Electricity and New Energy

BLDC Motors and Vector Control PMSM Drives

Courseware Sample

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By the staff of Festo Didactic

Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
⚡	Caution, risk of electric shock
🔥	Caution, hot surface
⚠	Caution, risk of danger
🏋	Caution, lifting hazard
✋	Caution, hand entanglement hazard
📡	Notice, non-ionizing radiation
⎓	Direct current
∿	Alternating current
∿	Both direct and alternating current
3∿	Three-phase alternating current
⏚	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
⏚	Protective conductor terminal
⏛	Frame or chassis terminal
⏚	Equipotentiality
|	On (supply)
○	Off (supply)
▣	Equipment protected throughout by double insulation or reinforced insulation
⊓	In position of a bi-stable push control
⊓	Out position of a bi-stable push control

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Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.
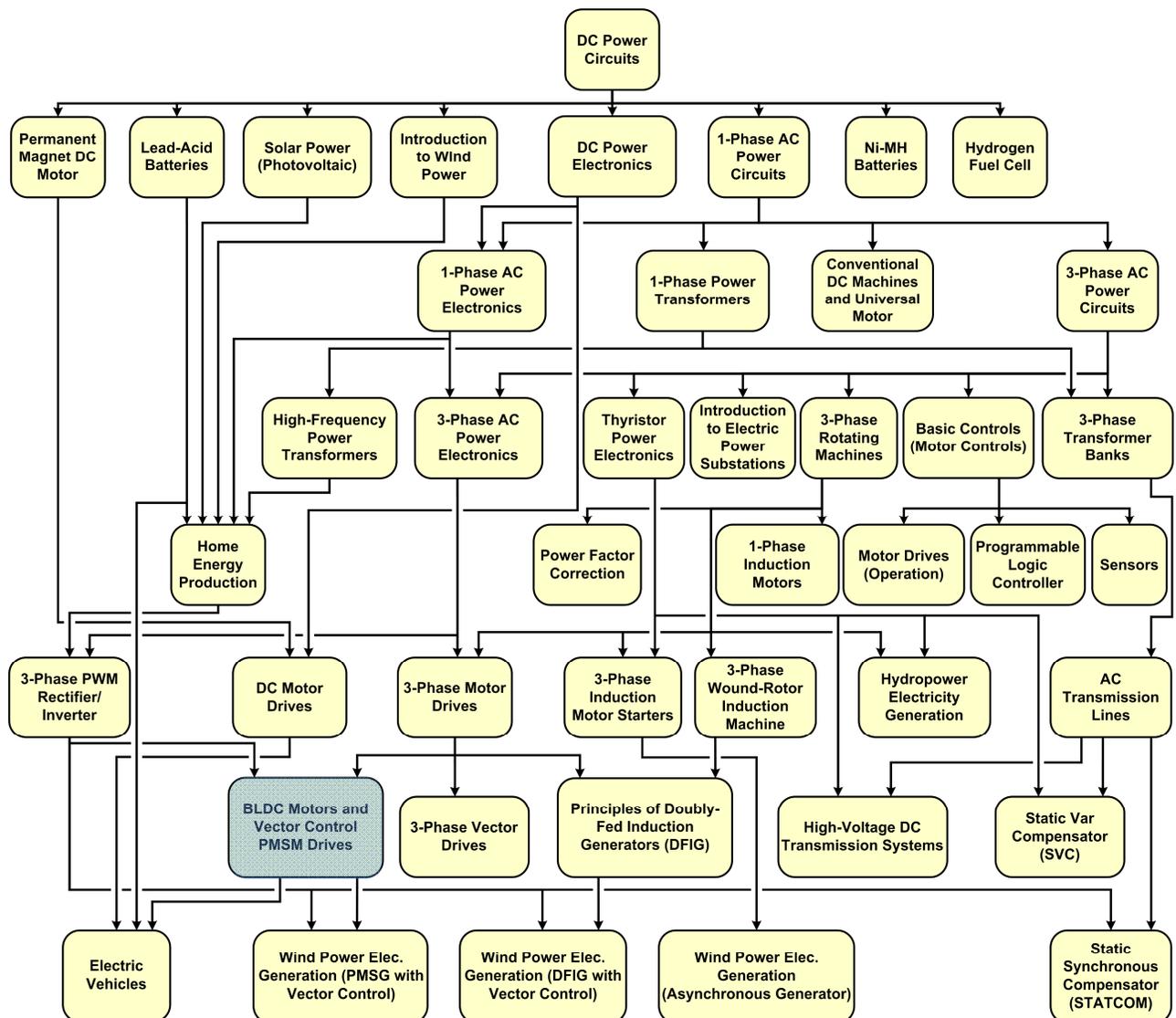
The Electric Power Technology Training Program.

Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

A permanent magnet synchronous machine (PMSM) is basically a conventional three-phase synchronous machine (i.e., a synchronous machine with a rotor electromagnet requiring slip rings and brushes) whose rotor windings are replaced by a permanent magnet. PMSMs present many advantages over conventional synchronous machines: they require less maintenance, have a higher power density, a higher efficiency, and are easier to cool.

PMSMs are primarily used to implement brushless dc (BLDC) motors and vector control PMSM drives. Both BLDC motors and vector control PMSM drives basically consist of a three-phase inverter, a PMSM, a shaft encoder, and a controller. The most common types of modulation used to control the converter in a BLDC motor are six-step 120° modulation and six-step PWM. On the other hand, the most common type of modulation used to control the converter in a vector control PMSM drive is vector control.

This course teaches the basic principles of operation of a PMSM. Students are introduced to both BLDC motors and vector control PMSM drives, and learn their different characteristics. They are also introduced to the most common types of modulation used to control the converter of BLDC motors and vector control PMSM drives. The theory presented in the manual is then verified by performing various circuit measurements and observations.

View of the stator and rotor of a typical PMSM.

About This Manual

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Prerequisite

As a prerequisite to this course, you should have read the manuals titled *DC Power Circuits*, p.n. 86350, *Lead-Acid Batteries*, p.n. 86351, *Solar Power*, p.n. 86352, *Introduction to Wind Power*, p.n. 86353, *DC Power Electronics*, p.n. 86356, *Single-Phase AC Power Circuits*, p.n. 86358, *Single-Phase AC Power Electronics*, p.n. 86359, *Single-Phase Power Transformers*, p.n. 86377, *Three-Phase AC Power Circuits*, p.n. 86360, *High-Frequency Power Transformers*, p.n. 86378, *Three-Phase AC Power Electronics*, p.n. 86362, *Three-Phase Rotating Machines*, p.n. 86364, *Home Energy Production*, p.n. 86361, *Three-Phase PWM Rectifier/Inverter*, p.n. 86366, and *Three-Phase Motor Drives*, p.n. 86368.

Systems of units

Units are expressed using the International System of Units (SI) followed by the units expressed in the U.S. customary system of units (between parentheses).

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Electric Power Technology Training Equipment must have been properly installed, according to the instructions given in the user guide Electric Power Technology Training Equipment, part number 38486-E.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

The Vector Control PMSM Drive

EXERCISE OBJECTIVE

When you have completed this exercise, you will know what a constant V/f ratio PMSM drive is and be familiar with its operation. You will also know what a vector control PMSM drive is and be familiar with its operation. You will also be familiar with the operation of the shaft encoder in a vector control PMSM drive. You will know how regenerative braking is implemented in a vector control PMSM drive. You will also be introduced to the current and speed feedback control loops in the controller of a vector control PMSM drive.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Constant V/f ratio PMSM drive
- Block diagram of a vector control PMSM drive
- Shaft encoder operation
- Objectives of the controller in a vector control PMSM drive
- Speed control in a vector control PMSM drive
- Torque control in a vector control PMSM drive
- Operation of a vector control PMSM drive in the four quadrants

DISCUSSION

Constant V/f ratio PMSM drive

A PMSM drive is similar to a three-phase, variable-frequency induction-motor drive (VFD), except that it is used to control a PMSM instead. Like the VFD, the primary purpose of a PMSM drive is to control the rotation speed of the machine by varying the frequency of the voltages applied to the stator windings. One of the most basic types of PMSM drives is the constant V/f ratio PMSM drive (it is somewhat the equivalent for PMSMs of the constant V/f ratio VFD). Figure 35 shows the block diagram of a typical constant V/f ratio PMSM drive.
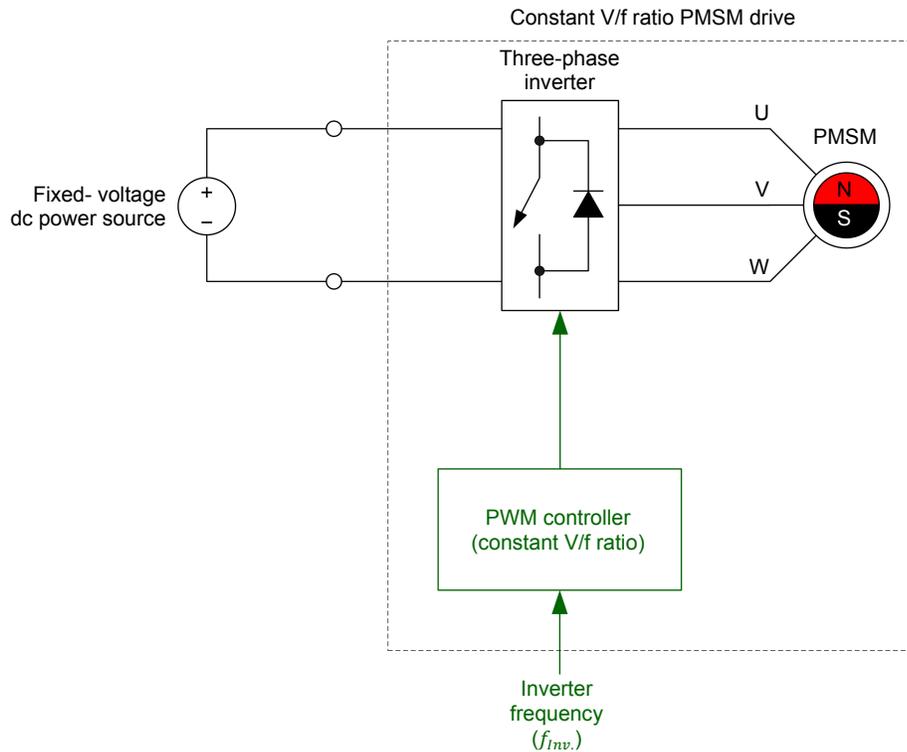
Figure 35. Block diagram of a typical constant V/f ratio PMSM drive.

