

Electricity and New Energy

Introduction to Wind Power

Course Sample

86353-10

Order no.: 86353-10
First Edition
Revision level: 03/2018

By the staff of Festo Didactic

© Festo Didactic Ltée/Ltd, Quebec, Canada 2010
Internet: www.festo-didactic.com
e-mail: did@de.festo.com

Printed in Canada

All rights reserved

ISBN 978-2-89640-435-3 (Printed version)

ISBN 978-2-89640-633-3 (CD-ROM)

Legal Deposit – Bibliothèque et Archives nationales du Québec, 2010

Legal Deposit – Library and Archives Canada, 2010

The purchaser shall receive a single right of use which is non-exclusive, non-time-limited and limited geographically to use at the purchaser's site/location as follows.

The purchaser shall be entitled to use the work to train his/her staff at the purchaser's site/location and shall also be entitled to use parts of the copyright material as the basis for the production of his/her own training documentation for the training of his/her staff at the purchaser's site/location with acknowledgement of source and to make copies for this purpose. In the case of schools/technical colleges, training centers, and universities, the right of use shall also include use by school and college students and trainees at the purchaser's site/location for teaching purposes.

The right of use shall in all cases exclude the right to publish the copyright material or to make this available for use on intranet, Internet and LMS platforms and databases such as Moodle, which allow access by a wide variety of users, including those outside of the purchaser's site/location.

Entitlement to other rights relating to reproductions, copies, adaptations, translations, microfilming and transfer to and storage and processing in electronic systems, no matter whether in whole or in part, shall require the prior consent of Festo Didactic.

















Information in this document is subject to change without notice and does not represent a commitment on the part of Festo Didactic. The Festo materials described in this document are furnished under a license agreement or a nondisclosure agreement.

Festo Didactic recognizes product names as trademarks or registered trademarks of their respective holders.

All other trademarks are the property of their respective owners. Other trademarks and trade names may be used in this document to refer to either the entity claiming the marks and names or their products. Festo Didactic disclaims any proprietary interest in trademarks and trade names other than its own.

Safety and Common Symbols

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

Symbol	Description
	DANGER indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
	WARNING indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
	CAUTION indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
	CAUTION used without the <i>Caution, risk of danger</i> 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. Consult the relevant user documentation.
	Caution, lifting hazard
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation
	Consult the relevant user documentation.
	Direct current

Safety and Common Symbols













Symbol	Description
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	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

Table of Contents

Preface	IX
About This Manual	XI
To the Instructor	XIII
Introduction Wind Turbines	1
DISCUSSION OF FUNDAMENTALS	1
Electrical energy measurement units	1
Wind turbine classification	1
Horizontal-axis wind turbines (HAWT)	2
Upwind turbines	3
Downwind turbines	3
Two-bladed wind turbines versus three-bladed wind turbines	3
Vertical-axis wind turbines (VAWT)	5
Small-scale wind power	6
Exercise 1 Voltage-Versus-Speed Characteristic of a Wind Turbine Generator	7
DISCUSSION	7
Magnetic field	7
Permanent magnets	8
Repulsion and attraction	9
Electromagnetic induction	9
Generators used in small-scale wind turbines	12
Construction	12
Operation	13
Period and frequency of electrical waveforms	14
Relationship between the rotation speed and the voltage induced by a wind turbine generator	14
PROCEDURE	16
Construction of a wind turbine generator	17
Wind-turbine generator voltage and frequency as a function of the rotation speed	18
Exercise 2 Torque-Versus-Current Characteristic of a Wind Turbine Generator	27
DISCUSSION	27
Torque	27
Force produced by interacting magnetic fields	29
Magnetic field around a conductor	30
Magnetic field in a loop of wire (electromagnet)	30
Loops of wire used in electric generators (generator windings)	31
Repulsion force opposing the rotation of a generator rotor ...	32

Table of Contents

PROCEDURE	33
Forces developed in the wind turbine generator due to magnetic field interaction.....	34
Repulsion force opposing the rotation of the wind turbine generator.....	35
Plotting the torque-versus-current curve of the wind turbine generator	36
Exercise 3 Power Versus Wind Speed.....	43
DISCUSSION	43
Air density	43
Kinetic energy in the wind.....	44
Calculating wind power.....	44
Relationship between wind power and wind speed.....	46
Relationship between torque, rotation speed, and rotational mechanical power	46
Conversion of wind power into rotational mechanical power and electrical power.....	47
Wind, rotor, and rotor efficiency coefficient C_p	48
Typical torque-versus-speed curve at the wind turbine rotor	49
Torque-versus-speed and mechanical power-versus-speed curves at the wind turbine rotor for different wind speeds	50
Current-versus-voltage and electrical power-versus-speed curves at the wind turbine generator output for different wind speeds.....	52
Wind turbine generator efficiency	53
PROCEDURE	56
Equipment setup and friction compensation calibration.....	56
Plotting the characteristic curves of the wind turbine for different wind speeds.....	58
Measurements at a wind speed of 4 m/s (14.4 km/h or 9.0 mph).....	59
Measurements at a wind speed of 7 m/s (25.2 km/h or 15.7 mph).....	61
Measurements at a wind speed of 10 m/s (36 km/h or 22.4 mph).....	64

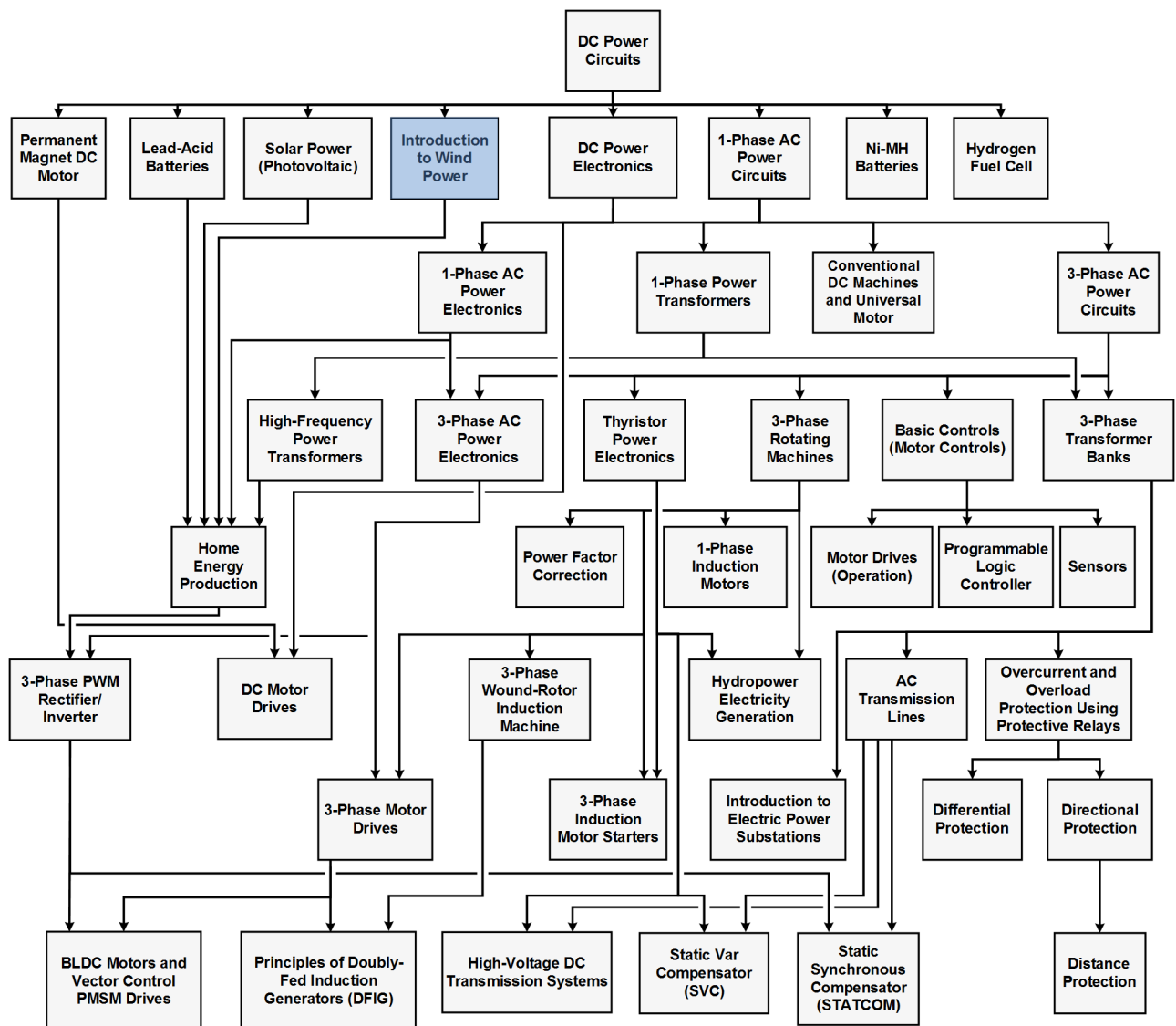
Table of Contents

Exercise 4	Storing the Energy Produced by Wind Turbines in Batteries	75
	DISCUSSION	75
	Storage of electrical energy	75
	Connection of a small-scale wind turbine to batteries	75
	Automatic tracking of the maximum power point (MPP)	76
	Protection against battery overcharging	78
	Protection against wind turbine overspeeding	78
	PROCEDURE	79
	Setup and connections	79
	Adjusting the maximum charge voltage (setpoint) of the wind-turbine controller	80
	Partially discharging the batteries in the Lead-Acid Battery Pack	82
	Plotting the electrical power-wind speed curve of the wind-turbine controller	83
	Battery overcharging protection	88
Appendix A	Equipment Utilization Chart	91
Appendix B	Glossary of New Terms	93
Appendix C	Impedance Table for the Load Modules	97
Appendix D	Preparation of the Lead-Acid Batteries	99
	Charging procedure	99
	Sulfation test	100
	Battery maintenance	101
Appendix E	Preparation of the Lead-Acid Battery Pack	103
	Charging procedure	103
	Sulfation test	104
	Battery maintenance	105
Appendix F	Detailed Connections of Typical Circuits	107
	Index of New Terms	109
	Bibliography	111

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 motor starters and drives, storage of electrical energy in batteries, home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, protective relaying, and smart-grid technologies (SVC, STATCOM, HVDC transmission systems, etc.).

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 course, *Introduction to Wind Power*, explains how a wind turbine produces electricity from wind power, as well as how to store this electric energy in batteries to ensure electrical power is available when there is no wind or during low wind periods. The course first covers the construction and operation of small-scale wind turbines. It presents the typical curves of a wind turbine: the speed, torque, and mechanical power curves at the wind turbine rotor, and the corresponding voltage, current, and electrical power curves of the wind turbine generator. The student learns how to maximize the electrical energy produced over a range of wind speeds and store this energy in batteries. Finally, the course introduces the student to automatic tracking of the maximum power point (MPP), as well as protection against battery overcharging and wind turbine overspeeding.

The training equipment for the course features a wind turbine generator, a controller module, and a four-quadrant dynamometer/power supply. The four-quadrant dynamometer/power supply is used as a prime mover in order to drive the wind turbine generator. By varying the rotation speed of the prime mover and the current through the generator windings, the student measures the generator parameters for different speeds and load values.



