Electricity and New Energy

Three-Phase Motor Drives

Courseware Sample

86368-F0

Order no.: 86368-10
Second Edition
Revision level: 07/2016

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Printed in Canada

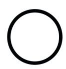
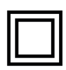
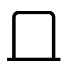
ISBN 978-2-89640-620-3 (Printed version)
ISBN 978-2-89640-621-0 (CD-ROM)
Legal Deposit – Bibliothèque et Archives nationales du Québec, 2013
Legal Deposit – Library and Archives Canada, 2013

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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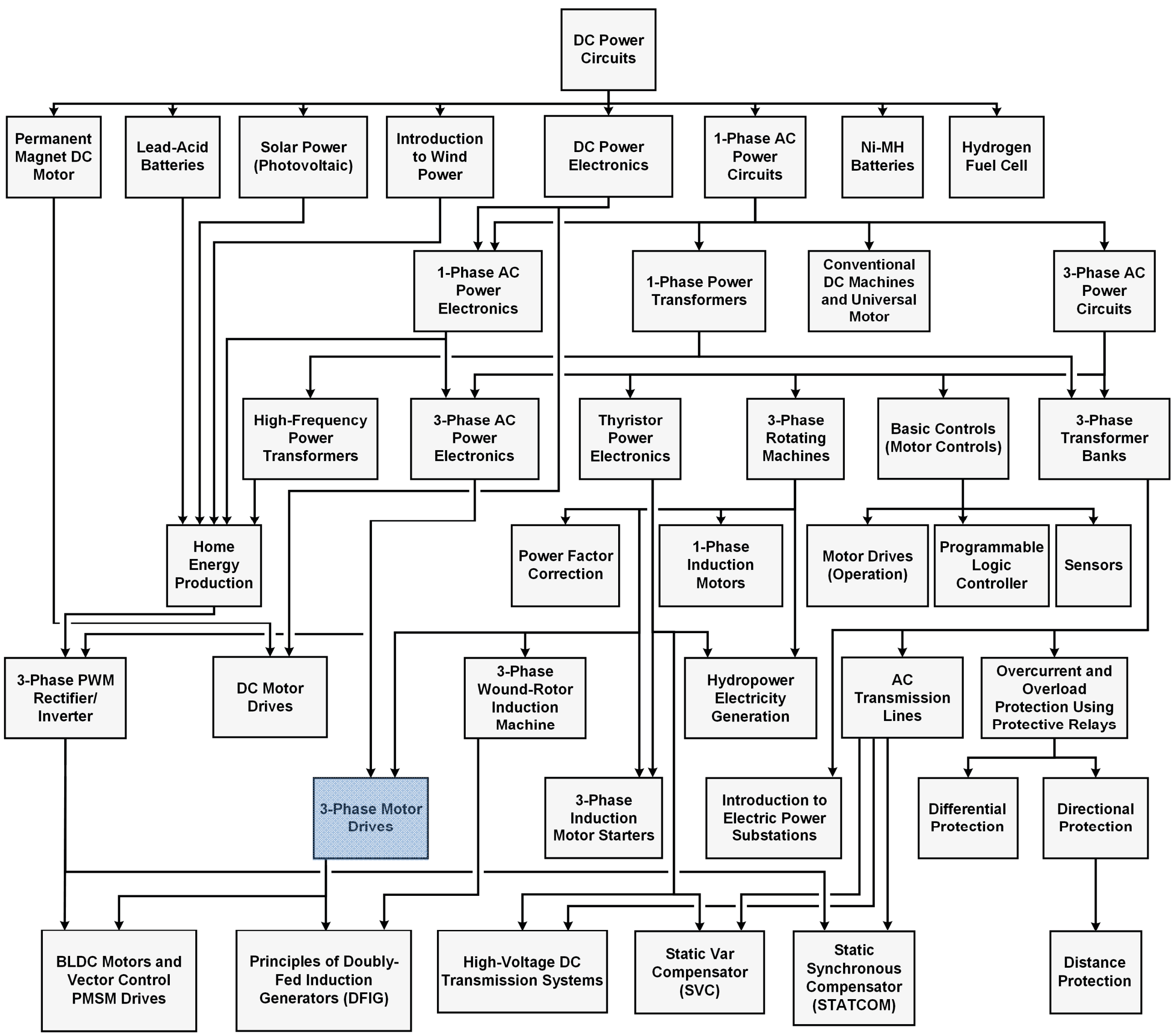
Preface

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.

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

This manual, *Three-Phase Motor Drives*, introduces the student to the operation of three-phase, variable-frequency induction-motor drives. Modern implementation of these drive systems allows better motor control which translates into improved power efficiency and significantly reduced power consumption.

The equipment for the course mainly consists of the IBGT Chopper/Inverter module, the Four-Quadrant Dynamometer/Power Supply, and the Four-Pole Squirrel Cage Induction Motor. The Four-Quadrant Dynamometer/Power Supply is a multifunctional module that is used for speed and torque measurements, and monitoring. The operation of the Four-Quadrant Dynamometer/Power Supply is controlled by the LVDAC-EMS software, which also provides the instrumentation (in conjunction with the Data Acquisition and Control Interface) required to measure and record the experimental data. The operation of the IBGT Chopper/Inverter module is controlled by the LVDAC-EMS software. The Rectifier and Filtering Capacitors module, the Three-Phase Filters, and the Power Supply module are also used to perform the exercises in 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*, part number 86350, *DC Power Electronics*, part number 86356, *Single-Phase AC Power Circuits*, part number 86358, *Single-Phase AC Power Electronics*, part number 86359, *Three-Phase AC Power Circuits*, part number 86360, *Three-Phase AC Power Electronics*, part number 86362, and *Three-Phase Rotating Machines*, part number 86364.

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

Three-Phase, Variable-Frequency Induction-Motor Drive

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with three-phase, variable-frequency induction-motor drives.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- The three-phase, variable-frequency induction-motor drive
- Torque developed in an induction motor versus the saturation of the motor stator
- The effect of frequency on saturation in an induction motor
- Measurement of the rms value of the fundamental-frequency component in the voltage at the output of a three-phase PWM inverter
- Overmodulation

DISCUSSION

The three-phase, variable-frequency induction-motor drive

The figure below shows the simplified diagram of a three-phase, **variable-frequency induction-motor drive**. In this drive, a power diode, three-phase full-wave rectifier converts three-phase ac voltage from a fixed-frequency power source into dc voltage that is applied to the dc side of a three-phase inverter. The three-phase ac voltage produced by the inverter is applied to the induction motor windings. The three-phase inverter control unit in this induction-motor drive uses PWM modulation; but other types of modulation could be used. Such a drive is commonly referred to as a three-phase, voltage-source inverter induction-motor drive because a voltage source powers the inverter.

