low Latency Hardware-in-the-Loop Platform for Rapid Validation of Power Electronics Designs," IEEE Trans. Ind. Electron., vol. 58, no. 10, pp. 4708-4716, Oct. 2011.