Offshore wind turbines in Copenhagen, Denmark.

About This Manual

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety and Common 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 manual titled *DC Power Circuits*.

Systems of units

Units are expressed using the International System of Units (SI) followed by 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.

Sample
Extracted from
Instructor Guide

Power Versus Wind Speed

EXERCISE OBJECTIVE

When you have completed this exercise, you will know how to calculate the power contained in the wind, and how wind power varies with wind speed. You will learn that only a fraction of the power in the wind intercepted by the blades of a wind turbine is transferred to the rotor, and then converted into electrical power. You will be familiar with the typical torque-versus-speed curve and mechanical power-versus-speed curve at the rotor of a wind turbine. You will be familiar with the corresponding current-versus-voltage curve and electrical power-versus-speed curve at the wind turbine generator output. You will know how all of these curves are affected by wind speed. You will also know what the optimum rotor speed and torque are, and how they are related to the maximum power point of the wind turbine.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Air density
- Kinetic energy in the wind
- Calculating wind power
- Relationship between wind power and wind speed
- Relationship between torque, rotation speed, and rotational mechanical power
- Conversion of wind power into rotational mechanical power and electrical power
- Typical torque-versus-speed curve at the wind turbine rotor
- Torque-versus-speed and mechanical power-versus-speed curves at the wind turbine rotor for different wind speeds
- Current-versus-voltage and electrical power-versus-speed curves at the wind turbine generator output for different wind speeds
- Wind turbine generator efficiency

DISCUSSION

Air density

The **air density**, symbolized by the Greek letter ρ (rho), is an important parameter to know in wind power applications. Air density is the mass of air per unit volume:

$$\rho = \frac{m}{V} \quad (3)$$

where

ρ	is the air density, in kilograms per cubic meter (kg/m ³) [pounds mass per cubic foot (lbm/ft ³)].
m	is the mass of air, in kilograms (kg) [pounds mass (lbm)].
V	is the volume, in cubic meters (m ³) [cubic feet (ft ³)].

The air density varies with atmospheric pressure, temperature, humidity, and altitude. In SI units, ρ is equal to **1.225 kg/m³** under **standard sea level conditions**, which are: a temperature of 15.5°C, an atmospheric pressure of 101.325 kPa, and a relative humidity of 36%.

In U.S. customary units, ρ is equal to **0.076 lbf/ft³** under standard (sea level) conditions, which are: a temperature of 60°F, an atmospheric pressure of 14.7 psia or 0 psig, and a relative humidity of 36%.

Kinetic energy in the wind

Any object or fluid in motion has kinetic energy. For example, wind, which is a mass of air in motion, has kinetic energy. The faster the speed of the wind, the higher the kinetic energy of the wind.

The kinetic energy in a mass of air in motion can be calculated by using the following equation:

$$E_K = \frac{mv^2}{2} \quad (4)$$

where

- E_K is the kinetic energy, in joules (J) [feet-pound force (ft-lbf)].
- m is the mass of air, in kilograms (kg) [pounds mass (lbm)].
- v is the velocity of the mass of air, in meters per second (m/s) [feet per second (ft/s)].
- 2 is a constant. When working in U.S. customary units, this constant must be multiplied by the **gravitational constant**, g_c (32.174 lbf·ft/lbm·s²).



The gravitational constant, g_c must be used to change from pounds mass (lbm) to pounds force (lbf). The equation for calculating kinetic energy is, therefore:

$$E_k = \frac{mv^2}{2g_c}$$

where g_c is equal to 32.174 lbf·ft/lbm·s².

Note that the term wind speed is also used to designate the wind velocity v .

Calculating wind power

Figure 26 shows wind of constant speed passing through a cross-sectional area A . This area could be, for example, the area swept by the blades of a wind turbine.

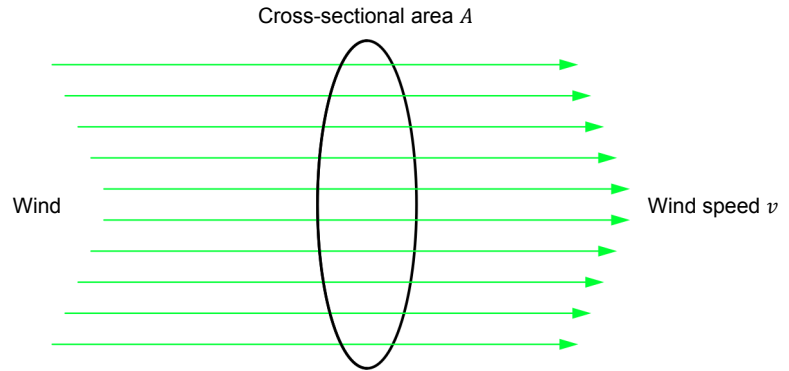


Figure 26. Wind flowing through a cross-sectional area.

In SI units, the power in the wind passing through the cross-sectional area is:

$$P_W = \frac{\rho A v^3}{2} \quad (5)$$

where

P_W	is the power in the wind, in watts (W, or $\text{kg}\cdot\text{m}^2/\text{s}^3$).
ρ	is the air density, in kilograms per cubic meter (kg/m^3).
A	is the cross-sectional area, in square meters (m^2).
v	is the wind speed (m/s).

In U.S. customary units, the power in the wind passing through the cross-sectional area is:

$$P_W = \frac{\rho A v^3}{2g_c} \quad (6)$$

where

P_W	the power in the wind, in feet-pound force per second (ft·lbf/s).
ρ	is the air density, in pounds mass per cubic foot (lbm/ft^3).
A	is the cross-sectional area, in square feet (ft^2).
v	is the wind speed, in feet per second (ft/s).
g_c	is the gravitational constant, equal to $32\,174\text{ lbm}\cdot\text{ft}/\text{lbf}\cdot\text{s}^2$.

The observations below can be made from the equation used to calculate the power in the wind.

- Any change in the temperature of the air, atmospheric pressure, or relative humidity causes the air density ρ to change, causing the wind power to change in the exact same way (for given wind speed and cross-sectional area). For instance, when the air density ρ increases by 5%, the wind power P_W also increases by 5%.
- When the cross-sectional area A swept by the blades of a wind turbine rotor is increased, the wind power intercepted by the blades increases in direct proportion.
- When the wind speed v increases, the wind power also increases.

Relationship between wind power and wind speed

As already mentioned, the wind power increases when the wind speed increases. More precisely, the wind power P_W varies with the **cube** (the third power) of the wind speed v , as Figure 27 shows.

- When the wind speed doubles, the wind power increases eight times ($2^3 = 8$).
- When the wind speed triples, the wind power increases 27 times ($3^3 = 27$).
- When the wind speed quadruples, the wind power increases 64 times ($4^3 = 64$).



1 meter/second (1 m/s) is equal to 3.6 kilometers per hour (3.6 km/h) or 2.237 miles per hour (2.237 mph).

Wind speed (m/s)	Power (W/m^2)	Wind speed (km/h)	Wind speed (mph)
0	0	0	0
1	0.69	3.6	2.24
2	4.9	7.2	4.47
3	17	10.8	6.71
4	39	14.41	8.95
5	77	18.02	11.19
6	132	21.6	13.42
7	210	25.21	15.66
8	314	28.82	17.9
9	447	32.41	20.13
10	613	36.02	22.37
11	815	39.62	24.61
12	1058	43.21	26.84
13	1346	46.82	29.08
14	1681	50.45	31.32
15	2067	54.03	33.56

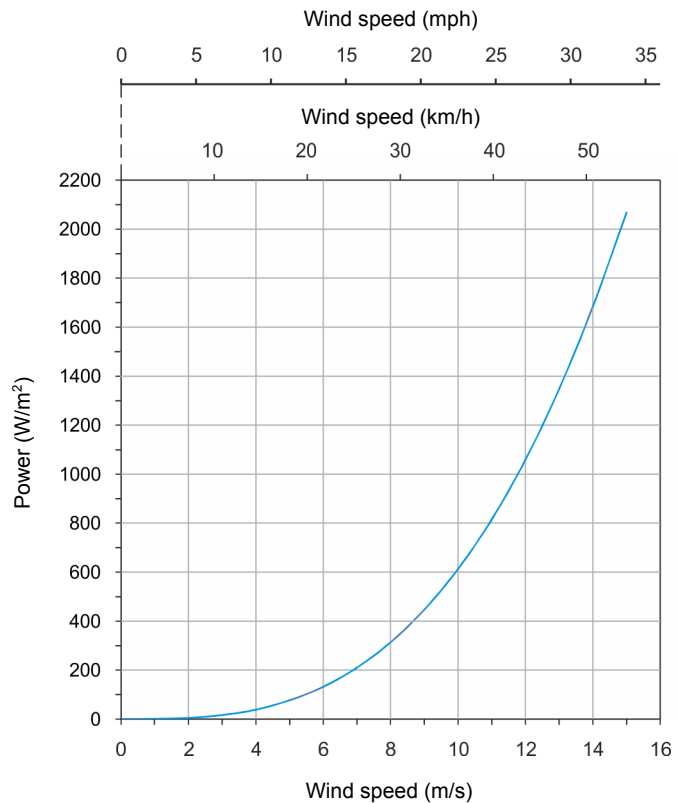


Figure 27. The wind power varies with the cube (the third power) of the wind speed.

Relationship between torque, rotation speed, and rotational mechanical power

When a force is applied to an object mounted on a rotation axis (such as the bladed rotor of a wind turbine), the object starts to rotate at a certain speed, as shown in Figure 28. The rotation speed n is expressed in revolutions per minute (r/min). One revolution is equal to 360° , or 2π (6.28) radians (rad), one radian (1 rad) being equal to 57.3° .

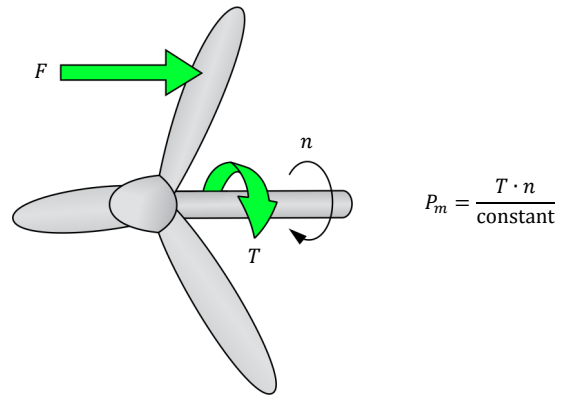


Figure 28. Torque, rotation speed, and rotational mechanical power.

The rotational mechanical power P_m produced at the rotating axis of the object is the product of the torque T developed at the rotating axis and the rotation speed n , divided by a constant.

The equation below allows the rotational mechanical power to be calculated in SI units.

$$P_m = \frac{T \cdot n}{9.55} \quad (7)$$

where P_m is the rotational mechanical power, in watts (W).
 T is the torque, in newton meters (N·m).
 n is the rotation speed, in revolutions per minute (r/min).
 9.55 is a constant.

In U.S. customary units, the equation is the same, but the constant is different:

$$P_m = \frac{T \cdot n}{84.51} \quad (8)$$

where P_m is the rotational mechanical power, in watts (W).
 T is the torque, in pound-force inches (lbf-in).
 n is the rotation speed, in revolutions per minute (r/min).
 84.51 is a constant.

