1) Introduction to wind power

Introduction

With this first experiment you should get in touch to the experiment equipment and learn how to use it. The sound level of the buzzer will show you how much power the wind turbine produces.

Learning Objects

Examine how wind turbine power is changing when moving the wind machine away from the wind turbine.

Examine how wind turbine power is changing when turning the wind turbine relative to the wind direction.

Concepts

Electrical circuits
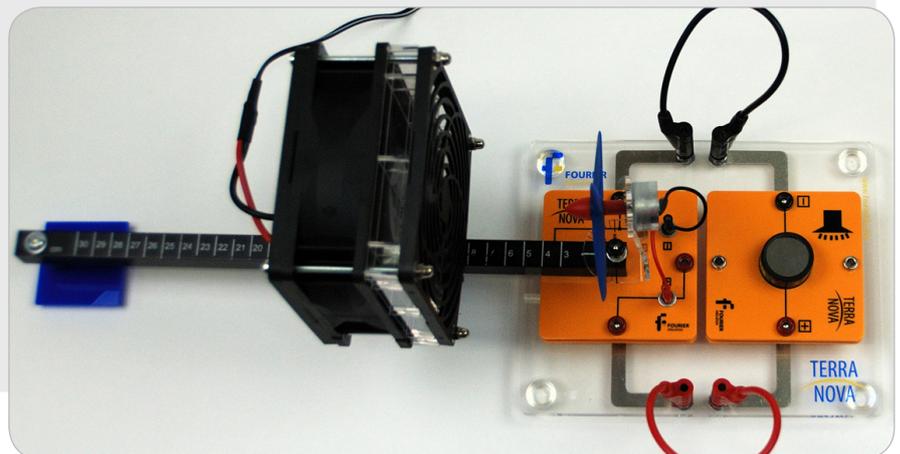
Time Frame

1 lesson

Equipment

1. Main board
2. Wind generator module
   with rail and power supply (12V)
3. Wind turbine module
   (with three rotor blades)
4. Buzzer
5. 2 cables

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!)
2. Fix the rail to the wind turbine module
3. Mount the wind turbine on top of the rail and connect the small cables to the module
4. Fix the wind machine to the rail at the 5 cm position

For this experiment no data logger is necessary. It can be used as easy introduction into the topic wind power and especially for acquainting the students with the experimental equipment.

The experiment only gives qualitative results. Instead of measuring voltages or currents the students have to use the buzzer module as "sensor".

Experimental Procedure

1. 1. Dependence of buzzer sound level on wind machine position - increase the distance of the wind machine from the wind turbine and listen to the sound level of the buzzer. How does it change?
2. Dependence of Buzzer sound level on turning angle of the wind turbine - fix the wind machine at the 20 cm position to the rail - change the angle of the wind turbine towards incoming wind and listen to the sound of the buzzer. How does it change?
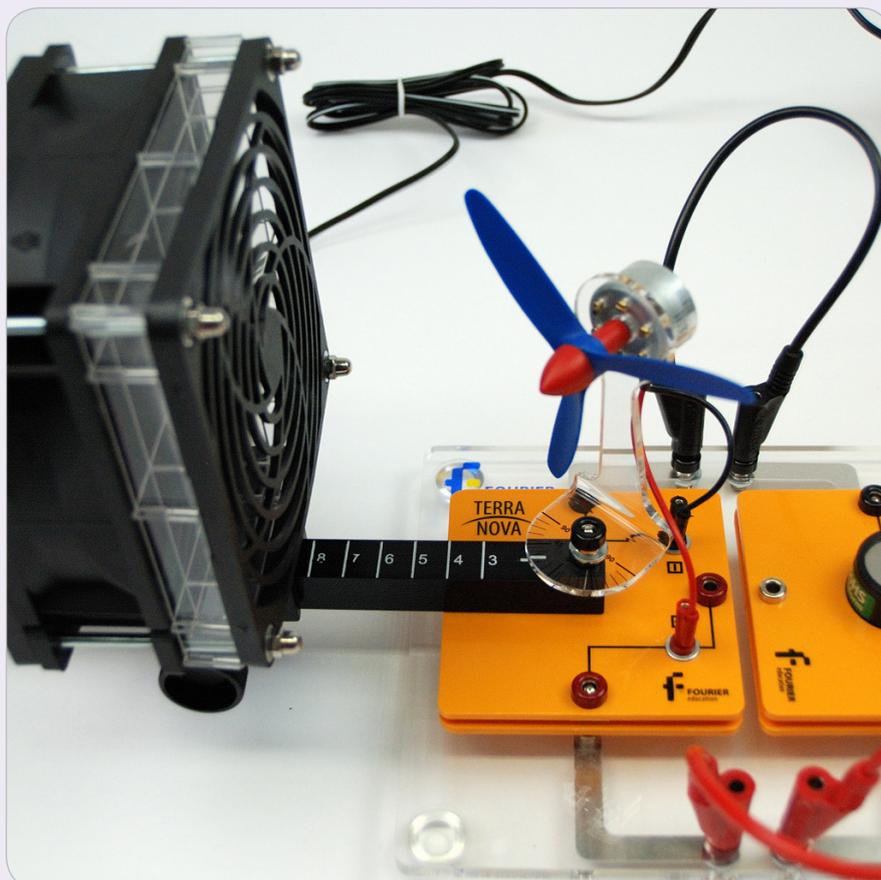
Questions

1. Which dependence of the sound level on distance between wind machine and wind turbine did you observe?
2. How did the sound level of the buzzer change when turning the wind turbine?

