Electricity and New Energy

Principles of Doubly-Fed Induction Generators (DFIG)

Courseware Sample

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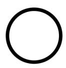
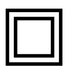
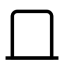
Safety and Common Symbols

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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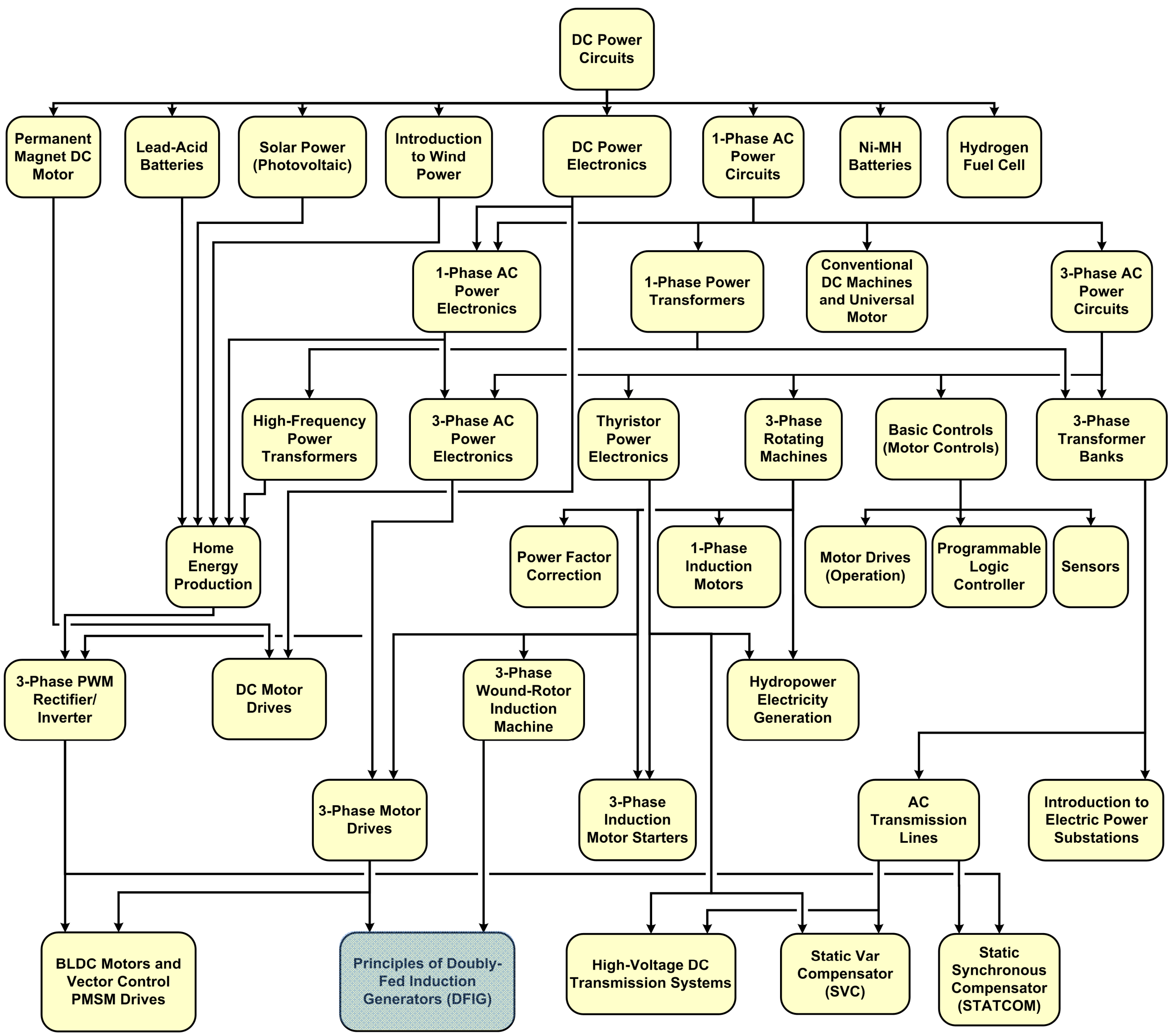
Preface

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

Doubly-fed electric machines are basically electric machines that are fed with ac currents into both their stator and rotor windings. Most doubly-fed electric machines in industry today are three-phase wound-rotor induction machines. Although their principles of operation have been known for decades, doubly-fed electric machines have only recently entered into common use. This is due almost exclusively to the advent of wind power technologies for electricity generation.

Doubly-fed induction generators (DFIGs) are by far the most widely used type of doubly-fed electric machine, and are one of the most common types of generator used to produce electricity in wind turbines. Doubly-fed induction generators have a number of advantages over other types of generators when used in wind turbines.

The primary advantage of doubly-fed induction generators when used in wind turbines is that they allow the amplitude and frequency of their output voltages to be maintained at a constant value, no matter the speed of the wind blowing on the wind turbine rotor. Because of this, doubly-fed induction generators can be directly connected to the ac power network and remain synchronized at all times with the ac power network. Other advantages include the ability to control the power factor (e.g., to maintain the power factor at unity), while keeping the power electronics devices in the wind turbine at a moderate size.

This manual, *Principles of Doubly-Fed Induction Generators (DFIG)*, covers the operation of doubly-fed induction generators, as well as their use in wind turbines. It also covers the operation of three-phase wound-rotor induction machines used as three-phase synchronous machines and doubly-fed induction motors. Although it is possible to use these machines by themselves, they are primarily studied as a stepping stone to doubly-fed induction generators.

Doubly-fed induction generators are commonly used in wind turbines to generate large amounts of electrical power.

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*, 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, *Three-Phase Rotating Machines*, part number 86364, *Three-Phase Motor Drives*, part number 86368, and *Three-Phase Wound-Rotor Induction Machine*, part number 86367.

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

Doubly-Fed Induction Generators

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the operation of three-phase wound-rotor induction machines used as doubly-fed induction generators. You will also know how doubly-fed induction generators are used in wind turbines to generate large amounts of electrical power.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Doubly-fed induction generator operation
- Using doubly-fed induction generators to produce fixed-frequency voltages
- Doubly-fed induction generators used in wind turbines

DISCUSSION

Doubly-fed induction generator operation

From now on, a three-phase wound-rotor induction machine operating as a doubly-fed induction generator will be referred to simply as a doubly-fed induction generator.

As seen in Exercise 2, a three-phase wound-rotor induction machine can be set up as a doubly-fed induction motor. In this case, the machine operates like a synchronous motor whose synchronous speed (i.e., the speed at which the motor shaft rotates) can be varied by adjusting the frequency f_{Rotor} of the ac currents fed into the rotor windings. The same wound-rotor induction machine setup can also serve as a doubly-fed induction generator. In this case, mechanical power at the machine shaft is converted into electrical power supplied to the ac power network via both the stator and rotor windings. Furthermore, the machine operates like a synchronous generator whose synchronous speed (i.e., the speed at which the generator shaft must rotate to generate power at the ac power network frequency $f_{Network}$) can be varied by adjusting the frequency of the ac currents fed into the rotor windings. The remainder of this exercise discussion deals with the operation of three-phase wound-rotor induction machines used as doubly-fed induction generators.

In a conventional three-phase synchronous generator, when an external source of mechanical power (i.e., a prime mover) makes the rotor of the generator rotate, the static magnetic field created by the dc current fed into the generator rotor winding rotates at the same speed (n_{Rotor}) as the rotor. As a result, a continually changing magnetic flux passes through the stator windings as the rotor magnetic field rotates, inducing an alternating voltage across the stator windings. Mechanical power applied to the generator shaft by the prime mover is thus converted to electrical power that is available at the stator windings.

In conventional (singly-fed) induction generators, the relationship between the frequency f_{Stator} of the ac voltages induced across the stator windings of the generator and the rotor speed n_{Rotor} is expressed using the following equation.

$$f_{Stator} = \frac{n_{Rotor} \times N_{Poles}}{120} \quad (3)$$

where f_{Stator} is the frequency of the ac voltages induced across the stator windings of the doubly-fed induction generator, expressed in hertz (Hz).

n_{Rotor} is the speed of the doubly-fed induction generator rotor, expressed in rotations per minute (r/min).

N_{Poles} is the number of poles in the doubly-fed induction generator per phase.

Using Equation (3), it is possible to determine that, when the speed n_{Rotor} of the generator rotor is equal to the generator synchronous speed n_S, the frequency f_{Stator} of the ac voltages induced across the stator windings of the generator is equal to the frequency $f_{Network}$ of the ac power network.

