

Application of a Software Configurable Digital Servo Amplifier to an Electric Machine Control Course

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Abstract

The various applications of the three-phase permanent magnet brushless dc motor (PMBDCM) in the industry are increasing. The main purpose of this paper is to describe the application of a new technology to academic electric machine control and/or power electronics drive courses. An easy method for the implementation of a fully software-configurable digital servo amplifier to drive a three-phase PMBDCM is presented in this paper. This developed servo amplifier may be suitable for an electric machine control course. The change of drive configuration requires additional development time and cost, especially in control software modification, which, in turn, depends on the specific application. The highlight of the paper is the GUI (Graphical User Interface)-based control software (Pro-Motion) setup for implementation of a software-configurable digital servo amplifier. The principle of the operation of the three-phase PMBDCM is discussed first, and then the requirement to develop three different types of servo amplifier-such as velocity, position, and torque servo amplifiers-to drive the three-phase PMBDCM, are explained. The details of a selected motor control integrated circuit (IC), MC73110 from PMD Corp., are introduced. The various capabilities of the IC that make fast implementation of a software-configurable digital servo amplifier possible are discussed. The MC73110 IC is incorporated into the servo amplifier design, resulting in an increased ease of use with software configuration. To validate the software-configurable digital controller, a step-by-step design example to develop a velocity servo amplifier is completely explained and some of the test results are discussed. As a conclusion, suitable teaching topics based on the proposed software-configurable PMBDCM drive for electric machine control and/or power electronics drive courses are summarized.

Introduction

Today, numerous industrial applications are increasingly adopting the PMBDCM due to its inherent variable speed drive aspect. Since the electronic commutation circuit is necessary to drive the PMBDCM, it may not be easy to implement the PMBDCM drive. In most cases, it is time-consuming and expensive to build instructional components for motor drives into existing electric machine control related courses [1, 5, 6]. The implementation of hardware and software usually takes time to complete. But many different types of development kits are available off the shelf for various types of motors [2]. These development kits are aimed mainly at the

industrial sector, but they look attractive for educational application because they provide not only hardware platforms, but also dedicated setup software.

The MC73110-based development kit may be suitable for the fast and easy development of the PMBDCM drive instructional components. This paper proposes the MC73110 motor control IC-based developer's kit for this purpose. This kit was chosen for the easy and cost-effective implementation of the instructional component of the PMBDCM drive in the electric machine control course. The PMBDCM drive is increasingly popular in the industry sector, but it has not been integrated into an academic curriculum. Consequently, it is the logical choice for incorporation into an academic course that will prepare students for industry. The development kit provides a hardware platform that contains all necessary analog and digital circuits on one PCB and user-friendly GUI-based configuration software. The two-volume user manual is also a good resource to use in the design of any size and type of PMBDCM drive.

It is suitable and timely to investigate the incorporation of the PMBDCM drive into the electric machine control course. The design of the PMBDCM drive has two major tasks, one in hardware and another in software design. To accomplish both design tasks, one should understand its principle of operation. The hardware design could be classified as, but not limited to, power circuitry that includes a power switching circuit, analog and/or digital sensor circuits, and controller circuitry. The development of application-specific software for a motor drive is not always an easy task. Fortunately, the MC73110-based development kit provides user-friendly drive configuration software for easy setup of the desired type of the PMBDCM drive.

In this paper, the technical concepts of the PMBDCM and its drive are explained first to provide a fundamental background of the overall drive system suitable to the conventional electric machine control and/or power electronics courses. Second, the characteristics of the MC73110 motor control IC will be explained.

Principle of Operation of the PMBDCM Drive

The PMBDCM is an electronically commutating permanent magnet motor. The applications of this motor are growing. Because of its inherent variable-speed drive nature, it is widely used in white goods, automobile, and machine-building industries. The commutation circuit for the three-phase PMBDCM can be implemented with discrete components or dedicated control IC. The design with discrete components provides many insights on the commutation circuit for students; at the same time, it requires lots of time and effort to build the hardware and to troubleshoot. The dedicated IC approach looks promising because little or no additional circuitry is required. Some manufacturers even offer dedicated setup software to use their IC.

The mechanical structure of the PMBDCM is the reverse of the conventional permanent magnet brushed dc motor (PMDCM); the rotor contains permanent magnets, and the motor windings are mounted on the stator [7]. The PMBDCM does not have brushes that are required for commutation of the PMDCM. Therefore, a maintenance-free motor drive system is possible with the PMBDCM.

To drive the PMBDCM, an electronic commutation circuit is required. This paper is concerned only with the position sensor-based commutation; therefore, the two common