Answers

1. The sound level of the buzzer decreases with increasing distance between wind machine and wind turbine. The reason is that wind speed decreases with distance.
2. By turning the wind turbine beginning with 0° the sound level of the buzzer decreases. With reaching 90° the wind turbine does not rotate anymore and the buzzer does not show any signal.

2) Measuring the wind velocity

Introduction

For this experiment kit you cannot use real wind outdoors because it is not constant enough for reproducible experiments. Hence, a wind machine is used. In this first experiment the possible wind speed in different distances from the wind machine should be measured.

Learning Objects	Concepts	Time Frame
Measure the wind speed at different distances from the wind machine.	Electrical circuits	1 lesson

Equipment

1. Main board
2. Wind generator module with rail and power supply (12V)
3. Anemometer
4. NOVA LINK

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!).
2. Fix the rail to the wind turbine module.
3. Mount the wind turbine on top of the rail and connect the small cables to the module.
4. Fix the wind machine to the rail at the 5 cm position.

MultiLab Setup

1. Launch MuliLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Click **Logger**.
4. Uncheck the **Auto ID function**.
5. Connect the Splitter cable output marked with ↑↓ to the NOVA LINK's sensor inputs I/O-1.
6. Connect the second Splitter cable output, marked with S to the NOVA LINK's sensor inputs I/O-2.
7. Click 🔆.
8. As **Input 1** select: Wind speed 4 – 280 km/h.
9. As **Input 2** select: Wind direction 0° - 360°.
10. Click **Next**.
11. Set **Select rate** to **Every second**.
12. Set **Select recording mode** to **Add**.
13. Click **Next**.
14. Set **by Time** to **50**.
15. Click **Finish**.

Notes

In this experiment the anemometer sensor that is originally designed for outdoor use is necessary. The students can either hold the anemometer at a constant position by hand or use a standard tripod.

Because the accuracy of this sensor is optimized for outdoor use the results are quite qualitative and cannot be used as calibration curve for further experiments. Please use the calibration curves given in the general part of this manual instead.

Pleas not, that the results of this experiment are rather influenced by constructive characteristics of the wind machine than by physical principles.

Experimental Procedure

1. Connect the power supply to the wind machine (12V).
2. Take the anemometer and hold it constant at the height, where normally the wind turbine is situated (alternatively use a tripod to fix the anemometer).
3. The nearest point of a paddle to the wind machine should be above the position where the wind turbine is normally situated.
4. Click ▶.
5. Disconnect the power supply.
6. Repeat steps1 to 5 for the distances of 10, 15, 20, and 25 cm.

Data Analysis

1. Click 〰.
2. Set the cursor to the first point of any graph which is not zero.
3. Click 〰.
4. Set the second cursor to the last point at the same graph
5. Go to the Menu **Graph** > **Crop**.

Table

1. Go to **Table** > **Add manual column**.
2. Set **column title** to **distance**.
3. Set **column unit** to **cm**.
4. Click **Ok**.
5. Again, go to **Table** > **Add manual column**.
6. Set **column title** to **wind speed**.
7. Set **column unit** to **km/h**.
8. Click **Ok**.
9. Click ▦.
10. Add the new columns **distance** and **wind speed**.

11. Set table name to wind speed – distance dependence.
12. Click **Ok**.
13. Click ▥.

Averaging

1. Click 〰.
2. Choose the graph of the measurement at 5 cm.
3. Go to the Menu **Analysis** > **Statistics**.
4. Write in the actual table the data of the distance and the average wind speed.
5. Click **OK**.
6. Repeat this steps for the other distances.

Graph

1. Cick ⌐Yx.
2. Set **X-axis** to **distance**.
3. Set **Y-axis** to **wind speed**.
4. Click **Ok**.

Expected Results

1. Can you identify a clear trend of the wind speed? Explain this behavior!
2. Classify the maximal wind speed in accordance to the Beaufort scale!
3. Explain the differences of your measurement to the calibration curve given in beginning of this manual.
4. Have a detailed look to the wind machine.
   Can you image why underneath the finger guard grid there is a second grid?

Answers

1. The wind speed decreases with the distance from the wind machine. On the one hand the wind coming from the wind machine is expanding in area and therefore loosing intensity and on the other hand it is decelerated by the air mass in front of it.
2. The maximal wind speed of 30km/h correlates to a Beaufort number of 5.
3. The main reasons for the deviations between the given calibration and the measurement is that the anemometer sensor is larger in diameter than the laminar wind field of the wind machine.
4. This second grid underneath the finger guard grid makes the air flow more laminar and avoids turbulent air circulations directly in front of the wind machine. Such turbulences would disturb the experiments.

