Electricity and New Energy

Introduction to Wind Power

Course Sample

603896

Order no.: 603896 (Printed version) 603981 (CD-ROM)
First Edition
Revision level: 10/2018

By the staff of Festo Didactic

Internet: www.festo-didactic.com
e-mail: did@de.festo.com

Printed in Canada

ISBN 978-2-89789-076-6 (Printed version)
ISBN 978-2-89789-078-0 (CD-ROM)
Legal Deposit – Bibliothèque et Archives nationales du Québec, 2018
Legal Deposit – Library and Archives Canada, 2018

Safety and Common Symbols

The following safety and common symbols may be used in this course 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 danger. Consult the relevant user documentation.
	Caution, risk of electric shock
	Caution, lifting hazard
	Caution, hot surface
	Caution, risk of fire
	Caution, risk of explosion
	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.

Safety and Common Symbols

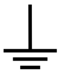
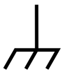
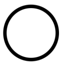
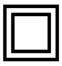
Symbol	Description
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

Table of Contents

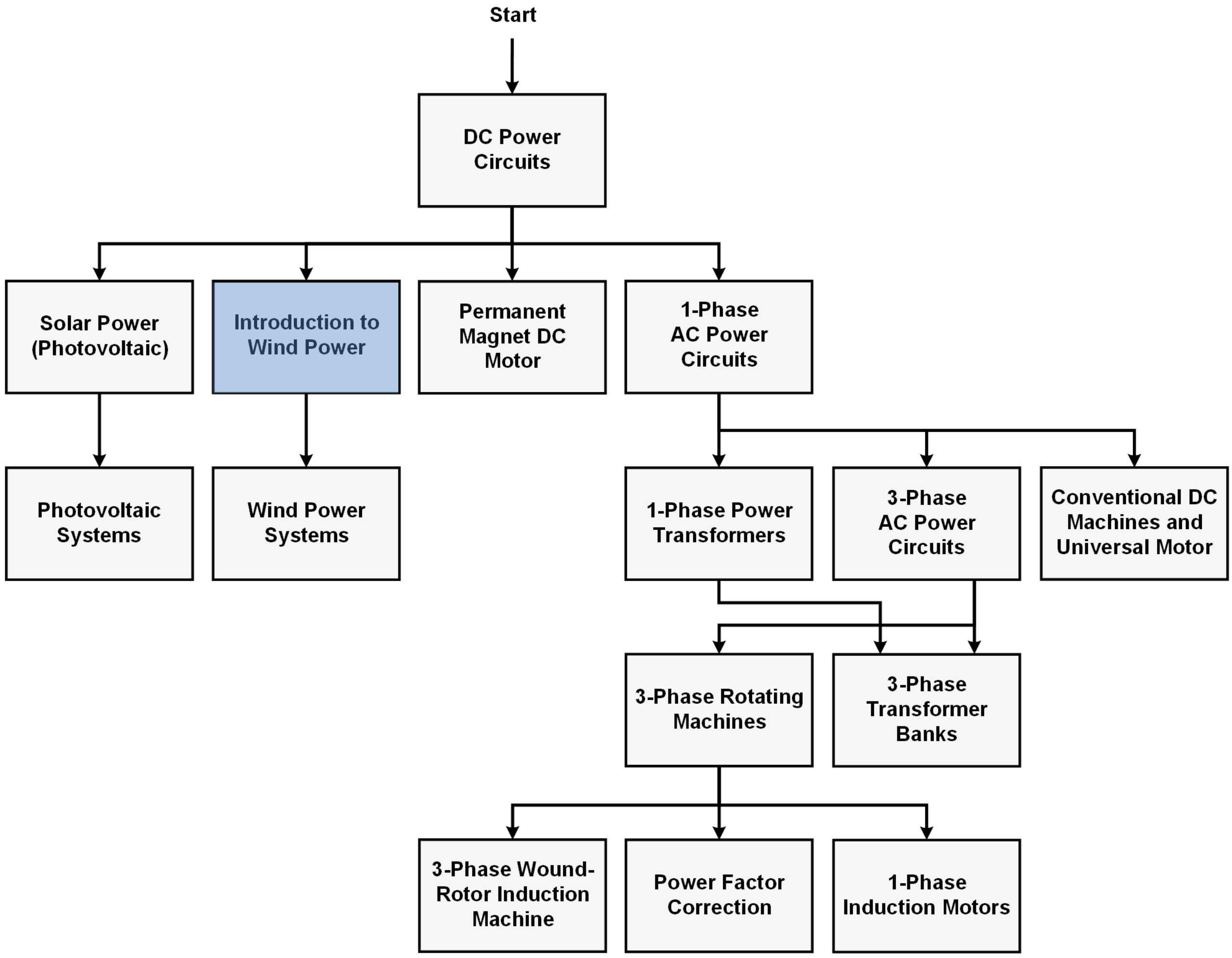
Table of Contents

Table of Contents

Preface

Electrical energy is part of our life since more than a century and the number of applications using electric power keeps increasing. This phenomenon is illustrated by the steady growth in electric power demand observed worldwide. In reaction to this phenomenon, the production of electrical energy using renewable natural resources (e.g., wind, sunlight, rain, tides, geothermal heat, etc.) has gained much importance in recent years since it helps to meet the increasing demand for electric power and is an effective means of reducing greenhouse gas (GHG) emissions.

To help answer the increasing needs for training in the wide field of electrical energy, Festo Didactic developed a series of modular courses. These courses are shown below as a flow chart, with each box in the flow chart representing a course.



Festo Didactic courses in electrical energy.

Teaching begins with course *DC Power Circuits* which introduces the student to the fundamentals of electricity such as the voltage, current, resistance, Ohm's Law, etc. Then, a series of courses provides in-depth coverage of various basic topics related to the field of electrical energy such as the ac power circuits, transformers, and rotating machines (motors and generators). Other courses also provide in-depth coverage of solar power and wind power. Finally, two courses deal with photovoltaic systems and wind power systems, with focus on practical aspects related to these systems.

Preface

We invite readers to send us their tips, feedback, and suggestions for improving the course.

Please send these to services.didactic@festo.com.

The authors and Festo Didactic look forward to your comments.

About This Course

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 and controller module, a 4 quadrant power supply and dynamometer controller, and a 4 quadrant dynamometer motor. The 4 quadrant power supply and dynamometer controller and the 4 quadrant dynamometer motor are used to drive the wind turbine generator in the wind turbine generator and controller module. By varying the rotation speed of the 4 quadrant dynamometer motor and the current through the generator windings, the student measures the generator parameters for different speeds and load values.

The 4 quadrant power supply and dynamometer controller and the 4 quadrant dynamometer motor are also used to emulate wind blowing onto the blades of a wind-turbine rotor. In this mode of operation, the torque-speed characteristic of the 4 quadrant dynamometer motor is identical to the torque-speed characteristic that would be obtained at the wind turbine rotor for different wind speeds. This allows the student to plot the typical curves of the wind turbine. Finally, the controller of the wind turbine generator is used to adjust the charging current of a battery in order to maximize the amount of energy stored in the battery at any wind speed.

Offshore wind turbines in Copenhagen, Denmark.

About This Course

Safety considerations

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

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 completed the course *DC Power Circuits*.

Systems of units

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

In some cases, units are also expressed using other systems of units.

To the Instructor

You will find in this Instructor version of the course all the elements included in the Student version of the course 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 course should be considered as a guide. Students who correctly perform the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation and use

In order for students to be able to safely perform the hands-on exercises in this course, the equipment must have been properly installed, i.e., according to the instructions given in the accompanying Safety Instructions and Commissioning manual. Also, the students must familiarize themselves with the safety directives provided in the Safety Instructions and Commissioning manual and observe these directives when using the 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:

$$\rho = \frac{m}{V} \tag{3}$$

where ρ is the air density, in kilograms per cubic meter (kg/m^3).
m is the mass of air, in kilograms (kg).
V is the volume, in cubic meters (m^3).