As Figure 35 shows, the drive consists of a three-phase inverter, a PMSM, and a conventional PWM controller (not a six-step PWM controller as in some BLDC motors) with a constant V/f ratio characteristic. Also, notice that no shaft encoder is required on the shaft of the PMSM. The rotation speed in a constant V/f ratio PMSM drive is directly proportional to the frequency of the voltages applied to the stator windings, which is determined by the value of the inverter frequency ($f_{Inv.}$) parameter input to the PWM controller. The direction of rotation is determined by the phase sequence of the voltages produced by the three-phase inverter. The rotating magnetic flux generated at the stator of the PMSM in a constant V/f ratio PMSM drive is identical to the magnetic flux generated at the stator of a conventional synchronous machine. Also, the behavior under load of the PMSM in a constant V/f ratio PMSM drive is similar to that of a conventional synchronous machine. This means that the lag of the rotor magnetic flux in relation to the stator magnetic flux is proportional to the load torque applied to the machine shaft. The higher the load torque, the greater the lag of the rotor magnetic flux in relation to the stator magnetic flux.

In a constant V/f ratio PMSM drive, the PWM controller maintains the V/f ratio at the PMSM constant by increasing the modulation index of the PWM inverter in direct proportion to the inverter frequency, until the voltage applied to the PMSM stator windings reaches the nominal value. Therefore, when the frequency of the voltages applied to the stator windings increases, the magnitude of these voltages increases proportionally, up to the knee voltage (this voltage is usually set to the nominal voltage of the PMSM stator windings) of the constant V/f ratio characteristic implemented in the inverter controller. This is necessary to prevent either saturation of the PMSM stator or the stator magnetic flux from becoming too weak, which causes the PMSM rotor to pull out of synchronization.

The constant V/f ratio PMSM drive shares some of the drawbacks associated with the control of a PMSM using a three-phase, six-step 120° modulation inverter (as discussed in Exercise 1). The two main drawbacks of a constant V/f ratio PMSM drive are listed below.

1. The rotation speed of the PMSM in a constant V/f ratio PMSM drive can only be varied by gradually adjusting the frequency of the voltages applied to the stator windings (i.e., the inverter frequency) to avoid the rotor from pulling out of synchronization. Any significant and sudden variation in the frequency of the voltages applied to the stator windings of the PMSM drive causes the magnetic flux produced at the stator to suddenly rotate at a faster speed and the rotor to pull out of synchronization because of its inertia and that of the load (if any). In other words, the torque required to accelerate the rotor in this situation exceeds the pull-out torque of the constant V/f ratio PMSM drive. Because of this, bringing the rotation speed of the PMSM in a constant V/f ratio PMSM drive to the desired value is a rather slow process.

2. Any significant and sudden increase in the mechanical load applied to the PMSM in a constant V/f ratio PMSM drive causes the rotor to pull out of synchronization. This is due to the lack of control over the torque produced by the PMSM in a constant V/f ratio PMSM drive. Consequently, it cannot be adjusted as required when the mechanical load applied to the PMSM varies suddenly, thereby causing the rotor to pull out of synchronization.

Due to these drawbacks, the constant V/f ratio PMSM drive is rarely used in actual applications to control a PMSM.

Block diagram of a vector control PMSM drive

Figure 36 shows the block diagram of a typical vector control PMSM drive.
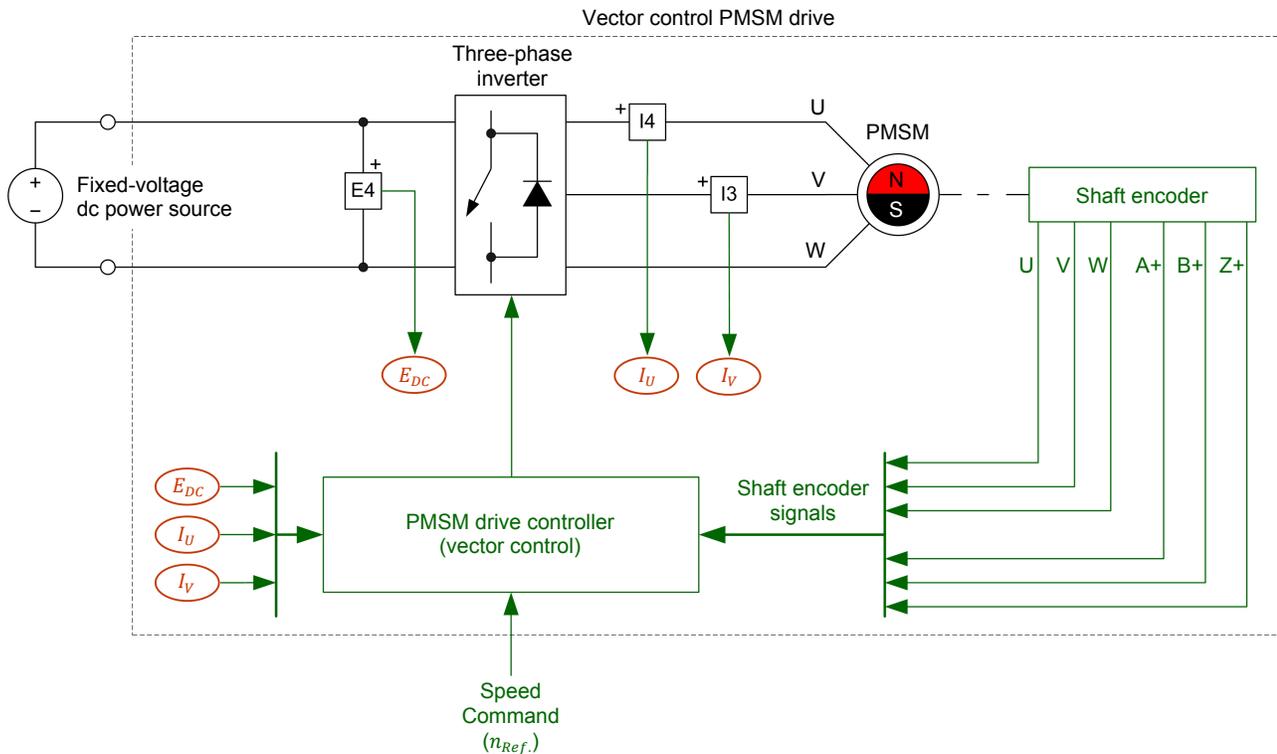
Figure 36. Block diagram of a typical vector control PMSM drive.

As Figure 36 shows, a vector control PMSM drive has a topology very similar to that of a BLDC motor (in fact, a BLDC motor can be considered a type of PMSM drive). The vector control PMSM drive includes a three-phase inverter, a PMSM, and a shaft encoder as in a BLDC motor. Furthermore, the shaft encoder signals are routed to the controller as in a BLDC motor. However, the shaft encoder in a vector control PMSM drive differs from the shaft encoder in a BLDC motor, as is discussed in the next section of this discussion. Furthermore, the controller in a vector control PMSM drive is much more complex than the controller in a BLDC motor which is either a six-step 120° modulation controller or a six-step PWM controller. By contrast, the controller in a vector control PMSM drive includes speed feedback and current feedback control loops, and uses both vector control and space vector modulation (a form of pulse-width modulation discussed in Appendix H) to optimize the drive performance as is discussed later in this discussion. In particular, the use of vector control in the current feedback control loop eliminates the drawbacks associated with the constant V/f ratio PMSM drive described in the previous section of this discussion by providing optimal control of the torque produced by the PMSM.

Vector control PMSM drives are typically used in the industry today in applications requiring high reliability, efficiency, and stability. This includes applications in the automotive industry (e.g., primary electrical motor, air conditioner compressor), as well as in more specific applications such as locomotives, steel rolling mills, elevators, and industrial servo-motors.

Shaft encoder operation

The shaft encoder in a vector control PMSM drive must provide signals allowing the rotor position to be measured with much more precision than the signals provided by the shaft encoder in a BLDC motor. This is because the vector control algorithm used in the PMSM drive controller requires much more precise rotor position feedback than the six-step 120° modulation controller or the six-step PWM controller used in a BLDC motor. The most commonly used shaft encoders in vector control PMSM drives are incremental rotary encoders and resolvers.

The shaft encoder in a vector control PMSM drive produces three signals commonly labeled A, B, and Z. Figure 37 shows an example of signals A, B, and Z produced by the shaft encoder in a vector control PMSM drive.
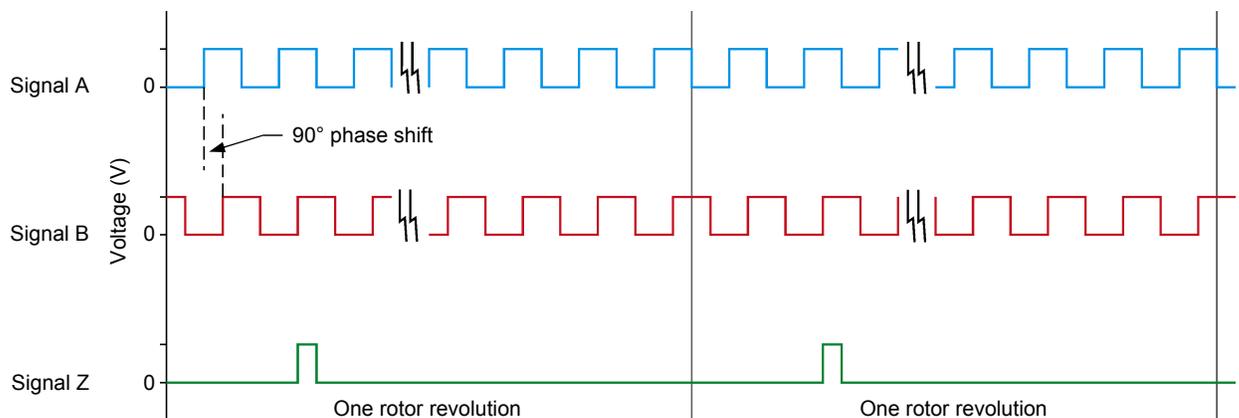
Figure 37. Typical A, B, and Z signals produced by the shaft encoder in a vector control PMSM drive.

> The number of times that the square wave in signal A or signal B repeats during a revolution is expressed in pulses per revolution or ppr.

Signals A and B are square waves that both repeat a predetermined number of times every revolution (e.g., 360 ppr, 720 ppr). The frequency of signals A and B is directly proportional to the rotation speed. The rotation speed can thus be determined by measuring the frequency of signals A and B. Also, the square wave in signal A is phase shifted by 90° from the square wave in signal B. The phase shift between signal A and B is +90° for one direction of rotation and -90° for the opposite direction of rotation. The polarity of the phase shift between signals A and B can thus be used to determine the direction of rotation.