Further Suggestions

1. Can you identify a clear trend of the wind speed? Explain this behavior!
2. Classify the maximal wind speed in accordance to the Beaufort scale!
3. Explain the differences of your measurement to the calibration curve given in beginning of this manual.
4. Have a detailed look to the wind machine.
   Can you image why underneath the finger guard grid there is a second grid?

3) Dependence of the wind turbine power on wind velocity

Introduction

Wind speed on land can vary much: from 1 Beaufort with wind speeds of less than 0.3 m/s up to 12 Beaufort with wind speeds of more than 33 m/s. Can a wind turbine use such low and high wind speeds and how does the power depend on wind speed? This is the main issue of this experiment.

Learning Objects	Concepts	Time Frame
Determine the output power of the wind turbine loaded with a fixed resistance in dependence on wind speed.	Electrical circuits Wind speed and Beaufort scale (experiment 2)	1 lesson

Equipment

1. Main board
2. Wind generator module with rail and power supply (12V)
3. Wind turbine module (with three rotor blades)
4. Potentiometer module
5. Voltage sensor
6. Current sensor
7. NOVA LINK

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!).
2. Fix the rail to the wind turbine module.
3. Mount the wind turbine on top of the rail and connect the small cables to the module.
4. Fix the wind machine to the rail at the 5 cm position.
5. Plug the potentiometer module onto the second place of the main board.
6. Turn the knob of the 1kΩ potentiometer to Rmin and the knob of the 100 Ω potentiometer ca. a third turn from Rmin to Rmax.

MultiLab Setup

1. Launch MuliLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the voltage sensor to I/0-1 port of the NOVA LINK.
4. Connect the current sensor to I/0-2 port of the NOVA LINK.
5. Click ⚙.
6. Click **Next**.
7. Set **Select rate** to **Manual**.
8. Set **Select recording mode Add**.
9. Click **Next**.
10. Set **by samples** to **50**.
11. Click **Finish**.

Notes

In this experiment students have to use the calibration curve given in the general part of the manual. In this calibration curve each distance between wind turbine and wind machine is correlated to the respective wind speed at the wind turbine (driven at 12 V). Students have to read the values from the graph and fill the value into the table by hand.

Experimental Procedure

1. Connect the power supply (12V) to the wind generator.
2. Wait until the wind generator and the wind turbine have maximum speed.
3. Click ▶.
4. Repeat step1 to 4 for 10 cm, 15 cm, 20 cm and 25 cm
5. At the end click ⏹.
6. Click 💾 to save your data.

Data Analysis

1. Click f_x .
2. Click **Functions**.
3. Set **Functions** to **Multiply**.
4. Select the voltage and current measurement datasets as G1 and G2, respectively.
5. Click **Ok**.
6. Go to **Table** > **add manual column**.
7. Set **Column name** to **distance**.
8. Set **Column unit** to **cm**.
9. Click **Ok**.
10. Click ▦ .
11. Add the columns of distance, the current and voltage measurement and of the calculated power function.
12. Click **Ok**.
13. Click 🗐.
14. Click ⌐ᵞₓ.
15. Set **X-axis** to **distance**.
16. Select the measured current and voltage datasets as **Y-axis**.
17. Set the Graph title to "**voltage/current - distance dependence**".
18. Click **Ok**.
19. Click 🗐.
20. Click ⌐ᵞₓ.
21. Set **X-axis** to distance
22. Set **Y-axis** to the calculated power.
23. Set the **Graph title** to "**Power - Distance Dependence**".
24. Click **Ok**.
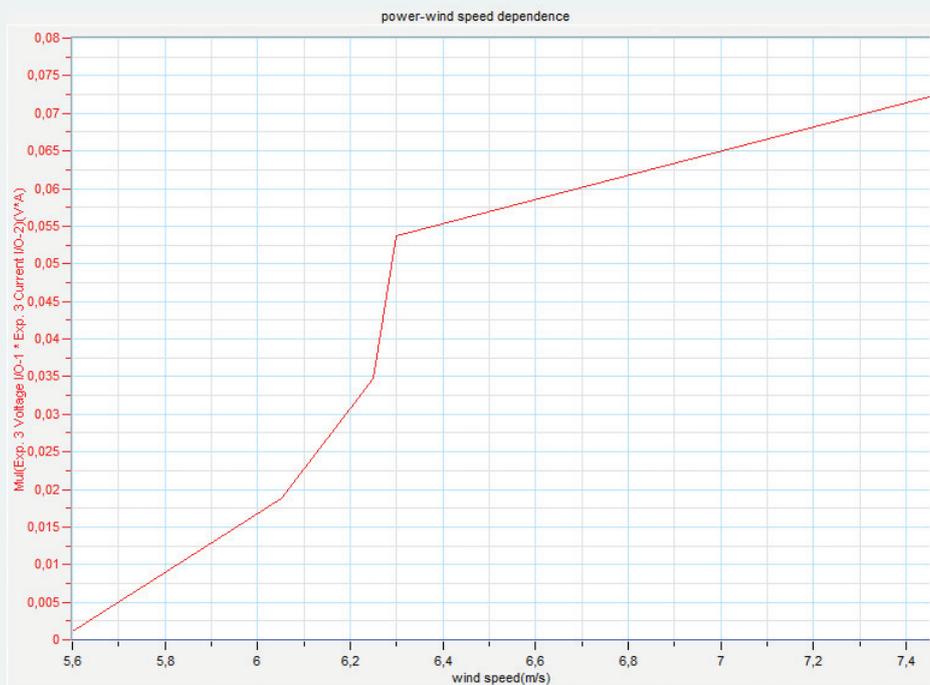
Expected Results

1. Describe the correlation between output and wind speed at the wind turbine.
2. What is the reason for the behavior at high wind speeds?
3. What conclusions can be drawn from this for the operation of real wind turbines?