The same operating principles apply in a doubly-fed induction generator as in a conventional (singly-fed) induction generator. The only difference is that the magnetic field created in the rotor is not static (as it is created using three-phase ac current instead of dc current), but rather rotates at a speed $n_{\Phi,rotor}$ proportional to the frequency of the ac currents fed into the generator rotor windings. This means that the rotating magnetic field passing through the generator stator windings not only rotates due to the rotation of the generator rotor, but also due to the rotational effect produced by the ac currents fed into the generator rotor windings. Therefore, in a doubly-fed induction generator, both the rotation speed n_{Rotor} of the rotor and the frequency f_{Rotor} of the ac currents fed into the rotor windings determine the speed $n_{\Phi,stator}$ of the rotating magnetic field passing through the stator windings, and thus, the frequency f_{Stator} of the alternating voltage induced across the stator windings.

Taking into account the principles of operation of doubly-fed induction generators, it can thus be determined that, when the magnetic field at the rotor rotates in the same direction as the generator rotor, the rotor speed n_{Rotor} and the speed $n_{\Phi,rotor}$ of the rotor magnetic field (proportional to f_{Rotor}) add up. This is shown in Figure 10a. The frequency f_{Stator} of the voltages induced across the stator windings of the generator can thus be calculated using the following equation:

$$f_{Stator} = \frac{n_{Rotor} \times N_{Poles}}{120} + f_{Rotor} \quad (4)$$

where f_{Rotor} is the frequency of the ac currents fed into the doubly-fed induction generator rotor windings, expressed in hertz (Hz).

Conversely, when the magnetic field at the rotor rotates in the direction opposite to that of the generator rotor, the rotor speed n_{Rotor} and the speed $n_{\Phi,rotor}$ of the rotor magnetic field subtract from each other. This is shown in Figure 10b. The frequency f_{Stator} of the voltages induced across the stator windings of the generator can thus be calculated using the following equation:

$$f_{Stator} = \frac{n_{Rotor} \times N_{Poles}}{120} - f_{Rotor} \quad (5)$$

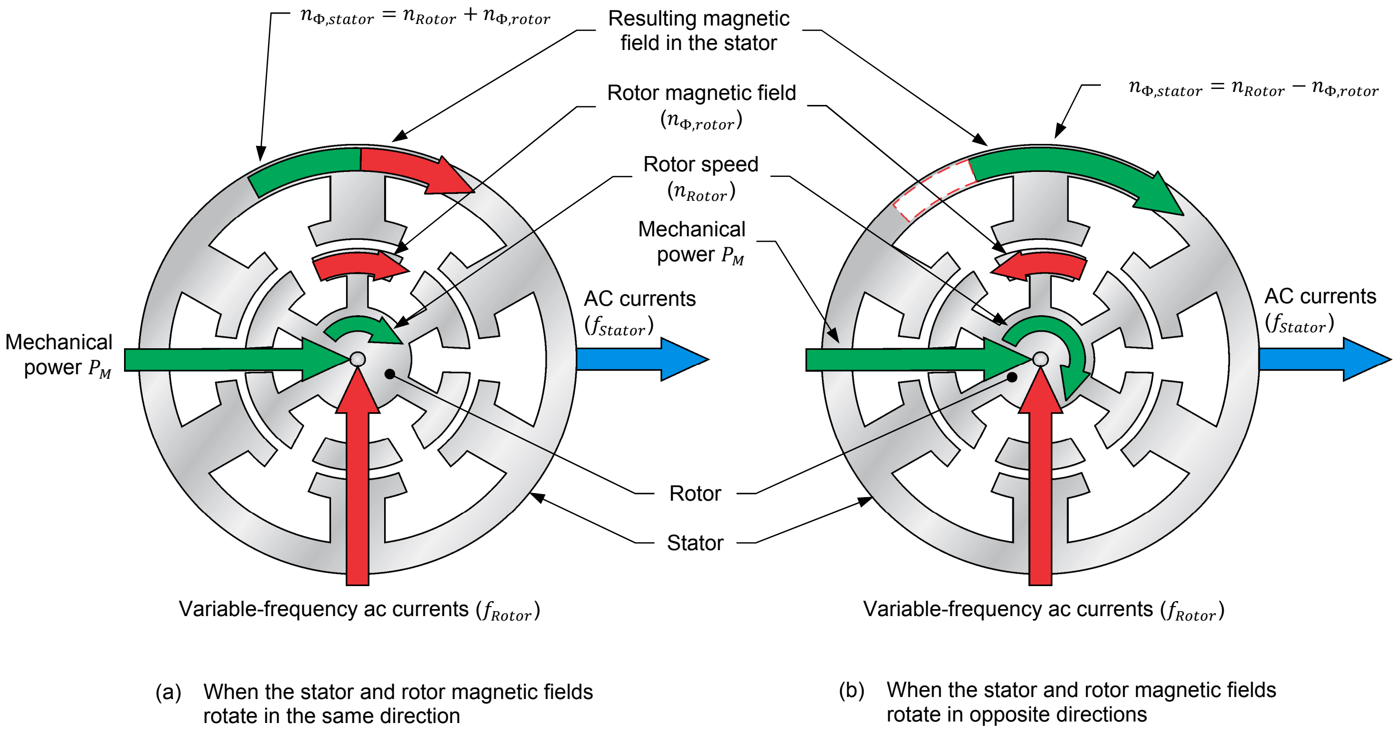


Figure 10. Interaction between the rotor speed and the frequency of the rotating magnetic field created in the rotor windings of a doubly-fed induction generator.

In other words, the frequency f_{Stator} of the ac voltages produced at the stator of a doubly-fed induction generator is proportional to the speed $n_{\Phi,stator}$ of the rotating magnetic field at the stator. The speed $n_{\Phi,stator}$ of the stator rotating magnetic field itself depends on the rotor speed n_{Rotor} (resulting from the mechanical power at the rotor shaft) and the frequency f_{Rotor} of the ac currents fed into the machine rotor.

Using doubly-fed induction generators to produce fixed-frequency voltages

The primary reason for using a doubly-fed induction generator is generally to produce three-phase voltage whose frequency f_{Stator} is constant, i.e., whose frequency f_{Stator}remains equal to the frequency $f_{Network}$ of the ac power network to which the generator is connected, despite variations in the generator rotor speed n_{Rotor} caused by fluctuations of the mechanical power provided by the prime mover (e.g., a wind turbine rotor) driving the generator. To achieve this purpose, the frequency f_{Rotor} of the ac currents fed into the rotor windings of the doubly-fed induction generator must be continually adjusted to counteract any variation in the rotor speed n_{Rotor} caused by fluctuations of the mechanical power provided by the prime mover driving the generator.

The frequency f_{Rotor} of the ac currents that need to be fed into the doubly-fed induction generator rotor windings to maintain the generator output frequency f_{Stator} at the same value as the frequency $f_{Network}$ of the ac power network depends on the rotation speed of the generator rotor n_{Rotor}, and can be calculated using the following equation:

$$f_{Rotor} = f_{Network} - \frac{n_{Rotor} \times N_{Poles}}{120} \qquad (6)$$

where f_{Rotor} is the frequency of the ac currents that need to be fed into the doubly-fed induction generator rotor windings for f_{Stator} to be equal to $f_{Network}$, expressed in hertz (Hz).

$f_{Network}$ is the frequency of the ac power network to which the doubly-fed induction generator is connected, expressed in hertz (Hz).

n_{Rotor} is the rotational speed of the generator rotor, expressed in rotations per minute (r/min).

N_{Poles} is the number of magnetic poles per phase in the doubly-fed induction generator.

Using Equation (6), it is possible to calculate that, if the generator rotor rotates at the nominal (singly-fed) synchronous speed n_S, the frequency f_{Rotor} of the ac currents that need to be fed into the generator rotor windings will be equal to 0 Hz (i.e., dc current). The machine would thus operate as a conventional (singly-fed) three-phase synchronous machine.

When the generator rotor speed n_{Rotor} decreases below the nominal synchronous speed n_S, the frequency f_{Rotor} of the ac currents that need to be fed into the generator windings increases accordingly and is of positive polarity. The positive polarity of the frequency f_{Rotor} indicates that the phase sequence of the three-phase ac currents fed into the rotor windings must make the rotor magnetic field rotate in the same direction as the generator rotor, as is illustrated in Figure 10a.