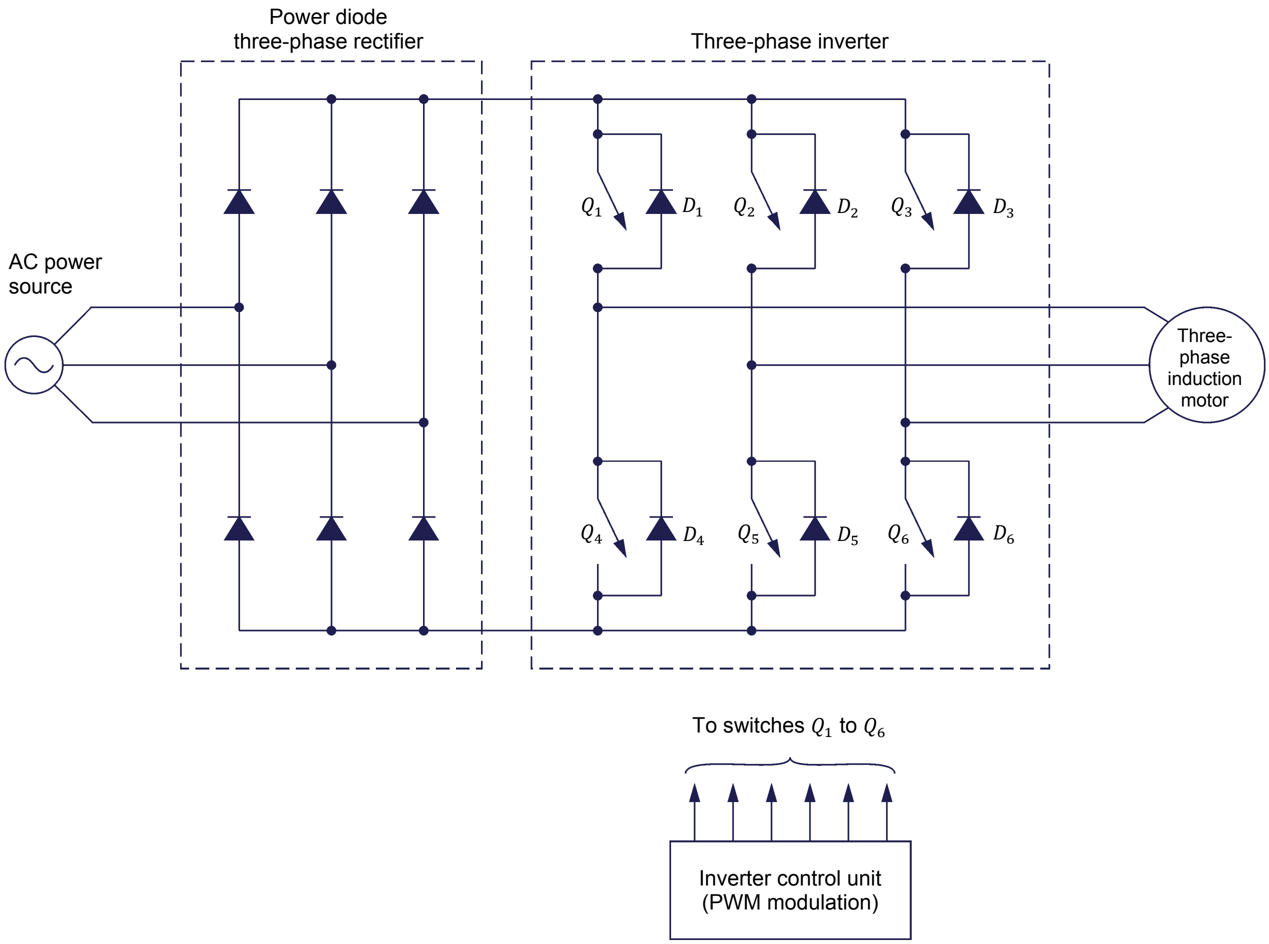


Figure 3. Simplified diagram of a three-phase induction-motor drive.

Figure 4 shows the same induction-motor drive using symbols that represent a power diode three-phase rectifier and a three-phase inverter.

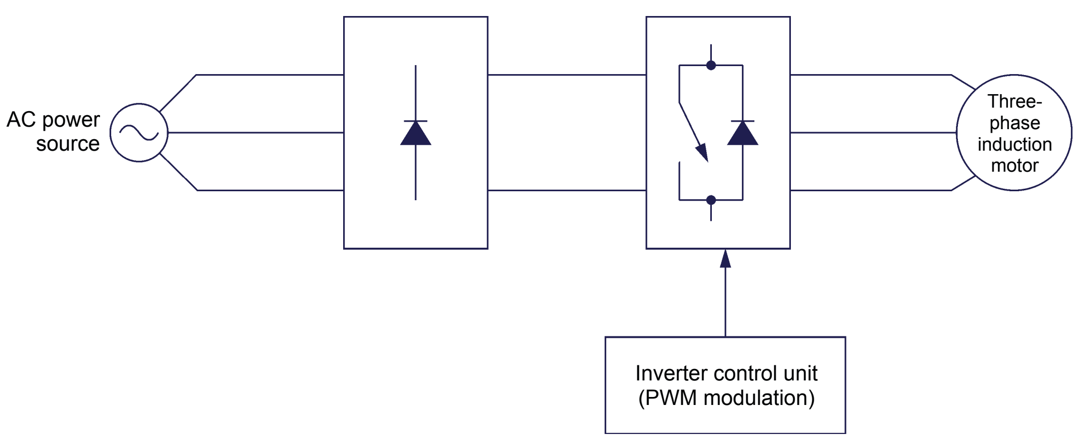


Figure 4. Simplified diagram of a three-phase induction-motor drive using symbols that represent a power diode three-phase rectifier and a three-phase inverter.

Since the frequency of the voltage applied to the induction motor can be varied, an induction-motor drive is commonly referred to as a variable-frequency induction-motor drive.

Varying the modulation index of the three-phase PWM inverter in the motor drive shown in Figure 4 allows the ac voltage at the inverter outputs, and therefore the ac voltage applied to the induction motor, to be varied. Varying the operating frequency of the inverter varies the frequency of the ac voltage applied to the induction motor. When the frequency increases, the speed of the induction motor increases proportionally, and vice versa. Reversing the connections of any two of the inverter outputs reverses the direction of rotation of the motor. In practice, however, the connections do not need to be physically reversed because the inverter control unit can accomplish the same result by electronically reversing the phase sequence of the ac voltages at the outputs of the inverter.

Torque developed in an induction motor versus the saturation of the motor stator

The **torque** produced by an induction motor is proportional to the current induced in the rotor and the magnetic flux density B in the motor. It is, therefore, desirable to maintain the magnetic flux density in the induction motor as high as possible so that the motor can develop the highest possible torque. The relationship between the rms value of the voltage E across the motor windings, the number N of turns in each motor winding, the surface area A of the stator core, the maximum flux density B_{max} in the induction motor stator, and the frequency f of the ac power source is based on the following equation:

The flux density B is measured in teslas (T) in the SI system and in gauss (G) in U.S. customary units. 1 T equals 10 000 G. The magnetic field intensity H is measured in ampere-turn per meter (A/m) in the SI system and in oersteds (Oe) in U.S. customary units. 1 A/m equals 0.0126 Oe.

$$E = \frac{2\pi}{\sqrt{2}} f N B_{max.} A \quad (1)$$

where E is the rms value of the voltage across the motor, expressed in volts.

f is the frequency of the ac power source, expressed in hertz.

N is the number of turns in each motor winding.

$B_{max.}$ is the maximum flux density in the induction motor stator, expressed in teslas (or gauss).

A is the surface area of the stator core, expressed in square meters. 1 m^2 equals 10.76 ft^2.

In this equation, the number N of turns in each motor winding and the surface area A of the stator core are constants for any given induction motor. Consequently, for a given frequency f, the maximum flux density B_{max} in the stator of the induction motor is directly proportional to the rms value of voltage E.

The stator current producing the magnetic field in an induction motor is referred to as the magnetizing current (I_O).

When the voltage E is increased, both the flux density B and the magnetic field intensity H in the motor stator increase in similar proportions. Because the peak value of the magnetizing current ($I_{O,max.}$) of the induction motor is directly proportional to the magnetic field intensity H in the motor stator, it is thus proportional to voltage E. This is illustrated by the typical saturation curve of an induction motor shown in Figure 5. However, when the voltage E reaches a certain value, certain parts of the stator core of the induction motor start to saturate, causing the magnetic field intensity H to increase much more rapidly than the magnetic flux density B. This causes the peak value of the magnetizing current ($I_{O,max.}$) to increase considerably.

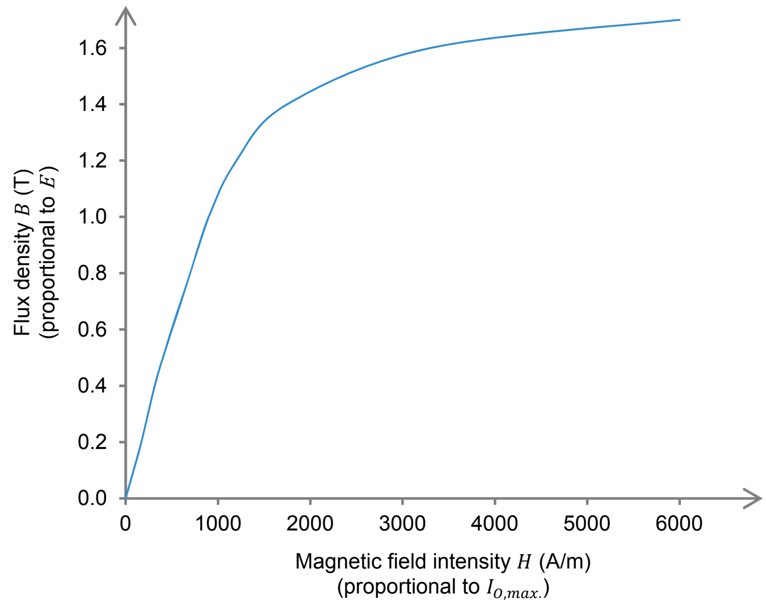


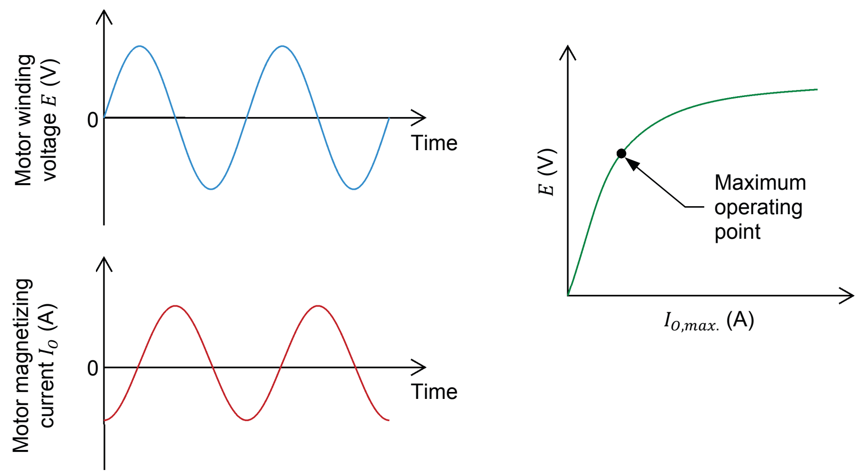
Figure 5. Typical saturation curve of an induction motor (flux density B as a function of the magnetic field intensity H).