Answers

1. The wind turbine output is larger when the wind speed is higher but the correlation is not linear. Hence, output and wind speed are not directly proportional to each other. The output goes into saturation for high wind speeds.
2. For high wind speed the stall effect occurs. This means that the air flow is not laminar anymore but turbulences occur that reduce the efficiency. This is mainly influenced by the profile of the turbine blades.
3. Real wind turbines only reach high output if the wind speed is high enough. The lower the wind speed at the wind turbine, the lower the output that it can generate.
   At high wind speeds the efficiency is lower but this is at the same time a protective mechanism that prevents the wind turbine from destruction at very high wind speeds.

Further Suggestions

If you have the possibility, have a look at a real wind turbine at different wind speeds. Especially the behavior during a storm is very interesting. If the wind turbine stops completely it is not only secured by the natural stall effect but the blades are turned so that no buoyancy at the blades occur and they stop. All modern wind turbines use this technique.

4) Comparing wind turbines with different number of rotor blades

Introduction

More than 99% of the worldwide installed wind turbines have three blades.
But there are also 2- and 4-blade rotors – even rotors with 1 blade exist. But why such rotors are used so seldom?

Learning Objects	Concepts	Time Frame
Examine the voltage of wind rotors with different number of rotor blades and compare them.	Electrical circuits	1 lesson

Equipment

1. Main board
2. Wind machine module with rail and power supply (12V)
3. Wind turbine module (with two, three and four rotor blades)
4. Voltage sensor
5. NOVA LINK

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!).
2. Fix the rail to the wind turbine module.
3. Mount the wind turbine on top of the rail and connect the small cables to the module.
4. Fix the wind machine to the rail at the 20 cm position.
5. Connect the voltage sensor to the wind generator

MultiLab Setup

1. Launch MuliLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the voltage sensor to I/0-1 port of the NOVA LINK.
4. Click ⚙.
5. Click **Next**.
6. Set **Select rate** to **Manual**.
7. Set **Select recording mode Add**.
8. Click **Next**.
9. Set **by samples** to **50**.
10. Click **Finish**.

Notes

In this experiment only the open circuit voltage of the wind generator is measured. Physically correct would be to measure the output power of the wind generator. But this would also require measuring a complete IV-curve to determine the maximum power point (MPP).

But measuring the open circuit voltage shows the same qualitative results.

Experimental Procedure

1. Attach the 2-blade rotor to the wind turbine.
2. Connect the power supply (12V) to the wind machine .
3. Wait until the wind machine and the wind turbine have maximum speed.
4. Click ▶ .
5. Disconnect the power supply from the wind generator and wait until the rotor blades stay still.
6. Repeat step 1 to 5 for the 3- and 4-blade rotors.
7. At the end click ⏹ .

Data Analysis

Table

1. Click **Table** on the main toolbar and select **Add manual column**.
2. Set **Column name** to be **# of rotor blades**.
3. Click **Ok**.
4. Click 🔲.
5. Add the column **# of rotor blades** to the table.
6. Click **Ok**.
7. Fill the number of the rotor blades into the new column.
8. Click 📋.

Graph

1. Cick ⌐ʸₓ.
2. Set **X-axis** to **# of rotor blades**.
3. Set **Y-axis** the voltage dataset.
4. Set the **Graph title** to "**Voltage - # of Rotor Blade Dependence**".
5. Click **Ok**.
6. Click 📊.
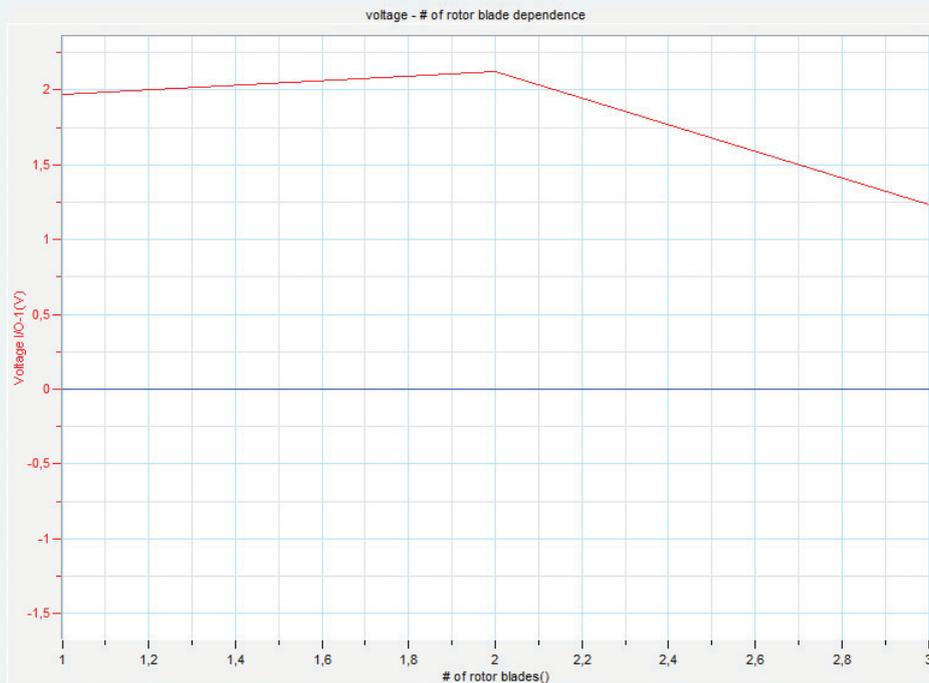
Expected Results