The air density varies with atmospheric pressure, temperature, humidity, and altitude. In SI units, ρ is equal to **1.225 kg/m^3** 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%.

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:

$$K = \frac{mv^2}{2} \tag{4}$$

where K is the kinetic energy, in joules (J).
m is the mass of air, in kilograms (kg).
v is the velocity of the mass of air, in meters per second (m/s).
2 is a constant.

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.

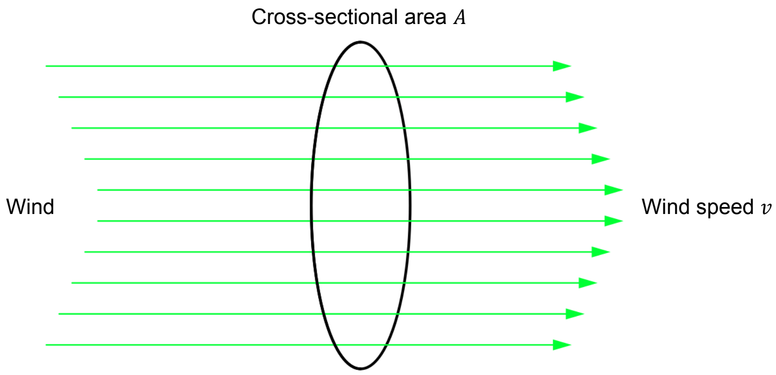


Figure 26. Wind flowing through a cross-sectional area.

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

$$P_W = \frac{\rho A v^3}{2} \tag{5}$$

where P_W is the power in the wind, in watts (W, or kg·m^2/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).

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 is equal to 3.6 kilometers per hour (3.6 km/h).

Wind speed (m/s)	Power (W/m²)	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

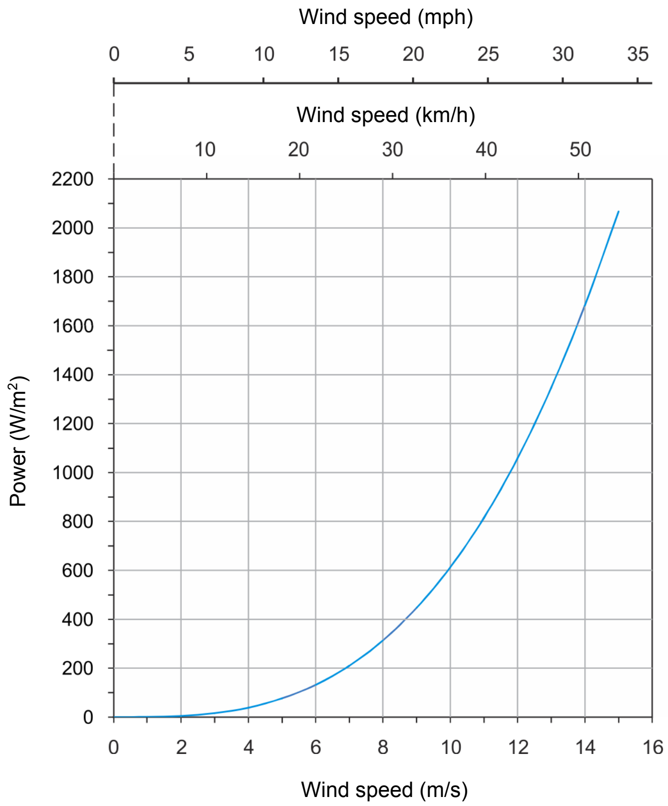


Figure 27. The wind power varies with the cube (the third power) of the wind speed.

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°.

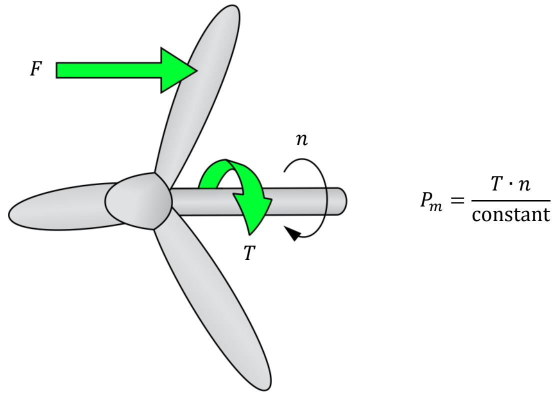


Figure 28. Torque, rotation speed, and rotational mechanical power.

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.

$$P_m = \frac{T \cdot n}{9.55} \qquad (6)$$

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.

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.

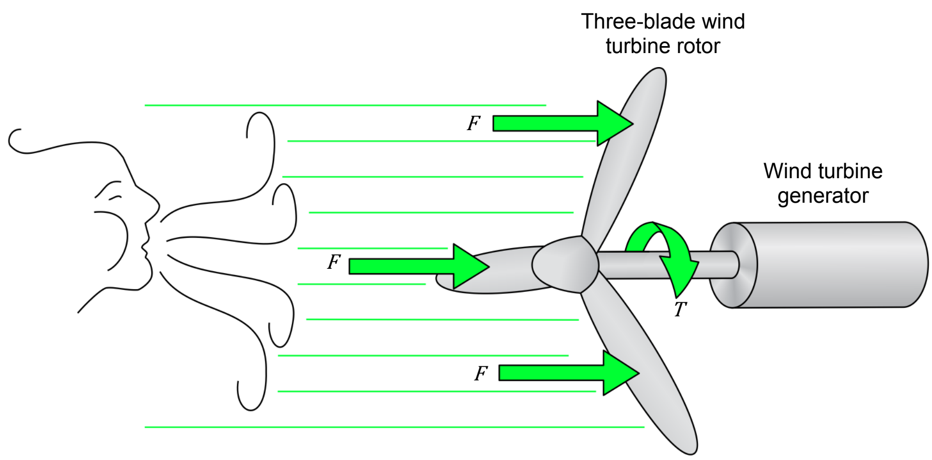


Figure 29. A fraction of the power in the wind intercepted by the blades of the turbine is converted into rotational mechanical power to drive the electric generator of the turbine.

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:

$$P_W = \frac{\rho A v^3}{2} \tag{7}$$

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:

$$P_m = P_W \cdot C_p = \frac{\rho A v^3}{2} \cdot C_p \tag{8}$$

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.