Conversion of wind power into rotational mechanical power and electrical power

When wind hits the blades of a wind turbine rotor, the pressure of the air acting on the surface of the blades creates a force, which applies a torque onto the rotor of the turbine, as Figure 29 shows.

When the wind is strong enough to produce a torque higher than the force (torque) opposing rotation, the wind turbine rotor starts to rotate at a certain speed. In this condition,

- the blades of the wind turbine convert a portion of the power contained in the wind they intercept (linear mechanical power) into rotational mechanical power that makes the wind turbine rotor turn.
- the rotational mechanical power produced at the wind turbine rotor drives an electric generator. The electric generator converts the rotational mechanical power into electrical power.

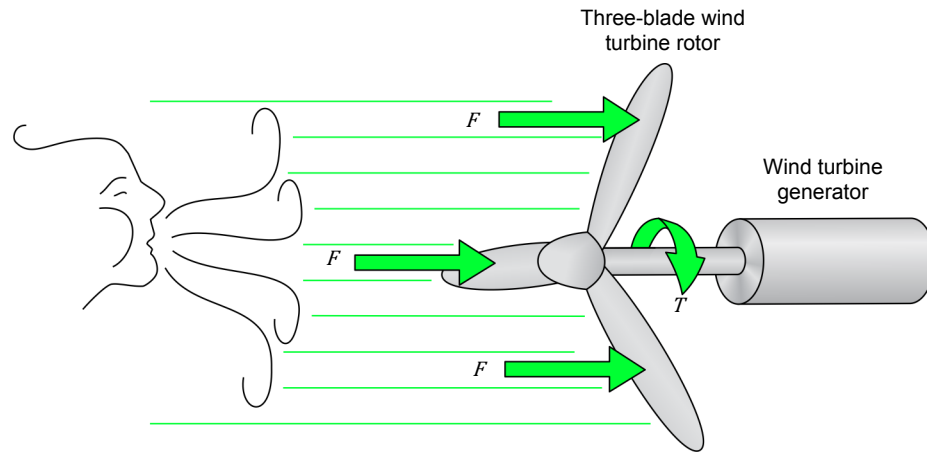


Figure 29. A fraction of the power in the wind intercepted by the blades of the turbine is converted into rotational mechanical power to drive the electric generator of the turbine.

Wind, rotor, and rotor efficiency coefficient C_p

As already mentioned, the power contained in the wind passing through the area swept by the blades of a wind turbine rotor is:

$$P_W = \frac{\rho A v^3}{2} \tag{9}$$

- where
- P_W is the power in the wind.
 - ρ is the air density.
 - A is the cross-sectional area swept by the wind turbine rotor.
 - v is the wind speed.

Not all the power in the wind passing through the swept area is transferred to the wind turbine rotor. Only a fraction of the available wind power is extracted by the blades and transferred to the rotor. This fraction indicates the efficiency of the wind turbine rotor in converting linear mechanical power into rotational mechanical power.

The fraction of wind power extracted by the blades and transferred to the rotor is called the rotor coefficient efficiency C_p . The rotor efficiency coefficient depends on the design (shape) of the rotor blades. The rotor efficiency coefficient is sometimes expressed as a percentage (rotor efficiency coefficient multiplied by 100%).

The rotor efficiency coefficient C_p is generally between 0.4 and 0.5 for most blade designs. The rotor efficiency coefficient C_p must be taken into account to determine the fraction of wind power P_W that is transferred to the wind turbine rotor. The formula used to calculate the mechanical power P_m at the wind turbine rotor is therefore:

$$P_m = P_W \cdot C_p = \frac{\rho A v^3}{2} \cdot C_p \quad (10)$$

The rotor efficiency coefficient C_p of a wind turbine is virtually constant over the normal wind speed range of the turbine. Therefore, the mechanical power at the wind turbine rotor varies in the same way as wind power, i.e., with the **cube** (the third power) of the wind speed.

Typical torque-versus-speed curve at the wind turbine rotor

Figure 30 shows a typical torque-versus-speed curve at the rotor of a wind turbine obtained for a given wind speed.

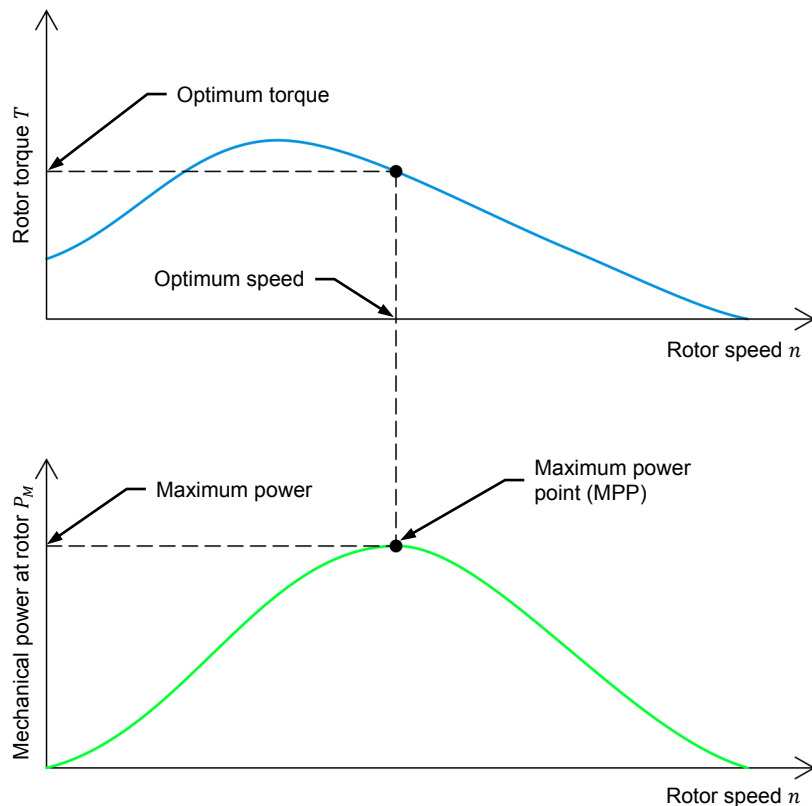


Figure 30. Typical torque-versus-speed curve and mechanical power-versus-speed curve at the rotor of a wind turbine, for a given wind speed.

As the rotor speed increases, the torque produced at the rotor increases until a point is reached, beyond which the torque gradually decreases to zero. Consequently, the mechanical power produced at the rotor also increases up to a certain maximum value, and then gradually decreases to zero, as Figure 30 shows. The point at which the mechanical power is maximum is referred to as

the **maximum power point (MPP)**. The rotor speed and torque at the MPP are commonly referred to as the **optimum speed** and **optimum torque**, respectively.

A wind turbine must be operated as close as possible to the optimum speed to maximize the mechanical power developed at the rotor and thus obtain the maximum amount of electrical power. This is performed by setting the rotor torque to the optimum value, through adjustment of the current drawn by the electrical load at the wind turbine generator output.



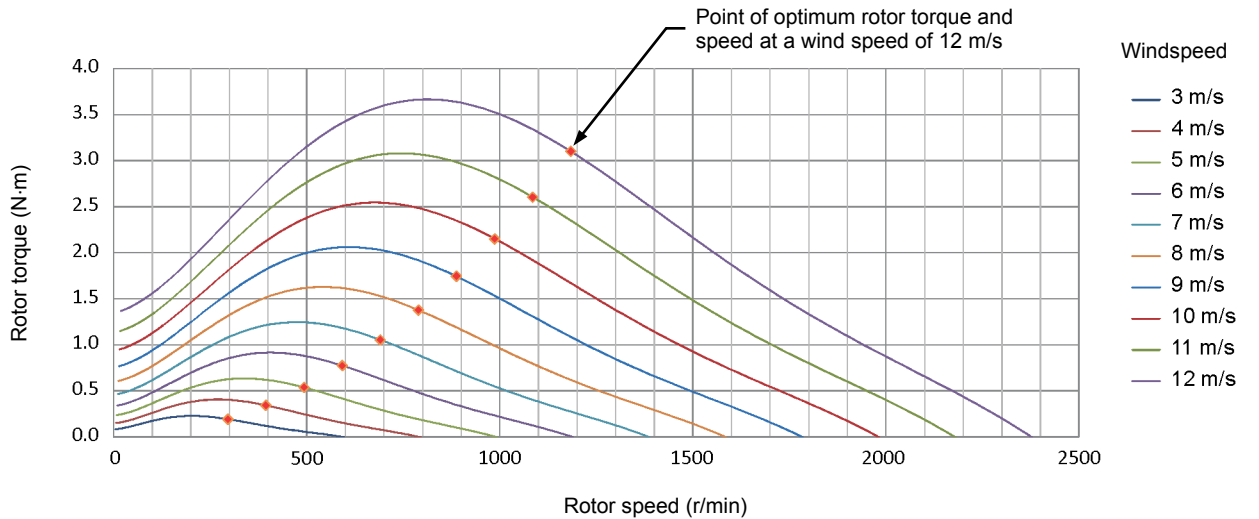
Figure 31. Small wind turbine for domestic use.

Torque-versus-speed and mechanical power-versus-speed curves at the wind turbine rotor for different wind speeds

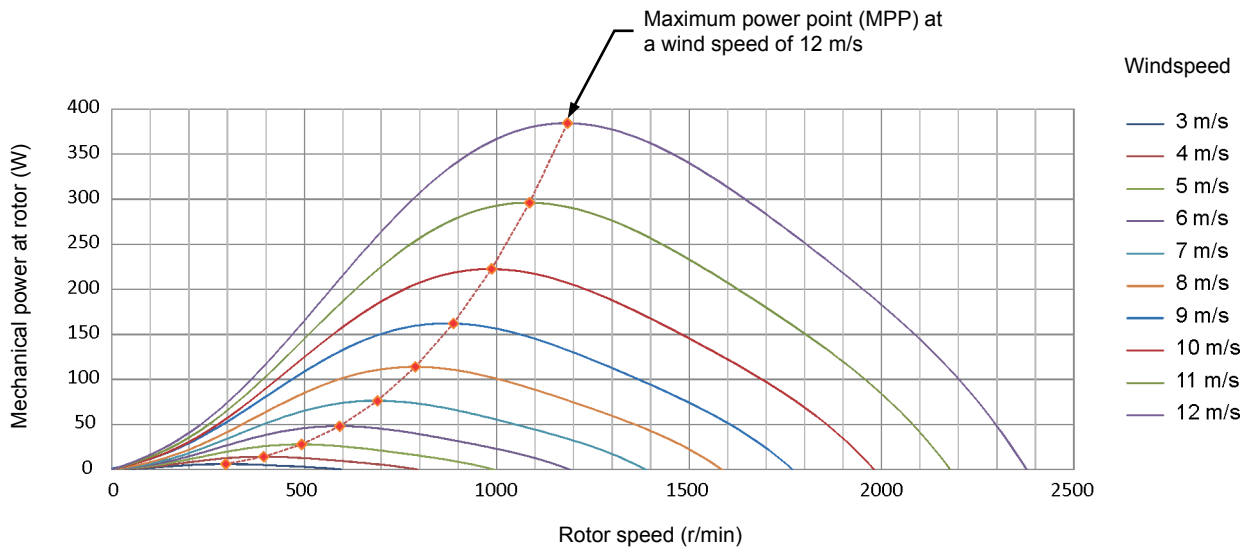
Figure 32 shows a set of typical curves at the rotor of a wind turbine, for different wind speeds: the torque-versus-speed curves (section a) and the mechanical power-versus-speed curves (section b).