Signal Z is an index signal that consists of one short rectangular pulse each time the PMSM rotor reaches a particular angular position. Consequently, signal Z repeats once every revolution of the PMSM rotor as is illustrated in Figure 37. When used in conjunction with signals A and B, signal Z allows the PMSM drive controller to determine the position of the PMSM rotor with great precision. The PMSM drive controller achieves this by counting the number of pulses in either signal A or signal B since the last pulse in signal Z. Knowing the number of ppr in signals A and B as well as the exact angular position of the PMSM rotor at each pulse in signal Z (this angular position is generally considered to be 0°), the PMSM drive controller can then determine the angular position of the PMSM rotor with great precision. For example, if signals A and B produce 720 ppr and have currently produced 120 pulses since the last pulse in signal Z, it results that the current position of the PMSM rotor is 60° [(120 ppr/720 ppr) x 360°]. Note

that the higher the number of pulses per revolution, the higher the resolution of the shaft encoder. This, in turn, allows the PMSM drive controller to determine the PMSM rotor position with better precision.

A major drawback of the high-resolution shaft encoder described above is that signals A, B, and Z cannot be used to determine the position of the PMSM rotor as long as the rotor has not passed by the angular position producing a pulse in signal Z at least once. This means that the angular position of the PMSM rotor cannot be determined during the first rotation of the PMSM rotor, and therefore, that vector control cannot be implemented properly at the instant the PMSM is started. To eliminate this drawback, it is common to add a low-resolution shaft encoder (such as the one used in BLDC motors) to a vector control PMSM drive in addition to the high-resolution shaft encoder in order to provide coarse rotor position feedback (via shaft encoder signals U, V, and W, as covered in Exercise 2) when the PMSM is started. The high-resolution shaft encoder then takes over from the low-resolution encoder as soon as the first pulse in signal Z is produced.

Objectives of the controller in a vector control PMSM drive

To optimize performance, the controller in a vector control PMSM drive pursues the following two primary objectives:

1. Maintain the angular relationship between the directions of the revolving magnetic flux at the stator and that at the rotor constant, so that the stator magnetic flux always leads the rotor magnetic flux by 90° (this is illustrated in Figure 39) when the PMSM operates as a motor. This ensures that the torque produced by the PMSM is optimal for any given magnitude of the currents flowing into the PMSM stator windings. This objective is achieved using a current feedback control loop implemented in the PMSM drive controller to control the PMSM stator currents. This current feedback control loop uses vector control.

2. Maintain the rotation speed of the PMSM as close as possible to the speed command despite variations in the mechanical load applied to the PMSM. This objective is achieved using a speed feedback control loop implemented in the PMSM drive controller.

Figure 38 shows the arrangement of the speed feedback control loop and current feedback control loop in the controller of a vector control PMSM drive.
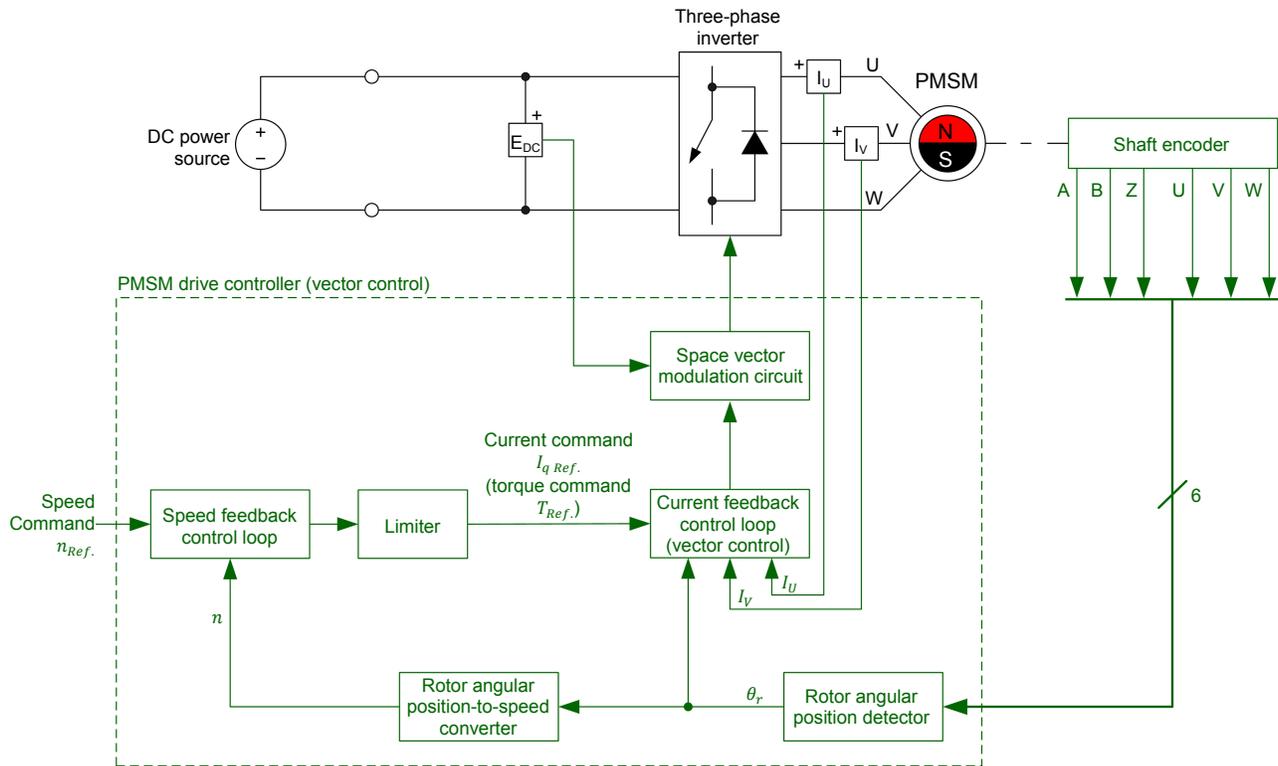
Figure 38. Block diagram of a vector control PMSM drive.

Speed control in a vector control PMSM drive

The vector control PMSM drive controller uses the signals provided by the shaft encoder to precisely determine the rotation speed n of the PMSM rotor. The speed feedback control loop compares the measured speed n to the speed command $n_{Ref.}$ to determine the error in the measured speed. The speed error, after some proportional and integral amplification, is routed to the current feedback control loop where it is used as the current command $I_{q\,Ref.}$. The polarity and magnitude of the current command $I_{q\,Ref.}$ determine the direction and magnitude, respectively, of the torque produced by the PMSM (as is explained later in the discussion). The resulting torque produced by the PMSM causes the rotation speed n of the PMSM to converge toward the speed command $n_{Ref.}$. Note that the speed error produced by the speed feedback control loop is passed through a limiter before being used as the current command of the current feedback control loop. This limits the maximum value of the current command $I_{q\,Ref.}$ and thus the maximum torque which the PMSM is allowed to produce.

The direction of rotation of the PMSM in a vector control PMSM drive depends on the polarity of the speed command of the PMSM drive controller. When the polarity of the speed command is positive, the polarity of the torque the PMSM produces is also positive, and the PMSM rotates in a given direction. Conversely, when the polarity of the speed command is negative, the polarity of the torque the PMSM produces is also negative, and the PMSM rotates in the opposite direction. No matter the direction of rotation of the PMSM, the current feedback

control loop uses vector control to ensure that the torque the PMSM produces is optimal, as is explained in the next section of the discussion.

Torque control in a vector control PMSM drive

As discussed in the previous exercise, the torque produced by any synchronous motor is optimal (i.e., the torque produced for any value of the stator currents is maximal) when the direction of the rotating magnetic flux at the stator leads the direction of the magnetic flux at the rotor by 90° (see the motor operation quadrant in Figure 20 of Exercise 2).

In a vector control PMSM drive, the current feedback control loop implemented in the controller automatically adjusts the magnitude and phase angle of the voltages produced by the three-phase inverter so that the resulting stator currents create a magnetic flux at the stator that is proportional to the magnitude of the current command $I_{q\,Ref.}$ and leads the magnetic flux at the rotor by 90° at all times when the PMSM operates as a motor, as illustrated in Figure 39. This ensures that the torque produced by the PMSM is proportional to the current command $I_{q\,Ref.}$ and is optimal (i.e., the torque produced is maximal for the current value of the currents fed into the PMSM stator windings). This also ensures that the torque produced is constant (i.e., free of any ripple). In certain applications, this is a significant advantage of vector control PMSM drives over BLDC motors, which produce some torque ripple, as explained in the discussion of Exercise 2. In brief, the higher the current command $I_{q\,Ref.}$, the higher the value of the stator currents and thus the higher the torque produced by the PMSM.
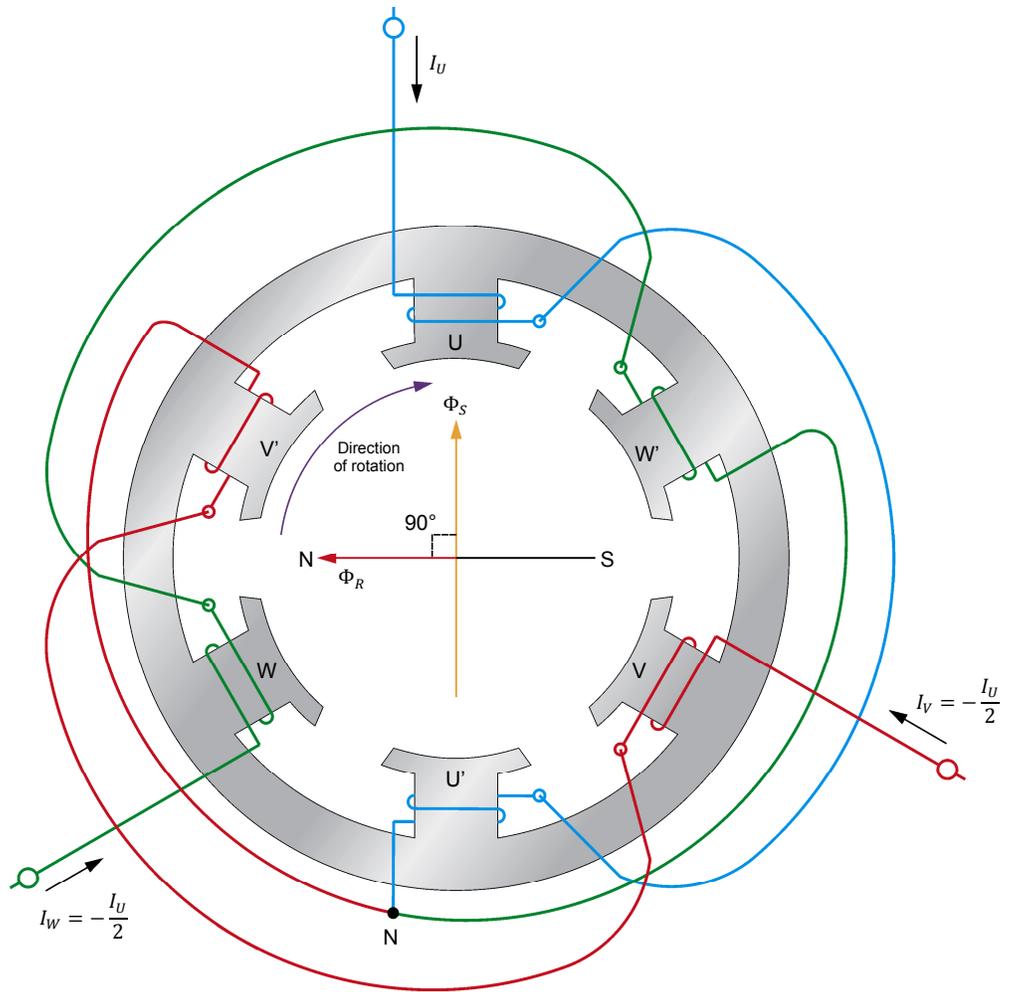
Figure 39. In a vector control PMSM drive, the stator magnetic flux leads the rotor magnetic flux by 90° at all times when the PMSM operates as a motor.