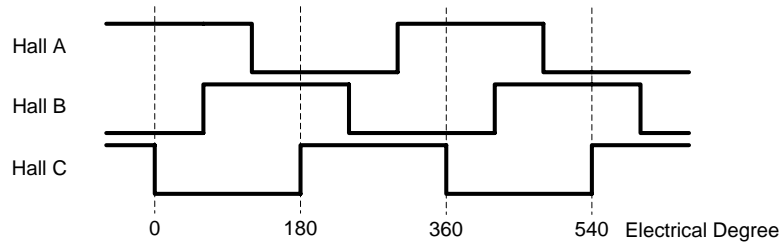


Figure 1. Three-phase Hall sensor timing chart with 120° angle separation

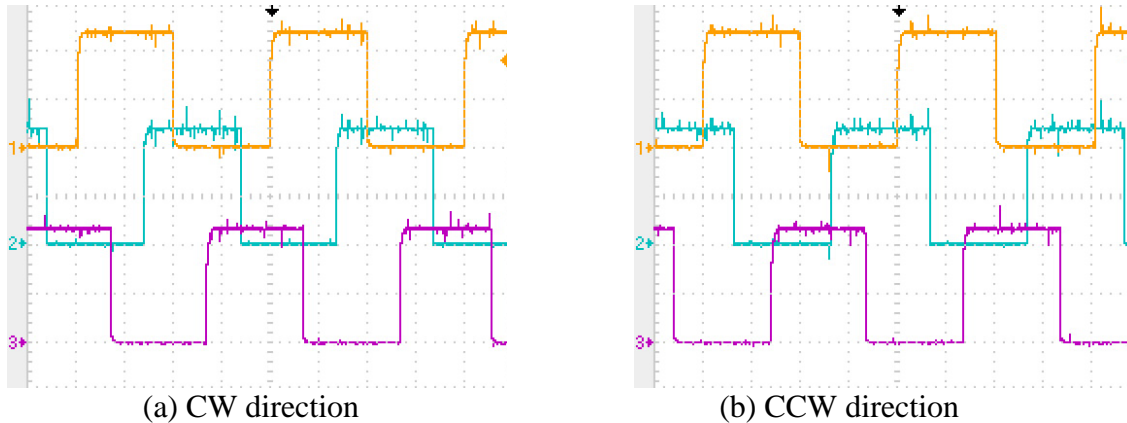


Figure 2. Measured Hall signals in CW and CCW direction at 1500r/min (CH1: Hall A, CH2: Hall B, CH3: Hall C)(Vertical: 2V/div, Time: 5ms/div)

position-sensing techniques are discussed. The first one is the Hall effect sensor, which is the most cost-effective method of rotor position sensing. The timing diagrams of three typical Hall sensors with 120° angle separation are shown in Figure 1. The experimental waveforms of the three Hall signals in both clockwise (CW) and counterclockwise (CCW) directions of motor rotation are shown in Figure 2. The direction of rotation is viewed at the motor shaft. The sequences of the Hall signals are Hall A-Hall B-Hall C in the CW direction and Hall B-Hall C-Hall A in the CCW direction.

The second method uses the optical encoder. The incremental encoder is widely used due to its lower cost than the absolute type. However, the optical encoder provides better resolution of position data than the Hall sensor, therefore making precise control of the PMBDCM possible.

There are two types of permanent magnet brushless dc motors, which depend on their back-electromotive force (EMF) waveforms [7]. The PMBDCM has the trapezoidal (six-step) back-EMF waveform. The one with the sinusoidal back-EMF is called the permanent magnet synchronous motor (PMSM). The PMSM provides nearly zero torque ripples. In this paper, only the PMBDCM with Hall sensor-based commutation will be discussed.

A simplified three-phase full-bridge power circuit for the PMBDCM is shown in Figure 3. The relationships between the three-phase back-EMF, motor current, and air-gap power are shown in