1. What is the result of your measurement? Which configuration is superior?
2. Try to find more reasons why 3-blade rotors dominate the wind power industry.

Answers

1. The voltage of a 2-blade and a 3-blade rotor does not differ much.
   The highest voltage is achieved with a 3-blade rotor.
2. There is only a small difference in output power between 2- and 3-blade rotors. From the economical point of view it would therefore be advantageous to use 2-blade rotors because cost of material is down by a third. But 2-blade rotors suffer from the problem of an unbalanced distribution of mass over the rotor plane. This results in a higher attrition compared to 3- or 4-blade rotors.
   The result of the experiment is also influenced by the fact that the rotors do not correspond exactly to reality. The 4 blades do not turn in one plane but are inserted as a pair 2 behind each other – this creates turbulence on the rotor blades that reduces the output. In reality 3- and 4-blade rotors give the same output. Because less material is needed, 3-blade rotors are superior.

5) Dependence of the wind turbine on wind direction

Introduction

Wind is very volatile! But not only wind speed can differ much in reality, also wind direction. How this affects a wind power plant should be investigated in this experiment.

Learning Objects

Examine the output of the wind rotor when the wind hits the wind turbine from different directions.

Concepts

Electrical circuits
Wind speed (experiment 2)

Time Frame

1 lesson

Equipment

1. Main board
2. Wind machine module with rail and power supply (12V)
3. Wind turbine module (with three rotor blades)
4. Voltage sensor
5. NOVA LINK

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!).
2. Fix the rail to the wind turbine module.
3. Mount the wind turbine on top of the rail and connect the small cables to the module.
4. Fix the wind machine to the rail at the 5 cm position.
5. Connect the voltage sensor to the turbine.
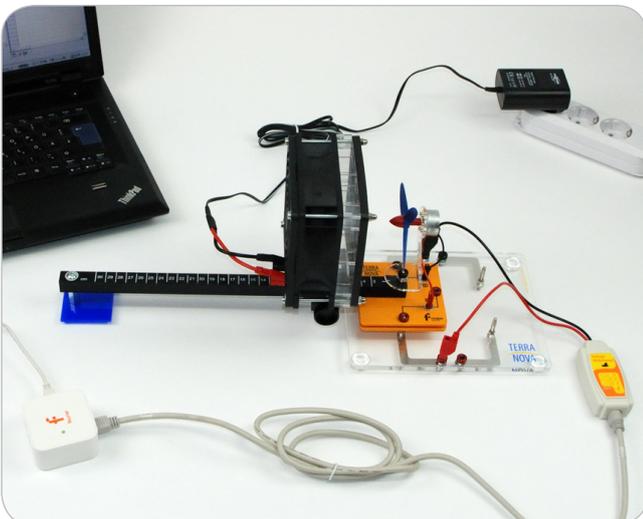
MultiLab Setup

1. Launch MuliLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the voltage sensor to I/O-1 port of the NOVA LINK.
4. Click ⚙.
5. Click **Next**.
6. Set **Select rate** to **Manual**.
7. Set **Select recording mode** to **Add**.
8. Click **Next**.
9. Set **by samples** to **50**.
10. Click **Finish**.

Notes

In this experiment only the voltage of the wind turbine is measured but not the power.

However, the dependencies are the same. This procedure makes the experiment much easier but nevertheless the qualitative results will be true.

Experimental Procedure

1. Set the angle of rotation to 0°.
   Hint: When setting the angle of rotation, it must be ensured that your line of vision is always perpendicular to the angular scale. The black 0° line must be directly visible over the white line of the rail.
2. Connect the power supply (12V) to the wind machine.
3. Wait until the wind machine and the wind turbine have maximum speed.
4. Click ▶.
5. Repeat step 2 to 4 for 10°,20°,30°,40°,50°,60°,70°,80° and 90°.
   CAUTION! When rotating the wind turbine, do not reach into the rotor blades – risk of injury! – to rotate, the wind machine can be turned off.
6. At the end click ⏹.
7. Click 💾 to save your data.