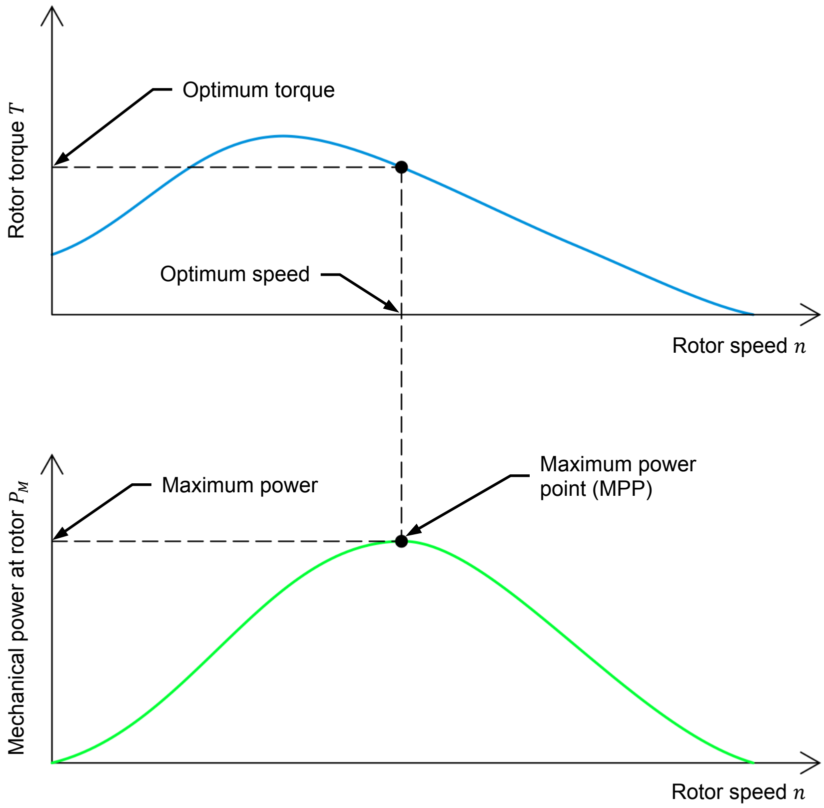


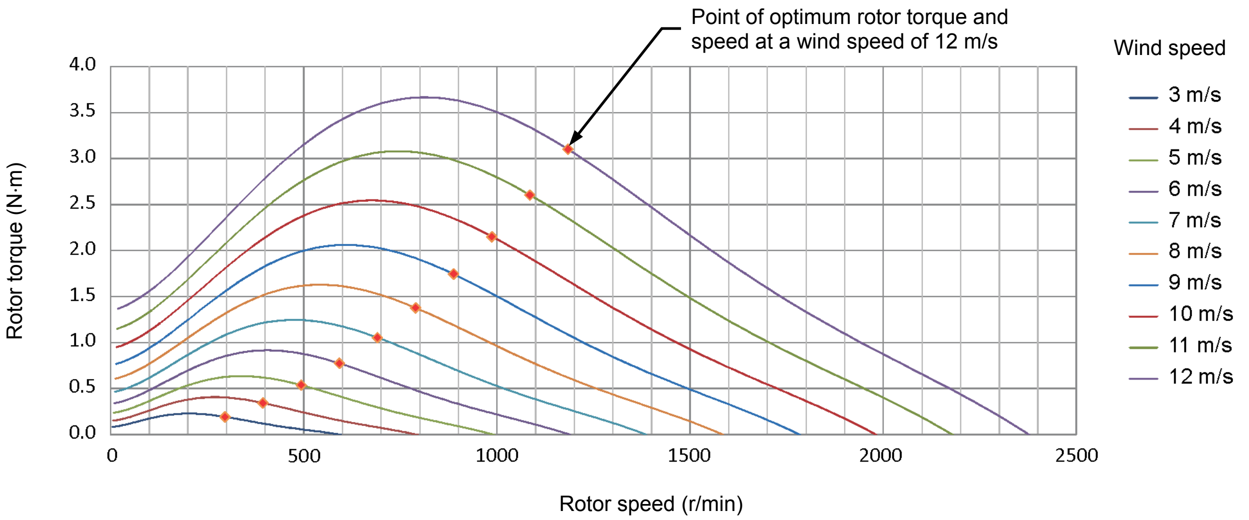
Figure 30. Typical torque-versus-speed curve and mechanical power-versus-speed curve at the rotor of a wind turbine, for a given wind speed.

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.

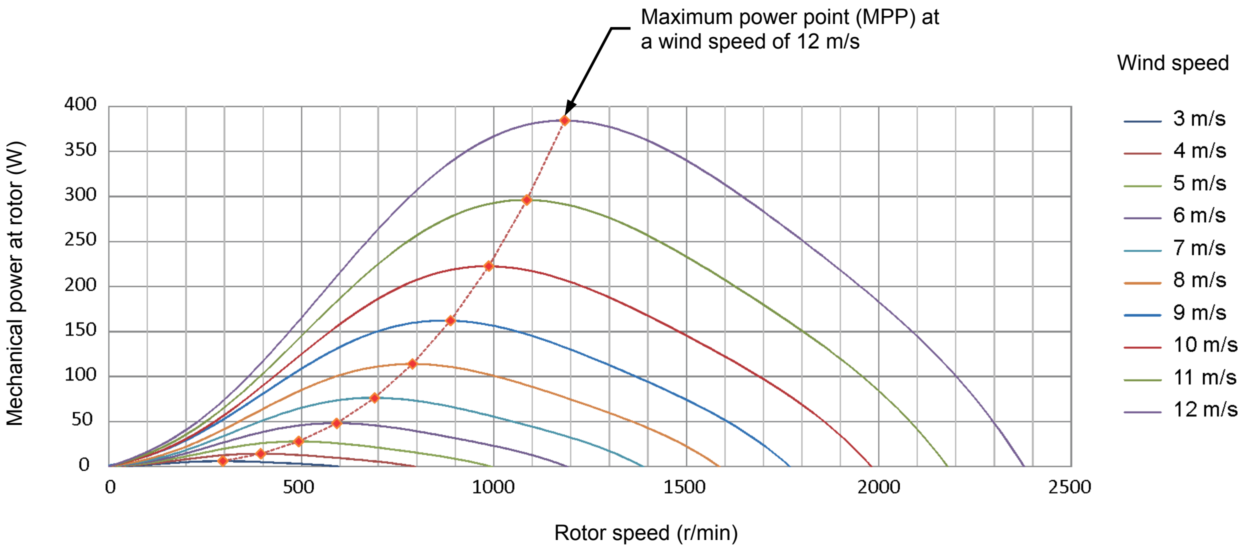
A wind turbine must be operated as close as possible to the optimum speed to maximize the mechanical power developed at the rotor and thus obtain the maximum amount of electrical power. This is performed by setting the rotor torque to the optimum value, through adjustment of the current drawn by the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

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

Figure 31 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).



(a) Torque-versus-speed curves



(b) Mechanical power-versus-speed curves

Figure 31. Family of typical curves at the bladed rotor of a wind turbine, for different wind speeds.

On each torque-versus-speed curve in Figure 31a, 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 31b.

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.

The following conclusions can be drawn from examination of the family of curves in Figure 31:

- Figure 31a 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 31b shows.

When the maximum power points on the various mechanical power curves in Figure 31b are connected together, they form a curve which increases exponentially (see dashed line in Figure 31b). 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.

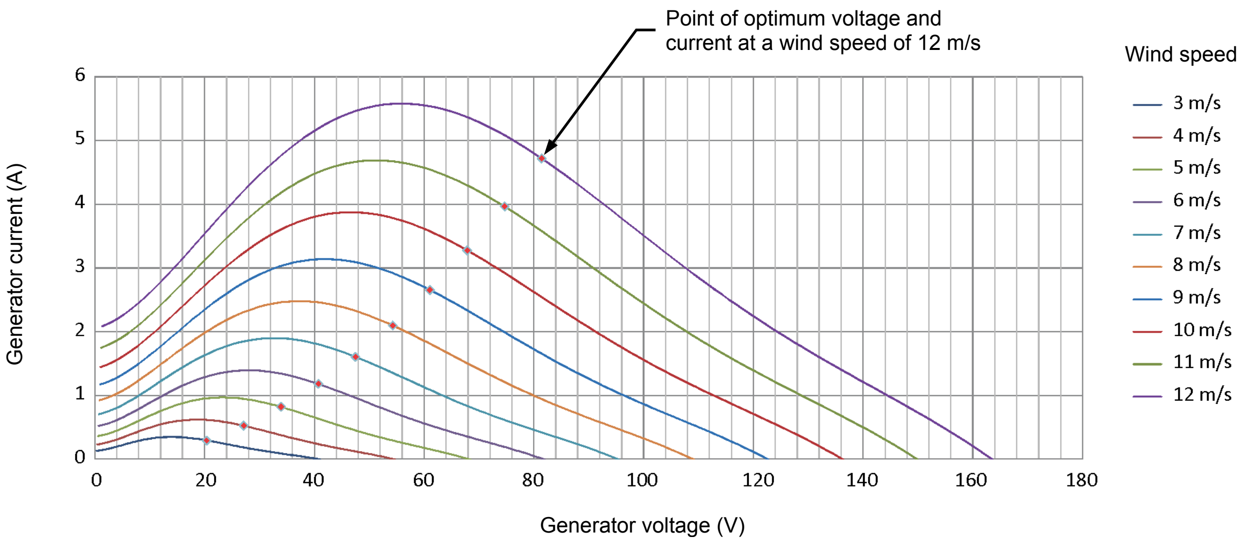
Current-versus-voltage and electrical power-versus-speed curves at the wind turbine generator output for different wind speeds

Figure 32 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).