To achieve the above objective, the current feedback control loop measures two of the three stator currents flowing in the PMSM, the third stator current being determined from the two other stator currents measured. Using the stator currents and the exact angular position of the rotor magnetic flux (determined from the A, B, and Z signals of the shaft encoder by a rotor angular position detector implemented in the drive controller), the current feedback control loop performs vector transformations to find the exact magnitude and phase angle of the voltages required at the three-phase inverter output to produce the desired stator currents (i.e., stator currents that create a magnetic flux at the stator that is proportional to the magnitude of the current command $I_{q\,Ref.}$ and leads the magnetic flux at the rotor by 90°). Space vector modulation (a form of pulse-width modulation discussed in Appendix H) is used to produce the switching control signals required at the three-phase inverter.

Operation of a vector control PMSM drive in the four quadrants

As mentioned earlier in the discussion, the current feedback control loop implemented in the controller of a vector control PMSM drive automatically adjusts the magnitude and phase angle of the three-phase voltages produced by the three-phase inverter so that the resulting stator currents create a magnetic flux at the stator that is proportional to the magnitude of the current command $I_{q\,Ref.}$ and leads the magnetic flux at the rotor by 90° at all times when the PMSM operates as a motor. This ensures that the torque produced by the PMSM is proportional to the current command $I_{q\,Ref.}$ and is optimal.

When the speed command $n_{Ref.}$ is decreased to reduce the motor speed, the magnitude of the speed error changes, but more importantly, the polarity of the speed error (i.e., the polarity of the current command $I_{q\,Ref.}$) momentarily reverses. This reversal of polarity modifies the phase angle of the voltages produced by the three-phase inverter in such a way that the phase angle of the resulting stator currents is shifted 180°, thereby reversing the direction of the magnetic flux at the stator. Consequently, this causes the magnetic flux at the stator to lag the magnetic flux at the rotor by 90°, as is shown in Figure 40. This, in turn, causes the polarity of the torque produced by the PMSM to reverse (i.e., this causes the PMSM to operate as a generator and produce torque that opposes rotation), thereby producing electromagnetic braking. The braking action continues until the rotation speed becomes equal to the speed command. The energy produced by the PMSM during braking is converted into dc power by the inverter and returned to the dc power source, thereby providing the drive with regenerative braking capability. The torque produced during regenerative braking is proportional to the magnitude of the current command $I_{q\,Ref.}$ and optimal because the magnetic flux at the stator is lagging the magnetic flux at the rotor by 90°(see the generator operation quadrant in Figure 20 of Exercise 2).
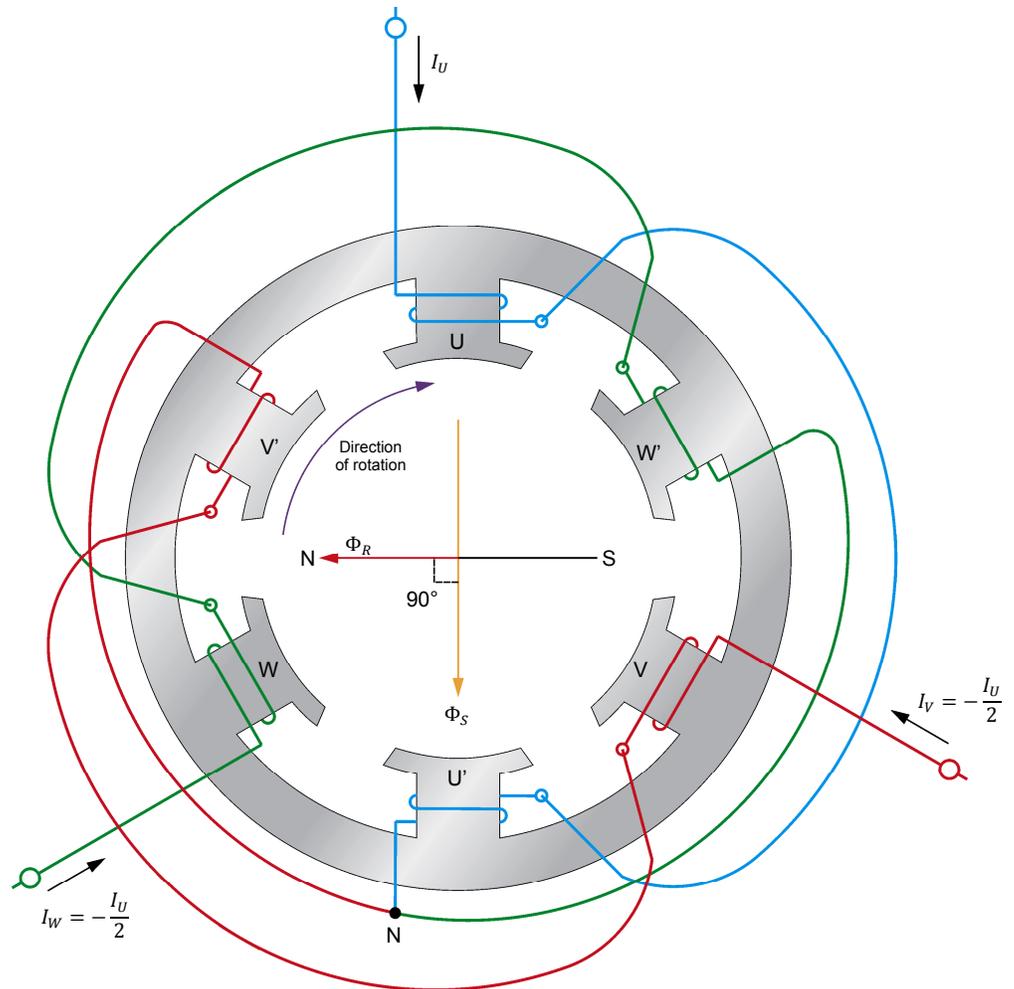
Figure 40. In a vector control PMSM drive, the stator magnetic flux lags behind the rotor magnetic flux by 90° at all times when the PMSM operates as a generator (e.g., during braking).

To summarize, when the rotation speed equals the speed command $n_{Ref.}$, the current command $I_{q\,Ref.}$ (i.e., the torque command $T_{Ref.}$) has a polarity and magnitude that makes the PMSM operate as a motor and produce torque proportional to the magnitude of $I_{q\,Ref.}$ (the torque produced is optimal because the direction of the stator magnetic flux is automatically maintained 90° ahead of the direction of the magnetic flux at the rotor). When the speed command $n_{Ref.}$ is decreased, the polarity of the current command $I_{q\,Ref.}$ reverses. This makes the PMSM operate as a generator and produce a torque proportional to the magnitude of $I_{q\,Ref.}$ (the torque produced is optimal because the direction of the stator magnetic flux is automatically maintained 90° behind of the direction of the magnetic flux at the rotor), thereby producing regenerative braking. The regenerative braking action lasts until the rotation speed once again becomes equal to the speed command $n_{Ref.}$.

As mentioned in a previous section, a vector control PMSM drive can operate in the clockwise direction as well as in the counterclockwise direction. Furthermore, a vector control PMSM drive can perform regenerative braking in either direction of rotation. Consequently, a vector control PMSM drive can operate in all four quadrants.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Equipment setup and friction compensation calibration
- Operation of a constant V/f ratio PMSM drive
- Operation of a vector control PMSM drive
- Regenerative braking in a vector control PMSM drive

PROCEDURE

Equipment setup and friction compensation calibration

In this section, you will set up a constant V/f ratio PMSM drive. You will then set up the measuring equipment to study the operation of the constant V/f ratio PMSM drive. You will also perform the calibration process on the Four-Quadrant Dynamometer/Power Supply so that its friction compensation curve takes into account the friction of the Permanent Magnet Synchronous Machine.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform this exercise.

Before beginning this exercise, measure the open-circuit voltage across each Lead-Acid Battery Pack module using a multimeter. If the open-circuit voltage of any module is lower than 51.2 V, ask your instructor for assistance as the Lead-Acid Battery Pack is probably not fully charged. Appendix E of this manual indicates how to prepare (fully charge) the Lead-Acid Battery Pack modules before each laboratory period.

Install the required equipment in the Workstation.

⚠ WARNING

Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the Permanent Magnet Synchronous Machine to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

2. Make sure the main power switch on the Four-Quadrant Dynamometer/Power Supply is set to the O (off) position, then connect its *Power Input* to an ac power outlet.

Connect the *Power Input* of the Data Acquisition and Control Interface to a 24 V ac power supply.

Connect the *Low Power Input* of the IGBT Chopper/Inverter module to the *Power Input* of the Data Acquisition and Control Interface. Turn the 24 V ac power supply on.

3. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

4. Turn the Four-Quadrant Dynamometer/Power Supply on, then set the *Operating Mode* switch to *Dynamometer*.

5. Turn the host computer on, then start the LVDAC-EMS software.

In the LVDAC-EMS Start-Up window, make sure the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure the *Computer-Based Instrumentation* and *BLDC Motor/PMSM Control* functions are available for the Data Acquisition and Control Interface module. Also, select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

6. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window. Set the *Function* parameter to *CW Constant-Speed Prime Mover/Brake* and the *Speed* parameter to 1800 r/min. Start the prime mover and let it operate for 5 minutes to 10 minutes. Then, stop the prime mover and proceed immediately to the next step.

This step ensures that the friction compensation calibration that will be done in the next step is optimal.

7. In the *Tools* menu of the Four-Quadrant Dynamometer/Power Supply window, select *Friction Compensation Calibration*. This brings up the Friction Compensation Calibration dialog box. Click *OK* in this box to start the calibration process. Observe that the prime mover starts to rotate at high speed, thereby driving the shaft of the Permanent Magnet Synchronous Machine. The prime mover speed is then automatically decreased by steps to perform the calibration process. Once the calibration process is completed (which takes a few minutes), the prime mover stops rotating, then the Friction Compensation Calibration dialog box indicates that the calibration process is finished. Click *OK* in the Friction Compensation Calibration dialog box to close this box. Restart the Four-Quadrant Dynamometer/Power Supply to apply the changes (i.e., the newly calibrated friction compensation curve) by setting the main power switch of this module to O (off), and then I (on).