Before saturation occurs, both the maximum flux density $B_{max.}$ and magnetic field intensity H increase in similar proportion as voltage E increases, and thus, the peak value of the magnetizing current ($I_{O,max.}$) is also proportional to the voltage E. Consequently, the power dissipated as heat in the stator windings (copper losses) increases in approximately the same proportion as the voltage E is increased (i.e., in the same proportion the maximum flux density $B_{max.}$ is increased). Furthermore, the iron losses in the motor increase as the maximum flux density $B_{max.}$ increases. When voltage E continues to increase, however, saturation eventually occurs and the peak value of the magnetizing current ($I_{O,max.}$) in the stator windings begins to increase considerably even if the maximum flux density $B_{max.}$ increases only slightly. This causes the power dissipated as heat in the stator windings (copper losses) to increase considerably. Therefore, it is not desirable to increase the maximum flux density $B_{max.}$ beyond saturation because the copper (RI^2) losses in the induction motor increase considerably while the maximum flux density $B_{max.}$ increases only a little. In brief, the maximum flux density $B_{max.}$ in the induction motor is mainly limited by saturation of the stator core.

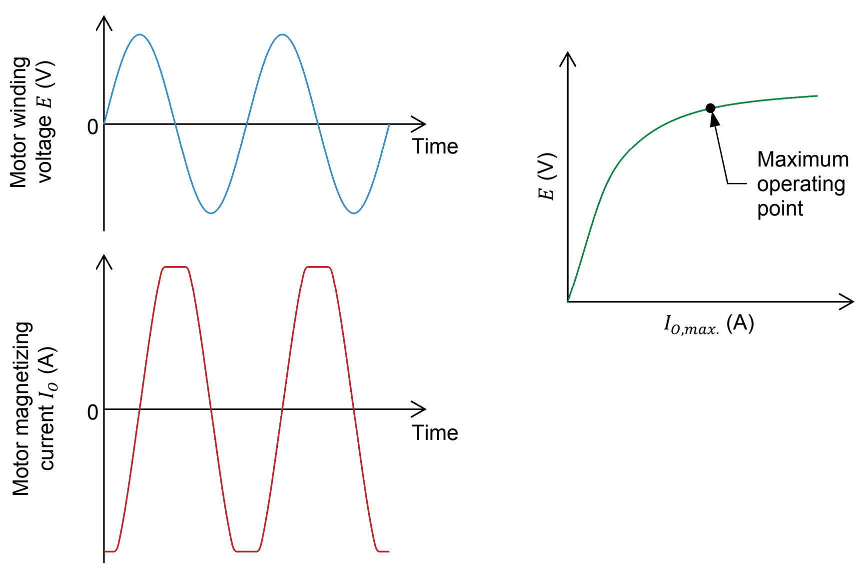
In practice, the maximum flux density $B_{max.}$ in an induction motor is generally maintained at a value that slightly saturates the core of the motor. That is, the induction motor usually operates around the knee of the saturation curve of the motor stator core. This allows a high maximum flux density $B_{max.}$ to be obtained with a magnetizing current that has a relatively low value. In other words, this allows the induction motor to develop the highest possible torque while maintaining the copper losses in the motor at an acceptable level.

Figure 6 shows the waveforms of the winding voltage and magnetizing current obtained with no saturation and with saturation. When there is no saturation, the magnetizing current has a reasonable peak value and is a sine wave (see Figure 6a). However, when saturation occurs, the peak value of the magnetizing current increases considerably and its waveform becomes distorted (i.e., the harmonic contents increase), which is not desirable (see Figure 6b).

The waveform of the actual voltages applied to the stator windings of an induction motor used in a variable-frequency motor drive is a train of bipolar rectangular pulses. This is because no filter is used at the PWM inverter output. The voltage waveforms shown in Figure 6 are the ones that would be obtained if the actual voltages at the PWM inverter output were filtered to remove all harmonics. In other words, the voltage waveforms shown in Figure 6 show the fundamental-frequency component contained in the actual voltages at the PWM inverter output, i.e., a voltage sine wave at the operating frequency of the PWM inverter.



(a) Without saturation



(b) With saturation

Figure 6. Waveforms of the winding voltage and magnetizing current obtained with no saturation and with saturation.

The effect of frequency on saturation in an induction motor

Equation (1) shows the relationship between the rms value of the voltage E across each motor winding, the number n of turns in each motor winding, the surface area A of the stator core, the maximum flux density B_{max} in the induction motor stator, and the frequency f of the ac power source. In this equation, the number N of turns in each motor winding and the surface area A of the stator core are constants for any given induction motor. Consequently, for a given voltage E, the maximum flux density $B_{max.}$ only depends on the frequency f of the ac voltage E applied to the motor windings. The maximum flux density $B_{max.}$ and, therefore, the peak value of the magnetizing current in the motor windings, decreases when the frequency f increases and vice versa. Therefore, using a higher frequency allows higher voltages E to be applied to the motor stator windings before saturation occurs. Conversely, using a lower frequency causes lower voltages E to produce saturation. To illustrate this phenomenon, Figure 7 shows the saturation curves of an induction motor (expressed as the motor voltage E as a function of the peak magnetizing current $I_{O,max.}$) at the nominal operating frequency ($f_{nominal}$) of the motor, at twice the nominal operating frequency ($2f_{nominal}$), and at half the nominal operating frequency ($1/2f_{nominal}$).

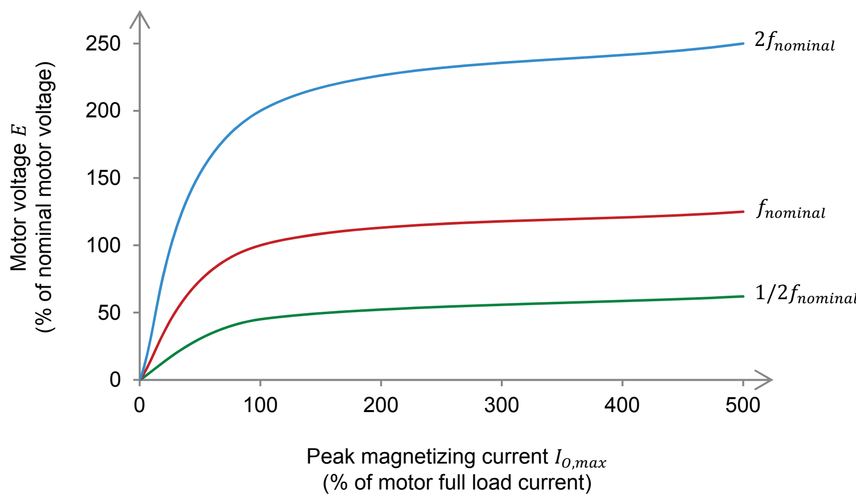


Figure 7. Typical saturation curves of an induction motor at various frequencies (motor voltage as a function of the magnetizing current).

Measurement of the rms value of the fundamental-frequency component in the voltage at the output of a three-phase PWM inverter

You have learned in the *Three-Phase AC Power Electronics* course, manual 86362, that the voltage waveforms at the output of a three-phase PWM inverter are trains of rectangular bipolar pulses, and that a filter made of inductors and capacitors is usually added at the PWM inverter output to obtain sinusoidal voltage and current waveforms.

When the load connected to the output of a three-phase PWM inverter is an induction motor (as is the case in a variable-frequency induction-motor drive), a filter is usually not used because the motor windings act as a filter and because the motor operation is only slightly affected by the harmonic content of the voltage waveforms. However, since the waveform of the voltages at the output of the PWM inverter is a train of bipolar rectangular pulses, the rms value of the voltage at the fundamental frequency (i.e., the frequency corresponding to the frequency of the sine wave modulating the duty cycle of each switching transistor in the PWM inverter) cannot be measured using a conventional voltmeter. To measure the rms value of the voltage at the fundamental frequency only (i.e., the rms value of the fundamental-frequency component in the voltage waveform), the harmonics in the voltage waveform must be rejected. A harmonic analyzer is an instrument that can measure the rms value of the fundamental-frequency component in any waveform, as well as the rms value of any harmonic component in the waveform. In the Procedure of this exercise, you will use the Harmonic Analyzer application in LVDAC-EMS to measure the rms value of the fundamental-frequency component in the voltage waveforms at the output of the three-phase PWM inverter.

Figure 8. Three-phase, variable-frequency motor drive used to regulate the speed of an HVAC (heating, ventilation, and air conditioning) system (© Siemens AG 2012, all rights reserved).

Overmodulation

You have learned in the *Three-Phase AC Power Electronics* course, manual 86362, that the average value of the voltage ($E_{O,avg.}$) at the output of a three-phase full-wave rectifier is 1.35 times the nominal value of the ac power network line voltage ($E_{O,avg.} = 1.35E_{L-L}$). When the voltage from this rectifier is applied to the input of a three-phase PWM inverter, the rms value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter (voltage obtained when m = 1) is significantly lower than the nominal line voltage of the ac power network, as shown in Table 1.

Table 1. RMS value of the fundamental-frequency component in the line voltage ($E_{line,max.}$) at the output of a three-phase PWM inverter for various ac power network line voltages (E_{L-L}).