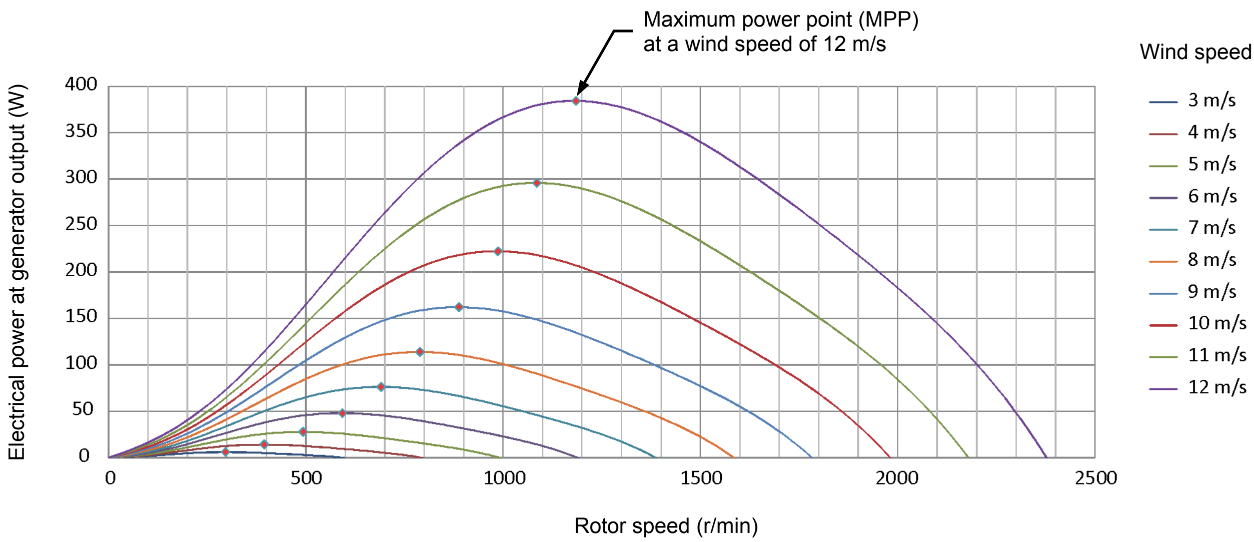
The following conclusions can be drawn by comparing the family of curves in Figure 32 with the family of curves in Figure 31:

- 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 32a) are similar to the torque-versus-speed curves at the wind turbine rotor (shown in Figure 31a).
- Also, the electrical power-versus-speed curves of the wind turbine generator (Figure 32b) are similar to the mechanical power-versus-speed curves at the wind turbine rotor (shown in Figure 31b).

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.



(a) Current-versus-voltage curves



(b) Electrical power-versus-speed curves

Figure 32. Family of typical curves related to the output of a wind turbine generator, for different wind speeds.

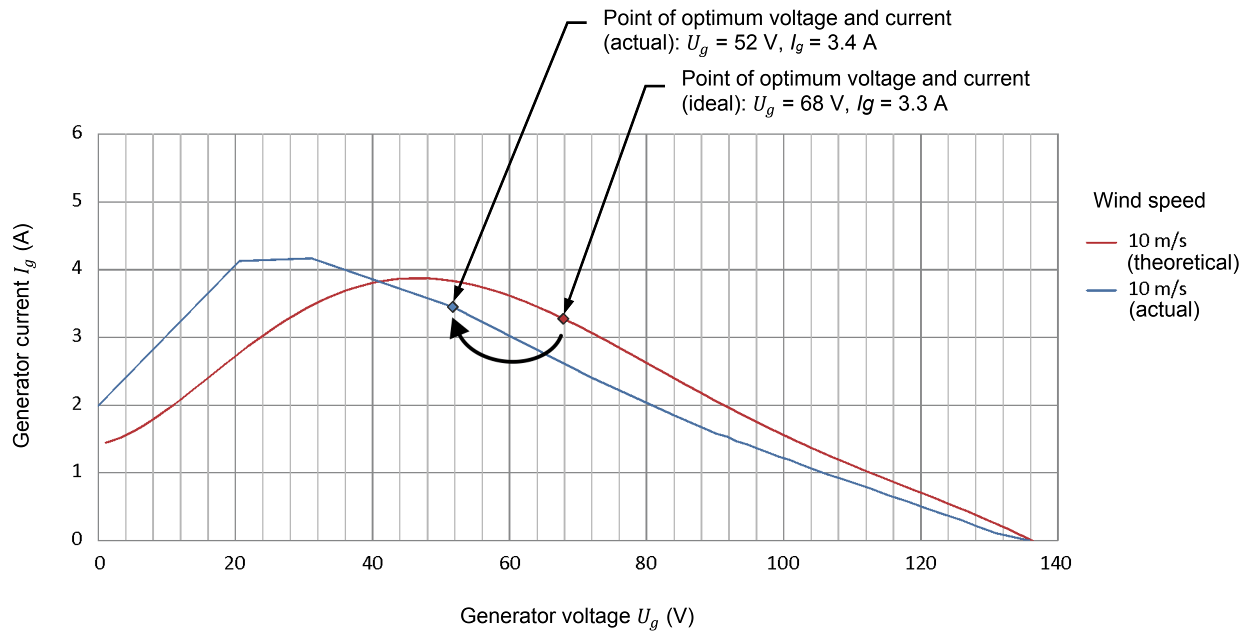
Wind turbine generator efficiency

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.

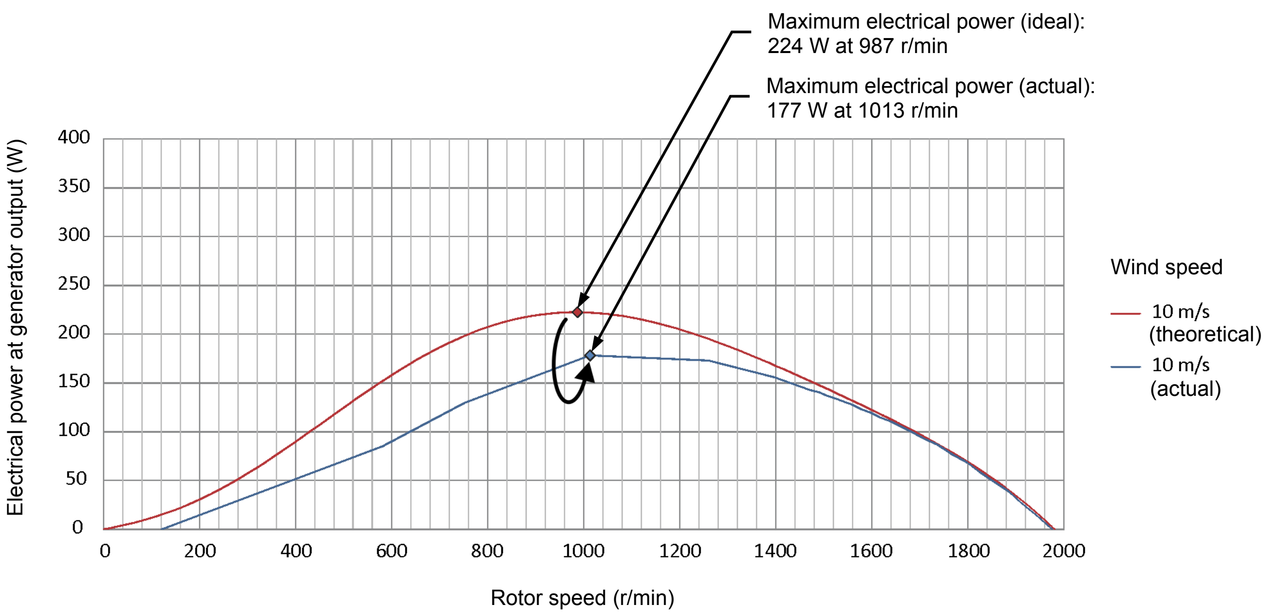
With a wind turbine generator (as well as any other generator), not all the mechanical power applied to the rotor shaft is converted into electrical power, due to power losses in the stator windings. These power losses are usually called I^2R losses. They decrease the efficiency of a wind turbine in 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 33 shows the ideal and actual curves related to a wind turbine generator at a wind speed of 10 m/s.