Similarly, when the generator rotor speed n_{Rotor} increases above the nominal synchronous speed n_S, the frequency f_{Rotor} of the ac currents that need to be fed into the generator windings increases accordingly and is of negative polarity. The negative polarity of the frequency f_{Rotor} indicates that the phase sequence of the three-phase ac currents fed into the rotor windings must make the rotor magnetic field rotate in the direction opposite to that of the generator rotor, as is illustrated in Figure 10b.

For example, consider a doubly-fed induction generator having 4 magnetic poles. The generator supplies power to a 60 Hz ac power network. Considering that an external source makes the generator rotate at a speed of 1980 r/min, the frequency f_{Rotor} of the ac currents that need to be fed into the generator rotor windings can be calculated so:

$$f_{Rotor} = f_{Network} - \frac{n_{Rotor} \times N_{Poles}}{120} = 60\ \text{Hz} - \frac{1980\ \text{r/min} \times 4\ \text{poles}}{120} = -6\ \text{Hz}$$

The frequency f_{Rotor} of the ac currents to be fed into the generator rotor windings so that the frequency f_{Stator} of the generator output voltage is equal to the frequency $f_{Network}$ of the ac power network is 6 Hz. The negative polarity of the frequency f_{Rotor} indicates that the magnetic field created in the rotor windings must rotate in the direction opposite to the direction of the rotor.

When a doubly-fed induction generator is used to produce power at the ac power network voltage and frequency, any deviation of the generator rotor speed n_{Rotor} from the synchronous speed n_S is compensated by adjusting the frequency f_{Rotor} of the ac currents fed into the generator rotor windings so that the frequency f_{Stator} of the voltage produced at the stator remains equal to the ac power network frequency $f_{Network}$. In other words, the frequency f_{Rotor} is adjusted so that the speed $n_{\Phi,stator}$ of the rotating magneting field passing through the stator windings remains constant. Consequently, to maintain the voltage produced at the stator equal to the ac power network voltage, a specific magnetic flux value must be maintained in the machine (more precisely at the stator windings). This can be achieved by applying a voltage to the generator rotor windings that is proportional to the frequency of the voltages applied to the rotor windings (this maintains the V/f ratio constant and ensures a constant magnetic flux value in the machine). The value of the V/f ratio is generally set so that the reactive power at the stator Q_{Stator} is equal to zero. This is similar to the common practice used with conventional (singly-fed) synchronous generators where the exciter current (dc current in the rotor) is adjusted so as to zero the reactive power at the stator Q_{Stator}.

Doubly-fed induction generators used in wind turbines

Most doubly-fed induction generators in industry today are used to generate electrical power in large (power-utility scale) wind turbines. This is primarily due to the many advantages doubly-fed induction generators offer over other types of generators in applications where the mechanical power provided by the prime mover driving the generator varies greatly (e.g., wind blowing at variable speed on the bladed rotor of a wind turbine). To better understand the advantages of using doubly-fed induction generators to generate electrical power in wind turbines, however, it is important to know a little about large-size wind turbines.

Large-size wind turbines are basically divided into two types which determine the behavior of the wind turbine during wind speed variations: fixed-speed wind turbines and variable-speed wind turbines. In fixed-speed wind turbines, three-phase asynchronous generators are generally used. Because the generator output is tied directly to the grid (local ac power network), the rotation speed of the generator is fixed (in practice, it can generally vary a little, since the slip is allowed to vary over a range of typically 2% to 3%), and so is the rotation speed of the wind turbine rotor. Any fluctuation in wind speed naturally causes the mechanical power at the wind turbine rotor to vary and, because the rotation speed is fixed, this causes the torque at the wind turbine rotor to vary accordingly. Whenever a wind gust occurs, the torque at the wind turbine rotor thus increases significantly while the rotor speed varies little. Therefore, every wind gust stresses the mechanical components (notably the gear box) in the wind turbine and causes a sudden increase in rotor torque, as well as in the power at the wind turbine generator output. Any fluctuation in the output power of a wind turbine generator is a source of instability in the power network to which it is connected.

In variable-speed wind turbines, the rotation speed of the wind turbine rotor is allowed to vary as the wind speed varies. This precludes the use of asynchronous generators in such wind turbines as the rotation speed of the generator is quasi-constant when its output is tied directly to the grid. The same is true for synchronous generators which operate at a strictly constant speed when tied directly to the grid.

This is where doubly-fed induction generators come into play, as they allow the generator output voltage and frequency to be maintained at constant values, no matter the generator rotor speed (and thus, no matter the wind speed). As seen in the previous section, this is achieved by feeding ac currents of variable frequency and amplitude into the generator rotor windings. By adjusting the amplitude and frequency of the ac currents fed into the generator rotor windings, it is possible to keep the amplitude and frequency of the voltages (at stator) produced by the generator constant, despite variations in the wind turbine rotor speed (and, consequently, in the generator rotation speed) caused by fluctuations in wind speed. By doing so, this also allows operation without sudden torque variations at the wind turbine rotor, thereby decreasing the stress imposed on the mechanical components of the wind turbine and smoothing variations in the amount of electrical power produced by the generator. Using the same means, it is also possible to adjust the amount of reactive power exchanged between the generator and the ac power network. This allows the power factor of the system to be controlled (e.g., in order to maintain the power factor at unity). Finally, using a doubly-fed induction generator in variable-speed wind turbines allows electrical power generation at lower wind speeds than with fixed-speed wind turbines using an asynchronous generator.

It would be possible to obtain similar results in variable-speed wind turbines using a three-phase synchronous generator and power electronics, as shown in Figure 11a. In this setup, the generator rotates at a speed that is proportional to the wind speed. The ac currents produced by the generator are converted into dc current by an AC/DC converter, then converted by another AC/DC converter back to ac currents that are synchronous with the ac power network. It is therefore necessary for the power electronics devices used in such a circuit to have the size and capacity to process 100% of the generator output power.

The power electronics devices used in doubly-fed induction generators, on the other hand, need only to process a fraction of the generator output power, i.e., the power that is supplied to or from the generator rotor windings, which is typically about 30% of the generator rated power. Consequently, the power electronics devices in variable-speed wind turbines using doubly-fed induction generators typically need only to be about 30% of the size of the power electronics devices used for comparatively sized three-phase synchronous generators, as illustrated in Figure 11b. This reduces the cost of the power electronics devices, as well as the power losses in these devices.