Line voltage at the input of the three-phase full wave rectifier E_{L-L} (V)	Voltage at the output of the three-phase full-wave rectifier $E_{O,avg.}$ (5) (V)	Voltage at the input of the three-phase PWM inverter E_{bus} (6) (V)	Phase voltage at the output of the three-phase PWM inverter, m = 1 (7) $E_{phase,max.}$ (V)	Line voltage at the output of the three-phase PWM inverter, m = 1 (8) $E_{line,max.}$ (V)
208 (1)	281	281	99	172
381 (2)	514	514	182	315
416 (3)	561	561	198	345
381 (4)	514	514	182	315

(1) 120/208 V, 60 Hz, ac power network
(2) 220/380 V, 50 Hz, ac power network
(3) 240/415 V, 50 Hz, ac power network
(4) 220/380 V, 60 Hz, ac power network
(5) $E_{O,\,avg.} = 1.35E_{L-L}$
(6) $E_{Bus} = E_{O,\,avg.}$
(7) $E_{phase,max.} = \frac{E_I \times m}{\sqrt{2}} = \frac{(E_{bus}/2) \times m}{\sqrt{2}}$ (fundamental-frequency component)
(8) $E_{line,max.} = \sqrt{3}\,E_{phase,max.}$ (fundamental-frequency component)

One means of increasing the rms value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter beyond the normal maximum value is to increase the amplitude of the sine wave that modulates the duty cycle of the switching transistors of the PWM inverter in such a way that the minimum and maximum duty cycle values (0% and 100%) are reached earlier in each cycle. This technique, which is referred to as overmodulation causes the rms value of the fundamental-frequency component in the voltage at the output of the three-phase PWM inverter to exceed the normal maximum value by modifying the waveform of the output voltage as shown in Figure 9. The red area in Figure 9 represents the increase in the rms value (area under the waveform) caused by the overmodulation. Note that the voltage waveform obtained with overmodulation is distorted significantly, thereby indicating an increase in the presence of harmonics.

The waveform of the actual voltages applied to the stator windings of an induction motor used in a variable-frequency motor drive is a train of bipolar rectangular pulses. This is because no filter is used at the PWM inverter output. The voltage waveforms shown in Figure 9 are the ones that would be obtained if the actual voltages at the PWM inverter output were filtered to reduce the harmonics.

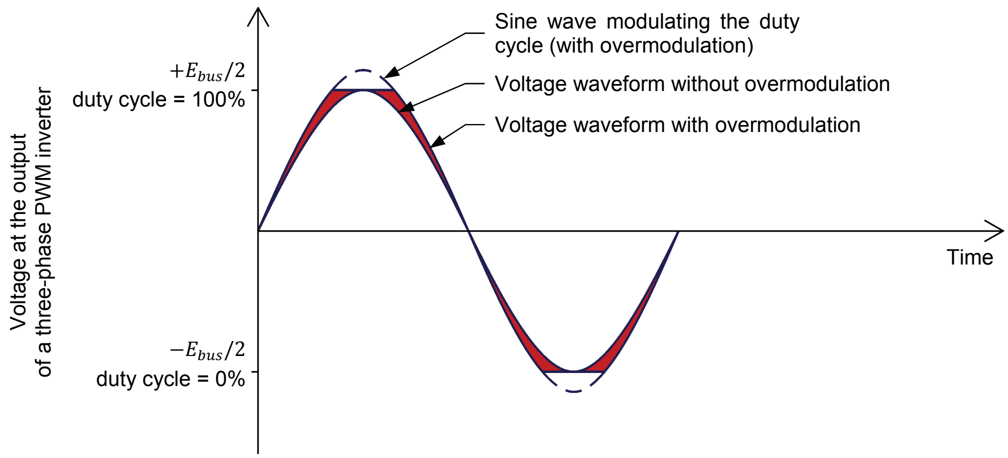


Figure 9. Voltage waveform at the output of a PWM inverter with and without overmodulation (after filtering).

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Measurement of the rms value of the fundamental-frequency component in the voltage (unfiltered) at the output of a three-phase PWM inverter
- Overmodulation
- Effect of the frequency on the induction motor speed and magnetizing current
  Operation at motor nominal frequency. Operation at 4/3 the motor nominal frequency. Operation at 1/2 the motor nominal frequency.
- Saturation curves

PROCEDURE

WARNING

High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

Setup and connections

In this part of the exercise, you will set up and connect the equipment.

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

   Install the equipment in the Workstation.

   Mechanically couple the Four-Pole Squirrel Cage Induction Motor to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

2. Make sure that the ac and dc power switches on the Power Supply are set to the O (off) position, then connect the Power Supply to a three-phase ac power outlet.

Make sure that 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.

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

> Notice that the prefix IGBT has been left out in this manual when referring to the IGBT Chopper/Inverter module.

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

4. 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.

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

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

In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure that the *Computer-Based Instrumentation* and *Chopper/Inverter Control* functions for the Data Acquisition and Control Interface are available. 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.

7. Connect the *Digital Outputs* of the Data Acquisition and Control Interface (DACI) to the *Switching Control Inputs* of the Chopper/Inverter using a DB9 connector cable.

On the Chopper/Inverter, set the *Dumping* switch to the O (off) position. The *Dumping* switch is used to prevent overvoltage on the dc bus of the Chopper/Inverter. It is not required in this exercise.

8. Set up the circuit shown in Figure 10. Use the diodes in the Rectifier and Filtering Capacitors to implement the three-phase full-wave rectifier. Use the Chopper/Inverter to implement the Three-phase inverter. Connect the *Thermistor Output* of the Four-Pole Squirrel Cage Induction Motor to the *Thermistor Input* of the Four-Quadrant Dynamometer/Power Supply.

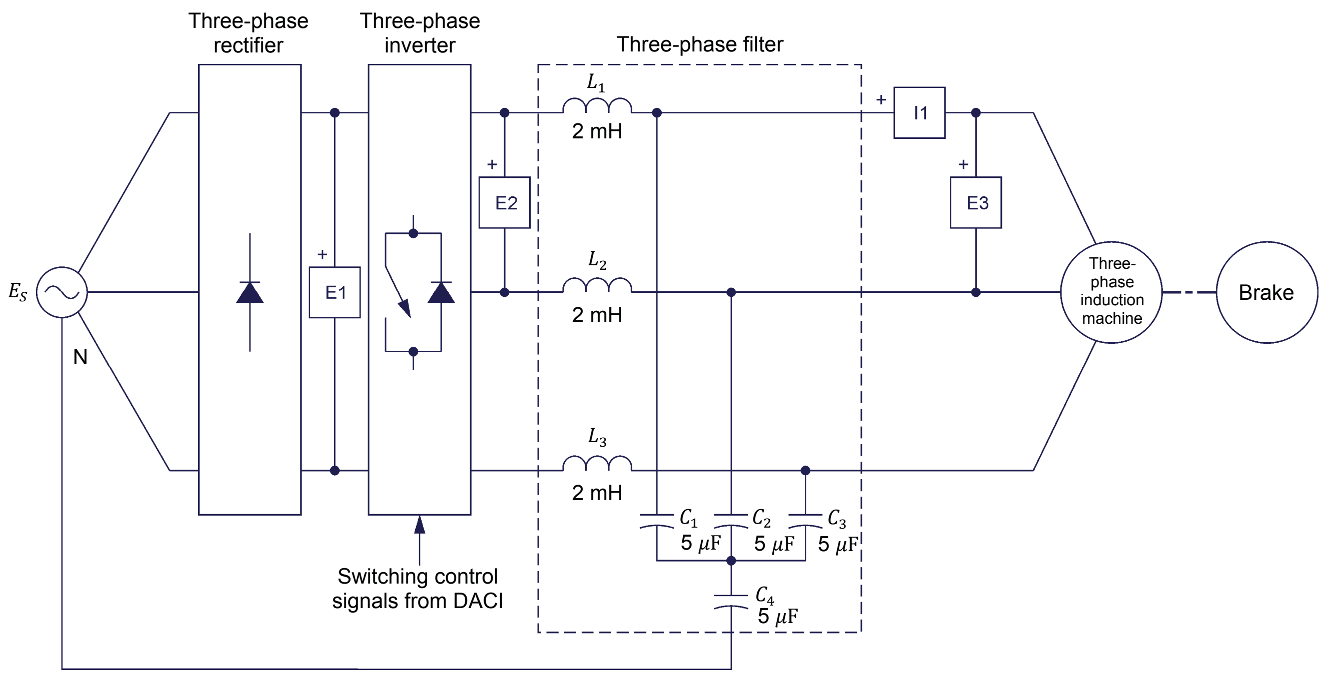


Figure 10. Three-phase, variable-frequency induction-motor drive (with three-phase filter).

Measurement of the rms value of the fundamental-frequency component in the voltage (unfiltered) at the output of a three-phase PWM inverter

In this part of the exercise, you will use the Harmonic Analyzer in LVDAC-EMS to measure the rms value of the fundamental-frequency component in the unfiltered voltage at the output of a three-phase PWM inverter. You will also observe that when the load connected to the three-phase PWM inverter output is inductive (like a motor), the current waveform at the output of the three-phase PWM inverter remains sinusoidal even with no filter.