Data Analysis

Table

1. Click **Table on the main toolbar and select Add manual column**.
2. Set **Column name** to be **angle**.
3. Set **Column unit** to be °.
4. Click **Ok**.
5. Click 🞖.
6. Add the columns of **angle to the table**.
7. Fill the angles in the angle's column.
8. Click **Ok**.
9. Click 🖼.

Cosine – calculation

1. Cick f_x.
2. Click **Functions**.
3. In the **Functions tab select Cosine**.
4. Select G1 as dataset for the **angle**.
5. Set B to **0.01745** (pi/180°).
6. Click **OK**.

Graph

1. Cick ⌐Yx.
2. Set **X-axis** to **angle**.
3. Select current and voltage datasets as set **Y-axis**.
4. Set the **Graph title** to "Voltage - Angle Dependence".
5. Click **Ok**.
6. Click 🖼.
7. Click ⌐Yx.
8. Set **X-axis** to **cos**.
9. Set **Y-axis** to **voltage**.
10. Set the Graph title to "Voltage – cos(alpha) Dependence".
11. Click **Ok**.

voltage-alpha dependence

voltage-cos(alpha) dependence
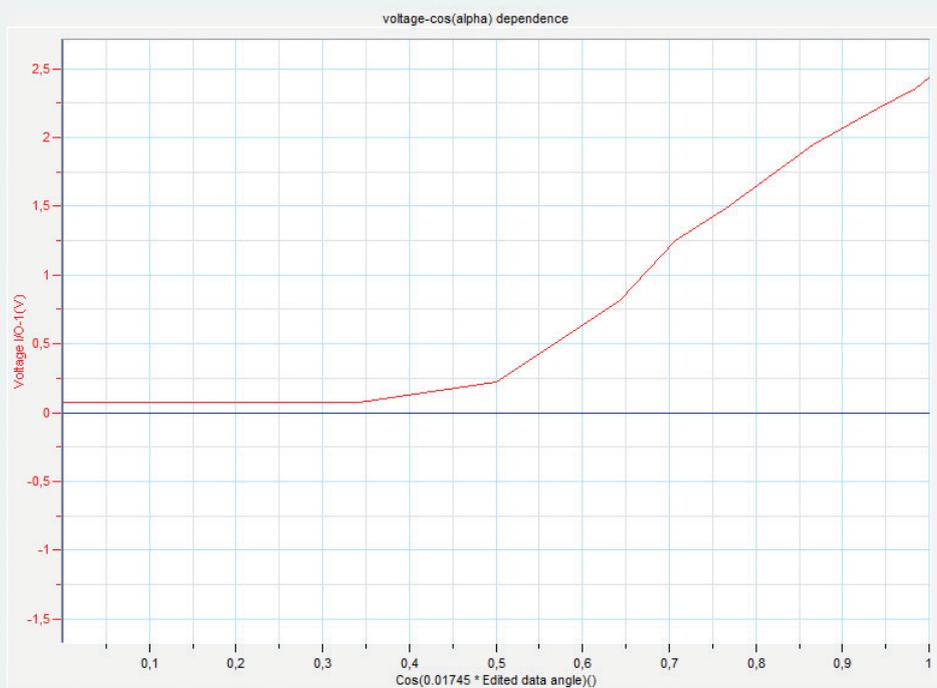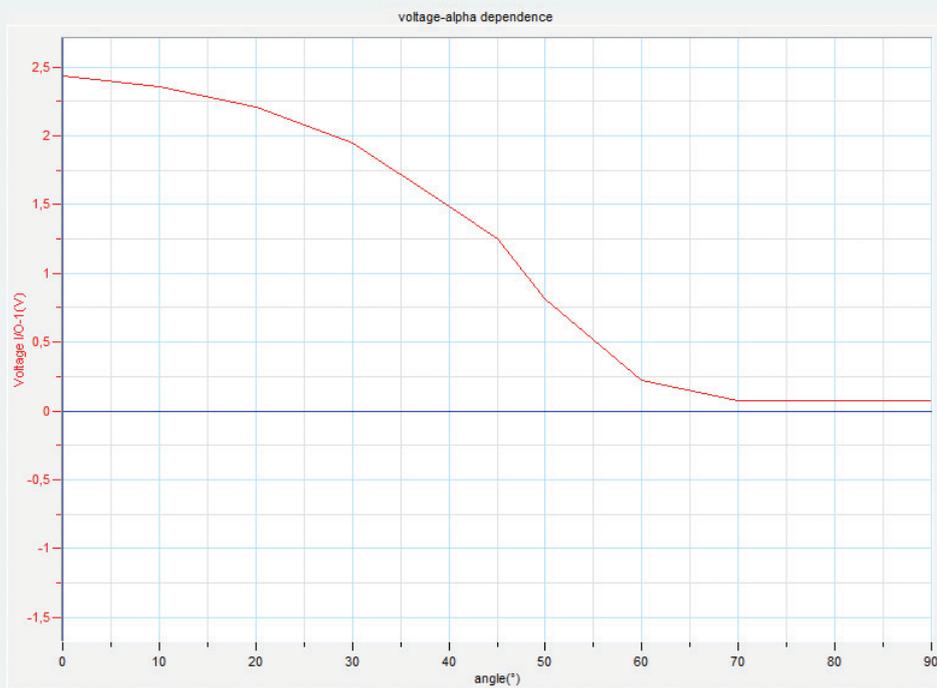
? Questions

1. How does the voltage of the wind turbine depend on the angle and which mathematical correlation does it equal?
2. In real wind turbines it is of great importance to always generate the highest possible output. How can you ensure that a wind turbine always generates the maximum output? Think of a possible technical implementation, how such a system can be aligned more optimally into the wind and describe your reasoning. Get information about the construction of real wind turbines.