- Figure 33a 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 33b 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 W ÷ 224 W).



(a) Current-versus-voltage curves



(b) Electrical power-versus-speed curves

Figure 33. Ideal and actual curves of the wind turbine generator (wind speed = 10 m/s).

Figure 34. Small wind turbine for domestic use.

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.

   To ensure optimal accuracy of torque measurements performed with the equipment, make sure that the code (usually a single letter) on the identification (ID) label affixed to the 4 Quadrant Dynamometer Motor is the same as the code on the motor identification (Motor ID) label affixed to the 4 Quadrant Power Supply and Dynamometer Controller.

   To ensure consistency between the results obtained during the various exercises, make sure that you are using the same 4 Quadrant Power Supply and Dynamometer Controller, 4 Quadrant Dynamometer Motor, and Wind Turbine Generator and Controller as in Exercise 1 (same serial numbers).

2. Install the 4 Quadrant Dynamometer Motor and the Wind Turbine Generator and Controller side by side on the work surface, with the 4 Quadrant Dynamometer Motor on the left-hand side of the Wind Turbine Generator and Controller.

   Install the 4 Quadrant Power Supply and Dynamometer Controller, the Resistive Load, the Wind Turbine Load Resistors, and the AC 24V Power Supply in the workstation.

3. Make the connections required to earth the equipment properly.

   If necessary, check with the instructor to ensure that the connections you made provide proper earthing of the equipment.

⚠ WARNING

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

4. Mechanically couple the Wind Turbine Generator and Controller to the 4 Quadrant Dynamometer Motor using the timing belt, then install the protective guard.

   If necessary, check with the instructor to ensure that the machines, the timing belt, and the protective guard are properly installed.

5. Connect the connection cable of the 4 Quadrant Dynamometer Motor to the corresponding connector on the 4 Quadrant Power Supply and Dynamometer Controller.

6. Make sure that the main power switch of the 4 Quadrant Power Supply and Dynamometer Controller is set to the *O* (off) position, then connect its *Power Input* to an ac power outlet that is properly protected.

   Make sure that the main power switch of the AC 24V Power Supply is set to the *O* (off) position, then connect its *Power Input* to an ac power outlet that is properly protected.

   If necessary, check with the instructor to ensure that the ac power outlets to which you connect the equipment are properly protected.

7. Connect the *Auxiliary Power Input* of the Wind Turbine Generator and Controller to the *Power Output* of the AC 24V Power Supply.

8. Ask your instructor to turn on (i.e., to unlock) electric power at your workstation, if applicable.

9. Turn the AC 24V Power Supply on.

10. Turn the 4 Quadrant Power Supply and Dynamometer Controller on.

11. Set the *Operating Mode* switch of the 4 Quadrant Power Supply and Dynamometer Controller to *Dynamometer*. This setting allows the 4 Quadrant Power Supply and Dynamometer Controller and the 4 Quadrant Dynamometer Motor to operate as a prime mover, a brake, or both, depending on the selected function.

12. Connect the USB port of the 4 Quadrant Power Supply and Dynamometer Controller to a USB port of the host computer.

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

    In LVDAC-EMS, make sure that the 4 Quadrant Power Supply and Dynamometer Controller is detected. Make sure that the *Standard Functions (computer-based control)* and *Turbine Emulator* are available for the 4 Quadrant Power Supply and Dynamometer Controller. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network.

14. In LVDAC-EMS, launch the coupling-friction compensation calibration process for timing belt coupling with a 24:32 pulley ratio. Follow the on-screen instructions to complete the calibration process.

    The 4 Quadrant Dynamometer Motor rotates at different speeds during the coupling-friction compensation calibration process. The process can take up to about 5 minutes to complete.

15. Set up the circuit shown in Figure 35. In this setup, the 4 Quadrant Dynamometer Motor drives the wind turbine generator, thereby producing an ac voltage across the generator windings (*-G1*). A diode rectifier (i.e., the *-T2* section) in the Wind Turbine Generator and 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 210 Ω and 4400 Ω, or with the Wind Turbine Load Resistors for resistance values between 5 Ω and 45 Ω.

Connect the diode rectifier output (+ and – terminals in the *-T2* section) of the Wind Turbine Generator and Controller to the Resistive Load module via a multimeter set as a dc ammeter. Connect the three resistor sections on the Resistive Load 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.

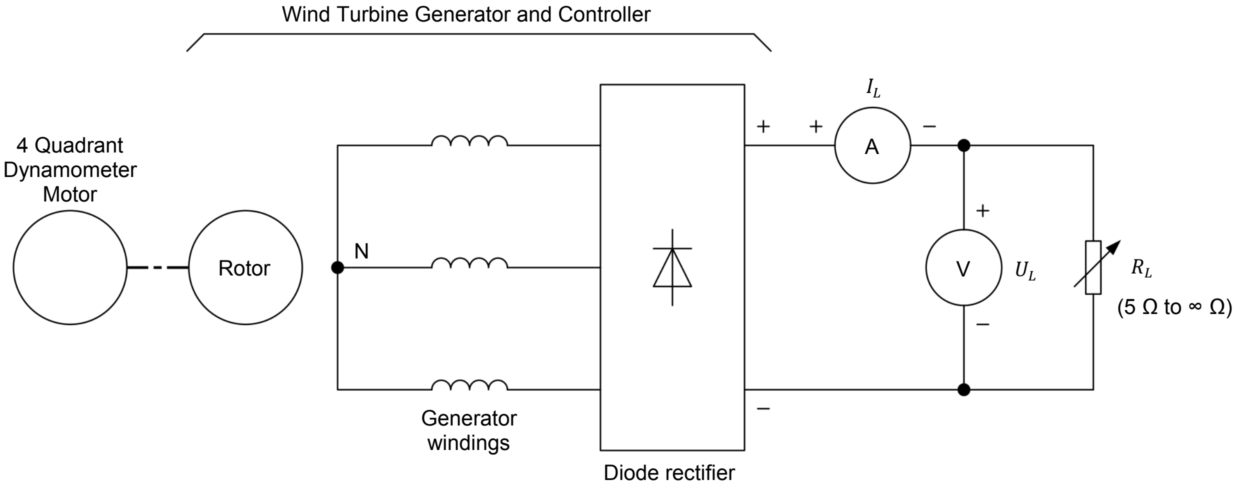


Figure 35. Equipment setup.

16. In LVDAC-EMS, do the settings required so that the 4 Quadrant Power Supply and Dynamometer Controller and the 4 Quadrant Dynamometer Motor operate as a wind turbine emulator, i.e., a prime mover emulating wind blowing onto the blades mounted at the end of a wind turbine rotor. Then, set the wind turbine emulator as follows:

- Wind turbine type: 1.15 m diameter, 3 blade rotor
- Wind speed control: manual (slider)
- Wind speed: 0 m/s

The above settings make the 4 Quadrant Power Supply and Dynamometer Controller and the 4 Quadrant Dynamometer Motor emulate a wind turbine having a 1.15 m diameter, 3 blade rotor. In other words, this emulates the torque-speed characteristic at the rotor of the wind turbine, but without the need for wind and rotor blades.

In LVDAC-EMS, enable continuous refresh of the speed, torque, power, and energy meters of the wind turbine emulator.

Do not start the wind turbine emulator for now. This will be done in the next section of the exercise.

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)

17. In LVDAC-EMS, set the wind speed of the wind turbine emulator to 4 m/s, then start the wind turbine emulator.

Observe that the wind turbine generator in the Wind Turbine Generator and Controller starts to rotate. In fact, the generator rotates as if wind were blowing at 4 m/s onto the rotor blades. Since the resistance of the load is maximum (∞ Ω), 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 LVDAC-EMS. 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).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m)	Mechanical power at the wind turbine rotor P_m (W)	Load voltage U_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed =					
210						
45						
30						
22.5						
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).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m)	Mechanical power at the wind turbine rotor P_m (W)	Load voltage U_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed = 772	0.01	0.9	54.6	0.0	0.0
210	607	0.14	9.4	40.2	0.19	7.6
45	377	0.36	14.1	22.7	0.50	11.4
30	297	0.41	12.6	16.9	0.56	9.5
22.5	236	0.39	9.6	12.4	0.55	6.8
15	141	0.32	4.6	6.6	0.44	2.9
7.5	72	0.22	1.7	2.3	0.31	0.7
5	59	0.20	1.2	1.5	0.29	0.4
0	Minimum speed = 35	0.18	0.7	0.0	0.27	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.