On each torque-versus-speed curve in Figure 32a, a diamond-shaped marker indicates the optimum rotor torque and speed at which the maximum amount of mechanical power is produced at the wind turbine rotor. The maximum power point (MPP) is also indicated by a diamond-shaped marker on each of the corresponding mechanical power curves in Figure 32b.

Note that the rotor speed at which the maximum amount of mechanical power is produced at the rotor of a wind turbine varies with the wind speed. Therefore, to operate the wind turbine at the maximum power point (MPP) and maximize the energy produced at any wind speed, the rotor speed must be continuously monitored and kept at the optimum value, through adjustment of the rotor torque when necessary. This is generally performed automatically by a controller in the wind turbine, as you will see in Exercise 4.



(a) Torque-versus-speed curves



(b) Mechanical power-versus-speed curves

Figure 32. Family of typical curves at the bladed rotor of a wind turbine, for different wind speeds.

The following conclusions can be drawn from examination of the family of curves in Figure 32:

- Figure 32a shows that higher speeds and torques are reached when the wind speed increases.
- Consequently, higher amounts of mechanical power are produced at the rotor when the wind speed increases, as Figure 32b shows.

When the maximum power points on the various mechanical power curves in Figure 32b are connected together, they form a curve which increases exponentially (see dashed line in Figure 32b). In fact, the mechanical power at the MPP's increases by **eight** whenever the wind speed **doubles**. This occurs because the power in the wind varies with the **cube** (the third power) of the wind speed.

Current-versus-voltage and electrical power-versus-speed curves at the wind turbine generator output for different wind speeds

Figure 33 shows a set of typical curves related to the output of a wind turbine generator, for different wind speeds: the current-versus-voltage curves of the generator output (section a) and the corresponding electrical power-versus-speed curves (section b).

The following conclusions can be drawn by comparing the family of curves in Figure 33 with the family of curves in Figure 32:

- The voltage and current at the output of the wind turbine generator are proportional to the speed and torque at the wind turbine rotor, respectively. Consequently, the current-versus-voltage curves of the wind turbine generator (Figure 33a) are similar to the torque-versus-speed curves at the wind turbine rotor (shown in Figure 32a).
- Also, the electrical power-versus-speed curves of the wind turbine generator (Figure 33b) are similar to the mechanical power-versus-speed curves at the wind turbine rotor (shown in Figure 32b).

Through proper control of the electrical load applied to the wind-turbine generator output, the rotor speed and torque can be adjusted in order to keep the generator operating at the maximum power point (MPP) at any wind speed.

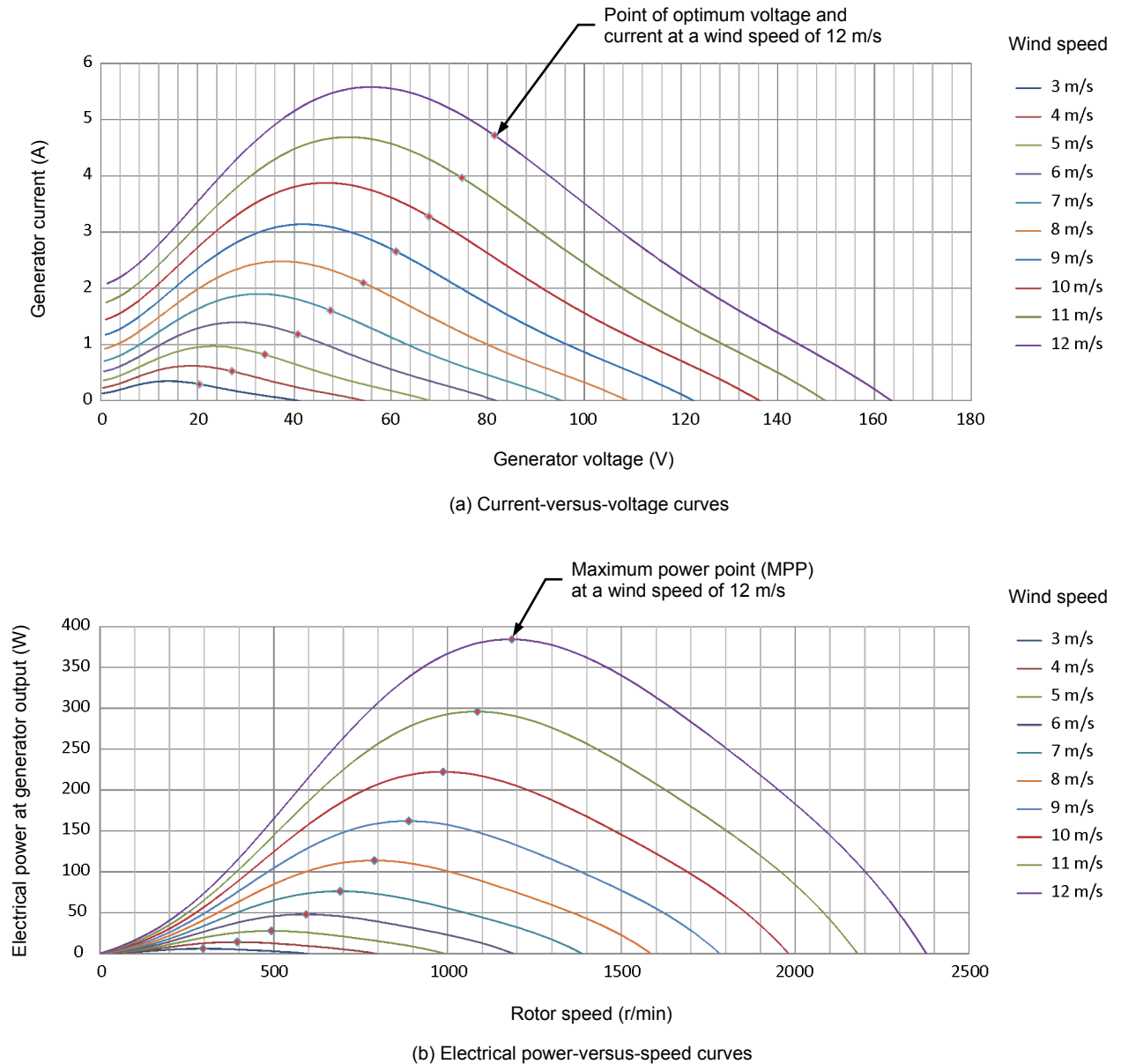


Figure 33. Family of typical curves related to the output of a wind turbine generator, for different wind speeds.

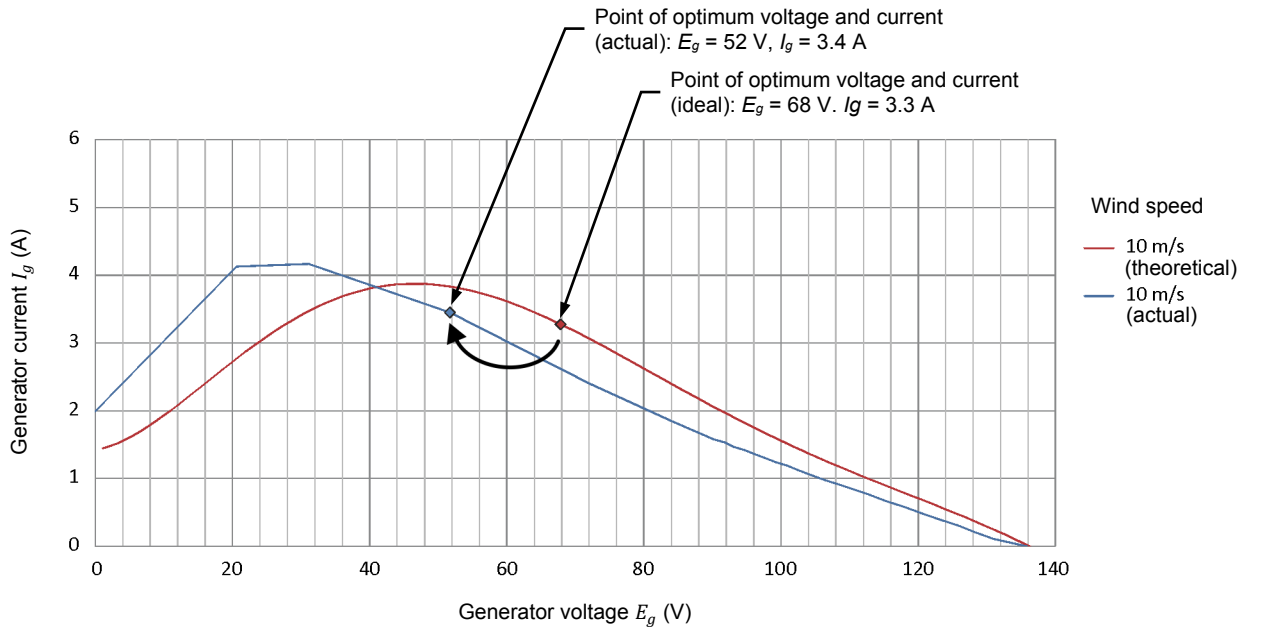
Wind turbine generator efficiency

Whenever a current flows through a conductor, power is lost as heat through the resistance of the conductor. The higher the current flowing through the conductor, the greater the power lost through the conductor. In fact, the amount of power lost increases with the square of the current through the conductor. The amount of power lost is also determined by the resistance of the conductor. This resistance is directly proportional to the length of the conductor and inversely proportional to the cross-sectional area of the conductor.

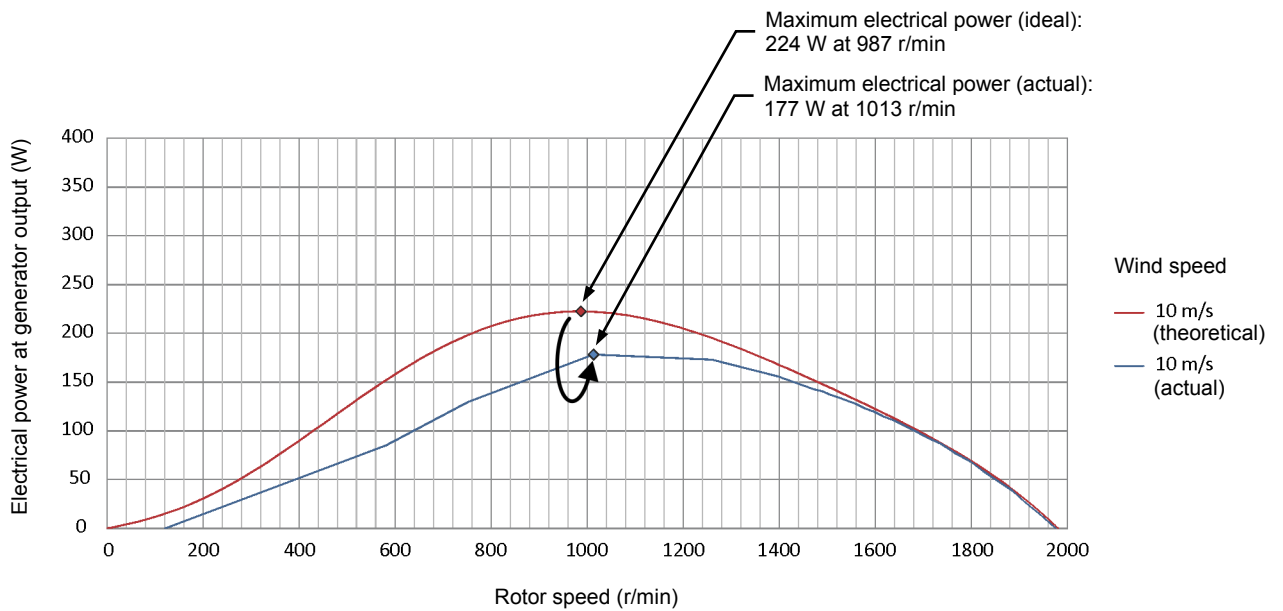
With a wind turbine generator (as well as any other generator), not all the mechanical power applied to the rotor shaft is converted into electrical power, due to power losses in the stator windings. These power losses are usually called I^2R losses. They decrease the efficiency of a wind turbine in converting mechanical power into electrical power. As a result, the actual curves of current versus voltage and electrical power versus speed of a wind turbine generator differ significantly from the ideal curves you have studied so far, both in shape and amplitude, particularly at high wind speeds.