8. In LVDAC-EMS, open the BLDC Motor/PMSM Control window, then make the following settings:

– Set the *Function* parameter to *PMSM Drive*. This function allows control of a PMSM drive implemented using a Data Acquisition and Control Interface and an IGBT Chopper/Inverter.

– Make sure the *Control Mode* parameter is set to *Constant V/f Ratio*. This setting makes the Data Acquisition and Control Interface operate as a constant V/f ratio PMSM drive controller.

– Make sure the *Switching Frequency* parameter is set to 20 000 Hz.

– Make sure the *Direction of Rotation* parameter is set to *Fwd*. This setting makes the PMSM drive controller send to the three-phase

PWM inverter the switching control signals required for rotation in the clockwise direction.

– Set the *Frequency* parameter to 5 Hz. This parameter determines the frequency of the ac voltages produced by the three-phase PWM inverter, and thus the frequency of the currents flowing through the PMSM stator windings.

– Make sure the *Knee Peak Voltage (% of DC Bus/2)* parameter is set to 100 %. This sets the amplitude (i.e., the peak value) of the ac voltages produced by the three-phase PWM inverter at the knee point of the voltage-frequency relationship to 100% of the dc bus voltage divided by two.

– Make sure the *Knee Frequency* parameter is set to 300 Hz. This sets the frequency at which the knee peak voltage is reached to 300 Hz.

– Make sure the *Low-Speed Boost Voltage (% of DC Bus/2)* is set to 20%. This prevents the amplitude of the ac voltages produced by the three-phase inverter from decreasing below 20% of the dc bus voltage divided by two at low speeds (i.e., when the PWM inverter operates at low frequencies). This is necessary to make sure that the ac voltages applied to the PMSM stator windings are high enough to allow the PMSM to overcome the system inertia and start rotating.

– Make sure the *Modulation Type* parameter is set to *Sinusoidal Pulse-Width Modulation*. This sets the type of modulation used by the PMSM drive controller to control the inverter. Consequently, this makes the three-phase PWM inverter produce sine-wave voltages.

– Make sure the *Acceleration Time (0 to knee)* parameter is set to 0 s. This setting determines the amount of time which the PMSM drive controller takes to increase the frequency of the three-phase PWM inverter from 0 Hz to the knee frequency.

– Make sure the *Deceleration Time (knee to 0)* parameter is set to 0 s. This setting determines the amount of time which the PMSM drive controller takes to decrease the frequency of the three-phase PWM inverter from the knee frequency to 0 Hz.

– Note that parameters *Q1* to *Q6* are set to *PWM*.

– Make sure the *Status* parameter is set to *Stopped*.

9. Connect the equipment as shown in Figure 41. Use three series-connected batteries (three Lead-Acid Battery Pack modules) to implement the fixed-voltage dc power source. Also, use the IGBT Chopper/Inverter module to implement the three-phase inverter. Use a shielded three-phase cable to interconnect the three-phase inverter and the PMSM, making sure to connect the shield of the shielded three-phase cable to ground. If necessary, refer to the *Show Connections* diagram in the BLDC Motor/PMSM Control window for an example of the constant V/f ratio PMSM drive connected using a shielded three-phase cable.
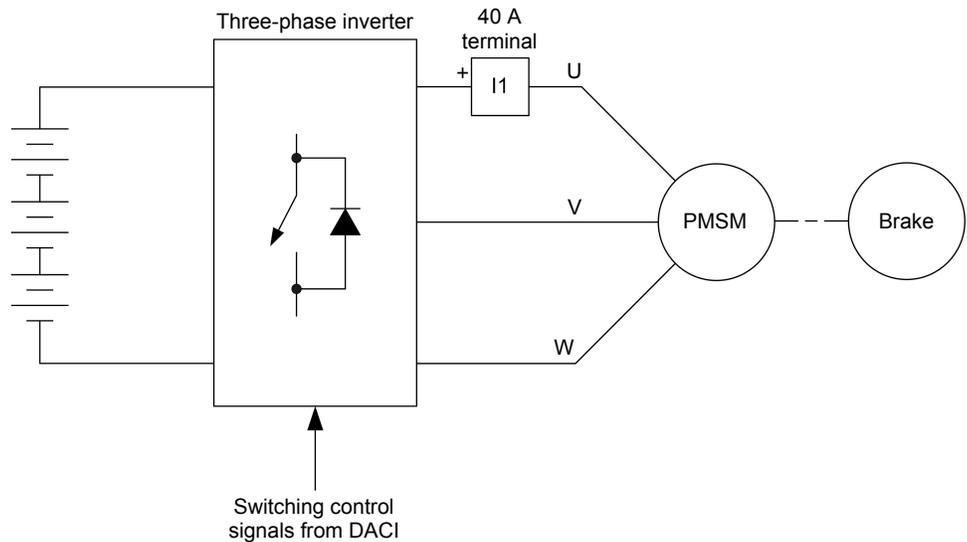
Figure 41. Constant V/f ratio PMSM drive connected to a brake.

10. Make all the low-power connections shown in Figure 42.

The connection of the *A+*, *B+*, and *Z+ Encoder Outputs* of the Permanent Magnet Synchronous Machine to the *A Encoder*, *B Encoder*, and *Sync. Digital Inputs* of the Data Acquisition and Control Interface is not required for the operation of the constant V/f ratio PMSM drive but is made only to obtain a signal indicating the angular position of the PMSM rotor (determined from the shaft encoder signals of the PMSM) as a function of time. This signal is available at *Analog Output 1* of the Data Acquisition and Control Interface (see below).

The connection of *Encoder Outputs U*, *V*, and *W* of the Permanent Magnet Synchronous Machine to *Analog Inputs 1*, *2*, and *3* of the Data Acquisition and Control Interface is not required for the operation of the constant V/f ratio PMSM drive but is made only to allow the signal from *Encoder Output U* of the Permanent Magnet Synchronous Machine to be used as a trigger signal when observing waveforms on the Oscilloscope.

Analog Output 1 provides a signal indicating the angular position of the PMSM rotor. The magnitude of this signal is related to the sine of the angular position of the PMSM rotor. When the PMSM is rotating, a sine-wave signal representing the rotor angular position is thus obtained at *Analog Output 1*. By measuring the phase shift between the sine-wave signal representing the angular position of the PMSM rotor and one of the sine-wave currents flowing in the stator windings of the PMSM, it is thus possible to determine the angular relationship between the magnetic flux at the stator and that at the rotor. On the Data Acquisition and Control Interface, the connection of *Analog Output 1* to *Analog Input 4* allows the observation of the signal indicating the angular position of the PMSM rotor.

On the Data Acquisition and Control Interface, the connection of *Analog Input 1* to *Analog Input 5* enables the observation of the U signal from the shaft encoder of the PMSM.
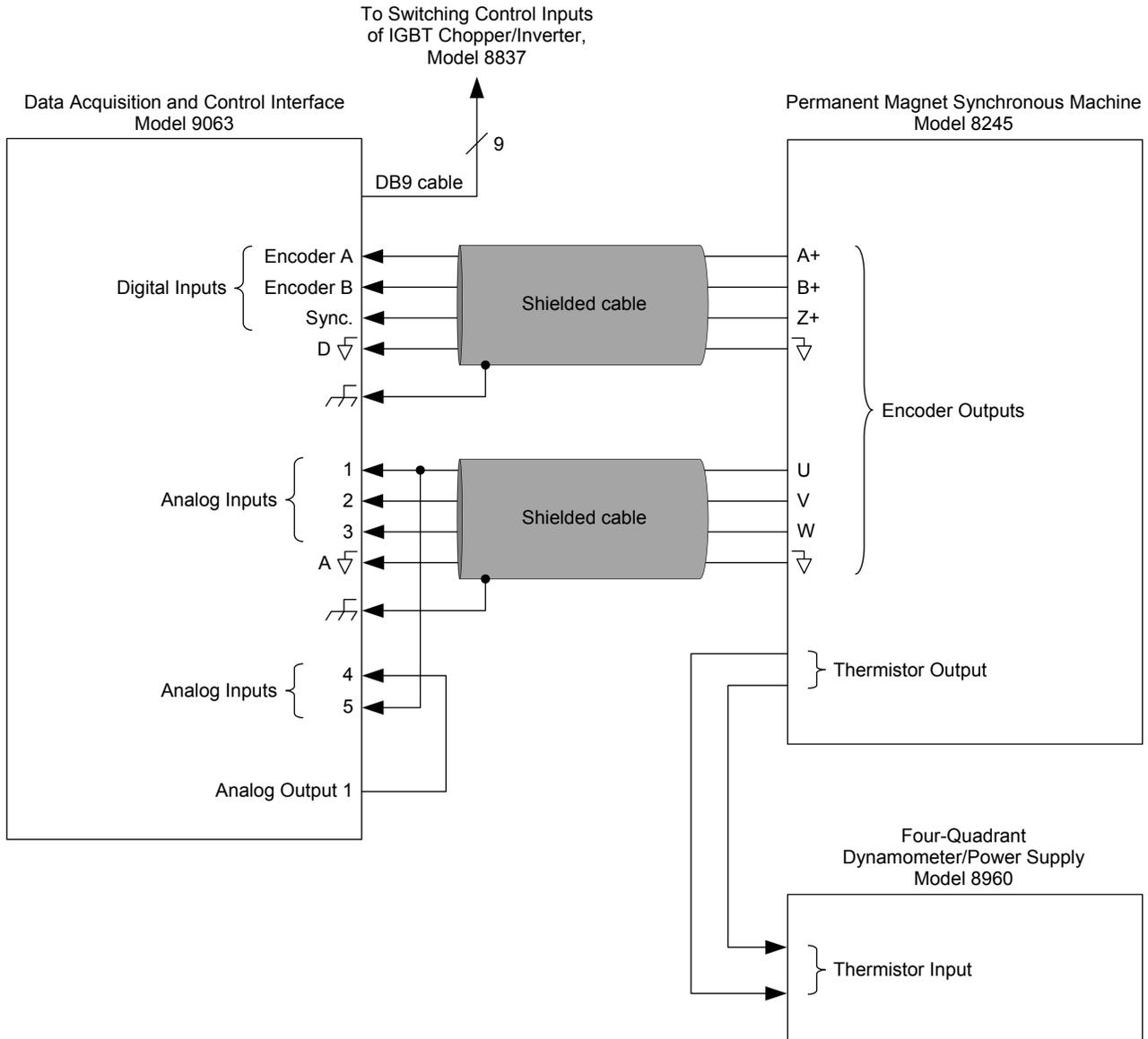
Figure 42. Low-power connections required to study the operation of the constant V/f ratio PMSM drive shown in Figure 41.

11. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:

– Set the *Function* parameter to *Negative Constant-Torque Prime Mover/Brake*.