18. 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: 210 Ω, 45 Ω, 30 Ω, 22.5 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 diode rectifier output (+ and - terminals in the -*T2* section) on the Wind Turbine Generator and Controller via the dc ammeter.

⚠ WARNING

Before modifying any connection between the resistors of the Wind Turbine Load Resistors, stop the wind turbine emulator in order to prevent the risk of an electric shock.

CAUTION

When using one of the 15 Ω resistors in the *Wind Turbine Load Resistors* module alone, take your measurements within one minute and then stop the wind turbine emulator to prevent this resistor from overheating.

Appendix C 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 210 Ω. To further decrease the load resistance, stop the wind turbine emulator. Then, disconnect the diode rectifier output of the Wind Turbine Generator and Controller from the Resistive Load module. Connect the diode rectifier output of the Wind Turbine Generator and Controller to the Wind Turbine Load Resistors and arrange 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 Ω and 45 Ω. 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 wind turbine emulator 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 wind turbine emulator before modifying any connection between the resistors of the Wind Turbine Load Resistors.

In LVDAC-EMS, stop the wind turbine emulator.

Remove the short-circuit at the diode rectifier output of the Wind Turbine Generator and Controller, and disconnect the Wind Turbine Load Resistors.

19. 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)

20. In LVDAC-EMS, make sure that the wind turbine emulator is stopped.

Connect the diode rectifier output of the Wind Turbine Generator and Controller to the Resistive Load module. Then, set the initial load resistance value to infinite (∞ Ω) 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 of the Wind Turbine Generator and Controller, as Figure 35 shows. Connect the multimeter set to measure dc voltage across the load, as Figure 35 shows.

21. In LVDAC-EMS, set the wind speed of the wind turbine emulator to 7 m/s to make the wind turbine generator operate as if wind were blowing at 7 m/s onto the rotor blades.

In LVDAC-EMS, start the wind turbine emulator. Since the resistance of the load is maximum (∞ Ω), 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 LVDAC-EMS. 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).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m)	Mechanical power at the wind turbine rotor P_m (W)	Load voltage U_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed =					
210						
45						
30						
22.5						
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).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m)	Mechanical power at the wind turbine rotor P_m (W)	Load voltage U_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed = 1393	0.0	0.0	97.5	0.0	0.0
210	1190	0.27	33.5	80.5	0.38	30.6
45	850	0.80	71.0	52.4	1.16	60.8
30	740	0.97	77.0	43.4	1.44	62.5
22.5	656	1.12	75.7	36.8	1.63	60.0
15	533	1.23	69.0	27.0	1.80	48.6
7.5	266	1.03	29.0	11.1	1.50	16.7
5	166	0.77	13.5	5.6	1.14	6.4
0	Minimum speed = 65	0.55	3.6	0.0	0.80	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 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: 210 Ω, 45 Ω, 30 Ω, 22.5 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 diode rectifier output on the Wind Turbine Generator and Controller via the dc ammeter.

⚠ WARNING

Before modifying any connection between the resistors of the Wind Turbine Load Resistors, stop the wind turbine emulator in order to prevent the risk of an electric shock.

CAUTION

When using one of the 15 Ω resistors in the *Wind Turbine Load Resistors* module alone, take your measurements within one minute and then stop the wind turbine emulator to prevent this resistor from overheating.

Appendix C 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 210 Ω. To further decrease the load resistance, stop the wind turbine emulator. Then, disconnect the diode rectifier output of the Wind Turbine Generator and Controller from the Resistive Load module. Connect the diode rectifier output of the Wind Turbine Generator and Controller to the Wind Turbine Load Resistors and arrange 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 Ω and 45 Ω. 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 wind turbine emulator and record the rotation speed, torque, and mechanical power at the wind turbine rotor in Table 4. Also, record the dc voltage and dc current supplied to the load by the wind turbine generator. Stop the wind turbine emulator before modifying any connection between the resistors of the Wind Turbine Load Resistors.

23. In LVDAC-EMS, stop the wind turbine emulator.

Remove the short-circuit at the diode rectifier output of the Wind Turbine Generator and Controller, and disconnect the Wind Turbine Load Resistors.

24. 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)

25. In LVDAC-EMS, make sure that the wind turbine emulator is stopped.

Connect the diode rectifier output of the Wind Turbine Generator and Controller to the Resistive Load module. Then, set the initial load resistance value to infinite (∞ Ω) 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 of the Wind Turbine Generator and Controller, as Figure 35 shows. Connect the multimeter set to measure dc voltage across the load, as Figure 35 shows.

26. In LVDAC-EMS, set the wind speed of the wind turbine emulator to 10 m/s to make the wind turbine generator operate as if wind were blowing at 10 m/s onto the rotor blades.

In LVDAC-EMS, start the wind turbine emulator. Since the resistance of the load is maximum (∞ Ω), 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 LVDAC-EMS. 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).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m)	Mechanical power at the wind turbine rotor P_m (W)	Load voltage U_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed =					
210						
45						
30						
22.5						
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).

Load resistor R_L (Ω)	Generator rotation speed n_g (r/min)	Torque at the wind turbine rotor T_g (N·m)	Mechanical power at the wind turbine rotor P_m (W)	Load voltage U_L (V)	Load current I_L (A)	Electrical power to the load P_L (W)
∞	Maximum speed = 1999	0.0	0.0	140.1	0.0	0.0
210	1816	0.36	69.0	121.0	0.58	70.2
45	1375	1.24	177	84.0	1.86	156
30	1238	1.56	203	71.5	2.38	170
22.5	1133	1.83	215	63.1	2.78	175
15	980	2.17	224	50.3	3.34	168
7.5	704	2.5	187	28.7	3.89	112
5	528	2.41	130	18.3	3.64	66.6
0	Minimum speed = 117	1.16	14.4	0.35	1.72	0.60

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.

27. 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: 210 Ω, 45 Ω, 30 Ω, 22.5 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 diode rectifier output of the Wind Turbine Generator and Controller via the dc ammeter.

⚠ WARNING

Before modifying any connection between the resistors of the Wind Turbine Load Resistors, stop the wind turbine emulator in order to prevent the risk of an electric shock.

CAUTION

When using one of the 15 Ω resistors in the *Wind Turbine Load Resistors* module alone, take your measurements within one minute and then stop the wind turbine emulator to prevent this resistor from overheating.

Appendix C 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 210 Ω. To further decrease the load resistance, stop the wind turbine emulator. Then, disconnect the diode rectifier output of the Wind Turbine Generator and Controller from the Resistive Load module. Connect the diode rectifier output of the Wind Turbine Generator and Controller to the Wind Turbine Load Resistors and arrange 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 Ω and 45 Ω. 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 wind turbine emulator and record the rotation speed, torque, and mechanical power at the wind turbine rotor in Table 5. Also, record the dc voltage and dc current supplied to the load by the wind turbine generator. Stop the wind turbine emulator before modifying any connection between the resistors of the Wind Turbine Load Resistors.

28. In LVDAC-EMS, stop the wind turbine emulator.

Remove the short-circuit at the diode rectifier output of the Wind Turbine Generator and Controller, and disconnect the Wind Turbine Load Resistors.

29. 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.