As an example, Figure 34 shows the ideal and actual curves related to a wind turbine generator at a wind speed of 10 m/s.

- Figure 34a shows that the actual current-versus-voltage curve is shifted toward left with respect to the ideal curve. This indicates that the actual generator voltage is lower than expected. For instance, on the ideal curve, the point of optimum voltage and current occurs at a generator voltage of 68 V and a generator current of 3.3 A. On the actual curve, the point of optimum voltage and current occurs at a lower generator voltage of 52 V and a current of 3.4 A. This occurs because the I^2R losses through the generator windings result in a certain voltage drop across these windings, causing the generator voltage to be lower than expected.
- Figure 34b shows that the actual electrical power produced by the generator is lower than the ideal power value over most of the rotor speed range. On the ideal curve, the maximum electrical power is 224 W, and it is reached when the rotor speed is 987 r/min. On the actual curve, the maximum electrical power is 177 W, and it is reached when the rotor speed is 1013 r/min. Therefore, the actual electrical power produced by the generator is lower than the ideal value by 47 W, which corresponds to a power conversion efficiency of about 79% ($177 \text{ W} \div 224 \text{ W}$).



(a) Current-versus-voltage curves



(b) Electrical power-versus-speed curves

Figure 34. Ideal and actual curves of the wind turbine generator (wind speed = 10 m/s).

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Equipment setup and friction compensation calibration
- Plotting the characteristic curves of the wind turbine for different wind speeds

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.

Equipment setup and friction compensation calibration

In this section, you will set up the equipment. You will use a prime mover to emulate the wind blowing onto the blades of a wind turbine rotor driving a generator.

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

WARNING



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

2. Install the equipment in the workstation.

Mechanically couple the [Wind Turbine Generator/Controller](#) module to the [Four-Quadrant Dynamometer/Power Supply](#).

3. Make sure that the main power switch of the [Four-Quadrant Dynamometer/Power Supply](#) is set to the *O (off)* position then connect its *Power Input* to an ac power outlet.
4. Set the *Operating Mode* switch of the [Four-Quadrant Dynamometer/Power Supply](#) to *Dynamometer*. This setting allows the [Four-Quadrant Dynamometer/Power Supply](#) to operate as a dynamometer or a prime mover, a brake, or both, depending on the selected function.
5. Turn the [Four-Quadrant Dynamometer/Power Supply](#) on.
6. Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

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

In the LVDAC-EMS Start-Up window, make sure that the Four-Quadrant Dynamometer/Power Supply is detected. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click on the OK button to close the LVDAC-EMS Start-Up window.

8. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window. In the Tools menu of this window, select Friction Compensation Calibration, which will bring up the Friction Compensation Calibration dialog box. Click OK in this box to start the calibration process. Observe that the prime mover starts to rotate at high speed, thereby driving the shaft of the wind turbine generator. The prime mover speed is then automatically decreased by steps to perform the calibration process. Once the calibration process is completed (which takes about two minutes), the prime mover stops rotating, then the Friction Compensation Calibration dialog box indicates that the calibration process is finished. Click OK in the Friction Compensation Calibration dialog box to close this box. Restart the Four-Quadrant Dynamometer/Power Supply to apply the changes (i.e., the newly calibrated friction compensation curve) by setting the main power switch of this module to O (off), and then I (on).
9. Set up the circuit shown in Figure 35. In this setup, the prime mover drives the wind turbine generator, thereby producing an ac voltage across the generator windings. A diode rectifier in the Wind Turbine Generator/Controller converts this ac voltage into dc voltage to supply electrical dc power to a variable resistive load, R_L (5 Ω to infinite Ω).

The resistive load is implemented with the Resistive Load module for resistance values between 57 Ω and 1200 Ω , or with the Load Resistors on the Wind Turbine Generator/Controller for resistance values between 5 Ω and 45 Ω .

Connect the Diode Rectifier output of the Wind Turbine Generator/Controller to the Resistive Load module. Connect the three resistor sections on this module in parallel. Then, set the initial load resistance value to infinite (∞ Ω) by placing the levers of all the toggle switches to the O (off) position.

Set a multimeter to measure dc voltage and connect it across the load, as Figure 35 shows.

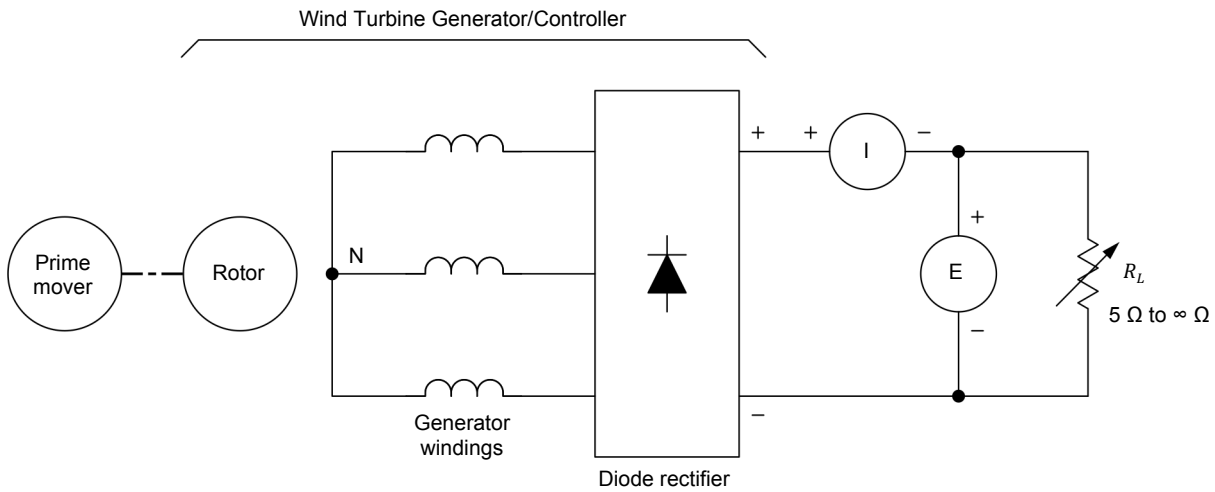


Figure 35. Equipment setup.

10. In the **Four-Quadrant Dynamometer/Power Supply** window of **LVDAC-EMS**, make the following settings:

- Set the *Function* parameter to *Wind-Turbine Emulator*. This setting makes the **Four-Quadrant Dynamometer/Power Supply** operate as a prime mover emulating wind blowing onto the blades mounted at the end of the wind turbine rotor. Therefore, the prime mover's torque-versus-speed characteristic is the same as the torque-versus-speed characteristic that would be obtained at the wind turbine rotor for different wind speeds. In other words, the wind turbine generator operates as if it were driven by wind blowing onto the rotor blades, but without the need for wind or blades.
- Make sure that the *Wind Control* parameter is set to *Slider*.
- Make sure that the *Wind Turbine Type* parameter is set to *1.15 m, 3 blades*.
- Make sure that the *Status* parameter is set to *Stopped*.
- Make sure that the continuous refresh of the meters is enabled.
- Leave the other parameters set to their default values.



The *Pulley Ratio* parameter is grayed out since it is automatically set to the required value (24:32).

Plotting the characteristic curves of the wind turbine for different wind speeds

In this section, you will plot the characteristic curves of the wind turbine. These curves are the torque-speed and mechanical power-speed curves at the wind turbine rotor, as well as the corresponding current-voltage and electrical power-speed curves of the wind turbine generator, for different wind speeds. You will compare the shapes of these curves, and describe how they vary with wind speed. You will determine the maximum power point for each wind speed.

Measurements at a wind speed of 4 m/s (14.4 km/h or 9.0 mph)

11. Make the wind turbine generator operate as if wind were blowing at 4 m/s onto the rotor blades by making the following settings in the **Four-Quadrant Dynamometer/Power Supply** window:

- Set the *Wind Speed* parameter to 4 m/s (14.4 km/h or 9 mph).
- Start the *Wind Turbine Emulator* by setting the *Status* parameter to *Started* or by clicking on the *Start/Stop* button.

Observe that the prime mover starts to rotate, thereby driving the rotor of the wind turbine generator as if wind were blowing at 4 m/s onto the rotor blades. Since the resistance of the load is maximum ($\infty \Omega$), the generator rotation speed is also maximum.

In Table 3, record the rotation speed, torque (absolute value), and mechanical power (absolute value) at the wind turbine rotor. These parameters are indicated by the *Speed*, *Torque*, and *Power* meters, respectively, in the **Four-Quadrant Dynamometer/Power Supply** window. Also, measure and record the dc voltage and dc current supplied to the load by the wind turbine generator.

Table 3. Measuring the parameters of the wind turbine at a wind speed of 4 m/s (14.4 km/h or 9.0 mph).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m or lbf·in)	Mechanical power at the wind turbine rotor P_m (W)	Load voltage E_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed =					
400						
150						
75						
45						
30						
15						
7.5						
5						
0	Minimum speed =					

Measuring the parameters of the wind turbine at a wind speed of 4 m/s (14.4 km/h or 9.0 mph).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m) [lbf·in]	Mechanical power at the wind turbine rotor P_m (W)	Load voltage E_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed = 766	$\cong 0.00$ N·m [$\cong 0.00$ lbf·in]	1.9	51.6	0.00	0.0
400	680	0.09 N·m [0.78 lbf·in]	6.3	44.7	0.11	4.7
150	572	0.17 N·m [1.51 lbf·in]	10.3	36.6	0.24	8.9
75	476	0.26 N·m [2.35 lbf·in]	13.2	29.4	0.39	11.5
45	404	0.33 N·m [2.96 lbf·in]	14.2	23.9	0.55	13.1
30	332	0.39 N·m [3.46 lbf·in]	13.6	18.7	0.62	11.6
15	179	0.36 N·m [3.20 lbf·in]	6.8	8.6	0.58	4.9
7.5	86	0.24 N·m [2.14 lbf·in]	2.2	2.9	0.38	1.1
5	65	0.21 N·m [1.87 lbf·in]	1.4	1.7	0.34	0.6
0	Minimum speed = 36	0.17 N·m [1.54 lbf·in]	0.7	0.02	0.29	0.0



At low power levels, the mechanical power measured at the wind turbine rotor may be lower than the electrical power to the load, due to the limited accuracy of torque measurement.