The Four-Quadrant Dynamometer/Power Supply is not used in this part of the exercise although it is mechanically coupled to the Four-Pole Squirrel Cage Induction Motor.

9. In LVDAC-EMS, open the Chopper/Inverter Control window, then make the following settings:

   – Set the *Function* parameter to *Three-Phase PWM inverter*.

   – Set the *Switching Frequency* parameter to 3000 Hz.

   – Make sure the *Phase Sequence* parameter is set to *Fwd (1-2-3)*.

   – Set the *Frequency* parameter to the motor nominal frequency indicated on the Four-Pole Squirrel Cage Induction Motor front panel.

– Set the *Peak Voltage* parameter to 100%. This parameter sets the modulation index m, i.e., it sets the amplitude of the sine-wave signal that modulates the duty cycle of the switching control signals. When the *Peak Voltage* parameter is set to 100%, the amplitude of the modulating signal is set to obtain a peak output voltage corresponding to 100% of half the dc bus voltage (100% of $E_{BUS}/2$). In other words, this sets the value of the modulation index to 1 (m = 1).

– Make sure the *Modulation Type* parameter is set to *Sinusoidal Pulse-Width Modulation*.

– Start the *Three-Phase PWM Inverter*.

10. On the Power Supply, turn the three-phase ac power source on. The motor should start to rotate.

11. In LVDAC-EMS, open the Oscilloscope. Use channel 1 to display the dc bus voltage (input *E1*), channels 2 and 3 to display the line voltage at the output of the three-phase PWM inverter before and after filtering (inputs *E2* and *E3*, respectively), and channel 4 to display the current flowing in the motor stator windings (input *I1*).

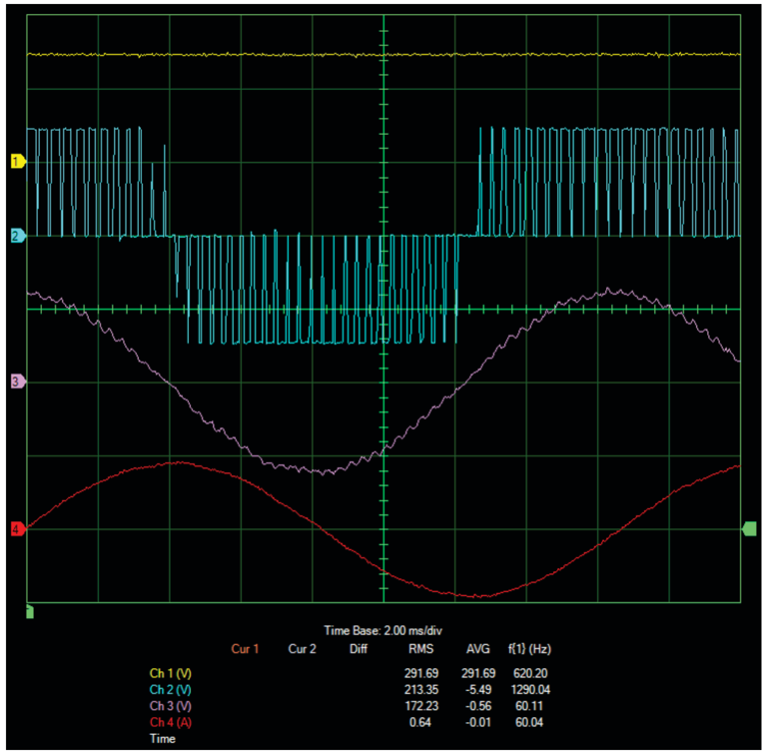
Select the *Continuous Refresh* mode, set the time base to display only one complete cycle of the voltage and current waveforms (this provides more precision for observing the trains of rectangular bipolar pulses produced by the three-phase PWM inverter), and set the trigger controls so that the Oscilloscope triggers when the waveform of the motor stator current passes through 0 A with a positive slope.

Select convenient vertical scale and position settings to facilitate observation of the waveforms.

12. Print or save the waveforms displayed on the Oscilloscope screen for future reference. It is suggested that you include these waveforms in your lab report.

The resulting waveforms are shown in the following figure.

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale ....200 V/div
Channel-1 Coupling ....DC
Channel-2 Input E2
Channel-2 Scale ....200 V/div
Channel-2 Coupling ....DC
Channel-3 Input E3
Channel-3 Scale ....200 V/div
Channel-3 Coupling ....DC
Channel-4 Input I1
Channel-4 Scale ....1 A/div
Channel-4 Coupling ....DC
Time Base............................. 2 ms/div
Trigger Type ....Software
Trigger Source Ch4
Trigger Level.....................................0
Trigger Slope ....Rising



Voltage and current waveforms obtained when the three-phase, variable-frequency induction-motor drive operates at motor nominal frequency.

13. Describe the waveform of the voltage at the output of the three-phase PWM inverter before and after filtering.

The waveform of the voltage at the output of the three-phase PWM inverter before filtering is a train of rectangular bipolar pulses, and it is sinusoidal after filtering.

14. Measure and record the rms value of the line voltage at the output of the three-phase PWM inverter before and after filtering.

RMS value of the line voltage at the output of the three-phase PWM inverter before filtering: _______ V

RMS value of the line voltage at the output of the three-phase PWM inverter after filtering: _______ V

RMS value of the line voltage at the output of the three-phase PWM inverter before filtering: 213 V

RMS value of the line voltage at the output of the three-phase PWM inverter after filtering: 172 V

15. Are the rms values of the line voltage at the output of the three-phase PWM inverter measured before and after filtering using the Oscilloscope equal? Explain briefly.

No, because the voltage waveform before filtering is a train of bipolar rectangular pulses containing harmonics whereas the voltage waveform after filtering is sinusoidal (i.e., virtually all harmonics have been removed).

16. Describe the waveform of the current flowing in each stator winding of the three-phase motor (input *I1*).

The waveform of the current flowing in each stator winding of the three-phase motor is sinusoidal.

17. In LVDAC-EMS, open the Harmonic Analyzer window, then make the following settings:

– Set the *Fundamental Frequency Type* parameter to *User*.

– Set the *Fundamental Frequency* parameter to the motor nominal frequency indicated on the Four-Pole Squirrel Cage Induction Motor front panel.

– Make sure the *Number of Harmonics* parameter is set to 40.

– Set the *Input* parameter to *E3*.

– Set the *Scale Type* parameter to V (voltage).

– Make sure the *Scale Setting* parameter is set to 50 V/div.

– Select the *Continuous Refresh* mode.

18. Measure and record the rms value of the fundamental-frequency component (1f) in the line voltage at the output of the three-phase PWM inverter after filtering (input *E3*), indicated in the Harmonic Analyzer display.

RMS value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter after filtering: _______ V

Compare the rms value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter after filtering measured using the Harmonic Analyzer with the rms value of the line voltage measured previously using the Oscilloscope. The values should be identical because the voltage waveform is sinusoidal.

RMS value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter after filtering: 172 V

19. In the Harmonic Analyzer window, set the *Input* parameter to *E2* to measure the line voltage at the output of the three-phase PWM inverter before filtering.

Measure and record the rms value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter before filtering (input *E2*), indicated in the Harmonic Analyzer display.

RMS value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter before filtering: _______ V

The rms value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter before filtering should be slightly higher than that after filtering because of the voltage drop across the three-phase filter.

RMS value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter before filtering: 177 V

20. Do your measurements confirm that the rms value of the fundamental-frequency component in the line voltage at the outputs of the three-phase PWM inverter before filtering can be measured using the Harmonic Analyzer? Explain briefly.

Yes, because the rms value of the fundamental-frequency component in the line voltage measured before and after filtering are very similar (the difference is due to the voltage drop across the three-phase filter) and equal to the rms value of the line voltage at the PWM inverter output after filtering measured using the Oscilloscope (see step 14). The Harmonic Analyzer is able to isolate the fundamental-frequency component from the harmonics when measuring the rms value of the fundamental-frequency component in the unfiltered voltage.

21. In the Chopper/Inverter Control window, stop the *Three-Phase PWM Inverter*.

On the Power Supply, turn the three-phase ac power source off.

Remove the three-phase filter from the circuit and disconnect voltage input *E3*. The circuit should be as shown in Figure 11.