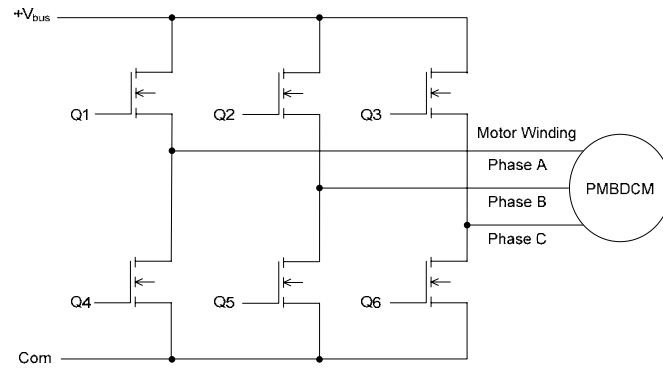


Figure 3. Three-phase full-bridge power circuit for PMBDCM drive

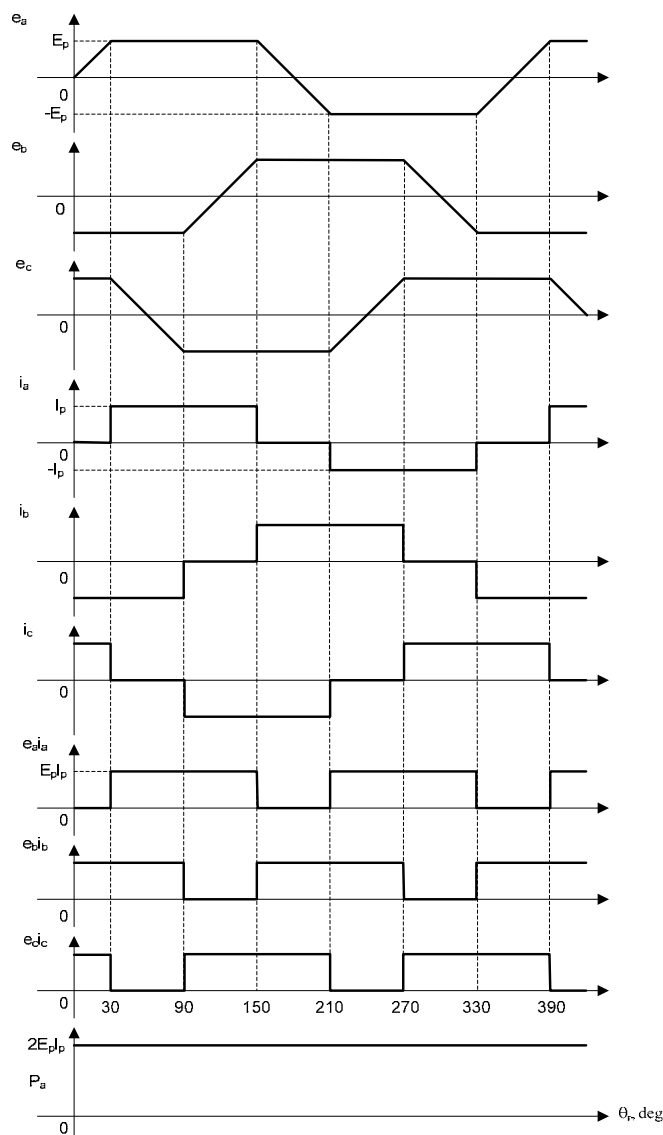


Figure 4. Relationship between back-EMF, motor current, and air-gap power for three-phase PMBDCM drive

Figure 4 [7]. The trapezoidal back-EMF ($e_{a, b, \text{ and } c}$) has a constant magnitude of E_p during 120 electrical degrees in both the positive and negative half-cycle. The air-gap power (P_a) and the electromagnetic torque are both continuous when applying motor current ($i_{a, b, \text{ and } c}$) during the same period in both half-cycles as shown in Figure 4. The Hall signals provide position information of the flat-top portions of the back-EMF in both half-cycles. Based on the position information, it can be seen that the pulse width modulated motor voltage; hence, the motor current is applied to generate the motor torque.

Introduction of the MC73110 Motor Control IC

For the fast-changing motor drive technology in industry, the provision of a new motor control IC was beneficial in developing a digital servo controller without time-consuming effort spent on control software development. The MC73110 motor control IC has developed into an advanced single-chip, single-axis device that can be used to implement an intelligent three-phase PMBDCM controller based on FPGA and ASIC technologies [3, 4]. It is packaged in a 64-pin thin quad flat pack (TQFP) measuring 12 mm by 12 mm and operates on 3.3V. It can be operated in internal velocity profile mode, velocity mode with an external analog, digital velocity command signal, or torque mode with an external torque command signal. It also can be operated as a standalone controller using pre-programmed parameters stored onto chip flash memory or through the RS-232 serial port using the Pro-Motion GUI setup software. The simplified functional block diagram of the MC73110 is shown in Figure 5.

The various functions useful for the development of the PMBDCM drive are embedded in the MC73110 IC. These functions include the three-phase PWM generation for three-phase full-bridge power circuit and three-signal PWM for single switch per phase power circuit configuration, Hall- or quadrature encoder-based commutation, digital current and velocity loops, profile generation, emergency stop, analog velocity command, and RS-232 serial communication port, for example. Both the six-step and sinusoidal commutation methods are possible with this IC. But a quadrature encoder is required in addition to the Hall-effect sensors to implement the sinusoidal drive.

The details of the six main functional modules in the MC73110 IC are listed below [3]:

- Profile Generator Module: This module generates a velocity- and acceleration-bounded profile by using the serial port commands. The instantaneous desired velocity value is put out to either the velocity integrator or the velocity loop module. A host processor (microprocessor or personal computer) is needed to utilize this module.
- Velocity Integrator Module: A desired velocity value from the profile generator module, or an external analog signal (AnalogCmd), or a synchronous serial digital 16-bit word data stream, serial peripheral interface (SPI) bus, will be applied to this module. This value integrates into an instantaneous desired position, which is compared with the actual position from the encoder, to develop either desired velocity or torque.
- Velocity Loop Module: Next, a desired velocity command emerges into this module. The velocity command with the current instantaneous velocity of the motor axis will be combined to determine a desired torque or voltage command in this module. The desired velocity command will be generated from the profile generator module, the velocity