- Gradually decrease the rotation speed of the wind turbine generator to obtain several points (eight to ten points) spread along the typical torque-versus-speed curve (see Figure 30). To do this, gradually decrease the load resistance and, for each resistance setting, record the rotation speed, torque (absolute value), and mechanical power (absolute value) at the wind turbine rotor in Table 3. Also, measure and record the dc voltage and dc current supplied to the load by the wind turbine generator.

The following resistance settings are suggested: 400 Ω , 150 Ω , 75 Ω , 45 Ω , 30 Ω , 15 Ω , 7.5 Ω , and 5 Ω . For the minimum generator rotation speed, set the load resistance to 0 Ω by short-circuiting the output of the *Diode Rectifier* on the *Wind Turbine Generator/Controller* via the dc ammeter.

⚠ WARNING



When the *Load Resistors* of the *Wind Turbine Generator/Controller* are used, stop the prime mover (wind-turbine emulator) before modifying any connection between these resistors to prevent the risk of an electric shock.

CAUTION

When using the $15\ \Omega$ *Load Resistor* alone, take your measurements within one minute and then stop the prime mover to prevent this resistor from overheating.



Appendix C of this manual lists the switch settings to be performed on the Resistive Load module in order to insert various resistance values into the circuit. The resistance provided by the Resistive Load module cannot be decreased below $57\ \Omega$. To further decrease the load resistance, stop the prime mover (wind-turbine emulator), then disconnect the Diode Rectifier output of the Wind Turbine Generator/Controller from the Resistive Load module. On the Wind Turbine Generator/Controller, connect the Diode Rectifier output to the Load Resistors and connect these resistors in order to set the load resistance to different values. The possible resistor arrangements (series, parallel, series-parallel) provide resistance values between $5\ \Omega$ and $45\ \Omega$. Be sure to include the ammeter and the voltmeter in the circuit in order to measure the dc voltage and dc current supplied to the load, as shown in Figure 35. For each load resistance setting, start the prime mover and record the rotation speed, torque, and mechanical power at the wind turbine rotor in Table 3. Also, record the dc voltage and dc current supplied to the load by the wind turbine generator. Stop the prime mover before modifying any connection between these Load Resistors.

13. Stop the prime mover.

Remove the short-circuit at the *Diode Rectifier* output, and disconnect the *Load Resistors*.

14. Based on the dc voltages and dc currents recorded in Table 3, calculate the electrical power supplied to the load for each rotation speed and record your results in the table.

Measurements at a wind speed of 7 m/s (25.2 km/h or 15.7 mph)

15. Ensure the prime mover is stopped. Connect the *Diode Rectifier* output of the *Wind Turbine Generator/Controller* to the *Resistive Load* module. Then, set the initial load resistance value to infinite ($\infty\ \Omega$) by placing the levers of all the toggle switches to the **O** (off) position.

Connect the multimeter set to measure dc current in series with the *Diode Rectifier* output, as Figure 35 shows. Connect the multimeter set to measure dc voltage across the load, as Figure 35 shows.

16. Make the wind turbine generator operate as if wind were blowing at 7 m/s onto the rotor blades by making the following settings in the **Four-Quadrant Dynamometer/Power Supply** window:

- Set the *Wind Speed* parameter to 7 m/s (25.2 km/h or 15.7 mph).
- Start the **Wind Turbine Emulator** by setting the *Status* parameter to *Started* or by clicking on the *Start/Stop* button. Since the resistance of the load is maximum ($\infty \Omega$), the generator rotation speed is also maximum.

In Table 4, record the rotation speed, torque (absolute value), and mechanical power (absolute value) at the wind turbine rotor. These parameters are indicated by the *Speed*, *Torque*, and *Power* meters, respectively, in the **Four-Quadrant Dynamometer/Power Supply** window. Also, measure and record the dc voltage and dc current supplied to the load by the wind turbine generator.

Table 4. Measuring the parameters of the wind turbine at a wind speed of 7 m/s (25.2 km/h or 15.7 mph).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m or lbf·in)	Mechanical power at the wind turbine rotor P_m (W)	Load voltage E_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed =					
240						
120						
71						
45						
30						
15						
7.5						
5						
0	Minimum speed =					

Measuring the parameters of the wind turbine at a wind speed of 7 m/s (25.2 km/h or 15.7 mph).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m) [lbf·in]	Mechanical power at the wind turbine rotor P_m (W)	Load voltage E_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed = 1385	$\cong 0.00$ N·m [$\cong 0.00$ lbf·in]	0.1	93.7	0.00	0.0
240	1236	0.21 N·m [1.85 lbf·in]	27.1	81.1	0.34	27.2
120	1107	0.37 N·m [3.32 lbf·in]	43.5	70.9	0.60	42.4
71	990	0.54 N·m [4.82 lbf·in]	56.5	62.0	0.88	54.5
45	890	0.72 N·m [6.37 lbf·in]	66.7	53.5	1.17	62.9
30	780	0.92 N·m [8.14 lbf·in]	75.1	45.0	1.47	66.1
15	577	1.20 N·m [10.62 lbf·in]	72.5	29.5	1.98	58.5
7.5	341	1.15 N·m [10.21 lbf·in]	41.2	14.3	1.903	27.3
5	213	0.90 N·m [7.97 lbf·in]	20.1	7.4	1.48	11.0
0	Minimum speed = 70	0.55 N·m [4.88 lbf·in]	4.0	0.0	0.92	0.0



At low power levels, the mechanical power measured at the wind turbine rotor may be lower than the electrical power to the load, due to the limited accuracy of torque measurement.

17. Complete the remainder of Table 4. Gradually decrease the generator rotation speed by decreasing the load resistance in order to obtain several points spread along the typical torque-versus-speed curve. For each resistance setting, record the rotation speed, torque (absolute value), and mechanical power (absolute value) at the wind turbine rotor in Table 4. Also, measure and record the dc voltage and dc current supplied to the load by the wind turbine generator.

The following resistance settings are suggested: 400 Ω , 150 Ω , 75 Ω , 45 Ω , 30 Ω , 15 Ω , 7.5 Ω , and 5 Ω . For the minimum generator rotation speed, set the load resistance to 0 Ω by short-circuiting the output of the *Diode Rectifier* on the *Wind Turbine Generator/Controller* via the dc ammeter.

⚠ WARNING



When the *Load Resistors* of the *Wind Turbine Generator/Controller* are used, stop the prime mover (wind-turbine emulator) before modifying any connection between these resistors to prevent the risk of an electric shock.

CAUTION

When using the 15 Ω *Load Resistor* alone, take your measurements within one minute and then stop the prime mover to prevent this resistor from overheating.

18. Stop the prime mover.

Remove the short-circuit at the *Diode Rectifier* output, and disconnect the *Load Resistors*.

19. Based on the dc voltages and dc currents recorded in Table 4, calculate the electrical power supplied to the load for each rotation speed and record your results in the table.

Measurements at a wind speed of 10 m/s (36 km/h or 22.4 mph)

20. Ensure the prime mover is stopped. Connect the *Diode Rectifier* output of the *Wind Turbine Generator/Controller* to the *Resistive Load* module. Then, set the initial load resistance value to infinite ($\infty \Omega$) by placing the levers of all the toggle switches to the **O** (off) position.

Connect the multimeter set to measure dc current in series with the *Diode Rectifier* output, as Figure 35 shows. Connect the multimeter set to measure dc voltage across the load, as Figure 35 shows.

21. Make the wind turbine generator operate as if wind were blowing at 10 m/s onto the rotor blades by making the following settings in the *Four-Quadrant Dynamometer/Power Supply* window:

- Set the *Wind Speed* parameter to 10 m/s (36 km/h or 22.4 mph).
- Start the *Wind Turbine Emulator* by setting the *Status* parameter to *Started* or by clicking on the *Start/Stop* button. Since the resistance of the load is maximum ($\infty \Omega$), the generator rotation speed is also maximum.

In Table 5, record the rotation speed, torque (absolute value), and mechanical power (absolute value) at the wind turbine rotor. These parameters are indicated by the *Speed*, *Torque*, and *Power* meters, respectively, in the *Four-Quadrant Dynamometer/Power Supply* window. Also, measure and record the dc voltage and dc current supplied to the load by the wind turbine generator.

Table 5. Measuring the parameters of the wind turbine at a wind speed of 10 m/s (36 km/h or 22.4 mph).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m or lbf·in)	Mechanical power at the wind turbine rotor P_m (W)	Load voltage E_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed =					
200						
86						
45						
30						
15						
7.5						
5						
0	Minimum speed =					

Measuring the parameters of the wind turbine at a wind speed of 10 m/s (36 km/h or 22.4 mph).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m) [lbf·in]	Mechanical power at the wind turbine rotor P_m (W)	Load voltage E_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed = 1983	$\cong 0.00$ N·m [$\cong 0.00$ lbf·in]	1.4	135	0.00	0.0
200	1808	0.35 N·m [3.10 lbf·in]	69.9	118	0.59	69.6
86	1605	0.72 N·m [6.37 lbf·in]	121	101	1.18	120
45	1411	1.12 N·m [9.91 lbf·in]	166	84.2	1.87	158
30	1276	1.44 N·m [12.74 lbf·in]	193	73.1	2.43	178
15	1033	2.05 N·m [18.14 lbf·in]	222	52.1	3.52	183
7.5	772	2.51 N·m [22.21 lbf·in]	202	32.6	4.28	139
5	600	2.52 N·m [22.30 lbf·in]	158	21.8	4.28	93.5
0	Minimum speed = 128	1.21 N·m [10.71 lbf·in]	16.2	0.0	2.02	0.0



At low power levels, the mechanical power measured at the wind turbine rotor may be lower than the electrical power to the load, due to the limited accuracy of torque measurement.

22. Complete the remainder of Table 5. Gradually decrease the generator rotation speed by decreasing the load resistance so as to obtain several points spread along the typical torque-versus-speed curve. For each resistance setting, record the rotation speed, torque (absolute value), and mechanical power (absolute value) at the wind turbine rotor in Table 5. Also, measure and record the dc voltage and dc current supplied to the load by the wind turbine generator.

The following resistance settings are suggested: 400 Ω , 150 Ω , 75 Ω , 45 Ω , 30 Ω , 15 Ω , 7.5 Ω , and 5 Ω . For the minimum generator rotation speed, set the load resistance to 0 Ω by short-circuiting the output of the *Diode Rectifier* on the *Wind Turbine Generator/Controller* via the dc ammeter.

⚠ WARNING



When the *Load Resistors* of the *Wind Turbine Generator/Controller* are used, stop the prime mover (wind-turbine emulator) before modifying any connection between these resistors to prevent the risk of an electric shock.

CAUTION

When using the 15 Ω *Load Resistor* alone, take your measurements within one minute and then stop the prime mover to prevent this resistor from overheating.

23. Stop the prime mover.

Remove the short-circuit at the *Diode Rectifier* output, and disconnect the *Load Resistors*.

24. Based on the dc voltages and dc currents recorded in Table 5, calculate the electrical power supplied to the load for each rotation speed and record your results in the table.