✔ Answers

1. The voltage of the wind turbine decreases as the angle increases. The mathematical correlation equals the cosine function. The voltage decreases with decreasing cos α. In other words, the voltage decreases with decreasing work surface area.
2. In changing wind speeds, a wind turbine must be aligned in such a way that the wind is perpendicular to the rotor plane.
   Creative possible answers would be: This can be done by having a wind direction meter indicating the direction of the wind. This sends a signal to an electrical control system, which in turn controls a motor in the gondola of the wind turbine. The motor always turns the entire gondola in such a way that the rotor plane stands perpendicular to the wind and in this way achieves the maximum output.

★ Further Suggestions

Have a look on real wind power plants on different days. In dependence on the wind direction on the particular day they will face in other directions.

6) Dependence of the wind turbine on wind direction

Introduction

In practical applications it is important that the wind turbine always generates the maximum output. This output also depends on the load that is connected to the turbine. In this experiment this dependency should be investigated and the maximum output under the specific conditions of the experiment be examined.

Learning Objects

Record the current-voltage characteristics of the wind generator. Also determine the load resistance at which the maximum output is achieved.

Concepts

Electrical circuits
IV - characteristics

Time Frame

1 lesson

Equipment

1. Main board
2. Wind machine module with rail and power supply (12V)
3. Wind turbine module (with three rotor blades)
4. Potentiometer module
5. Voltage sensor
6. Current sensor
7. NOVA LINK

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!).
2. Fix the rail to the wind turbine module.
3. Mount the wind turbine on top of the rail and connect the small cables to the module
4. Fix the wind machine to the rail. at the 5 cm position.
5. Connect the voltage sensor parallel to the wind turbine.
6. Connect the current sensor in series to the wind turbine and the potentiometer so that the circuit is closed.

MultiLab Setup

1. Launch MultiLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the current sensor to I/0-1 port of the NOVA LINK.
4. Connect the voltage sensor to I/0-2 port of the NOVA LINK.
5. Click ⚙.
6. Click **Next**.
7. Set **Select rate** to **25 Samples per second**.
8. Set **Select recording mode** to **Add**.
9. Click **Next**.
10. Set **by samples** to **Continuous**.
11. Click **Finish**.

Experimental Procedure

1. Connect the power supply (12V) to the wind machine.
2. Turn the knob of the 1kΩ-potentiometer to Rmin.
3. Turn the knob of the 100Ω-potentiometer to Rmax.
4. Wait until the wind machine and the wind turbine have maximum speed.
5. Click ▶.
6. Turn the knob of the 100Ω-potentiometer anti-clockwise continuously.
7. At the end click ⏹.
   If you did not achieve a smooth curve repeat the measurement and try to turn the knob slower.
8. Click 💾 to save your data.

Data Analysis

**Cropping data and calculating power**

1. Click ∿ and set the cursor to the first voltage point which is at the beginning of the decreasing part of the graph.
2. Click ∿ and set the second cursor to a point on the graph where the voltage has saturated.
3. Go to the Menu **Graph** and click **Crop**.
4. Click f_x.
5. Click **Functions**.
6. Set **Functions** to **Multiply**.
7. Select the cropped voltage and current datasets as **G1** and **G2**, respectively.
8. Click **Ok**.
9. Click ▦.
10. Add the column of the calculated power function.
11. Click Ok.
12. Click ▤.

Graph

1. Click ⌐Yx.
2. Set **X-axis** to the cropped **voltage**.
3. Set **Y-axis** to the cropped **current**.
4. Set the **Graph title** to "**IV-Curve**".
5. Click **Ok**.
6. Click ▤.
7. Click ⌐Yx.
8. Set **X-axis** to the **cropped voltage**.
9. Set **Y-axis** to the **calculated power**.
10. Set the **Graph title** to "**Power –Voltage Curve**".
11. Click Ok.