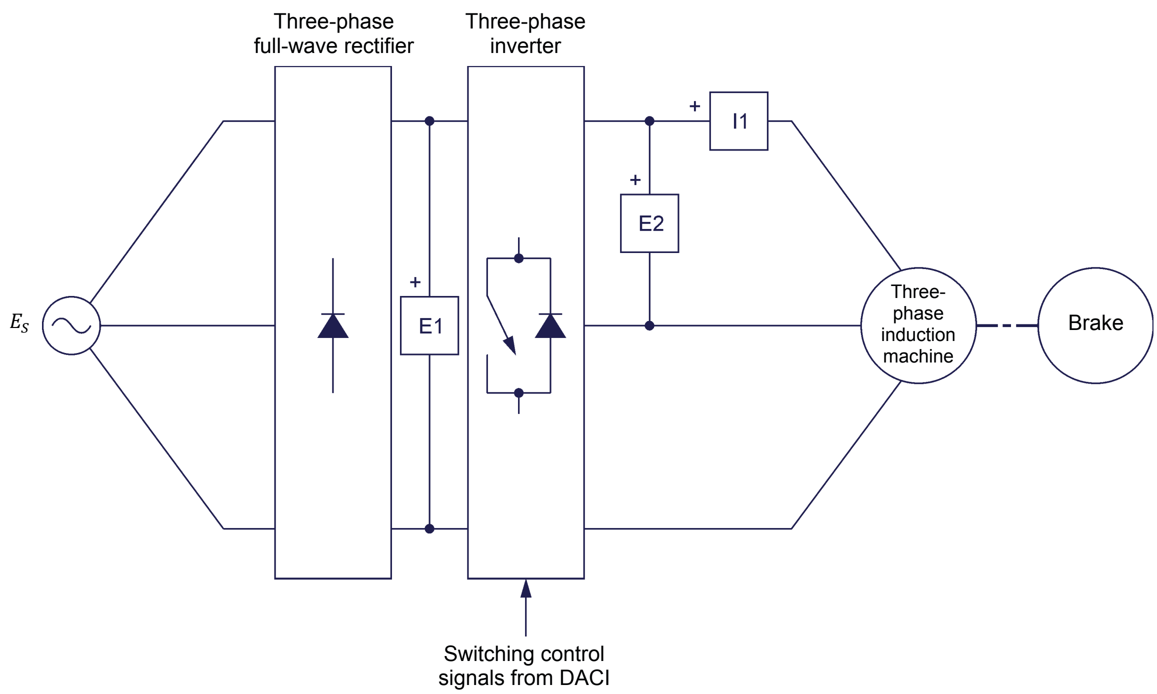


Figure 11. Three-phase, variable-frequency induction-motor drive (without three-phase filter).

22. In the Chopper/Inverter Control window, start the *Three-Phase PWM Inverter*.

On the Power Supply, turn the three-phase ac power source on.

Measure and record the rms value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter indicated in the Harmonic Analyzer display.

RMS value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter: _______ V

Compare the rms value of the fundamental-frequency component in the line voltage measured without filter to that measured in step 19 when the filter was in the circuit.

RMS value of the fundamental-frequency component in the line voltage at the output of the three-phase PWM inverter without filtering: 177 V

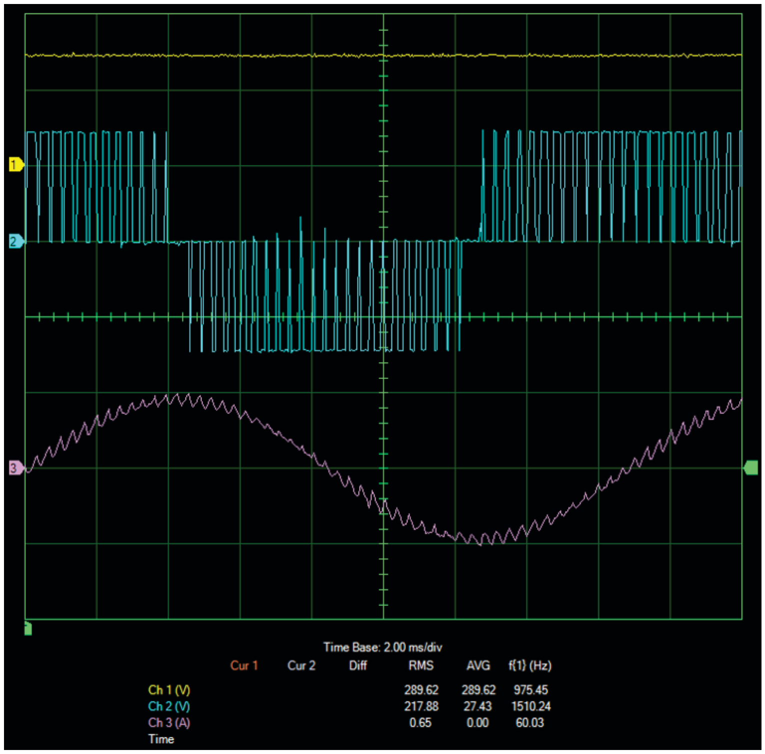
23. On the Oscilloscope, use channel 1 to display the dc bus voltage (input *E1*), channel 2 to display the voltage at the output of the three-phase PWM inverter (input *E2*), and channel 3 to display the current flowing in one of the motor stator windings (input *I1*).

Select convenient vertical scale and position settings to facilitate observation of the waveforms.

24. Print or save the waveforms displayed on the Oscilloscope screen for future reference. It is suggested that you include these waveforms in your lab report.

The resulting waveforms are shown in the following figure.

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale ....200 V/div
Channel-1 Coupling ....DC
Channel-2 Input E2
Channel-2 Scale ....200 V/div
Channel-2 Coupling ....DC
Channel-3 Input I1
Channel-3 Scale ....1 A/div
Channel-3 Coupling ....DC
Time Base............................. 2 ms/div
Trigger Type ....Software
Trigger Source Ch3
Trigger Level.....................................0
Trigger Slope ....Rising



Voltage and current waveforms obtained when the three-phase, variable-frequency drive operates at motor nominal frequency (without overmodulation).

25. Explain why the waveform of the motor stator current displayed on the Oscilloscope screen is sinusoidal even if the filter is removed.

The waveform of the motor stator current is sinusoidal because of the inductive reactance of the motor windings make them operate as a filter removing all harmonics.

Overmodulation

In this part of the exercise, you will increase the rms value of the line voltage at the output of a three-phase PWM inverter by increasing the amplitude of the sine wave that modulates the duty cycle of the switching transistors of the PWM inverter to a level that causes overmodulation.

For the remaining of this exercise, the rms value of the line voltage at the output of the three-phase PWM inverter always refers to the rms value of the fundamental-frequency component in the line voltage (i.e., the rms value of the 1f component measured with the Harmonic Analyzer).

26. Compare the rms value of the line voltage at the output of the three-phase PWM inverter measured in step 22 with the nominal line voltage of the Four-Pole Squirrel Cage Induction Motor (indicated on its front panel). Does the maximum line voltage which can be obtained at the outputs of the three-phase PWM inverter without overmodulation (i.e., with modulation index set to 1) allow the induction motor to be operated at its nominal voltage?

❑ Yes ❑ No

No

27. In order to increase the voltage at the output of the three-phase PWM inverter (i.e., the voltage applied to the motor windings), set the *Peak Voltage* parameter in the Chopper/Inverter Control window to 117% of the dc bus voltage/2 (this corresponds to the maximum *Peak Voltage* value available in the Chopper/Inverter Control window). This setting increases the amplitude of the sine-wave signal that modulates the duty cycles of the switching control signals to a level that causes overmodulation.

28. Using the Harmonic Analyzer, measure and record the rms value of the line voltage at the output of the three-phase PWM inverter obtained when overmodulation is used.

RMS value of the line voltage at the output of the three-phase PWM inverter (with overmodulation): _______ V

RMS value of the line voltage at the output of the three-phase PWM inverter (with overmodulation): 207 V

29. Is the value measured in the previous step close to the nominal line voltage of the Four-Pole Squirrel Cage Induction Motor?

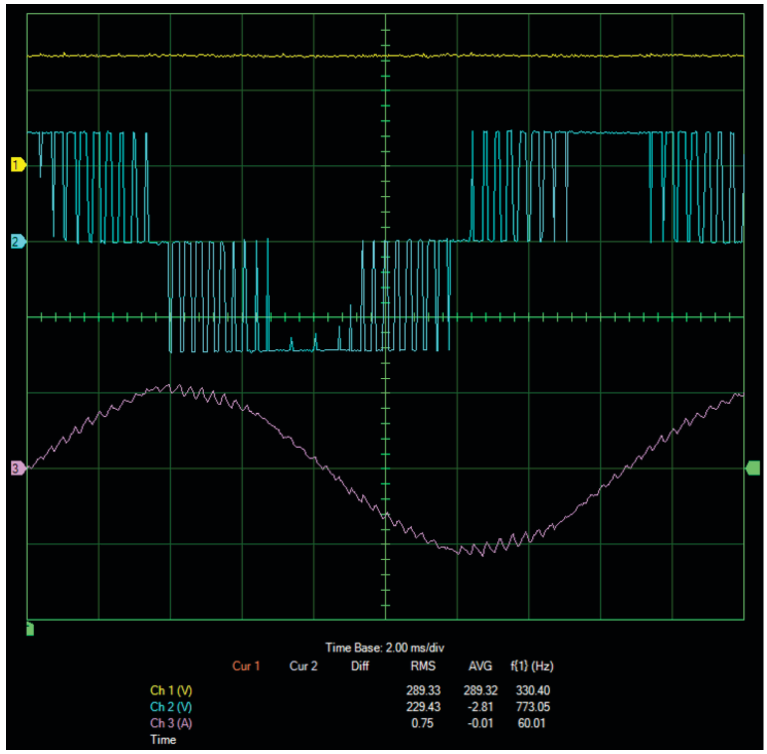
❑ Yes ❑ No

Yes

30. Print or save the waveforms displayed on the Oscilloscope screen for future reference. It is suggested that you include these waveforms in your lab report.