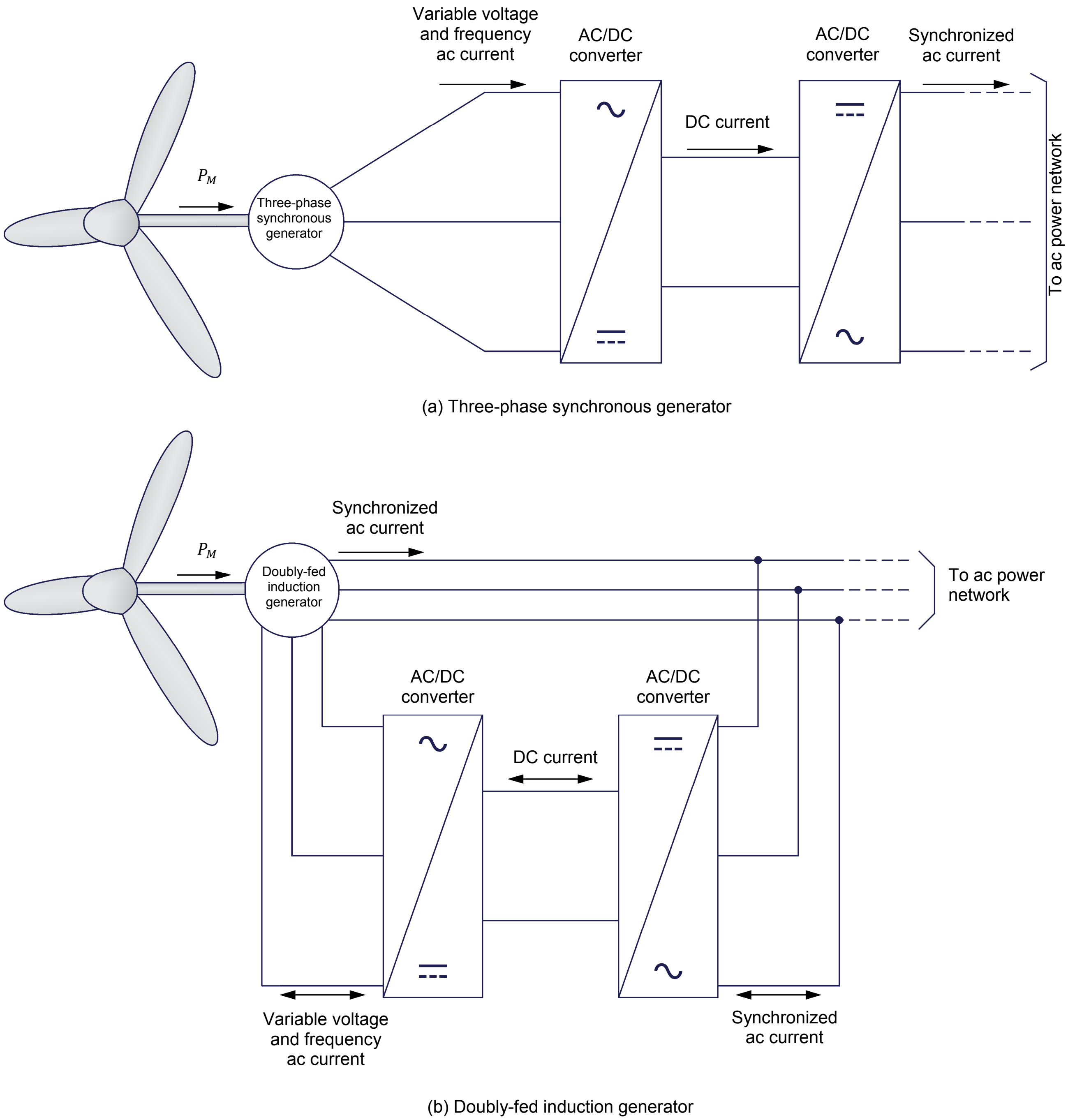


Figure 11. Circuit topologies for two types of generators found in variable-speed wind turbines.

To summarize, using a doubly-fed induction generator instead of an asynchronous generator in wind turbines offers the following advantages:

1. Operation at variable rotor speed while the amplitude and frequency of the generated voltages remain constant.

2. Optimization of the amount of power generated as a function of the wind available up to the nominal output power of the wind turbine generator.

3. Virtual elimination of sudden variations in the rotor torque and generator output power.

4. Generation of electrical power at lower wind speeds.

5. Control of the power factor (e.g., in order to maintain the power factor at unity).

On the other hand, the doubly-fed induction generator requires complex power conversion circuitry which the asynchronous generator does not need. Also, the slip rings on the wound-rotor induction machine used to implement the doubly-fed induction generator require periodic maintenance while no such rings are required on the rotor of the squirrel-cage induction machine used to implement the asynchronous generator.

Using a synchronous generator in wind turbines offers the same advantages (see above) as when a doubly-fed induction generator is used. Both types of generator require two AC/DC converters. However, the two AC/DC converters in doubly-fed induction generators are significantly smaller than those in synchronous generators of comparable output power. This is because the AC/DC converters in doubly-fed induction generators convey only about 30% of the nominal generator output power while the AC/DC converters in synchronous generators convey 100% of the nominal generator output power.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Doubly-fed induction generator hyposynchronous operation
- Doubly-fed induction generator hypersynchronous operation

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 section, you will set up a circuit containing a three-phase wound-rotor induction machine coupled to a prime mover. You will then set the measuring equipment required to study the three-phase wound-rotor induction machine operating as a doubly-fed induction generator.

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

   Make sure that a 24 teeth pulley is installed on the shaft of the Three-Phase Wound-Rotor Induction Machine. If not, ask your instructor to install the pulley required on the shaft of the machine.

   Appendix E shows how to replace the pulley installed on the shaft of a machine.

   Install the required equipment in the Workstation.

   Mechanically couple the Three-Phase Wound-Rotor Induction Machine 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 wall 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 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. Connect the equipment as shown in Figure 12. On the IGBT Chopper/Inverter, make sure that the *Dumping* switch is set to the **I** position.

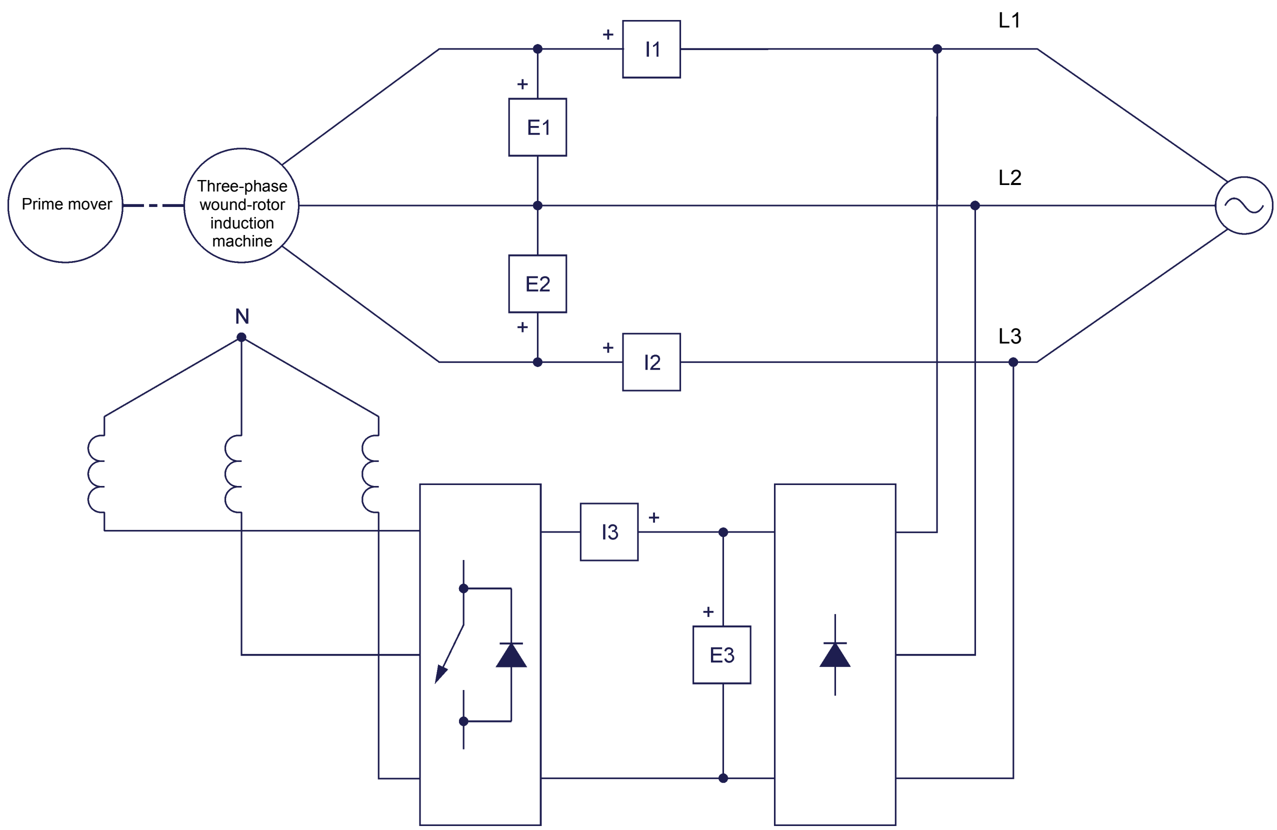


Figure 12. Three-phase wound-rotor induction machine operating as a doubly-fed induction generator.

The two AC/DC converters used to implement the doubly-fed induction generator shown in the figure above are a three-phase rectifier and a three-phase PWM inverter (implemented using the IGBT Chopper/Inverter). The three-phase rectifier allows power to flow from the ac power source to the generator rotor windings only. Therefore, make sure that the Dumping switch on the IGBT Chopper/Inverter is set to the I position. This allows power that come from the generator rotor windings under certain operating conditions to be dissipated into a dump resistor integrated into the three-phase PWM inverter, as is done in many actual doubly-fed induction generators. In certain other doubly-fed induction generators, two bidirectional AC/DC converters (three-phase PWM rectifier/inverter) are used to allow power flow in both directions. This allows power coming from the generator rotor winding to be returned to the ac power source, thereby increasing the total power supplied to the source. The operation principles of the three-phase PWM rectifier/inverter, however, are beyond the scope of this manual.

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

5. Turn the Four-Quadrant Dynamometer/Power Supply on, then set the *Operating Mode* switch to *Dynamometer*. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a prime mover, a brake, or both, depending on the selected function.