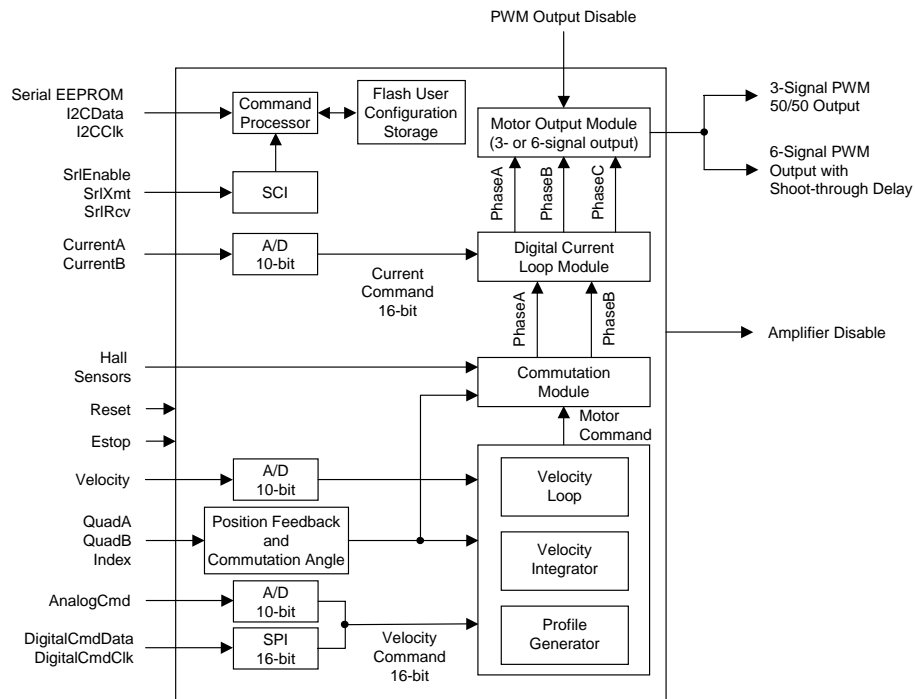


Figure 5. Simplified functional block diagram of MC73110 motor control IC

integrator module, the AnalogCmd, or the digital SPI data stream. The instantaneous velocity emerges from an analog signal through either the velocity pin of the chip or the quadrature encoder. The velocity estimator provides velocity feedback to the digital PI velocity loop from the encoder or Hall feedback. Users can disable this module easily with Pro-Motion GUI. In this case, the MC73110 operates in either torque or voltage mode, depending on the state of the current control module.

- **Commutator Module:** A single-phase desired torque or voltage command will be applied to this module depending on whether the Current Loop Module explained below is enabled, and this command will be vectorized into three-phase commands—one for each motor phase connection. This module supports two commutation methods: Hall-based and sinusoidal. The Hall signals, when Hall-based is selected, must be connected through Hall1, Hall2 and Hall3 pins. When the sinusoidal commutation is selected, the quadrature encoder data must be connected through the QuadA, QuadB, and Index pins in addition to the Hall signals. This module will remain enabled at all times.
- **Current Loop Module:** The target current for two motor phase coils (PhaseA and PhaseB) will be applied to this module. It uses two sensed analog feedback signals, CurrentA and CurrentB, to develop three PWM output values for a three-phase PMBDCM. When the MC73110 operates the motor in the voltage mode, this module can be disabled.
- **Motor Output Module:** The desired voltage for each of the three motor phase coils will be applied to this module. Then it generates the PWM signal in either three-signal mode (one signal per phase) or six-signal mode (high-side and low-side signals for each phase

Table 1. Three different operation modes

Operation Mode	Modules Encoded	Minimal Connections
Torque	Current Loop	Hall A, B, and C CurrentA/B QuadA/B (sinusoidal commutation only) DigitalCmdClk/Data or AnalogCmd
Velocity	Current Loop, Velocity Loop	Hall A, B, and C CurrentA/B QuadA/B (sinusoidal commutation only) or Tachometer DigitalCmdClk/Data or AnalogCmd
Intelligent Motion Controller	Current Loop, Velocity Integrator, Profile Generator	Hall A, B, and C CurrentA/B QuadA/B SrlXmt/Rcv

leg). The generated PWM output signals are symmetric waveforms; they are synchronized to the master PWM output switching frequency at 20kHz.

The MC73110 can be configured as different types of amplifiers, as summarized in Table 1. Most applications may fall under one of the three standard configurations explained below:

- **Torque Amplifier:** The torque command will be either an analog signal or an SPI digital data stream. The typical target application of this mode may be the position servo with external position loop and position feedback. The position feedback signal can be analog with analog feedback devices or digital with a microprocessor. One example of the position feedback is the potentiometer, which provides continuously varying voltage that is proportional to the rotor position. The torque amplifier can be a standalone or can employ a host processor. The MC73110 motor control IC has a 20 kHz digital current loop. The two motor current feedback signals (CurrentA/B) are required to close the current loop.
- **Velocity Amplifier:** This amplifier can be another standalone application with the velocity loop enabled. The MC73110 has an internal digital velocity loop with a rate frequency of 10 kHz. The velocity command signal will be the same as for the torque amplifier; the difference is that the command signal represents velocity rather than torque in the torque amplifier. The Hall signal or the encoder or the tachogenerator can be used as the velocity feedback.
- **Intelligent Motion Controller:** This configuration needs a host processor or computer to generate a command signal through the profile generator. In this case the MC73110 works as an intelligent programmable motion controller. The command signal will be applied through the RS-232 serial port.