The resulting waveforms are shown in the following figure.

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale .... 200 V/div
Channel-1 Coupling .... DC
Channel-2 Input E2
Channel-2 Scale .... 200 V/div
Channel-2 Coupling .... DC
Channel-3 Input I1
Channel-3 Scale .... 1 A/div
Channel-3 Coupling .... DC
Time Base .... 2 ms/div
Trigger Type .... Software
Trigger Source Ch3
Trigger Level 0
Trigger Slope .... Rising



Voltage and current waveforms obtained when the three-phase, variable-frequency drive operates at motor nominal frequency (with overmodulation).

31. Compare the voltage waveforms at the output of the three-phase PWM inverter obtained with and without overmodulation (i.e., obtained in step 30 and step 24, respectively). Do you observe that the voltage waveform obtained with overmodulation contains less rectangular pulses, indicating that overmodulation occurs?

❑ Yes ❑ No

Yes

32. Do your observations confirm that overmodulation allows the rms value of the maximum voltage at the output of a three-phase PWM inverter to be increased?

❑ Yes ❑ No

Yes

33. In the Chopper/Inverter Control window, stop the *Three-Phase PWM Inverter*.

Effect of the frequency on the induction motor speed and magnetizing current

In this part of the exercise, you will use the same circuit as in the previous section (see Figure 11) to observe the effect of the frequency on the speed and magnetizing current of the three-phase induction motor.

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

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

– Make sure that the *Torque Control* parameter is set to *Knob*. This allows the torque command of the prime mover/brake to be controlled manually.

– Set the *Torque* parameter to 0.00 N·m (0.0 lbf·in), thereby ensuring that the Four-Pole Squirrel Cage Induction Motor operates with no mechanical load.

– Set the *Pulley Ratio* parameter to 24:24. The first and second numbers in this parameter specify the number of teeth on the pulley of the Four-Quadrant Dynamometer/Power Supply and the number of teeth on the pulley of the machine under test, respectively. The pulley ratio between the Four-Quadrant Dynamometer/Power Supply and the Four-Pole Squirrel Cage Induction Motor is 24:24.

– Set the *Thermistor Type* parameter to *LV Type 2*. This setting is required to match the characteristics of the thermistor in the Four-Pole Squirrel Cage Induction Motor with the *Thermistor Input* in the Four-Quadrant Dynamometer/Power Supply.

– Start the *Positive Constant-Torque Primer Mover/Brake* by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button.

– Select the *Continuous Refresh* mode of the meters by clicking on the corresponding button.

Operation at motor nominal frequency

35. In the Chopper/Inverter Control window, make the following settings:

– Make sure the *Function* parameter is set to *Three-Phase PWM inverter*.

– Set the *Switching Frequency* parameter to 2000 Hz.

– Make sure the *Phase Sequence* parameter is set to *Fwd (1-2-3)*.

– Make sure the *Frequency* parameter is set to the motor nominal frequency indicated on the Four-Pole Squirrel Cage Induction Motor front panel.

– Set the *Peak Voltage* parameter to 100%.

– Make sure the *Modulation Type* parameter is set to *Sinusoidal Pulse-Width Modulation*.

– Start the *Three-Phase PWM Inverter*.

36. The induction motor should rotate at a speed slightly below the synchronous speed n_S of the three-phase induction motor. Record the motor speed of rotation indicated by the *Speed* meter in the Four-Quadrant Dynamometer/Power Supply window in Table 2.

The synchronous speed n_S of the Four-Pole Squirrel Cage Induction Motor is 1500 r/min at a local ac power network frequency of 50 Hz and 1800 r/min at a local ac power network frequency of 60 Hz.

Table 2. Effect of the frequency on the induction motor speed and magnetizing current.

Frequency	Motor speed of rotation (r/min)	DC bus voltage (V)	RMS value of the motor magnetizing current (A)	Amplitude of the motor magnetizing current (peak value) (A)
Nominal frequency				
4/3 the nominal frequency				
1/2 the nominal frequency				

The results are presented in the following table.

Effect of the frequency on the induction motor speed and magnetizing current.

Frequency	Motor speed of rotation (r/min)	DC bus voltage (V)	RMS value of the motor magnetizing current (A)	Amplitude of the motor magnetizing current (peak value) (A)
Nominal frequency	1788	289	0.59	0.83
4/3 the nominal frequency	2381	290	0.44	0.63
1/2 the nominal frequency	899	289	1.73	2.45

> The stator current measured when an induction motor operates with no mechanical load is virtually equal to the motor magnetizing current.

37. On the Oscilloscope, use channel 1 to display the dc bus voltage (input *E1*), and channel 2 to display the motor stator current (input *I1*).

Select convenient vertical scale and position settings to facilitate observation of the waveforms.

38. Measure and record the dc bus voltage as well as the rms value and amplitude of the motor magnetizing current in Table 2.

Operation at 4/3 the motor nominal frequency

39. In the Chopper/Inverter Control window, gradually increase the frequency of the three-phase PWM inverter up to about 4/3 the motor nominal frequency while observing the motor speed and magnetizing current.

Measure and record the motor speed, the dc bus voltage, as well as the rms value and amplitude of the motor magnetizing current in Table 2.

40. Gradually decrease the frequency of the three-phase PWM inverter to the motor nominal frequency.

41. Compare the motor speed measured at 4/3 the nominal frequency to that measured at the motor nominal frequency. Does the motor speed increase in direct proportion with the increase in frequency?

❑ Yes ❑ No

Yes

42. Compare the motor magnetizing current measured at 4/3 the motor nominal frequency to that measured at the motor nominal frequency. How does the motor magnetizing current vary when the frequency is increased? Explain why.

The motor magnetizing current decreases when the frequency of the three-phase PWM inverter increases. The voltage applied to the motor stator windings being fixed, the motor magnetizing current decreases when the frequency increases because the inductive reactance of the stator windings increases ($X_L = 2\pi fL$).

43. How does the motor magnetizing current variation affect the maximum magnetic flux density B_{max} in the motor?

The decrease in the motor magnetizing current causes the maximum magnetic flux density B_{max} in the motor to decrease.

Operation at 1/2 the motor nominal frequency

CAUTION

In the next steps, the current in the motor stator windings will exceed the nominal value. Perform your manipulations rapidly to prevent motor overheating. Also, make sure that the motor peak current never exceeds four times the nominal current shown on the Four-Pole Squirrel Cage Induction Motor front panel or the motor temperature never exceeds 80°C (176°F).

44. Gradually decrease the frequency of the three-phase PWM inverter down to about 1/2 the motor nominal frequency while observing the motor speed and magnetizing current.

Measure and record the motor speed, the dc bus voltage, as well as the rms value and amplitude of the motor magnetizing current in Table 2.

45. In the Chopper/Inverter Control window, stop the *Three-Phase PWM Inverter*.

On the Power Supply, turn the three-phase ac power source off.

46. Compare the motor speed measured at 1/2 the motor nominal frequency to that measured at the motor nominal frequency. Does the motor speed decrease in direct proportion with the decrease in frequency?

❑ Yes ❑ No

Yes

47. How does the motor magnetizing current vary when the frequency is decreased? Explain why.

The motor magnetizing current increases when the frequency of the three-phase PWM inverter decreases. The voltage applied to the motor stator windings being fixed, the motor magnetizing current increases when the frequency decreases because the inductive reactance of the stator windings decreases ($X_L = 2\pi f L$).

48. Compare the magnetizing current measured at 1/2 the motor nominal frequency to that measured at the motor nominal frequency as well as to the motor full-load current rating indicated on the Four-Pole Squirrel Cage Induction Motor front panel. What are the consequences of decreasing the frequency to 1/2 the motor nominal frequency while keeping the voltage constant?

Decreasing the frequency to 1/2 the motor nominal frequency while keeping the voltage constant causes saturation in the induction motor, thus making the motor magnetizing current increase so considerably (it more than doubles) that it even exceeds the motor full-load current rating. Consequently, the maximum flux density $B_{max.}$ increases, thereby allowing the motor to produce more torque, but not in the same proportions as the magnetizing current. Also, the large increase in the magnetizing current value considerably increases the copper losses (RI^2) of the induction motor, and thus, decreases the motor power efficiency (this results in more heating of the motor which can eventually be problematic).

Saturation curves

In this part of the exercise, you will plot the saturation curves of the three-phase induction motor at the motor nominal frequency, 2/3 the nominal frequency, 1/2 the nominal frequency, and 1/3 the nominal frequency.

CAUTION

In the next steps, the current in the motor stator windings will exceed the nominal value. Perform your manipulations rapidly to prevent motor overheating. Also, make sure that the motor peak current never exceeds four times the nominal current shown on the Four-Pole Squirrel Cage Induction Motor front panel or the motor temperature never exceeds 80°C (176°F).

49. Remove the timing belt that mechanically couples the Four-Pole Squirrel Cage Induction Motor to the Four-Quadrant Dynamometer/Power Supply.