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* function for the Data Acquisition and Control Interface is 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. 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*. This makes the Four-Quadrant Dynamometer/Power Supply operate as a prime mover/brake with a positive (applied in clockwise direction) torque setting corresponding to the *Torque* parameter.

   – Set the *Torque* parameter to 1.5 N·m (13.3 lbf·in) if your ac power network frequency is 60 Hz, or set it to 1.8 N·m (15.9 lbf·in) if your ac power network frequency is 50 Hz.

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

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

   – Select the *Three-Phase, PWM Inverter* function.

   – Set the *Switching Frequency* to 1000 Hz.

   – Set the *Phase Sequence* to *Fwd/Rev*.

   – Set the *Frequency* to 0.0 Hz.

   – Set the *Peak Voltage (% of DC Bus/2)* parameter to 25%.

   – Make sure that the Q_1 to Q_6 parameters are set to *PWM*.

9. In LVDAC-EMS, start the Metering application. Make the required settings in order to measure the doubly-fed induction generator active power at the stator P_{Stator} and reactive power at the stator Q_{Stator} using the two-wattmeter method (meter function *PQS1 + PQS2*). Set another meter to measure the active power P_{Rotor} that is supplied to the motor rotor windings.

Doubly-fed induction generator hyposynchronous operation

In this section, you will make the doubly-fed induction generator rotate at the synchronous speed with a constant torque. You will confirm that the machine operates as a three-phase synchronous generator. You will adjust the amount of current fed into the generator rotor so that the generator reactive power at the stator is virtually equal to zero. You will then record the generator speed, mechanical power, active power at the stator, reactive power at the stator, active power at the rotor, and rotor frequency in the Data Table. You will increase the generator rotor frequency (with the same sequence at the rotor and stator) by steps of 1 Hz, each time adjusting the reactive power at the stator to 0 var, and recording the generator parameters in the Data Table. You will stop increasing the generator rotor frequency when it is no longer possible to adjust the reactive power at the stator to 0 var.

10. On the Three-Phase Wound-Rotor Induction Machine, press and hold the *Protection Override* push-button in order to momentarily override the overvoltage protection then, on the Power Supply, turn the three-phase ac power source on. Release the *Protection Override* push-button.

> *The first time the three-phase ac power source of the Power Supply is turned on, the circuit breaker (i.e., the switch) of the ac power source may trip, due to a large capacitive current inrush into the IGBT Chopper/Inverter. If so, repeat the manipulation above as many times as necessary for the motor to start to rotate without tripping the circuit breaker.*

Before starting the prime mover, make sure that the Three-Phase Wound-Rotor Induction Machine is rotating in the clockwise direction. If so, proceed directly to the next step. Otherwise, turn the three-phase ac power source off, invert the connections at two of the three phase terminals of the machine stator windings, then repeat this step from the beginning.

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

In the Four-Quadrant Dynamometer/Power Supply window, start the *Positive Constant-Torque Prime Mover/Brake*.

Is the three-phase wound-rotor induction machine now rotating at the synchronous speed, thus confirming that the machine operates as a three-phase synchronous machine?

❑ Yes ❑ No

Yes

Is the three-phase wound-rotor induction machine active power at the stator P_{Stator} indicated in the Metering window positive, indicating that active power is supplied from the machine to the three-phase ac power source and thus, that the machine operates as a generator?

❑ Yes ❑ No

Yes

Do your observations confirm that the three-phase wound-rotor induction machine is operating as a doubly-fed induction generator?

❑ Yes ❑ No

Yes

12. In the Chopper/Inverter Control window, adjust the value of the *Peak Voltage (% of DC Bus/2)* parameter until the doubly-fed induction generator reactive power at the stator Q_{Stator} is virtually equal to 0 var.

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

Set the Data Table to record the doubly-fed induction generator speed n, and mechanical power P_M indicated in the Four-Quadrant Dynamometer/Power Supply window.

Also, set the Data Table to record the doubly-fed induction generator active power at the stator P_{Stator}, reactive power at the stator Q_{Stator}, and active power at the rotor P_{Rotor} indicated in the Metering application.

Finally, set the Data Table to record the frequency f_{Rotor} of the ac currents fed into the rotor of the doubly-fed induction generator.

14. In the Data Table, click on the *Record Data* button to record the current values of the doubly-fed induction generator speed n, mechanical power P_M, active power at the stator P_{Stator}, reactive power at the stator Q_{Stator}, active power at the rotor P_{Rotor}, and rotor frequency f_{Rotor}.

15. In the Chopper/Inverter Control window, increase the *Frequency* parameter by 1.0 Hz.

Adjust the value of the *Peak Voltage (% of DC Bus/2)* parameter until the doubly-fed induction generator reactive power at the stator Q_{Stator} is virtually equal to 0 var.

16. Repeat steps 14 and 15 until the value of the *Peak Voltage (% of DC Bus/2)* parameter required to zero the reactive power at the stator Q_{Stator} of the doubly-fed induction generator reaches 100%.

In the Four-Quadrant Dynamometer/Power Supply window, stop the *Positive Constant-Torque Prime Mover/Brake*.

Proceed with the next section of the exercise and make sure to keep the data recorded in the Data Table, since this data will be used later to plot graphs.

Doubly-fed induction generator hypersynchronous operation

In this section, you will set the doubly-fed induction generator rotor frequency back to 0 Hz, and make the generator rotate at the synchronous speed with a constant torque. You will adjust the generator reactive power at the stator to 0 var. You will then reverse the phase sequence of the currents fed into the rotor windings and increase the generator rotor frequency (the phase sequence at the rotor is now opposite to that at the stator) by steps of 1 Hz, each time adjusting the generator reactive power at the stator to 0 var, and recording the generator parameters in the Data Table. You will stop increasing the generator rotor frequency when it is not possible anymore to adjust the generator reactive power at the stator to 0 var, or when the maximum power output of the prime mover is reached. You will export the data to a spreadsheet, and calculate the generator total power and efficiency using the recorded generator parameters. You will also extrapolate the generator active power at the rotor when power is returned to the three-phase ac power source. You will plot the generator mechanical power, active power at the stator, active power at the rotor, and total power as a function of the generator speed on the same graph, and analyze the results. Finally, you will plot the generator efficiency as a function of the generator speed, and analyze the results.

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

Make the following settings:

– Set the *Frequency* to 0.0 Hz.

– Set the *Peak Voltage (% of DC Bus/2)* parameter to 25%.

– Start the *Three-Phase, PWM Inverter*.

In the Four-Quadrant Dynamometer/Power Supply window, start the *Positive Constant-Torque Prime Mover/Brake*.

18. In the Chopper/Inverter Control window, adjust the value of the *Peak Voltage (% of DC Bus/2)* parameter until the doubly-fed induction generator reactive power at the stator Q_{Stator} is virtually equal to 0 var.

19. In the Chopper/Inverter Control window, decrease the *Frequency* parameter by 1.0 Hz.

> *The polarity of the Frequency parameter is negative, indicating that the phase sequence at the three-phase inverter output is reversed. Therefore, whenever the Frequency parameter is decreased (e.g., when it passes from -2.0 Hz to -3.0 Hz), the frequency of the ac currents fed into the rotor windings actually increases (e.g., it passes from 2.0 Hz to 3.0 Hz).*

Adjust the value of the *Peak Voltage (% of DC Bus/2)* parameter until the doubly-fed induction generator reactive power at the stator Q_{Stator} is virtually equal to 0 var.

20. In the Data Table, click on the *Record Data* button to record the current value of the doubly-fed induction generator speed n, mechanical power P_M, active power at the stator P_{Stator}, reactive power at the stator Q_{Stator}, active power at the rotor P_{Rotor}, and rotor frequency f_{Rotor}.

Each time you record the generator parameters on the Data Table, observe if the *Dumping* LED on the IGBT Chopper/Inverter turns on intermittently, indicating that power is returned from the generator rotor windings to the three-phase PWM inverter and then dumped in capacitor C_{Bus} of the IGBT Chopper/Inverter. Record the generator speed n below when you observe for the first time that the *Dumping* LED turns on intermittently.

21. Repeat steps 19 and 20 until the value of the *Peak Voltage (% of DC Bus/2)* parameter required to zero the reactive power at the stator Q_{Stator} of the doubly-fed induction generator reaches 100% (117% if your local ac power network voltage is 240 V ac).