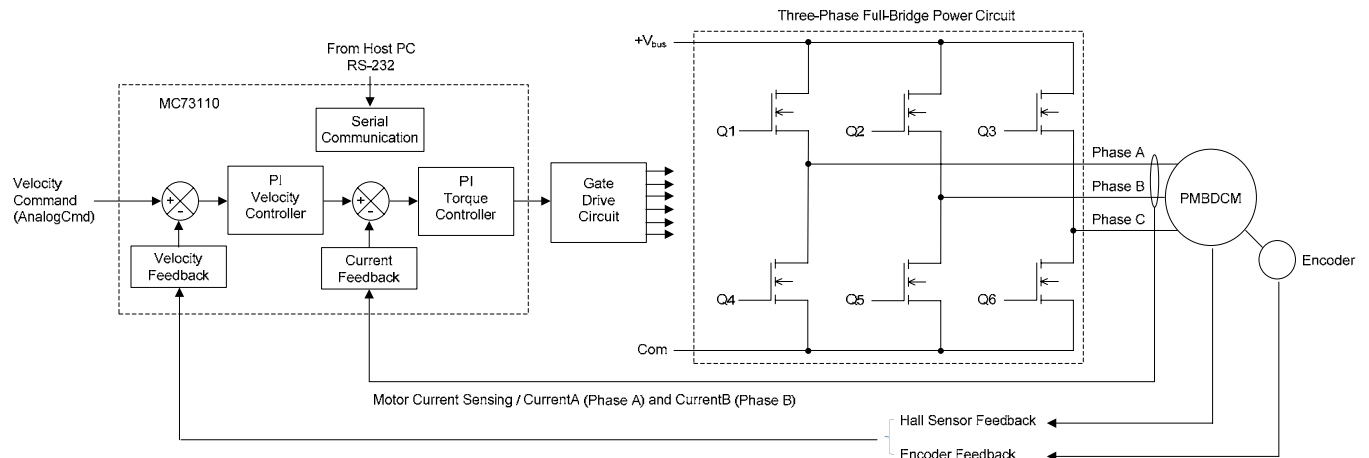
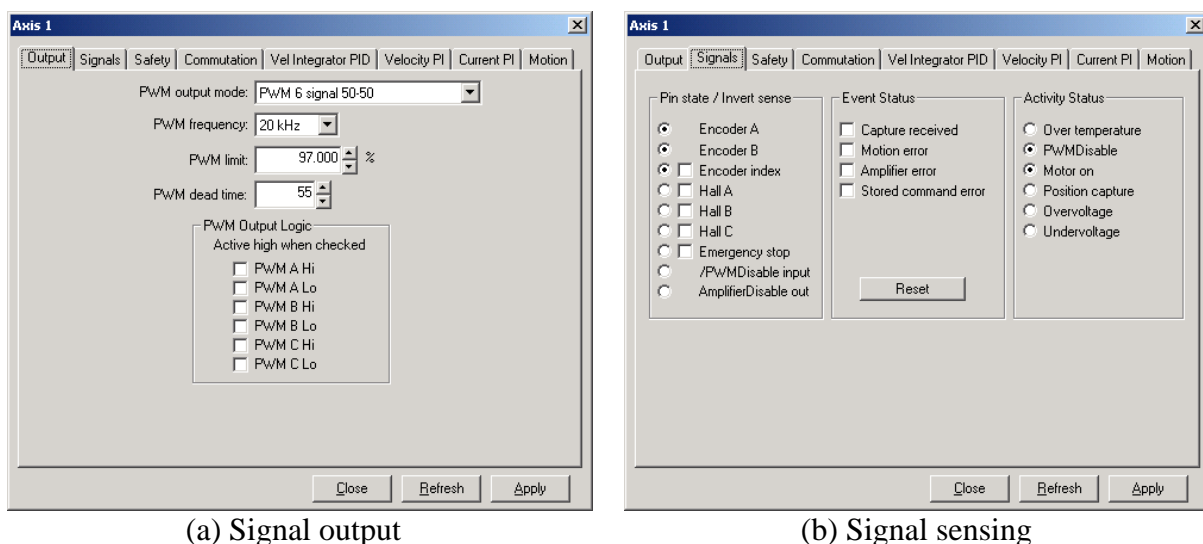


Figure 6. Simplified block diagram of the proposed velocity servo amplifier

Design Example of a Digital Velocity Servo Amplifier

To prove the capability of the MC73110, a digital velocity servo amplifier was designed. The experimental results will be discussed in this section. The major benefit of the servo amplifier design, used with the MC73110, is the flexibility of control loop configurations and the setup of its parameter values. The previously mentioned amplifier types can be software configurable by using the interactive Windows-based Pro-Motion GUI software. Since this software is royalty-free, the development of any industrial applications with MC73110 can be cost-effective.

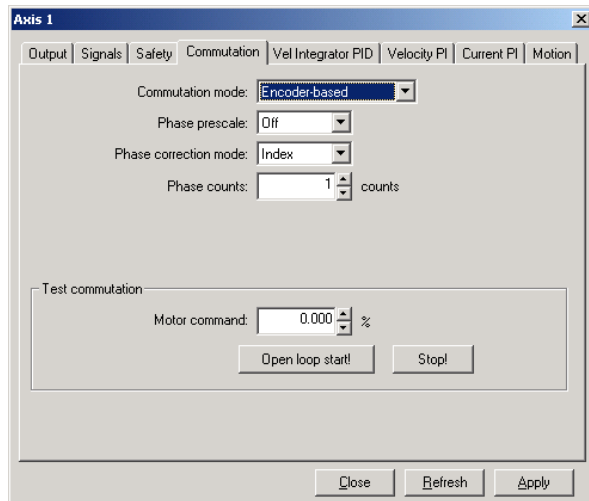
The simplified overall block diagram of the proposed velocity servo amplifier is shown in Figure 6. In this example, the explanation of hardware connections will be omitted. Rather, the focus will be on the verification of software setup. After completion of hardware setup and successful connection between the host PC and the MC73110, the MC73110 developer's kit will be activated, first by invoking Axis Setup Wizard on the Pro-Motion window [4].