50. In the Chopper/Inverter Control window, make the following settings.

- Make sure the *Function* parameter is set to *Three-Phase PWM inverter*.
- Make sure the *Switching Frequency* parameter is set to 2000 Hz.
- Make sure the *Phase Sequence* parameter is set to *Fwd (1-2-3)*.
- Set the *Frequency* parameter to the motor nominal operating frequency indicated on the Four-Pole Squirrel Cage Induction Motor front panel.
- Set the *Peak Voltage* parameter to 117%.
- Start the *Three-Phase PWM Inverter*.

51. On the Power Supply, turn the three-phase ac power source on.

For each value of the *Peak Voltage* parameter shown in Table 3, measure the rms value of the line voltage applied to the motor stator windings using the Harmonic Analyzer and the peak value of the current flowing in the motor stator windings (peak magnetizing current) using the Oscilloscope (use the horizontal cursors to make the measurement). To obtain optimal results, begin your measurements with the highest *Peak Voltage* setting as shown in Table 3.

To reduce the data acquisition time and to prevent the motor from overheating, it is strongly recommended to use the Data Table in LVDAC-EMS to record the circuit parameters measured.

Table 3. RMS value of the motor stator winding voltage (at the fundamental frequency) and peak magnetizing current of the three-phase induction motor at various frequencies.

Peak voltage (% of dc bus/2) (%)	$f_{nominal}$		$2/3 f_{nominal}$		$1/2 f_{nominal}$		$1/3 f_{nominal}$	
	Motor line voltage (V)	Peak magnetizing current (A)	Motor line voltage (V)	Peak magnetizing current (A)	Motor line voltage (V)	Peak magnetizing current (A)	Motor line voltage (V)	Peak magnetizing current (A)
117								
110								
100								
90								
80								
70								
60								
50								
40								
30								

The results are presented in the following table.

RMS value of the motor stator winding voltage (at the fundamental frequency) and peak magnetizing current of the three-phase induction motor at various frequencies.

Peak voltage (% of dc bus/2) (%)	$f_{Nom.}$		$2/3f_{Nom.}$		$1/2f_{Nom.}$		$1/3f_{Nom.}$	
	Motor line voltage (V)	Peak magnetizing current (A)	Motor line voltage (V)	Peak magnetizing current (A)	Motor line voltage (V)	Peak magnetizing current (A)	Motor line voltage (V)	Peak magnetizing current (A)
117	208	1.03	206	1.97	203	3.71	(1)	(1)
110	196	0.93	194	1.74	192	3.12	(1)	(1)
100	178	0.87	176	1.50	175	2.57	(1)	(1)
90	160	0.77	159	1.24	158	2.01	157	4.30
80	142	0.68	141	1.07	141	1.62	140	3.37
70	125	0.61	124	0.89	123	1.29	124	2.57
60	106	0.52	106	0.73	106	1.04	106	1.93
50	88.3	0.45	88.3	0.60	88.0	0.83	88.5	1.41
40	70.5	0.41	70.5	0.47	70.3	0.65	70.9	1.04
30	52.4	0.37	52.6	0.37	52.5	0.48	53.2	0.74

(1) The peak value of the current flowing in the motor stator windings exceeds four times the nominal current of the Four-Pole Squirrel Cage Induction Motor.

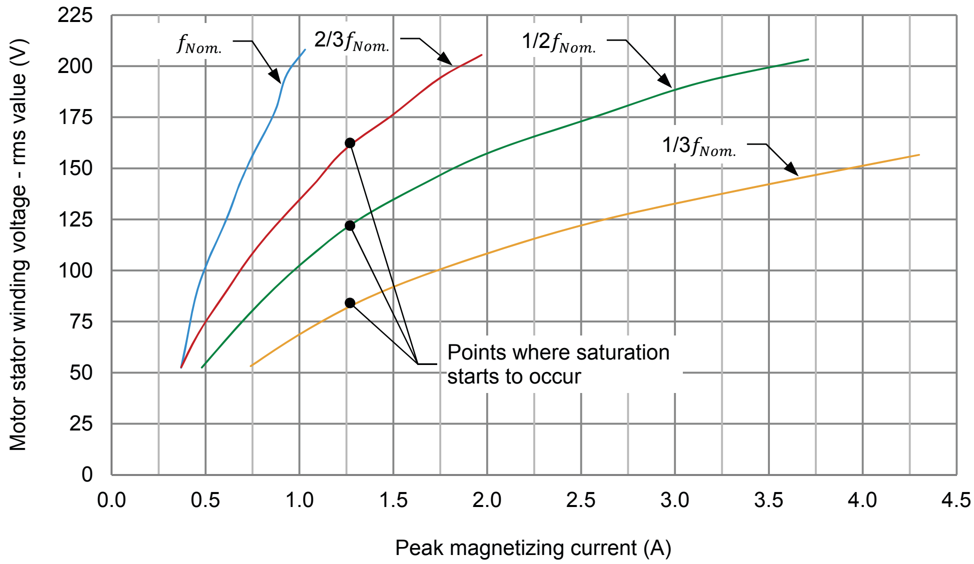
52. Repeat the previous step at the following three other frequencies: $2/3\,f_{nominal}$, $1/2f_{nominal}$, and $1/3f_{nominal}$. As mentioned earlier, make sure that the motor peak current never exceeds four times the nominal current indicated on the Four-Pole Squirrel Cage Induction Motor front panel or the temperature never exceeds 80°C (176°F), particularly at $1/2$ and $1/3$ the nominal motor operating frequency.

Use the 40 A terminal of input I1 *on the DACI and set the* Range *of input* I1 *to* High *in the* Data Acquisition and Control Settings *window of LVDAC-EMS as soon as the motor stator current reaches 4 A. Temporarily turn the ac power source off before making these changes.*

53. Plot on the same graph the saturation curves (rms value of the motor stator winding voltage as a function of the peak magnetizing current) of the Four-Pole Squirrel Cage Induction Motor at each of the frequencies in Table 3.

You will probably not observe any saturation at nominal frequency because the voltage applied to the motor windings cannot be increased sufficiently.

The resulting graph is shown below.



Saturation curves of the three-phase induction motor at various operating frequencies.

54. Do the saturation curves you plotted in the previous step show that, when the motor stator winding voltage is increased, the peak magnetizing current increases in similar proportions until the voltage reaches a value at which saturation in the stator core of the induction motor starts to occur, causing the peak magnetizing current to increase much more rapidly than the motor stator winding voltage?

❑ Yes ❑ No

Yes

55. Do your observations confirm that increasing the frequency allows higher voltages to be applied to the motor stator windings before saturation starts to occur?

❑ Yes ❑ No

Yes

56. Close LVDAC-EMS, turn off all equipment, and remove all leads and cables.

CONCLUSION

In this exercise, you learned that a three-phase, variable-frequency induction-motor drive consists of a power diode, three-phase full-wave rectifier and a three-phase PWM inverter. You learned that varying the operating frequency of the PWM inverter varies the frequency of the ac voltage applied to the induction motor, and thus, the motor speed. You also learned that varying the modulation index of the PWM inverter allows the voltage applied to the motor stator windings to be adjusted. You were introduced to the use of overmodulation in the PWM inverter to increase the maximum voltage that can be applied to the motor stator windings. You saw that for a given frequency, the maximum flux density ($B_{max.}$) in the stator of the motor is directly proportional to the rms value of voltage applied to the motor stator windings. You also saw that when the voltage increases and reaches a certain value, saturation occurs in the stator causing the motor magnetizing current to start increasing at a rate which largely exceeds that of the motor voltage. You learned that for a given voltage, the maximum flux density is inversely proportional to the frequency of the ac voltage applied to the motor windings, and consequently, the magnetizing current of the motor decreases when the frequency increases and vice versa. You were introduced to the use of a harmonic analyzer to measure the rms value of the fundamental-frequency component of a non-sinusoidal signal (e.g., the unfiltered voltage at the output of a three-phase PWM inverter).

REVIEW QUESTIONS

1. How can the ac voltage at the output of a three-phase PWM inverter be varied?

   The ac voltage at the output of a three-phase PWM inverter can be varied by varying the modulation index.

2. How does the magnetizing current vary when saturation starts to occur in the stator of an induction motor?

   When saturation occurs in an induction motor, the magnetizing current starts to increase much more rapidly than the voltage applied to the motor.

3. What should be done for an induction motor to be able to produce the highest possible torque?

   It is desirable to maintain the maximum magnetic flux density ($B_{max.}$) in the induction motor as high as possible so that the motor can develop the highest possible torque.

4. How do the maximum flux density ($B_{max.}$) and peak magnetizing current of an induction motor vary when the PWM inverter frequency decreases and the voltage at the PWM inverter output (motor stator voltage) remains constant?

   The maximum flux density ($B_{max.}$) and peak magnetizing current of an induction motor increase when the PWM inverter frequency decreases and the voltage at the PWM inverter output (motor stator voltage) remains constant.

5. Explain why the rms value of the fundamental-frequency component in the voltage (unfiltered) at the output of a three-phase PWM inverter cannot be measured using a conventional voltmeter.

The rms value of the fundamental-frequency component in the voltage (unfiltered) at the output of a three-phase PWM inverter cannot be measured using a conventional voltmeter because the voltage is a train of bipolar rectangular pulses which has a large harmonic content.

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