> *During the course of this manipulation, the Four-Quadrant Dynamometer/Power Supply reaches its maximum mechanical power output value before the peak voltage limit is reached. When so, continue the manipulation as rapidly as possible to avoid tripping the thermal overload protection in the Four-Quadrant Dynamometer/Power Supply.*

Generator speed n at which the rotor windings begin to supply power: _______ r/min

Generator speed n at which the rotor windings begin to supply power: 2160 r/min

22. In the Four-Quadrant Dynamometer/Power Supply window, stop the *Positive Constant-Torque Prime Mover/Brake*.

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

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

23. In the Data Table window, save the recorded data, then export it to a spreadsheet application. Sort the data by using the generator speed n as the reference parameter, from the lowest value to the highest.

In the spreadsheet application, invert the polarity of the generator mechanical power P_M. The polarity of the generator mechanical power P_M is now positive.

For the purpose of plotting graphs, it is more convenient to consider the mechanical power parameter as mechanical power supplied by the prime mover to the generator (i.e., as a positive mechanical power value) than as mechanical power used by the generator (i.e., as a negative mechanical power value).

In the spreadsheet application, delete the values of generator active power at the rotor P_{Rotor} that are equal to or lower than about 2 W. Using the remaining values of rotor active power P_{Rotor} in the speadshet column, calculate the rate at which the generator active power at the rotor P_{Rotor} varies with the generator speed n. Then, use this rate to extrapolate the actual values of active power at the rotor P_{Rotor} when power is supplied from the generator rotor windings to the three-phase ac power source.

The doubly-fed induction generator setup used in this exercise does not allow power produced by the generator rotor windings to be returned to the three-phase ac power source. Because of this, it is necessary to extrapolate the actual values of active power at the rotor P_{Rotor} when power is returned to the three-phase ac power source using the directly proportional function relating the generator active power at the rotor P_{Rotor} to the generator speed n.

In the spreadsheet application, add a new parameter to the results: the total power P_{Total} generated by the doubly-fed induction generator. To calculate the generator total power P_{Total}, subtract the active power at the rotor P_{Rotor} from the active power at the stator P_{Stator}. The generator total power P_{Total} is thus equal to the amount of power supplied to the three-phase ac power source by the generator minus the amount of power that the three-phase ac power source supplies to the generator rotor. This means that, when the active power at the rotor P_{Rotor} is negative and that power is supplied by the generator rotor windings, the active power at the rotor P_{Rotor} adds to the active power at the stator P_{Stator} when calculating the generator total power P_{Total}.

Finally, add another parameter to the results: the doubly-fed induction generator efficiency η. To calculate the generator efficiency η, divide each total power value P_{Total} by the corresponding mechanical power value P_M, then multiply the result by 100 to express the efficiency η as a percentage.

The results obtained are presented below.

Doubly-fed induction generator speed n, mechanical power P_M, active power at the stator P_{Stator}, reactive power at the stator Q_{Stator}, active power at the rotor P_{Rotor}, rotor frequency f_{Rotor}, total power P_{Total}, and efficiency η.

Speed n (r/min)	Mechanical power P_M (W)	Stator active power P_{Stator} (W)	Stator reactive power Q_{Stator} (var)	Rotor active power P_{Rotor} (W)	Rotor frequency f_{Rotor} (Hz)	Total power P_{Total} (W)	Efficiency η (%)
1470	230.6	264.5	4.49	107.30	11	157.2	68.2
1500	235.4	267.0	4.55	99.50	10	167.5	71.2
1530	240.1	264.7	-1.03	95.71	9	169.0	70.4
1559	244.5	264.7	5.53	93.88	8	170.8	69.9
1590	249.6	265.9	1.64	87.05	7	178.9	71.7
1620	254.0	266.8	1.26	78.97	6	187.8	73.9
1650	258.9	264.0	2.84	75.63	5	188.4	72.8
1680	263.6	265.1	-0.79	71.01	4	194.1	73.6
1709	268.3	263.9	0.33	65.36	3	198.5	74.0
1740	273.2	264.3	-1.03	60.14	2	204.2	74.7
1769	277.2	264.3	2.89	55.81	1	208.5	75.2
1800	282.4	265.8	9.78	50.58	0	215.2	76.2
1830	287.0	263.7	-0.28	48.91	-1	214.8	74.8
1860	291.5	266.2	-0.33	44.21	-2	222.0	76.2
1890	296.4	265.0	3.88	39.56	-3	225.4	76.1
1919	300.8	264.4	2.25	35.67	-4	228.7	76.0
1950	305.7	265.1	-2.95	29.29	-5	235.8	77.1
1980	310.5	265.5	0.57	24.10	-6	241.4	77.7
2009	315.1	267.0	0.43	19.82	-7	247.2	78.4
2040	319.9	267.0	0.91	16.50	-8	250.5	78.3
2069	324.6	266.8	-1.19	9.74	-9	257.1	79.2
2099	328.7	267.3	-3.22	5.16	-10	262.1	79.8
2129	333.9	266.1	3.14	0.33*	-11	265.8	79.6
2160	338.6	268.9	-2.96	-4.50*	-12	273.4	80.7
2190	343.0	268.4	3.49	-9.33*	-13	277.7	80.8
2220	347.8	268.1	2.31	-16.16*	-14	284.3	81.7
2249	352.7	266.9	0.48	-18.99*	-15	286.0	81.1
2280	357.2	265.6	3.61	-23.82*	-16	289.4	81.0
2309	362.0	266.6	-4.64	-26.65*	-17	293.3	81.0

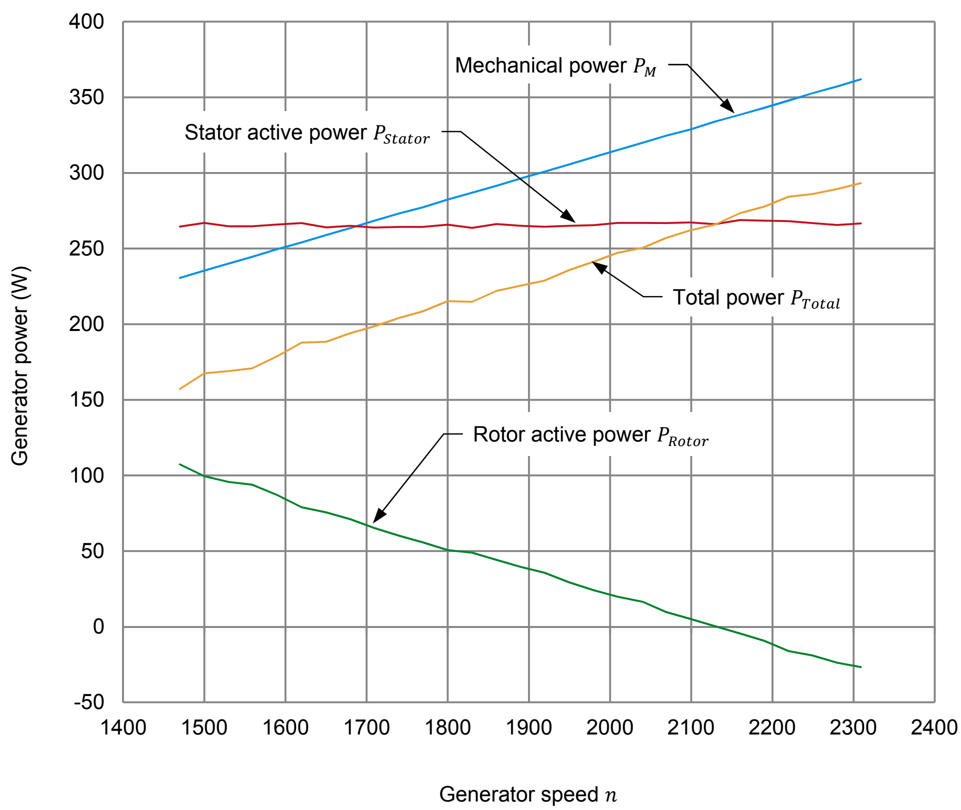
* Indicates that the results were obtained through extrapolation.

24. Do the results you obtained confirm that a doubly-fed induction machine operates like a variable-speed synchronous generator? Briefly explain why.

Yes, because the doubly-fed induction generator rotates at the synchronous speed and the synchronous speed of the generator can be modified by adjusting the value of the rotor frequency f_{Rotor}.

25. On the same graph, plot curves of the doubly-fed induction generator mechanical power P_M, active power at the stator P_{Stator}, active power at the rotor P_{Rotor}, and total power P_{Total} as a function of the generator speed n using the results you exported to the spreadsheet application.