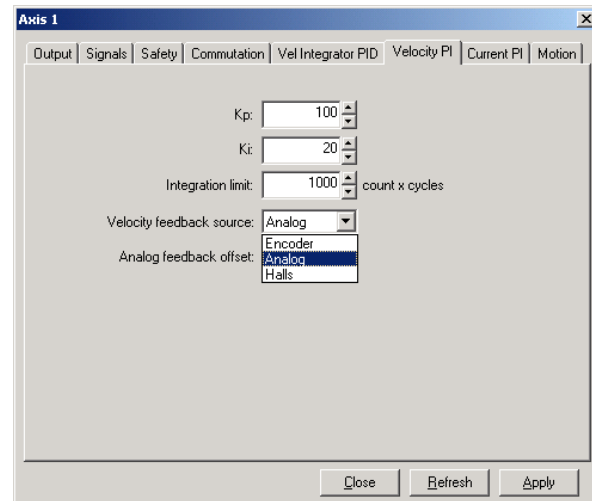
(a) Signal output

(b) Signal sensing

Figure 7. Signal output and sensing settings



(a) Commutation



(b) Velocity PI

Figure 8. Commutation and velocity PI settings

The first page of the wizard is the signal output setting window, as shown in Figure 7(a). The PWM output mode can be either three-signal mode for a three-phase half-bridge power circuit or six-signal mode for a three-phase full-bridge circuit. The PWM dead time will activate only with six-signal mode to prevent a possible shoot-through fault in the phase leg. It can be set to range from 0 to 12 μ s.

The PWM limit allows enough off-time for charging the bootstrap capacitor in the bootstrap power supply for a high-side switch. The PWM output logic can be checked for the polarity inversion of the gate drive logic signals. The signal-sensing window provides the necessary inversion of the polarity of feedback signals from Hall sensors and/or an encoder. During normal operation, black dots in white circles blink, indicating the change of signals through feedback sensors. The default signal sense is set to “active low.”

The commutation setup window is shown in Figure 8(a). The commutation mode can be trapezoidal with Hall sensor feedback or sinusoidal with encoder feedback. The sinusoidal commutation mode may be effective with a PMSM to generate near-zero torque ripples [7].

The “Open loop start!” button can be used to check the phasing of Hall signals and motor windings in open loop mode. When the PMBDCM commutates properly, it gives smooth motion in both CW and CCW directions of rotation. This function is very useful during initial setup of

Motor Phase Winding					Hall Effect Sensor			
PH A	PH B	PH C	S1		S2	S3		
1	A	B	C	}	H1	H2	H3	1
2	A	C	B		H1	H3	H2	2
3	B	A	C		H2	H1	H3	3
4	B	C	A		H2	H3	H1	4
5	C	A	B		H3	H1	H2	5
6	C	B	A		H3	H2	H1	6

Figure 9. Possible combinations of motor windings and Hall signals

matching Hall signals with relevant motor windings. Without this function, all possible combinations of Hall signals and motor windings should be checked for correct phase matching. The 36 possible combinations are shown in Figure 9. The one combination of each group of motor phase windings and Hall signals should provide an even response for the bipolar command signal.

The setup of velocity loop parameters depends on feedback devices, as shown in Figure 8(b). The allowable velocity feedback sources are analog (tachogenerator), encoder, and Hall signals. The values of PI parameters will be selected by trial and error through the command window. The GetLoopError instruction gives the value of the velocity error. The optimum values of PI parameters can be found by observing the minimal change in the returning velocity error values in either positive or negative polarity. Since the MC73110 does not have the capability of graphical representation of error values, this procedure may be tedious and time-consuming.

The same procedure could be applied to the current loop to find out optimum PI parameter values, as shown in Figure 10. The motion window provides for the selection of servo loops and motor dynamics. For the standalone application, such as the velocity servo amplifier example in this paper, the velocity command source should be analog. The typical analog velocity command value will be the industry standard $\pm 10\text{V}$ dc voltage.

The experimental setup is shown in Figure 11. The velocity command is $\pm 10\text{V}$ dc voltage (labeled as Analog Command in front). The communication between the MC73110 and the Pro-Motion software is performed with an RS-232 serial cable. The PMBDCM under testing is the Maxon EC-Max 30, order number 272769. A PMDCM is connected back to back with the PMBDCM to form a motor-generator set. The PMDCM and PMBDCM specifications are listed in Table 2.

The pulse width modulated motor terminal voltage between Phase A and B and Phase A line current is shown in Figure 12. Since the commutation is Hall-based trapezoidal (six-step), the measured current waveform resembles the trapezoidal waveform except in the zero-crossing area and top flat portions in both half-cycles.