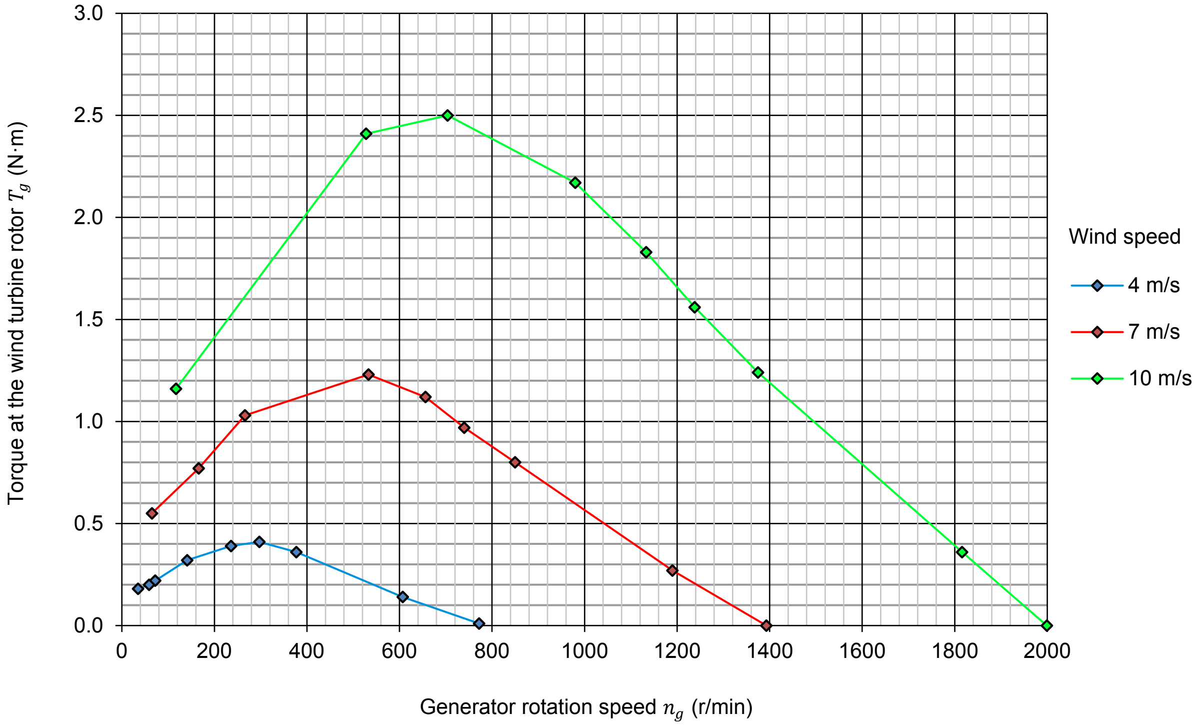
30. From the results recorded in Table 3, Table 4, and Table 5, plot in one graph the torque-versus-speed curves at the wind turbine rotor for wind speeds of 4, 7, and 10 m/s.

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.

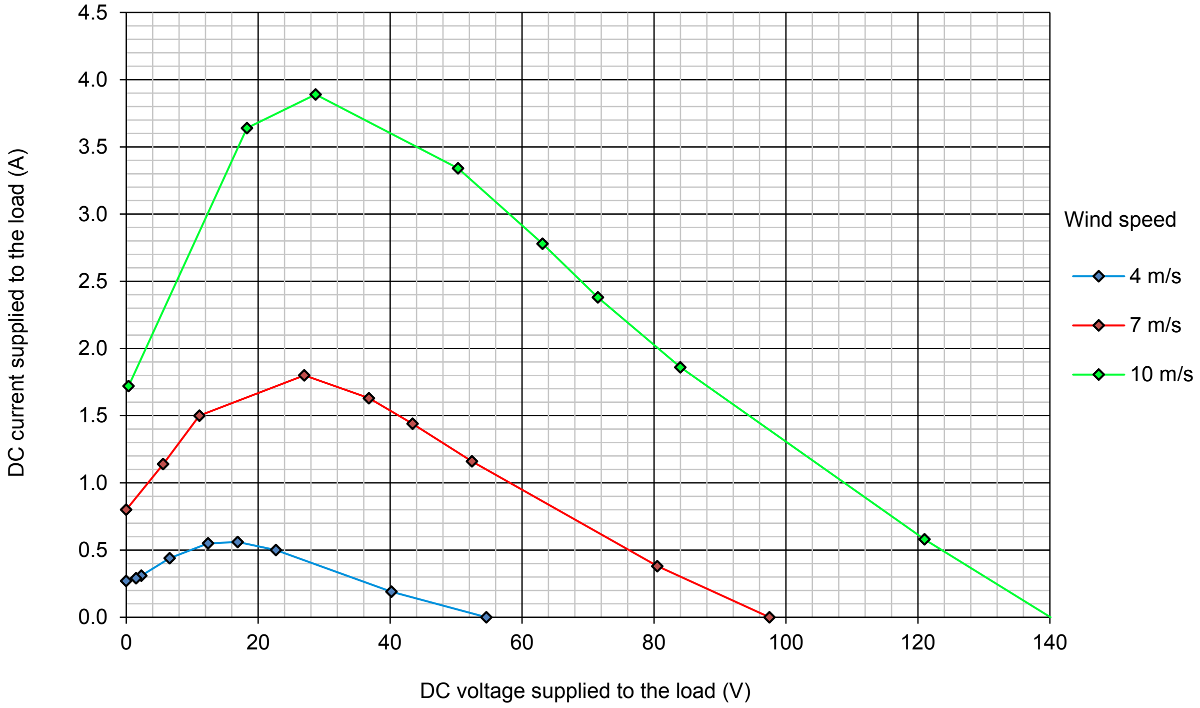
Compare the plotted curves. Do the dc current-versus-dc voltage curves have a shape similar to that of the torque-versus-speed?

❑ Yes ❑ No

Yes (see curves plotted below).



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.

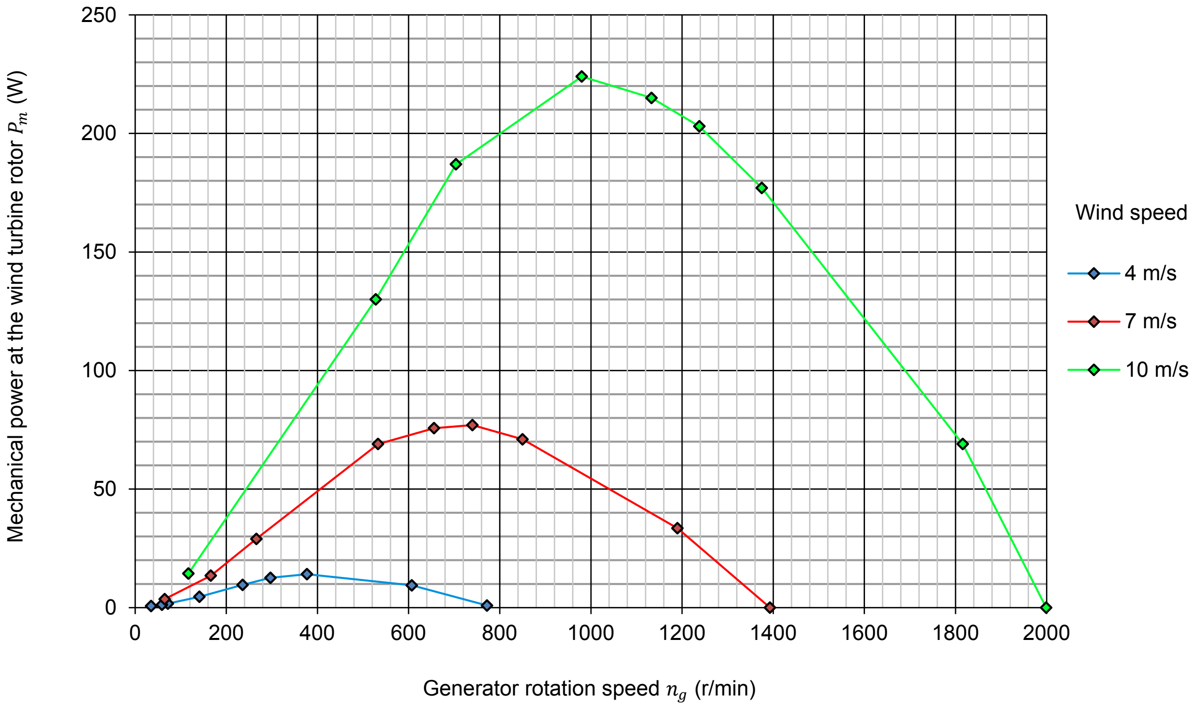
31. From the results recorded in Table 3, Table 4, and Table 5, plot in one graph the mechanical power-versus-speed curves at the wind turbine rotor for wind speeds of 4, 7, and 10 m/s.