The resulting graph is shown below.



Doubly-fed induction generator mechanical power P_M, active power at the stator P_{Stator}, active power at the rotor P_{Rotor}, and total power P_{Total} as a function of the generator speed n.

26. Consider the three schemas shown in Figure 13 (see next page) representing the doubly-fed induction generator when the generator rotates at minimum speed, singly-fed synchronous speed, and maximum speed. Using the results you exported to the spreadsheet application, draw the power balance of the doubly-fed induction generator by filling in the arrows representing power values in the three schemas of Figure 13.

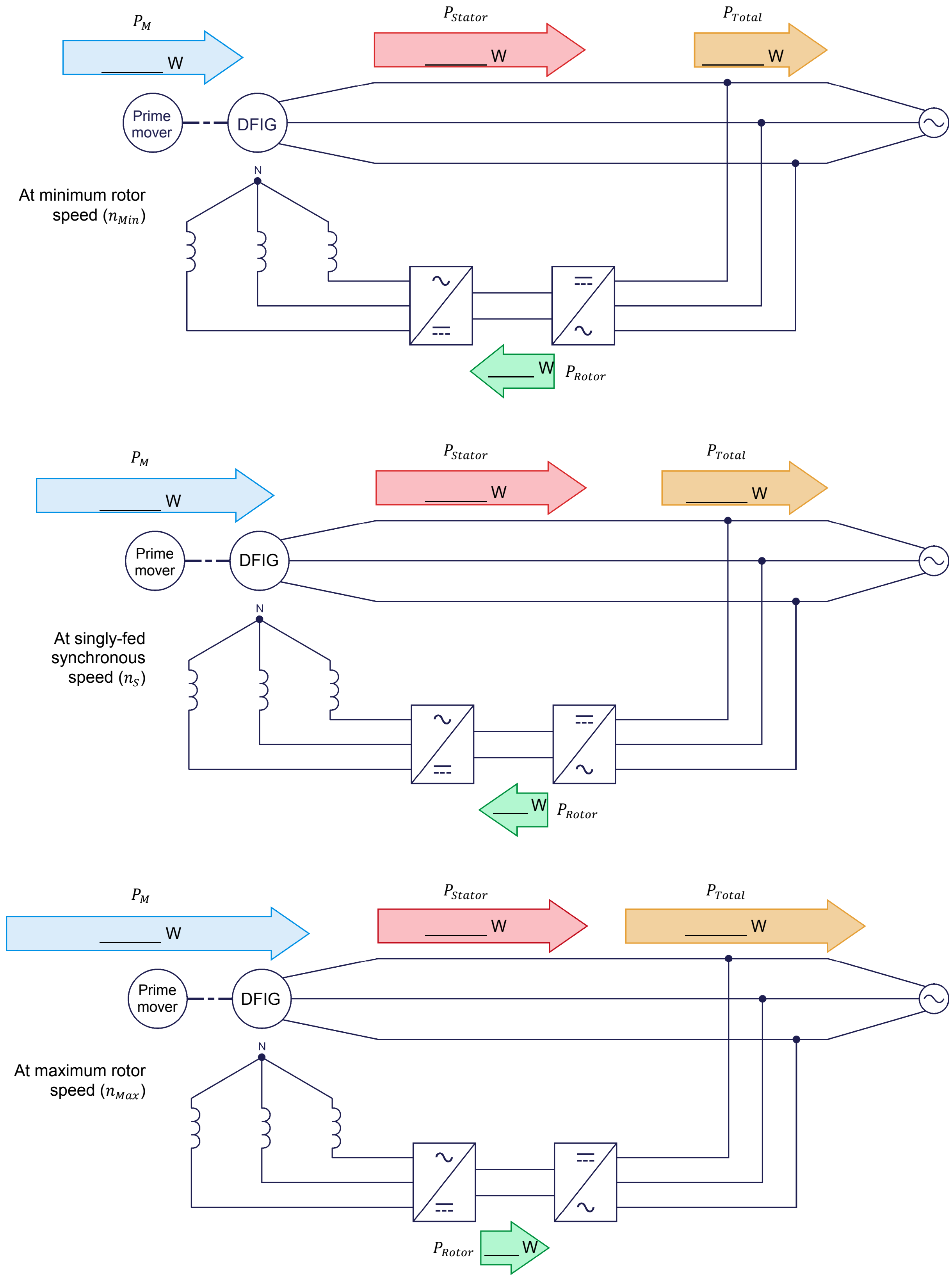
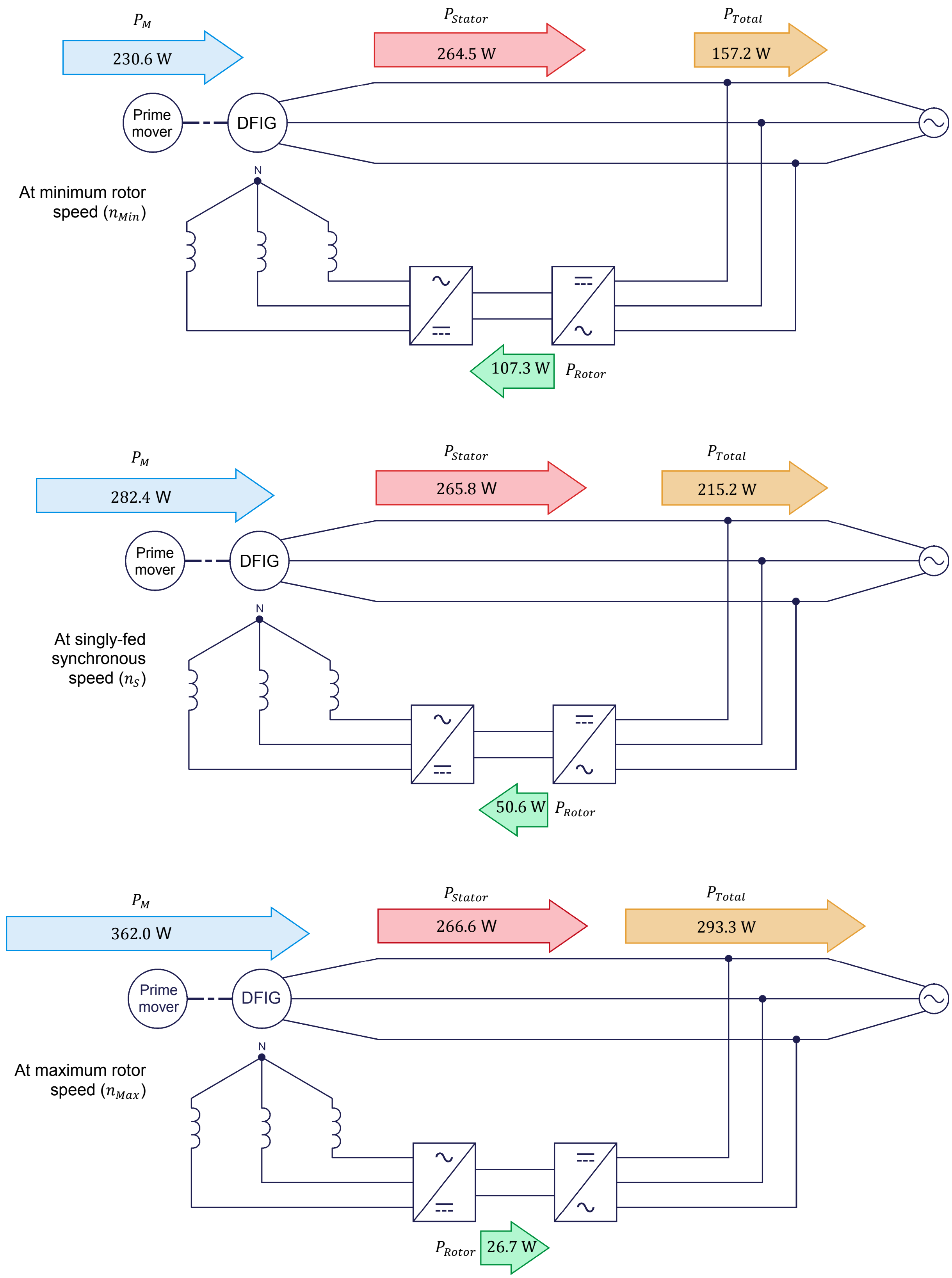


Figure 13. Power balance of the doubly-fed induction generator when the generator rotates at minimum speed, singly-fed synchronous speed, and maximum speed.