– Make sure the *Torque Control* parameter is set to *Knob*.

– Make sure the *Torque* parameter is set to 0.00 N·m (lbf·in).

– Set the *Pulley Ratio* parameter to 24:12.

– Set the *Thermistor Type* parameter to *LV Type 3*.

– Make sure the *Status* parameter is set to *Stopped*.

12. In LVDAC-EMS, open the Metering window. Make the required settings in order to measure the rms value of the current I_U flowing in the PMSM stator windings (input *I1*).

13. In the Data Acquisition and Control Settings window of LVDAC-EMS, make sure the *A/B Encoder (PPR)* parameter is set to 2048 pulses per revolution (PPR). This setting indicates to LVDAC-EMS the number of pulses which the shaft encoder of the Permanent Magnet Synchronous Machine produces per revolution.

In the Data Acquisition and Control Settings window of LVDAC-EMS, set the *Range* setting of current input *I1* to *High*.

Operation of a constant V/f ratio PMSM drive

In this section, you will start the constant V/f ratio PMSM drive. You will confirm that varying the frequency of the voltages applied to the PMSM stator windings varies the rotation speed of the PMSM. You will observe what happens during significant and sudden changes in the frequency of the voltages applied to the PMSM stator windings. You will increase by increments the load torque applied to the PMSM, and for each load torque value, record the rms value of the current flowing in the PMSM stator windings and the angular difference between the directions of the stator magnetic flux and rotor magnetic flux. You will then analyze the results.

14. In the Four-Quadrant Dynamometer/Power Supply window, start the negative constant-torque prime mover/brake.

In the BLDC Motor/PMSM Control window, start the constant V/f ratio PMSM drive.

What happens when you start the constant V/f ratio PMSM drive?

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Record the speed n of the PMSM below.

Speed $n =$ _____ r/min

15. In the BLDC Motor/PMSM Control window, slowly increase the *Frequency* parameter of the constant V/f ratio PMSM drive to 240 Hz.

If the PMSM stops rotating and begins vibrating, stop the constant V/f ratio PMSM drive in the BLDC Motor/PMSM Control window. Then, set the inverter frequency back to 5 Hz, start the constant V/f ratio PMSM drive, and redo the present step, increasing the inverter frequency at a slower rate.

What happens to the speed n of the PMSM as you slowly increase the *Frequency* parameter of the constant V/f ratio PMSM drive (i.e., the frequency of the ac voltages produced by the three-phase inverter) to 240 Hz?

Record the speed n of the PMSM below.

Speed $n =$ _____ r/min

16. In the BLDC Motor/PMSM Control window, slowly decrease the *Frequency* parameter of the constant V/f ratio PMSM drive to 120 Hz.

Record the speed n of the PMSM below.

Speed $n =$ _____ r/min

17. In the BLDC Motor/PMSM Control window, set the *Frequency* parameter of the constant V/f ratio PMSM drive to 140 Hz. As you do so, observe what happens for a few seconds.

In the BLDC Motor/PMSM Control window, stop the constant V/f ratio PMSM drive.

In the Four-Quadrant Dynamometer/Power Supply window, stop the negative constant-torque prime mover/brake.

What happens as you suddenly increase the *Frequency* parameter of the constant V/f ratio PMSM drive (i.e., the frequency of the ac voltages produced by the three-phase inverter) from 120 Hz to 140 Hz? Explain briefly.

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18. From your observations, can you conclude that it is possible to make a constant V/f ratio PMSM drive rotate at various speeds?

❏ Yes ❏ No

From your observations, is it possible to effectively and rapidly control the rotation speed of a constant V/f ratio PMSM drive? Explain briefly.

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19. In the Four-Quadrant Dynamometer/Power Supply window, start the negative constant-torque prime mover/brake.

In the BLDC Motor/PMSM Control window, set the *Frequency* parameter to 5 Hz, then start the constant V/f ratio PMSM drive.

CAUTION

When performing the following manipulations, the rms value of the currents flowing in the stator windings can exceed the nominal current of the Permanent Magnet Synchronous Machine. Therefore, make sure to perform these manipulations in as little time as possible in order to prevent the Permanent Magnet Synchronous Machine from overheating.

20. In the BLDC Motor/PMSM Control window, slowly increase the *Frequency* parameter of the constant V/f ratio PMSM drive to 180 Hz.

21. In LVDAC-EMS, open the Oscilloscope, then make the appropriate settings in order to observe the waveforms of the current I_U flowing in the PMSM stator windings (input *I1*), the signal (a sine wave) indicating the angular position of the PMSM rotor (*Analog Input 4*), and the U signal of the PMSM shaft encoder (*Analog Input 5*).

> *The phase angle of current I_U flowing in the PMSM stator windings roughly corresponds to the direction of the stator magnetic flux in the PMSM. Consequently, the phase shift between the waveform of current I_U and the signal (also a sine wave) indicating the angular position of the PMSM rotor is very close to the angular difference between the directions of the magnetic flux at the stator and that at the rotor of the PMSM.*

Select the U signal of the PMSM shaft encoder (*Analog Input 5*) as the trigger source of the Oscilloscope and set the Trigger Level to 1 V. Also, set the *Time Base* parameter to observe approximately one cycle of each signal. Finally, click the button for displaying the vertical cursors, then set the *Channel Data* section so that the position of each vertical cursor is indicated as a phase angle.

> *When the position of each vertical cursor is indicated as a phase angle in the Channel Data section of the Oscilloscope, it becomes easy to determine the phase shift between signals. Note, however, that the phase angle values indicated in the Channel Data section are calculated assuming that the frequency of the signals displayed on the Oscilloscope is equal to the ac power network frequency. Since the frequency of the currents flowing through the PMSM stator windings and the frequency of the sine-wave signal indicating the angular position of the PMSM rotor are usually different from the ac power network frequency, it is necessary to multiply each phase angle value indicated in the Channel Data section of the Oscilloscope by a factor equal to the actual frequency of the displayed signals divided by the ac power network frequency. For instance, when the actual frequency of the displayed signals is 180 Hz and the ac power network frequency is 60 Hz, all phase angle values indicated in the Channel Data section of the Oscilloscope must be multiplied by 3.*

22. On the Oscilloscope, adjust the position of vertical cursor 1 so that it intersects the waveform of current I_U at the instant it passes through zero with a positive slope, then adjust the position of vertical cursor 2 so that it intersects the waveform of the signal indicating the angular position of the PMSM rotor at the instant it passes through zero with a positive slope. Figure 43 shows an example of what you should observe on the Oscilloscope once the position of each vertical cursor has been adjusted. The phase angle difference $\Delta\theta$ indicated in the *Channel Data* section of the Oscilloscope represents the phase shift between the sine-wave current I_U and the sine-wave signal indicating the angular position of the PMSM rotor.

Oscilloscope Settings
Channel-1 Input I1
Channel-1 Scale ....2 A/div
Channel-1 Coupling ....DC
Channel-2 Input AI-4
Channel-2 Scale ....5 V/div
Channel-2 Coupling ....DC
Channel-3 Input AI-5
Channel-3 Scale ....5 V/div
Channel-3 Coupling ....DC
Time Base............................. 1 ms/div
Trigger Type ....Software
Trigger Source Ch3
Trigger Level.......................................1
Trigger Slope ....Rising
Filtering ....On
V. Cursor PositionPhase   Angle
In LVDAC-EMS, open the Data Table
windo
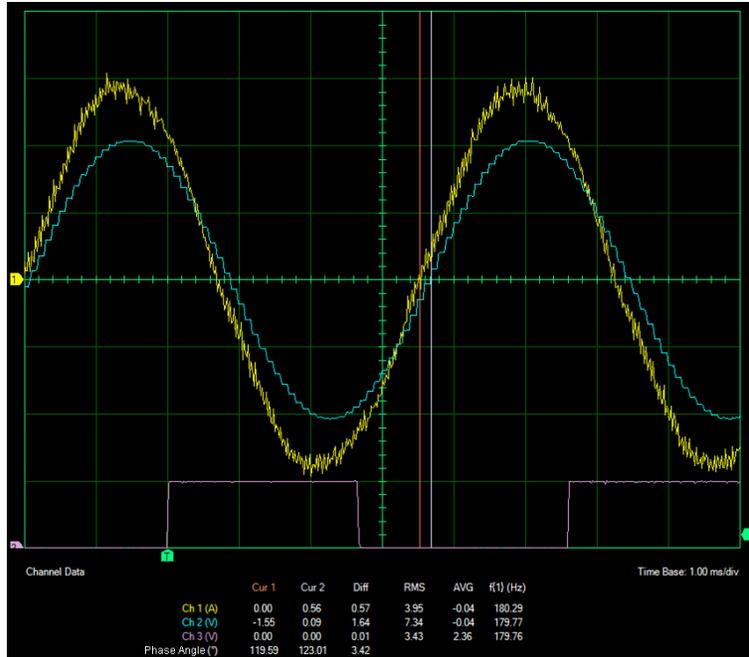
Figure 43. Phase angle difference $\Delta\theta$ between the vertical cursors of the Oscilloscope (i.e., phase angle difference between the waveform of current I_U and the waveform of the signal indicating the angular position of the PMSM rotor) when the amount of torque T produced by the PMSM is equal to 0.00 N·m (0.00 lbf·in).

23. In LVDAC-EMS, open the Data Table window.

Set the Data Table to record the PMSM torque T (indicated in the Four-Quadrant Dynamometer/Power Supply window), the current I_U flowing in the PMSM stator windings (indicated in the Metering window), and the phase angle *difference* $\Delta\theta$ (i.e., the phase shift) between the vertical cursors of the Oscilloscope. Click the *Record Data* button to record the current values of the PMSM torque T, current I_U flowing in the PMSM stator windings, and phase angle difference $\Delta\theta$ between the vertical cursors of the Oscilloscope.

24. In the Four-Quadrant Dynamometer/Power Supply window, vary the *Torque* parameter from 0.00 N·m (0.00 lbf·in) to -0.55 N·m (-4.87 lbf·in) by steps of 0.05 N·m (about 0.44 lbf·in).

For each torque value, readjust the position of vertical cursor 1 so that it intersects the waveform of current I_U at the instant it passes through zero with a positive slope, then readjust the position of vertical cursor 2 so that it intersects the waveform of the signal indicating the angular position of the PMSM rotor at the instant it passes through zero with a positive slope. Then, in the Data Table window, click the *Record Data* button to record the PMSM torque T, the current I_U flowing in the PMSM stator windings, and the phase angle difference $\Delta\theta$ between the vertical cursors of the Oscilloscope.

25. In the BLDC Motor/PMSM Control window, stop the constant V/f ratio PMSM drive.

In the Four-Quadrant Dynamometer/Power Supply window, stop the negative constant-torque prime mover/brake.

26. In the Data Table window, save the recorded data, then export it to a spreadsheet. Identify the data file by indicating the type of PMSM drive used (constant V/f ratio PMSM drive).