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.

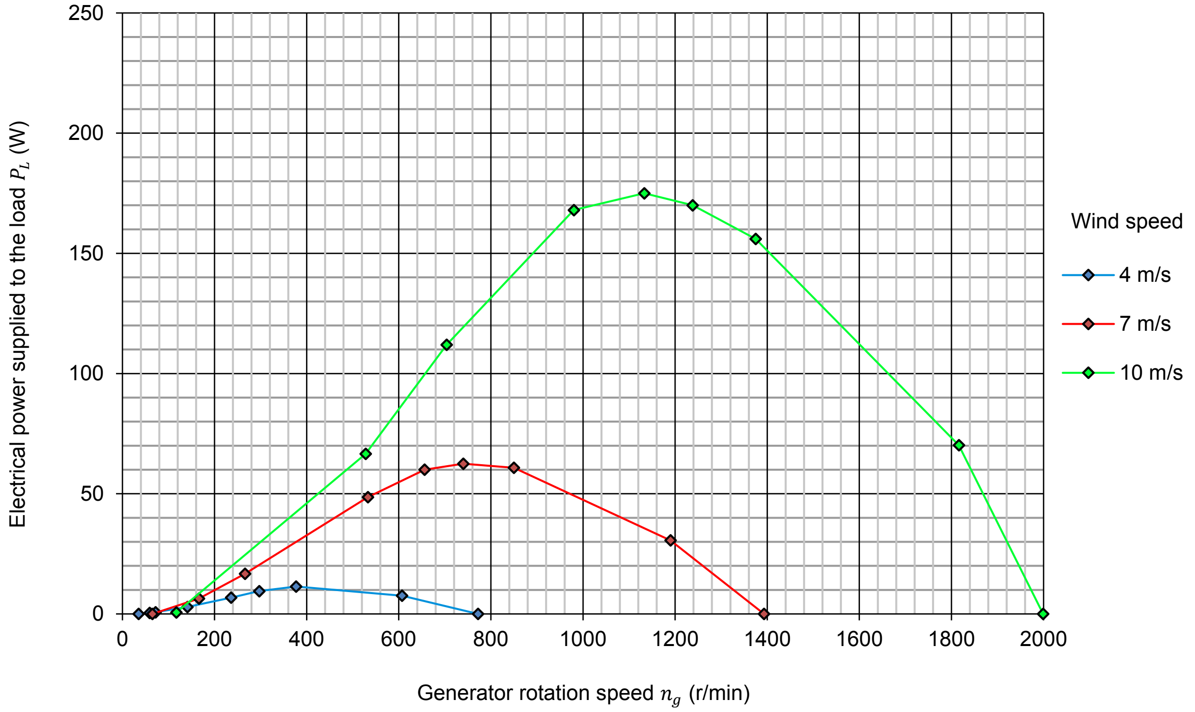
Compare the plotted curves. Do the electrical power-versus-speed curves have a shape similar to that of the mechanical power-versus-speed curves?

❑ Yes ❑ No

Yes (see curves plotted below).



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.

32. On the mechanical power-versus-speed curve, notice that for each wind speed, the power is maximum at a particular rotation speed. Notice that the electrical power produced by the wind turbine generator is also maximum at this rotation speed. In Table 6, record the maximum mechanical power for each wind speed. Also, record the electrical power as well as the rotation speed and torque at the wind turbine rotor measured when the mechanical power is maximum. These speed and torque values correspond to the optimum speed and optimum torque.

The electrical power produced by the wind turbine generator should be maximum when the mechanical power at its rotor is maximum. At a wind speed of 10 m/s, however, the electrical power may not be maximum when the mechanical power is maximum. This is mainly because the power losses through the generator windings (I^2R losses) increase exponentially with the load current.

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)	Generator efficiency (%)
4 m/s (14.4 km/h)					
7 m/s (25.2 km/h)					
10 m/s (36 km/h)					

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)	Generator efficiency (%)
4 m/s (14.4 km/h)	14.1	11.4	377	0.36	80.9
7 m/s (25.2 km/h)	77.0	62.5	740	0.97	81.2
10 m/s (36 km/h)	224	168	980	2.17	75.0

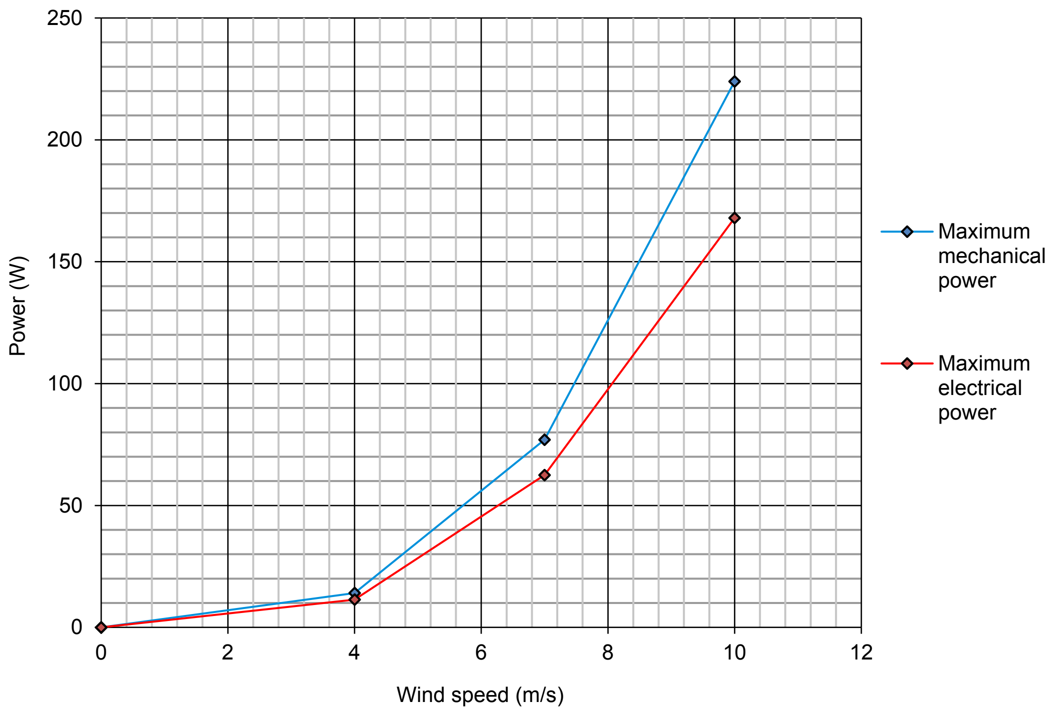
Notice that for each wind speed in Table 6, the maximum electrical power is lower than the maximum mechanical power, especially at a wind speed of 10 m/s. Briefly explain why.

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.

33. 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. The decrease in generator efficiency is particularly obvious at a wind speed of 10 m/s.

34. 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.

35. Close LVDAC-EMS.

Turn the 4 Quadrant Power Supply and Dynamometer Controller off and AC 24V Power Supply off.

Turn electric power off at your workstation, if applicable. Remove all circuit connections, finishing with the equipment earthing connections.

Remove the protective guard. Remove the timing belt that mechanically couples the 4 Quadrant Dynamometer Motor to the Wind Turbine Generator and Controller.

Return all equipment to its storage location.

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, the wind speed v is 4.5 m/s, and the air density ρ is 1.225 kg/m^3.

The power P_W in the wind is equal to

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

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 31 and Figure 32. 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.