The power balance of the doubly-fed induction generator when the generator rotates at minimum speed, singly-fed synchronous speed, and maximum speed are presented on the following page.



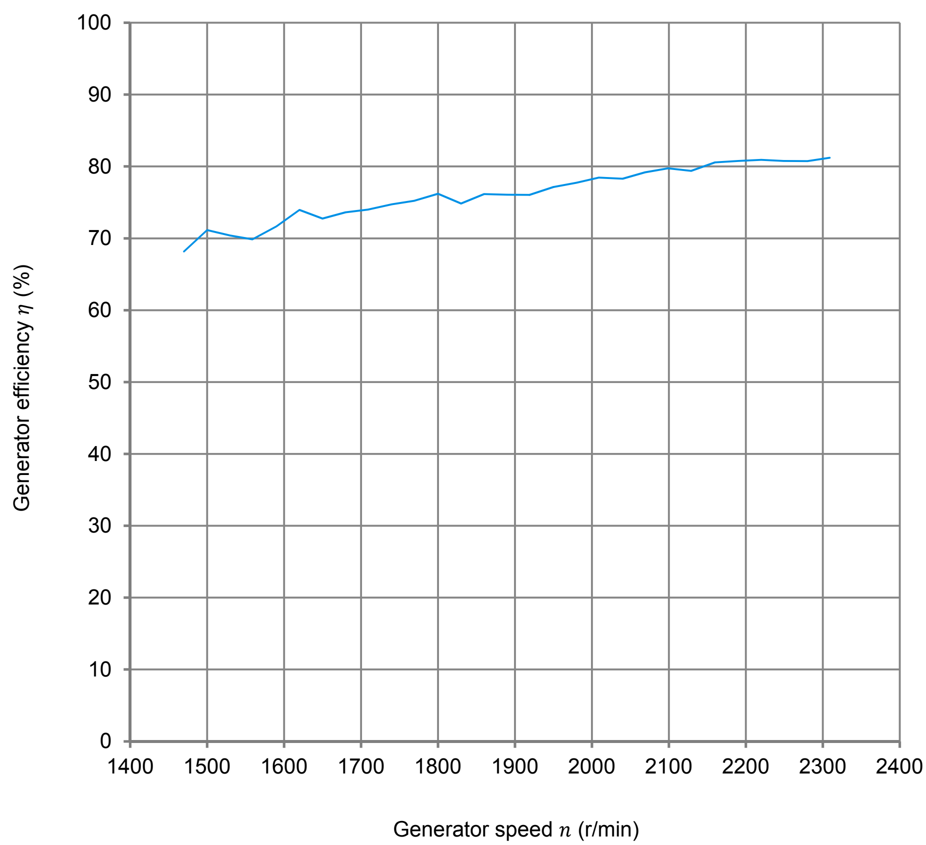
Power balance of the doubly-fed induction generator when the generator rotates at minimum speed, singly-fed synchronous speed, and maximum speed.

Describe what happens to the doubly-fed induction generator power balance as the generator speed n increases and the magnetic flux in the generator is maintained at the optimal value (i.e., when the reactive power at the stator Q_{Stator} is equal to 0 var).

As the doubly-fed induction generator speed n increases and the magnetic flux in the generator is maintained at the optimal value, the active power at the stator P_{Stator} remains constant, while the active power at the rotor P_{Rotor} decreases. Consequently, the generator total power P_{Total} increases. Furthermore, when the generator speed n reaches a certain value (in hypersynchronous operation), the rotor begins supplying active power (the polarity of active power at the rotor P_{Rotor} becomes negative), which adds up to the active power P_{Stator} supplied by the stator.

27. Plot the curve of the doubly-fed induction generator efficiency η as a function of the generator synchronous speed n_S using the results you exported to the spreadsheet application.

The resulting graph is shown below.



Doubly-fed induction generator efficiency η as a function of the generator synchronous speed n_S.

Observe the graph. Describe the relationship between the doubly-fed induction generator efficiency η and the generator speed n when the magnetic flux in the generator is maintained at the optimal value (i.e., when the reactive power at the stator Q_{Stator} is equal to 0 var).

The doubly-fed induction generator efficiency η increases slightly with the generator speed n.

The relatively low efficiency of the doubly-fed induction generator is primarily due to its small size. In large doubly-fed induction generators such as the ones used in wind turbines, the generator efficiency is much higher.

28. Considering the results you obtained in this exercise, is it preferable for a doubly-fed induction generator to operate at hyposynchronous speed, synchronous speed, or hypersynchronous speed? Explain.

It is preferable for a doubly-fed induction generator to operate at hypersynchronous speed as the generator efficiency η increases with the generator speed of rotation.

29. 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 how three-phase wound-rotor induction machines can operate as doubly-fed induction generators. You saw that doubly-fed induction generators operate like variable-speed synchronous generators. You also saw how doubly-fed induction generators are used in wind turbines to generate large amounts of electrical power. You learned the advantages of using doubly-fed induction generators in wind turbines.

Review Questions

1. How is it possible to vary the rotor speed of a doubly-fed induction generator while the amplitude and frequency of the ac power network to which the generator is connected remains constant?

The rotor speed n_{Rotor} of a doubly-fed induction generator can be varied by adjusting the frequency f_{Rotor} of the ac currents fed into the generator rotor, even though the amplitude and frequency of the ac power network to which the generator is connected remains constant.

2. Consider a doubly-fed induction generator whose rotor rotates in the counterclockwise direction. If the ac currents fed into the generator rotor windings create a magnetic field rotating in the clockwise direction, will the amplitude and frequency of the voltages produced by the generator be lower than, equal to, or higher than during singly-fed operation (at the same rotor speed)?

If the rotor of a doubly-fed induction generator rotates in the opposite direction to the magnetic field created in the rotor, the amplitude and frequency of the voltages produced by the generator will be lower than during normal singly-fed operation (at the same rotor speed).

3. Consider a doubly-fed induction generator having 8 magnetic poles. The generator supplies power to a 50 Hz ac power network. Knowing that a prime mover makes the generator rotate at a speed of 900 r/min, calculate the frequency of the ac currents that need to be fed into the generator rotor windings so that the generator is synchronized with the ac power network. Also, determine the direction of rotation of the rotating magnetic field created by the ac currents fed into the generator rotor windings.

The frequency of the ac currents that need to be fed into the doubly-fed induction generator rotor windings so that the generator is synchronized with the ac power network is calculated below.

$$f_{Rotor} = f_{Network} - \frac{n_{Rotor} \times N_{Poles}}{120} = 50\ \text{Hz} - \frac{900\ \text{r/min} \times 8\ \text{poles}}{120} = -10\ \text{Hz}$$

As the polarity of the rotor frequency f_{Rotor} is negative, the rotating magnetic field created by the ac currents fed into the generator rotor windings must rotate in the opposite direction to the generator rotor.

4. Consider a doubly-fed induction generator having four magnetic poles. The generator supplies power to a 60 Hz ac power network. Knowing that a prime mover makes the generator rotate at a speed of 1530 r/min, calculate the frequency of the ac currents that need to be fed into the generator rotor windings so that the generator is synchronized with the ac power network.

   Also, determine the direction of rotation of the rotating magnetic field created by the ac currents fed into the generator rotor windings.

The frequency of the ac currents that need to be fed into the doubly-fed induction generator rotor windings so that the generator is synchronized with the ac power network is calculated below.

$$f_{Rotor} = f_{Network} - \frac{n_{Rotor} \times N_{Poles}}{120} = 60\ \text{Hz} - \frac{1530\ \text{r/min} \times 4\ \text{poles}}{120} = 9\ \text{Hz}$$

As the polarity of the rotor frequency f_{Rotor} is positive, the rotating magnetic field created by the ac currents fed into the generator rotor windings must rotate in the same direction as the generator rotor.

5. What are the main advantages of using doubly-fed induction generators instead of asynchronous generators in wind turbines?

Using doubly-fed induction generators in wind turbines instead of asynchronous generators offers the following advantages:

1. Operation at variable rotor speed while the amplitude and frequency of the generated voltages remain constant;

2. Optimization of the amount of power generated as a function of the wind available up to the nominal output power of the wind turbine generator;

3. Virtual elimination of sudden variations in the rotor torque and generator output power;

4. Generation of electrical power at lower wind speeds;

5. Control of the power factor (e.g., in order to maintain the power factor at unity).

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