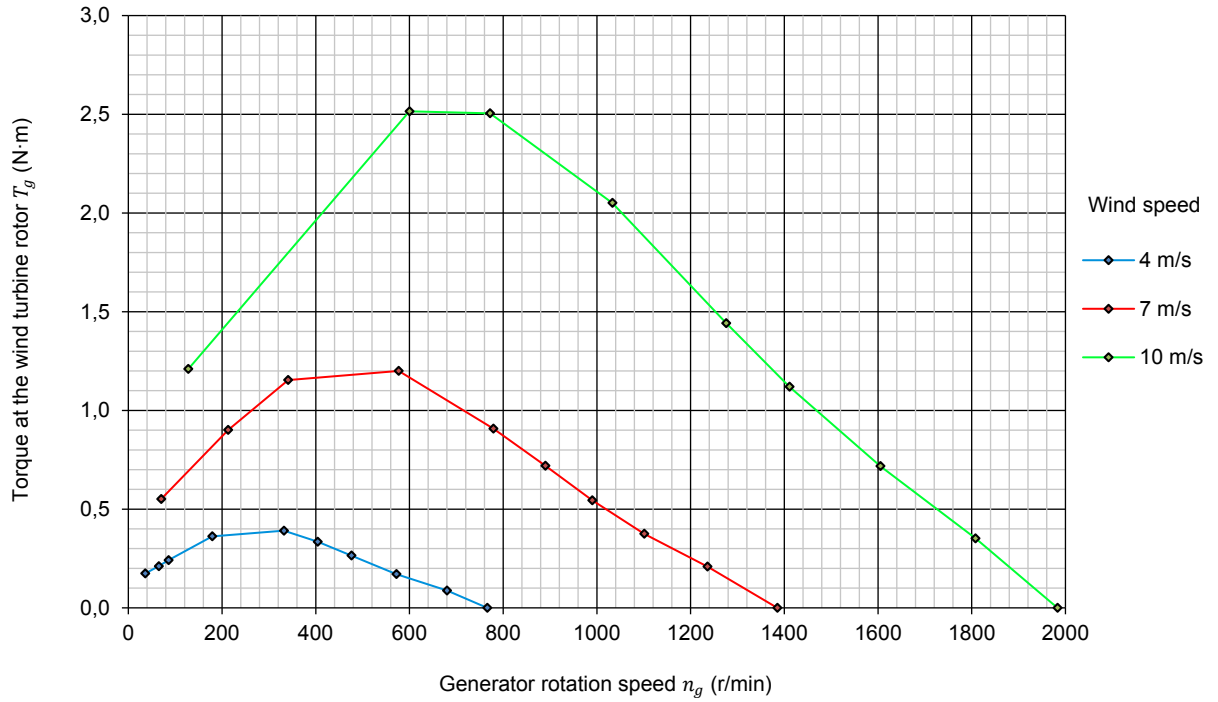
25. From the results recorded in Table 3, Table 4, and Table 5, plot in one graph the torque-versus-speed curves at the wind turbine rotor for wind speeds of 4, 7, and 10 m/s.

Then, plot in one graph the dc current-versus-dc voltage curves of the wind turbine generator for wind speeds of 4, 7, and 10 m/s.

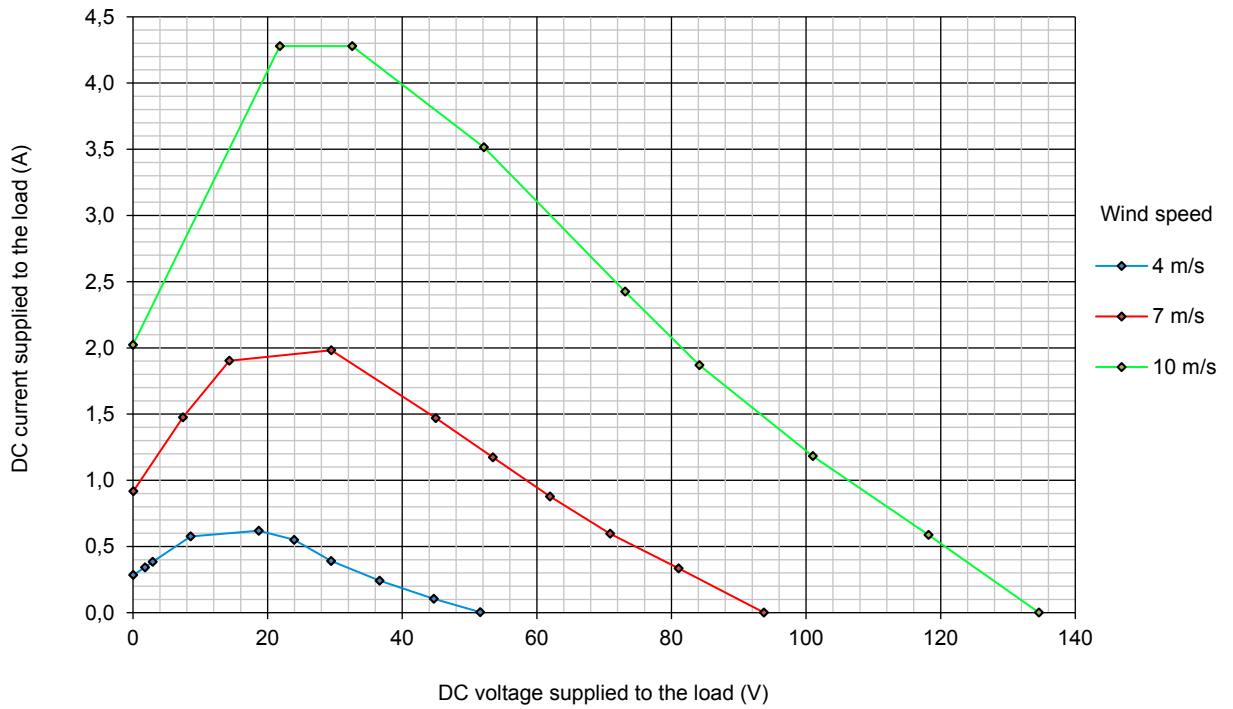
Compare the plotted curves. Do the dc current-versus-dc voltage curves have a shape similar to that of the torque-versus-speed?

- Yes No

Yes



Torque-versus-speed curves at the wind turbine rotor for different wind speeds.



DC current-versus-dc voltage curves of the wind turbine generator for different wind speeds.

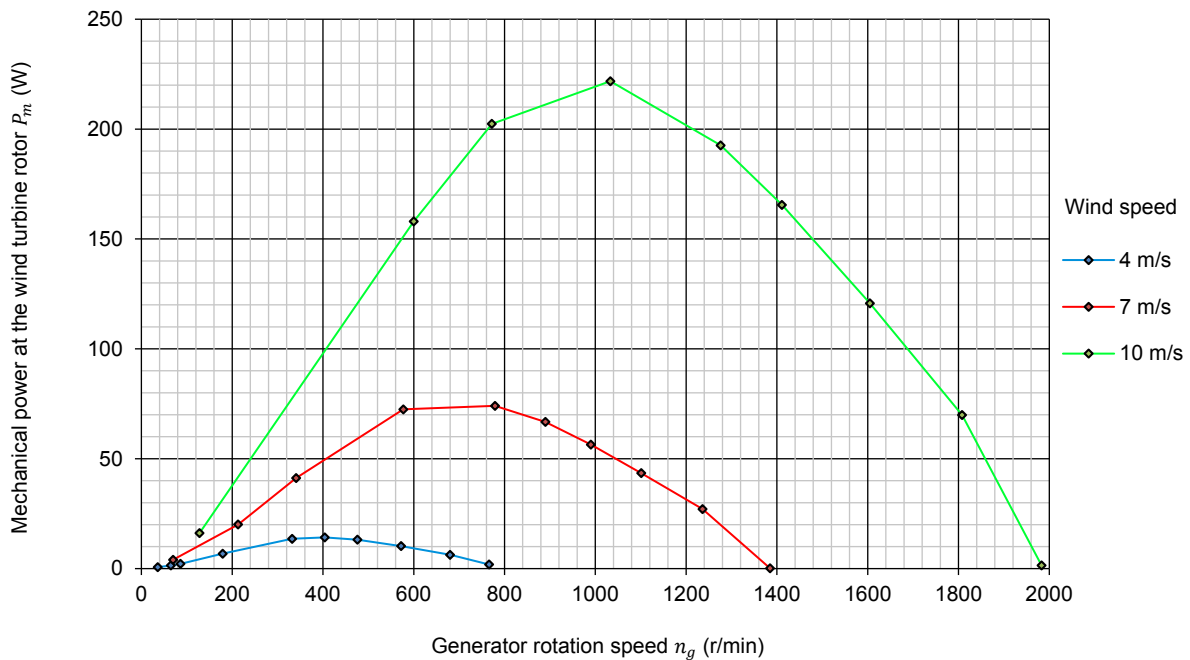
26. From the results recorded in Table 3, Table 4, and Table 5, plot in one graph the mechanical power-versus-speed curves at the wind turbine rotor for wind speeds of 4, 7, and 10 m/s.

Then, plot in one graph the electrical power-versus-speed curves of the wind turbine generator for wind speeds of 4, 7, and 10 m/s.

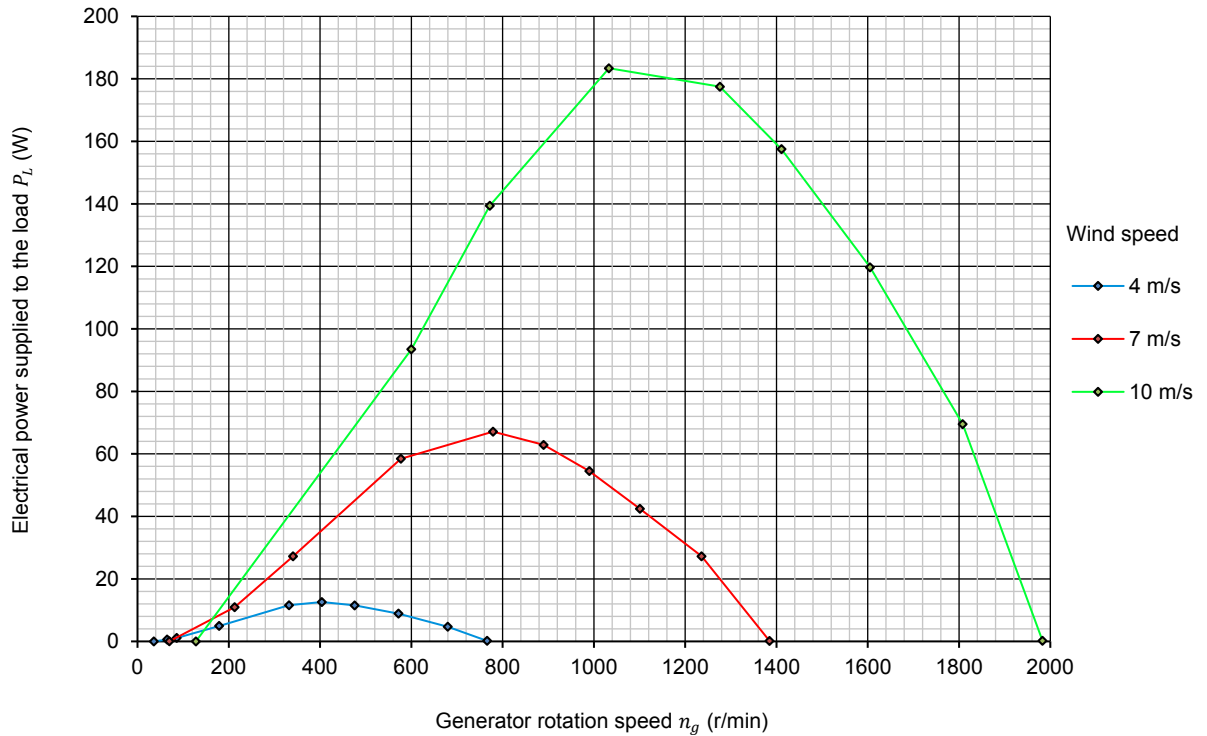
Compare the plotted curves. Do the electrical power-versus-speed curves have a shape similar to that of the mechanical power-versus-speed curves?