In the spreadsheet application, multiply each phase angle difference $\Delta\Phi$ between the vertical cursors of the Oscilloscope by 180 Hz, then divide the result by the ac power network frequency. The result is the angular difference $\Delta\theta_{S-R}$ between the direction of the stator magnetic flux and the direction of the rotor magnetic flux.

In the space below, record the angular difference $\Delta\theta_{S-R}$ between the direction of the stator magnetic flux and the direction of the rotor magnetic flux when the amount of torque T produced by the PMSM is equal to 0.00 N·m (0.00 lbf·in). Since the rotor magnetic flux should be aligned with the stator magnetic flux (i.e., the angular difference $\Delta\theta_{S-R}$ should be equal to 0°) when the PMSM torque T is equal to 0.00 N·m (0.00 lbf·in), the angular difference $\Delta\theta_{S-R}$ below represents the error in the measured values of the angular difference $\Delta\theta_{S-R}$. This error has to be subtracted from each measured value of the angular difference $\Delta\theta_{S-R}$ to obtain the corrected (actual) angular difference $\Delta\theta_{S-R,\ corrected}$ between the direction of the stator magnetic flux and the direction of the rotor magnetic flux (this calculation is performed in the next step).

Error in the measured angular difference $\Delta\theta_{S-R} = $ _____ °

27. In the spreadsheet application, add two new parameters to the results: the corrected angular difference $\Delta\theta_{S-R,\ corrected}$ and the torque-per-ampere ratio T/I (in N·m/A or in lbf·in/A).

- To calculate the corrected angular difference $\Delta\theta_{S-R,\ corrected}$, subtract the angular error recorded in the previous step from each angular difference $\Delta\theta_{S-R}$. The resulting values correspond to the corrected (actual) angular difference $\Delta\theta_{S-R,\ corrected}$ between the direction of the stator magnetic flux and the direction of the rotor magnetic flux for the various amounts of torque T produced by the PMSM.

- To calculate the torque-per-ampere ratio T/I, divide each amount of torque T produced by the PMSM by the corresponding rms value of the current I_U flowing in the PMSM stator windings. This results in the torque-per-ampere ratio T/I for each amount of torque T produced by the PMSM. The higher the torque-per-ampere ratio T/I, the more effective the constant V/f ratio PMSM drive is at converting the currents fed into the PMSM stator windings in a torque at the PMSM shaft.

28. What happens to the corrected angular difference $\Delta\theta_{S-R,\ corrected}$ measured in the constant V/f ratio PMSM drive as the amount of torque T produced by the PMSM increases? Explain briefly.

What happens to the torque-per-ampere ratio T/I in the constant V/f ratio PMSM drive as the amount of torque T produced by the PMSM increases? Briefly explain what this means.

Operation of a vector control PMSM drive

In this section, you will set up a vector control PMSM drive. You will start the vector control PMSM drive and confirm that it is possible to control the rotation speed of the PMSM. You will observe what happens during significant and sudden changes in the speed command applied to the PMSM drive. You will increase by increments the load torque applied to the PMSM, and for each load torque value, record the rms value of the current flowing in the PMSM stator windings, the angular difference between the directions of the stator magnetic flux and rotor magnetic flux, and the current command produced in the PMSM drive controller. You will then analyze the results.

29. In the BLDC Motor/PMSM Control window, make the following settings:

– Make sure the *Function* parameter is set to *PMSM Drive*.

– Set the *Control Mode* parameter to *Vector Control*. This setting makes the Data Acquisition and Control Interface operate as a vector control PMSM drive controller.

– Make sure the *Switching Frequency* parameter is set to 20 000 Hz.

– Make sure the *Direction of Rotation* parameter is set to *Fwd*.

– Make sure the *Status* parameter is set to *Stopped*.

Speed Control

– Make sure the *Command Input* parameter is set to *Knob*. This allows the speed command of the vector control PMSM drive to be set manually using a control knob.

– Set the *Speed Command* parameter to 0 r/min. This setting determines the rotation speed which the PMSM drive controller tries to maintain.

– Make sure that the *Acceleration Time (0 to 6000 r/min)* parameter is set to 0 s. This setting determines the amount of time which the PMSM drive controller takes to increase the speed command from 0 r/min to 6000 r/min.

– Make sure that the *Deceleration Time (6000 to 0 r/min)* parameter is set to 0 s. This setting determines the amount of time which the PMSM drive controller takes to decrease the speed command from 6000 r/min to 0 r/min.

– Make sure the *Controller Prop. Gain (Kp3)* parameter is set to 25.

– Make sure the *Controller Int. Gain (Ki3)* parameter is set to 2.

Vector Control

– Make sure the *Direct Current (*I_d*) Command* parameter is set to 0 A. This setting determines the rms value at which the PMSM drive controller tries to maintain the direct component I_d of the ac currents fed into the PMSM stator windings.

– Make sure the *Quadrature Current Limit (*$I_{q\,Limit}$*) parameter* is set to 3.5 A. This setting determines the rms value at which the PMSM drive controller limits the quadrature component I_q of the ac currents fed into the PMSM stator windings.

– Make sure the *Rotor Magnetic Flux Control Prop. Gain (Kp1)* parameter is set to 0.1.

– Make sure the *Rotor Magnetic Flux Control Int. Gain (Ki1)* parameter is set to 0.05.

– Make sure the *Torque Control Prop. Gain (Kp2)* parameter is set to 0.2.

–   Make sure the *Torque Control Int. Gain (Ki2)* parameter is set to 0.05.

PWM Inverter

–   Make sure that parameters *Q1* to *Q6* are set to *PWM*.

30. Connect the equipment as shown in Figure 44. Note that voltage inputs *E2* and *E4* as well as current inputs *I2*, *I3*, and *I4* are added to the circuit. All other connections (including the low-power connections) remain the same. Use shielded three-phase cables to interconnect the three-phase inverter, current inputs *I1*, *I3*, and *I4*, and the PMSM, making sure to connect the shield of each shielded three-phase cable to ground. If necessary, refer to the *Show Connections* diagram in the BLDC Motor/PMSM Control window for an example of the vector control PMSM drive connected using shielded three-phase cables.

> In the circuit of Figure 44, inputs E4, I3, and I4 are used to measure the circuit parameters necessary for vector control of the PMSM. Because of this, inputs E4, I3, and I4 cannot be used for circuit parameter measurement and observation in this exercise.
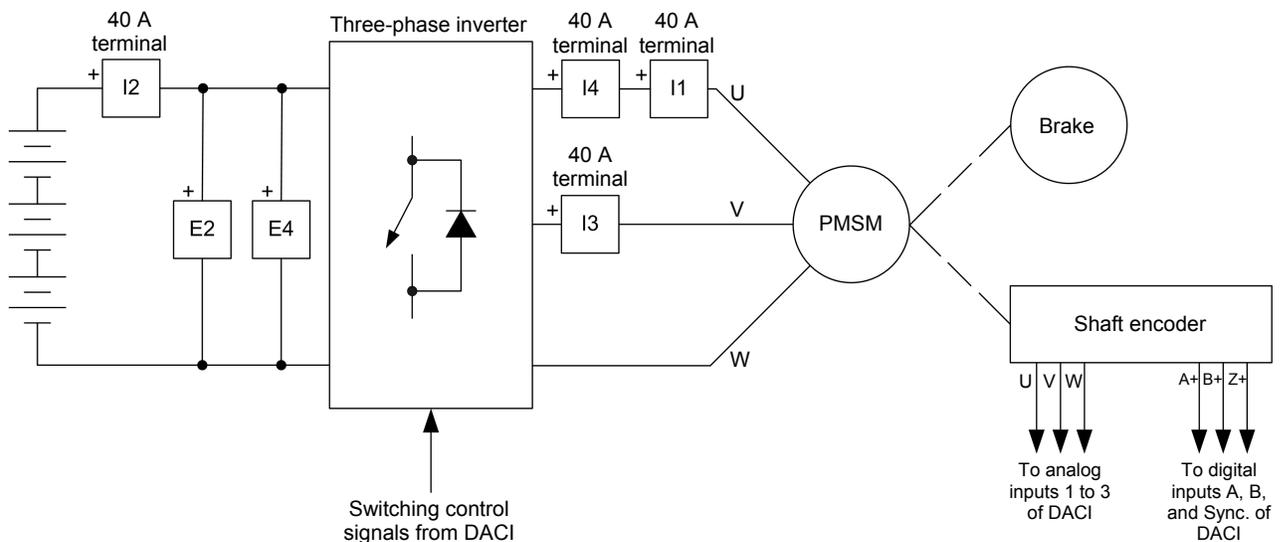
Figure 44. Vector control PMSM drive connected to a brake.

31. In the Data Acquisition and Control Settings window of LVDAC-EMS, set the *Range* setting of current inputs *I2*, *I3*, and *I4* to *High*.

32. In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to 0.00 N·m (lbf·in), then start the negative constant-torque prime mover/brake.

In the BLDC Motor/PMSM Control window, start the vector control PMSM drive.

33. In the BLDC Motor/PMSM Control window, progressively increase the *Speed Command* parameter of the vector control PMSM drive to 4800 r/min.

Does the rotation speed of the PMSM increase as you increase the speed command of the vector control PMSM drive?

❑ Yes   ❑ No

34. In the BLDC Motor/PMSM Control window, progressively decrease the *Speed Command* parameter of the vector control PMSM drive to 2400 r/min.

Does the rotation speed of the PMSM decrease as you decrease the speed command of the vector control PMSM drive?

❑ Yes   ❑ No

From your observations, is the vector control PMSM drive controller able to adjust the rotation speed of the PMSM at the exact value of the speed command?

❑ Yes   ❑ No

35. In the BLDC Motor/PMSM Control window, set the *Speed Command* parameter of the vector control PMSM drive to 4800 r/min while observing what happens. This corresponds to an increase in the inverter frequency of 120 Hz to 240 Hz.

What happens as you suddenly increase the *Speed Command* parameter of the vector control PMSM drive from 2400 r/min to 4800 r/min? Compare this to what happened in the constant V/f ratio PMSM drive when you suddenly increased the frequency of the voltages applied to the PMSM stator windings from 120 Hz to 140 Hz (refer to step 17 of this exercise).

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36. In the Four-Quadrant Dynamometer/Power Supply window, momentarily set the *Torque* parameter to -0.20 N·m (-1.77 lbf·in) and observe what happens to the rotation speed of the PMSM.

From your observations, is the vector control PMSM drive controller able to maintain the rotation speed of the PMSM at the exact value of the speed command when the load torque varies?

❑ Yes   ❑ No

37. In the Data Table window, clear all recorded data. Then, add the current command $I_{q\,Ref.}$ produced in the PMSM drive controller (indicated in the BLDC Motor/PMSM Control window) to the list of parameters to be recorded.