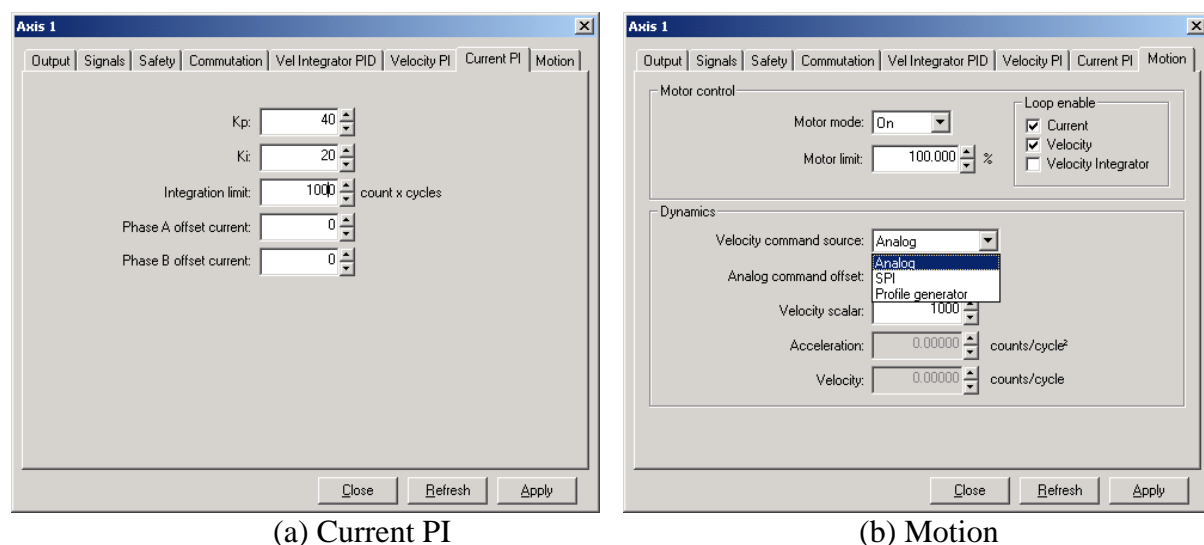


Figure 10. Current PI and motion settings

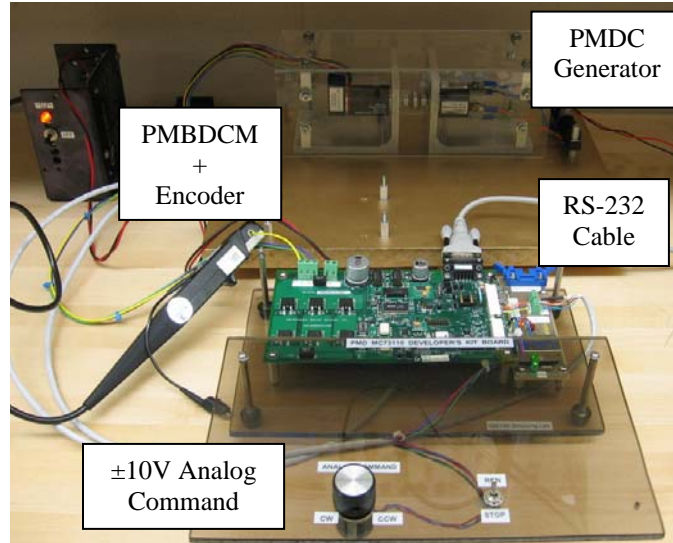


Figure 11. Experimental setup with the MC73110-based PMBDCM drive

Table 2. Specifications of the PMBDCM and PMDCM under testing

PMBDCM (Maxon EC-Max 30, 272769)		PMDCM (Moog)	
Nominal Voltage, V	36.0	Nominal Voltage, V	26.0
No Load Speed, r/min	9160	No Load Speed, r/min	10346
No Load Current, mA	73.20	Peak Torque, oz-in	50
Nominal Speed, r/min	7080	Continuous Torque, oz-in	7.5
Nominal Current, mA	97.60	Torque Sensitivity, oz-in/A	3.42
Torque Constant, mNm/A	36.8	Back-EMF, V/rad/s	0.024
Speed Constant, r/min/V	259		
Mechanical Time Constant, ms	6.98		

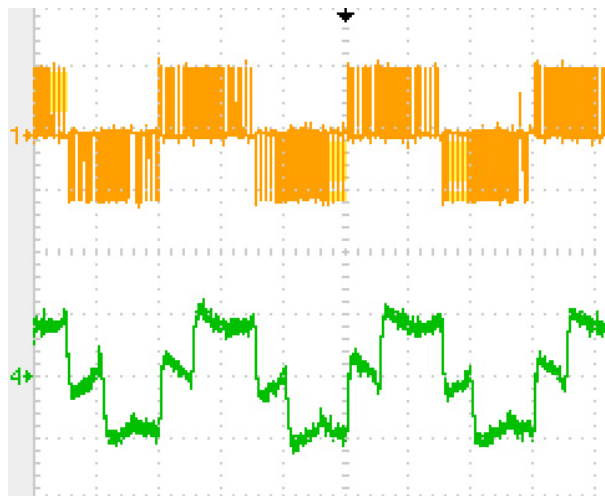


Figure 12. PMBDCM terminal voltage (V_{AB}) and Phase A line current with trapezoidal commutation, Vertical: CH1: 25V/div, CH4: 0.1A/div (center zero), Horizontal: 5ms/div

Teaching Components with the Proposed Servo Amplifier for the PMBDCM

The proposed digital servo amplifier based on a highly integrated MC73110 motor control IC provides various teaching components to enhance the electric machine control and/or power electronics drive courses. Possible teaching topics and their brief explanations are listed below:

- Power Circuit and Gate Drive Circuit: The MC73110 IC supports not only conventional three-phase full-bridge power circuits with six power switching devices but also three-phase half-bridge power circuits with three power switching devices. Further, a three-phase half-bridge power circuit can be applied to the switched reluctance motor (SRM) drive with Hall position feedback sensors. In this case, the motor winding of SRM or PMBDCM is preferably Y-connection with the center point accessible. Usually, the half-wave power circuit produces less output power than the full-wave power circuit [7]. The gate drive for the high-side switching devices requires isolation when an N-type metal-oxide field effect transistor (MOSFET) device is used. By using a P-type MOSFET device, the free of isolation of gate drive is possible. The various aspects of the types of power switching devices and gate drive selection will be attractive topics to be discussed in detail. The method of the heat-sinking of power switching devices should be addressed with power circuit topologies.
- PWM Method: The various PWM strategies to generate PWM gate signals to drive three-phase power circuits can be introduced. Among them, the symmetric three-phase PWM method is implemented in the MC73110 IC.
- Back-EMF Types and Commutation Method: Two types of commutation strategy can be introduced: six-step (trapezoidal) and sinusoidal. Six-step commutation can be implemented with Hall position feedback sensors only. It is suitable to the PMBDCM that has trapezoidal back-EMF waveform. On the other hand, the sinusoidal commutation needs a quadrature encoder in addition to Hall position sensors. This method is applied to the PMSM with sinusoidal back-EMF waveform. But the different effects can be investigated when both commutation methods are applied to the PMBDCM.
- Control Loop Closure: The velocity and torque loops are embedded on the MC73110. The basic open-loop and closed-loop control systems can be demonstrated to the class. The observation of effects when closing either or both control loops will be an interesting task for students. Also, the effects of the various proportional (P) and integral (I) gain values in the control loop can be observed through experiment. Because of the lack of graphical representation capability in Pro-Motion setup software, the continuous monitoring of various control variables is not possible. Instead, as an example, the GetLoopError instruction makes monitoring of discrete velocity and torque loop error values possible. To implement a position servo controller, a position loop can be added externally to the velocity command. It can be realized with few external analog components or with a tiny microcontroller. The velocity loop must be disabled to accommodate an external position loop.

- RS-232 Serial Communication: Serial communication is an industry standard means of transmitting and receiving data between a computer and a peripheral device. It is one of the most popular communication methods because the RS-232 serial port is installed on most computers. It should be noted that the MC73110-based servo amplifier could be configured as a standalone unit. In this case, the necessary control parameters should be downloaded into an on-chip flash memory in the MC73110 IC.
- Current Sensing Circuit: To close the current loop, the MC73110 requires two motor phase currents' (phases A and B) information. The phase C current is generated internally by combining those currents. Various current sensing techniques can be discussed: the passive way with a current sensor resistor and Hall sensor based current sensing IC. The different implementation methods of the analog signal processing circuit need to be discussed along with the current sensing circuitry. The analog signal processing circuit for the current sensor varies widely depending on the current sensing technique.

The following topics are relevant to broaden the coverage further:

- IC Packaging Type: Various package types of modern surface mount devices (SMDs) can be introduced to the class. The MC73110 IC is built on a 64-pin TQFP. Some of the IC package types that may be found on the MC73110 development board are small-outline package (SOP), small-outline integrated circuit (SOIC), thin shrink small-outline package (TSSOP), and discrete packaging (D²PAK) for power switching devices.
- Protection of the Dc Voltage Polarity Reversal: The required voltage type for the MC73110 development kit is dc. The addition of the protection circuit against the dc polarity reversal is a must for practical application.
- Regenerative Braking Circuit: A regenerative braking circuit should be included for the four-quadrant operation of the servo amplifier to dissipate the regenerative energy flows back to the bus when the PMBDCM operates in regeneration mode. It can be easily implemented with a comparator with the bus voltage sensing circuit, a power-switching device (N-type MOSFET), and a power resistor to dissipate the regenerated energy.
- Level Shift Circuit: The MC73110 is powered with 3.3V. Therefore, the various higher input signal levels, such as 5V and 10V, should be converted into 3.3V. A level shift circuit with an operational amplifier can be addressed as an example of a real-world application of an operational amplifier.
- Electromagnetic Interference (EMI) or Radio Frequency Interference (RFI): The EMI/RFI issue directly relates to the clock and PWM frequency in the proposed servo amplifier. The proper management of the printed circuit board (PCB) design is required to minimize the EMI/RFI effect. It is important to address this issue and examine the PCB design. The grounding technique, the use of power and ground planes in multilayer PCB design, and the elimination of ground loop may be worthy topics for discussion.

Conclusion

This paper addresses the feasibility of employing the digital PMBDCM drive in electric machine control and/or power electronics drive courses. The low cost and time-saving way to develop a software-configurable digital servo amplifier for the PMBDCM drive was confirmed with a velocity servo drive example. The MC73110 developer's kit is extremely useful in implementing a software-configurable digital servo amplifier without spending high development costs and time. The attainable teaching components with the proposed PMBDCM digital servo amplifier are the characteristics of the PMBDCM, the distinction between sinusoidal and trapezoidal drive, and the uniqueness of Hall-sensor and encoder-based commutation methods. The difference between three-phase full- and half-bridge power circuits, the assorted gate drive circuitry, a variety of current sensing methods, the aspects of velocity and current PI controllers, and the various analog signal conditioning methods are also suitable.

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Biography

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