Yes No

Yes



Mechanical power-versus-speed curves at the wind turbine rotor for different wind speeds.



Electrical power-versus-speed curves of the wind turbine generator for different wind speeds.

27. On the mechanical power-versus-speed and electrical power-versus speed curves, notice that, for each wind speed, the mechanical power and electrical power are both maximum at a particular rotation speed. In Table 6, record the maximum mechanical power and maximum electrical power for each wind speed. Also, record the rotation speed and torque at the wind turbine rotor when the mechanical power and electrical power are maximum. These speed and torque values correspond to the optimum speed and optimum torque.

Table 6. Maximum power points, optimum speed, and optimum torque at each wind speed.

Wind speed	Maximum mechanical power (W)	Maximum electrical power (W)	Optimum speed at the wind turbine rotor (r/min)	Optimum torque at the wind turbine rotor (N·m or lbf·in)	Generator efficiency (%)
4 m/s (14.4 km/h or 9.0 mph)					
7 m/s (25.2 km/h or 15.7 mph)					
10 m/s (36 km/h or 22.4 mph)					

Maximum power points, optimum speed, and optimum torque at each wind speed.

Wind speed	Maximum mechanical power (W)	Maximum electrical power (W)	Optimum speed at the wind turbine rotor (r/min)	Optimum torque at the wind turbine rotor (N·m) [lbf·in]	Generator efficiency (%)
4 m/s (14.4 km/h or 9.0 mph)	14.2	13.1	404	0.33 N·m [2.96 lbf·in]	92.2
7 m/s (25.2 km/h or 15.7 mph)	75.1	66.1	780	0.92 N·m [8.14 lbf·in]	88.0
10 m/s (36 km/h or 22.4 mph)	222	183	1033	2.05 N·m [18.14 lbf·in]	82.4

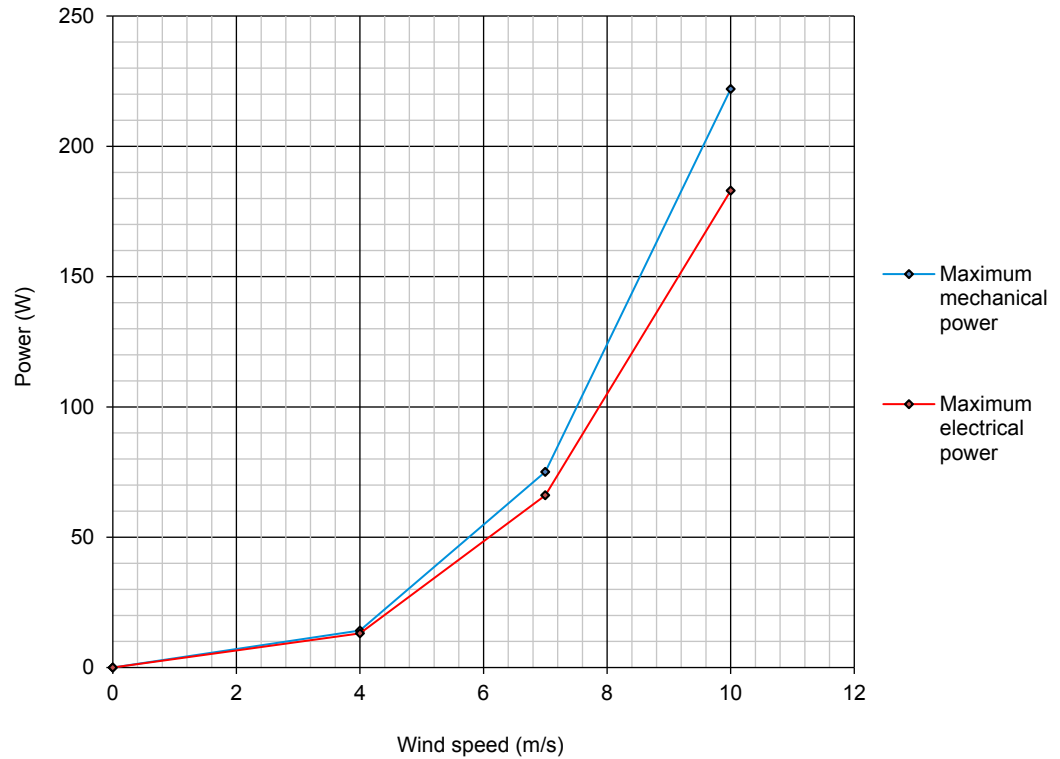
Notice that for each wind speed in Table 6, the maximum electrical power is lower than the maximum mechanical power, especially at a wind speed of 10 m/s. Briefly explain why.

The maximum electrical power is lower than the maximum mechanical power, especially at a wind speed of 10 m/s, because as the wind speed increases, the current flowing through the generator windings increases, causing the power losses through the generator windings (I^2R losses) to also increase.

28. Calculate the wind turbine generator efficiency at the maximum power points for each wind speed. Record your results in Table 6. Based on your results, how does the generator efficiency vary when the wind speed increases? Why?

The generator efficiency decreases when the wind speed increases. This occurs because, as the wind speed increases, the current flowing through the generator windings increases, causing the power losses through the generator windings (I^2R losses) to also increase.

29. Based on the results recorded in Table 6, plot a rough curve of the maximum mechanical power as a function of wind speed. Also, plot on the same graph a rough curve of the maximum electrical power as a function of wind speed.



Rough curves of the maximum mechanical and electrical power as a function of wind speed.

Does the curve of maximum mechanical power as a function of wind speed confirm that the mechanical power developed at the wind turbine rotor is approximately proportional to the cube (the third power) of the wind speed?

- Yes No

Yes. The curve of maximum mechanical power versus wind speed shows that the maximum mechanical power is approximately proportional to the cube (the third power) of the wind speed.

Does the curve of maximum electrical power as a function of wind speed show that the maximum electrical power at the wind turbine generator is proportional to the cube (the third power) of the wind speed? If not, explain why.

No. The curve of maximum electrical power versus wind speed has a slope less steep than the curve of maximum mechanical power versus wind speed, due to increasing power losses that occur in the generator windings.

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

31. Close LVDAC-EMS, then turn off all equipment. Remove all leads and cables.

CONCLUSION

In this exercise, you learned that the power contained in the wind varies with the cube (the third power) of the wind speed. You learned that only a fraction of the power passing through the area swept by the blades of a wind turbine rotor is extracted by the blades and transferred to the rotor. This fraction is proportional to the rotor efficiency coefficient, noted C_p . You became familiar with the torque-versus-speed curve at the rotor of a wind turbine. You saw that, for any wind speed, there is a point of optimum speed and optimum torque, at which the mechanical power produced at the rotor is maximum. At that point, called the maximum power point or MPP, the electrical power produced by the wind turbine generator is also maximum. You learned that the maximum mechanical power point varies with the cube (the third power) of the wind speed. Therefore, to operate a wind turbine at the maximum power point and maximize the energy produced at any wind speed, the rotor speed must be continuously monitored and kept at the optimum value, through adjustment of the rotor torque.

REVIEW QUESTIONS

1. Calculate the amount of power P_W in the wind passing through the area swept by a wind turbine rotor if the swept area A is 10 m^2 (107.6 ft^2), the wind speed v is 4.5 m/s (14.8 ft/s), and the air density ρ is 1.225 kg/m^3 (0.076 lbf/ft^3).

The power P_W in the wind is equal to

In SI units:

$$P_W = \frac{\rho A v^3}{2} = \frac{1.225 \text{ kg/m}^3 \cdot 10 \text{ m}^2 \cdot (4.5 \text{ m/s})^3}{2} = 558 \text{ W}$$

In US customary units:

$$P_W = \frac{\rho A v^3}{2g_c} = \frac{0.076 \text{ lbf/ft}^3 \cdot 107.6 \text{ ft}^2 \cdot (14.8 \text{ ft/s})^3}{2 \cdot 32.174 \text{ lbf} \cdot \text{ft/lbf} \cdot \text{s}^2} = 412 \text{ ft} \cdot \text{lbf/s}$$

2. By how much does the power in the wind passing through a given cross-sectional area increase, when the wind speed doubles? When the wind speed triples? Explain by describing how the power in the wind varies with wind speed.

When the wind speed doubles, the power in the wind passing through a given cross-sectional area increases eight times ($2^3 = 8$). When the wind speed triples, the power in the wind increases 27 times ($3^3 = 27$). This occurs because the power in the wind varies with the **cube** (the third power) of the wind speed.

3. What is meant by the rotor efficiency coefficient? What does it indicate? Calculate the amount of mechanical power P_M transferred at the rotor of a wind turbine when the wind power P_W swept by the rotor blades is 500 W, and the rotor efficiency coefficient C_p is 0.47.

The rotor efficiency coefficient C_p is the fraction of the available wind power extracted by the blades of the wind turbine rotor and transferred to the rotor. This coefficient indicates the efficiency of the wind turbine rotor in converting linear mechanical power into rotational mechanical power, and is dependent upon the design (shape) of the rotor blades.

$$P_M = P_W \cdot C_p = 500 \text{ W} \cdot 0.47 = 235 \text{ W}$$

4. Describe how the torque developed at the rotor of a wind turbine varies as a function of the rotor speed. Explain what is meant by the maximum power point (MPP), and why the wind turbine must be operated as close as possible to the optimum speed.

As the rotor speed increases, the torque produced at the rotor increases until a point is reached, beyond which the torque gradually decreases to zero. The maximum power point (MPP) is the point at which the mechanical power developed at the wind turbine rotor is maximum. The wind turbine must be operated as close as possible to the optimum speed to maximize the mechanical power at the rotor and thus obtain the maximum amount of electrical power.

5. Refer to the mechanical power-versus-speed curves and electrical power-versus-speed curves of Figure 32 and Figure 33. How does the mechanical power at the maximum power point (MPP) vary with rotor speed? Why? Does the maximum electrical power produced by the wind turbine generator vary in the same way as the MPP with rotor speed?

The mechanical power at the maximum power point (MPP) increases by eight whenever the wind speed doubles. This occurs because the power in the wind varies with the cube (the third power) of the wind speed.

Bibliography

Hau, Erich, *Wind Turbines, Fundamentals, Technologies, Application, Economics*, 2nd edition, Springer Berlin Heidelberg New York, 2006, ISBN 13-978-3-540-24240-6.

Masters, Gilbert M., *Renewable and Efficient Electric Power Systems*, New Jersey: John Wiley & Sons, Inc., 2004, ISBN 0-471-28060-7.