38. In the BLDC Motor/PMSM Control window, set the *Speed Command* parameter of the vector control PMSM drive to 3600 r/min.

39. In the Four-Quadrant Dynamometer/Power Supply window, vary the *Torque* parameter from -0.05 N·m (-0.44 lbf·in) to -0.55 N·m (-4.87 lbf·in) by steps of 0.05 N·m (about 0.44 lbf·in).

For each torque value, readjust the position of vertical cursor 1 so that it intersects the waveform of current I_U at the instant it passes through zero with a positive slope, then readjust the position of vertical cursor 2 so that it intersects the waveform of the signal indicating the angular position of the PMSM rotor at the instant it passes through zero with a positive slope. Then, in the Data Table window, click the *Record Data* button to record the PMSM torque T, the current I_U flowing in the PMSM stator windings, the phase angle difference $\Delta\theta$ between the vertical cursors of the Oscilloscope, and the current command $I_{q\,Ref.}$ produced in the PMSM drive controller.

40. In the BLDC Motor/PMSM Control window, stop the vector control PMSM drive.

In the Four-Quadrant Dynamometer/Power Supply window, stop the negative constant-torque prime mover/brake.

41. In the Data Table window, save the recorded data, then export it to a new spreadsheet. Identify the data file by indicating the type of PMSM drive used (vector control PMSM drive).

In the spreadsheet application, multiply each phase angle difference $\Delta\theta$ between the vertical cursors of the Oscilloscope by 180 Hz, then divide the result by the ac power network frequency. The result is the angular difference $\Delta\theta_{S-R}$ between the direction of the stator magnetic flux and the direction of the rotor magnetic flux.

42. In the spreadsheet application, add two new parameters to the results: the corrected angular difference $\Delta\theta_{S-R,\ corrected}$ and the torque-per-ampere ratio T/I (in N·m/A or in lbf·in/A).

- To calculate the corrected angular difference $\Delta\theta_{S-R,\ corrected}$, subtract the angular error recorded in step 26 from each angular difference $\Delta\theta_{S-R}$. The resulting values correspond to the corrected (actual) angular difference $\Delta\theta_{S-R,\ corrected}$ between the direction of the stator magnetic flux and the direction of the rotor magnetic flux for the various amounts of torque T produced by the PMSM.

- To calculate the torque-per-ampere ratio T/I, divide each amount of torque T produced by the PMSM by the corresponding rms value of the current I_U flowing in the PMSM stator windings. This results in the torque-per-ampere ratio T/I for each amount of torque T produced by the PMSM. The higher the torque-per-ampere ratio T/I, the more effective the vector control PMSM drive is at converting the currents fed into the PMSM stator windings in a torque at the PMSM shaft.

43. Using the data you just recorded, determine what happens to the corrected angular difference $\Delta\theta_{S-R,\ corrected}$ measured in the vector control PMSM drive as the amount of torque T produced by the PMSM increases?

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44. Using the data you recorded in this exercise procedure, plot a curve of the torque-per-ampere ratio T/I in the constant V/f ratio PMSM drive as a function of the amount of torque T produced by the PMSM. Then, plot on the same graph a curve of the torque-per-ampere ratio T/I in the vector control PMSM drive as a function of the amount of torque T produced by the PMSM.

What happens to the torque-per-ampere ratio T/I in the vector control PMSM drive as the amount of torque T produced by the PMSM increases. Why? Briefly explain what this means.

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Using the graph you just plotted, as well as the data you recorded previously, compare the torque-per-ampere ratio T/I obtained in the vector control PMSM drive to that obtained in the constant V/f ratio PMSM drive. Briefly explain why they differ so much.

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45. Using the data you recorded in this exercise procedure, plot a curve of the current I_U fed into the stator windings of the PMSM in the constant V/f ratio PMSM drive as a function of the amount of torque T produced by the PMSM. Then, plot on the same graph a curve of the current I_U fed into the stator windings of the PMSM in the vector control PMSM drive as a function of the amount of torque T produced by the PMSM.

Observe the graph you just plotted. Compare the rms value of the current I_U fed into the stator windings of the PMSM in the constant V/f ratio PMSM drive to the rms value of the current I_U fed into the stator windings of the PMSM in the vector control PMSM drive for any given amount of torque T produced by the PMSM. Briefly explain why they differ so much.

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46. Observe the data you recorded for the vector control PMSM drive. Is the rms value of the current I_U fed into the stator windings of the PMSM equal to the current command $I_{q\,Ref.}$ no matter the amount of torque produced by the PMSM? Why?

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Using the graph you plotted in the previous step, determine the relationship between the amount of torque T produced by the PMSM and the rms value of the current I_U fed into the stator windings of the PMSM in the vector control PMSM drive. Explain briefly.

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Regenerative braking in a vector control PMSM drive

In this section, you will set the Four-Quadrant Dynamometer/Power Supply to operate as a mechanical load. You will make the vector control PMSM drive rotate at a speed of 4800 r/min. You will measure the PMSM speed, torque, and mechanical power, the current command, as well as the dc bus current and power. You will then brake the PMSM by suddenly decreasing the speed command and, as you do so, observe what happens to the angular difference between directions of the stator magnetic flux and rotor magnetic flux in the PMSM, the torque produced by the PMSM, the current command, and the dc bus current and power. You will then analyze the results.

47. In the Four-Quadrant Dynamometer/Power Supply window, make the following settings:

- Set the *Function* parameter to *Mechanical Load*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a mechanical load.

- Make sure the *Load Type* parameter is set to *Flywheel*. This setting determines the type of load which the Four-Quadrant Dynamometer/Power Supply emulates.

- Set the *Inertia* parameter to 0.025 kg·m^2 (0.59 lb/ft^2). This setting determines the magnitude of the inertia of the load applied to the PMSM shaft.

–   Make sure the *Friction Torque* parameter is set to 0.20 N·m (1.78 lbf·in). This setting determines the friction torque of the load applied to the PMSM shaft.

–   Set the *Pulley Ratio* parameter to 24:12.

–   Set the *Thermistor Type* parameter to *LV Type 3*.

–   Make sure the *Status* parameter is set to *Stopped*.

48. In the Metering window, make the required settings in order to measure the dc bus current I_{DC} (input *I2*) and power P_{DC} [metering function *PQS2 (E2, I2)*].

49. In the Four-Quadrant Dynamometer/Power Supply window, start the mechanical load.

In the BLDC Motor/PMSM Control window, start the vector control PMSM drive.

50. In the BLDC Motor/PMSM Control window, set the *Speed Command* parameter of the vector control PMSM drive to 4800 r/min.

51. In the Four-Quadrant Dynamometer/Power Supply window, measure the PMSM speed n, torque T, and mechanical power P_M. In the BLDC Motor/PMSM Control window, measure the current command $I_{q\,Ref.}$. In the Metering window, measure the dc bus current I_{DC} and power P_{DC}. Record all values below.

Speed $n =$ _____ r/min

Torque $T =$ _____ N·m (lbf·in)

Mechanical power $P_M =$ _____ W

Current command $I_{q\,Ref.} =$ _____ A

Current $I_{DC} =$ _____ A

Power $P_{DC} =$ _____ W

What can you conclude from the respective polarity of the speed n, torque T, mechanical power P_M, and current command $I_{q\,Ref.}$ you just recorded? Explain briefly.

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What can you conclude from the values of the dc power source current I_{DC} and power P_{DC} you just recorded? Explain briefly.

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52. In the BLDC Motor/PMSM Control window, reduce the *Speed Command* parameter of the vector control PMSM drive from 4800 r/min to 2400 r/min. As you do so, observe on the Oscilloscope what happens to the angular difference between the directions of the stator magnetic flux and rotor magnetic flux in the PMSM. At the same time, observe what happens to the polarity of the current command $I_{q\ Ref.}$ in the vector control PMSM drive and to the polarity of the torque T produced by the PMSM.

> *Repeat this step as often as required in order to make all required observations.*

Describe what happens in the vector PMSM drive as the speed command is suddenly decreased from 4800 r/min to 2400 r/min? Explain briefly.

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53. In the BLDC Motor/PMSM Control window, set the *Speed Command* parameter of the vector control PMSM drive to 4800 r/min. Then, reduce the *Speed Command* parameter of the vector control PMSM drive to 2400 r/min. As you do so, observe on the Oscilloscope what happens to the angular difference between the directions of the stator magnetic flux and rotor magnetic flux in the PMSM. At the same time, observe what happens to the dc power source current I_{DC} and power P_{DC}.

> *Repeat this step as often as required in order to make all required observations.*

What happens to the polarity of the dc power source current I_{DC} and to that of the power P_{DC} as the speed command of the vector control PMSM drive is suddenly decreased from 4800 r/min to 2400 r/min? Explain briefly.

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54. Do your results confirm that regenerative braking occurs when the speed command of a vector control PMSM drive is suddenly decreased?

❑ Yes   ❑ No

55. In the BLDC Motor/PMSM Control window, stop the vector control PMSM drive by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

In the Four-Quadrant Dynamometer/Power Supply window, stop the mechanical load by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

56. In the *Tools* menu of the Four-Quadrant Dynamometer/Power Supply window, select *Reset to Default Friction Compensation*. This will bring up the Reset Friction Compensation dialog box. Click *Yes* in this window to reset the friction compensation to the factory default compensation.

57. Close LVDAC-EMS, then turn off all the equipment. Disconnect all leads and return them to their storage location.

CONCLUSION

In this exercise, you learned what a constant V/f ratio PMSM drive is and familiarized yourself with its operation. You also learned what a vector control PMSM drive is and familiarized yourself with its operation. You also became familiar with the operation of the shaft encoder in a vector control PMSM drive. You learned how regenerative braking is implemented in a vector control PMSM drive. You were introduced to the current and speed feedback control loops in the controller of a vector control PMSM drive.

REVIEW QUESTIONS

1. Briefly describe the main components and operating characteristics of a constant V/f ratio PMSM drive.

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2. What are the two main drawbacks of the constant V/f ratio PMSM drive? Explain each one briefly.

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3. What are the two primary objectives pursued by the controller of a vector control PMSM drive? Explain each one briefly.

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4. How does the controller of a vector control PMSM drive achieve speed control of the PMSM? Explain briefly.

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5. How does the controller of a vector control PMSM drive achieve torque control of the PMSM? Explain briefly.

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Bibliography

Krishnan, R., *Permanent Magnet Synchronous and Brushless DC Motor Drives*, Boca Raton: CRC Press, 2009, ISBN 978-0824753849.

Husain, Iqbal, *Electric and Hybrid Vehicles Design Fundamentals*, 2nd ed., Boca Raton: CRC Press, 2010, ISBN 978-1439811757.

Wildi, Theodore, *Electrical Machines, Drives, and Power Systems*, 6th ed., Upper Saddle River: Prentice Hall, 2005, ISBN 978-0131776913.