IV-characteristic of wind turbine

Power-voltage dependence
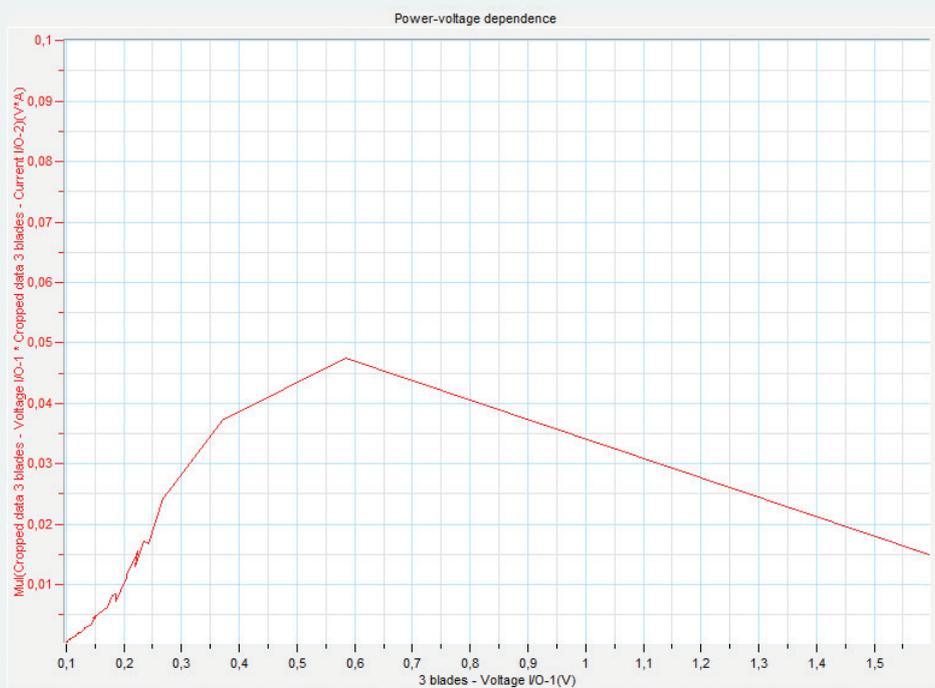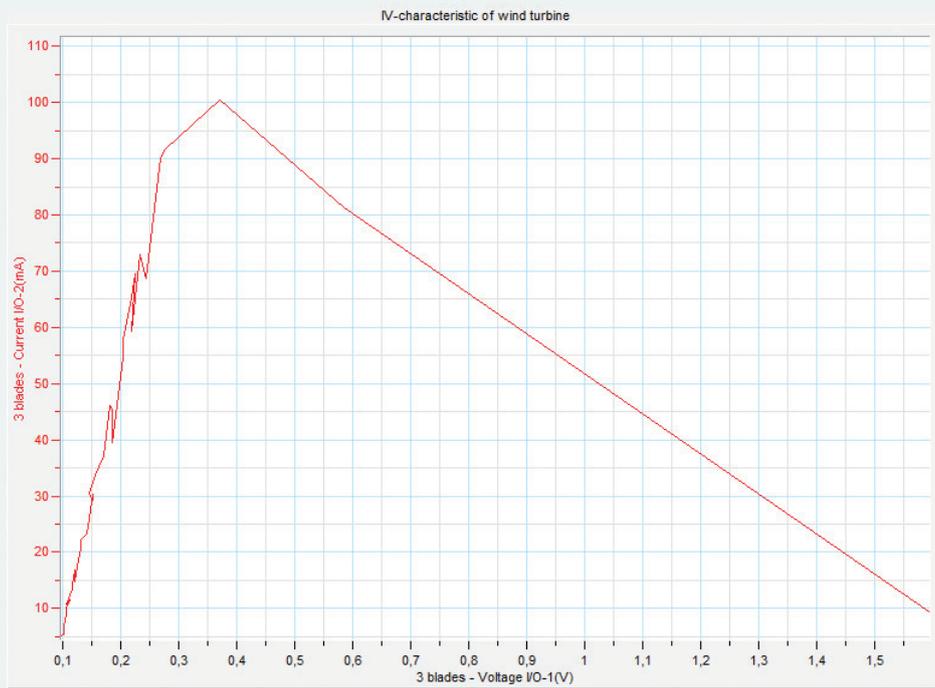
1. Using the First cursor ∿ , determine the voltage value at which the output of the wind turbine has its maximum. Calculate the load resistance at which the maximum output at the turbine is achieved!
2. What consequence follows from these results for the operation of real wind turbines?
3. The maximum output of a wind turbine depends on the load resistance at the turbine. Name possible effects or physical variables that could also have an effect on the output of a wind turbine.

Answers

1. Umax= 0,37V
   Rmax= 0,37V / 100,5mA = 3,7 Ω.
2. A wind turbine reaches its maximum output when the rotor generates a specific voltage.
   Which also means a wind turbine reaches its maximum output when it is loaded by a specific resistance.
3. Rotor blade shape
   Wind speed
   Rotor size

7) IV-characteristics with different rotor blades

Introduction

Wind power plants in practice almost exclusively have 3 rotor blades per turbine. But is this the optimum? In this experiment the output of a wind turbine with either 2, 3 and 4 bladed should be compared in detail. Hence, not only voltage should be measured but the complete IV-characteristics.

Learning Objects

Measure the IV-characteristics of a wind turbine with 2, 3 and 4 rotor blades.

Concepts

Electrical circuits
IV - characteristics

Time Frame

1 lesson

Equipment

1. Main board
2. Wind machine module with rail and power supply (12V)
3. Wind turbine module (with two/three/four rotor blades)
4. Potentiometer module
5. Voltage sensor
6. Current sensor
7. NOVA LINK

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!).
2. Fix the rail to the wind turbine module.
3. Mount the wind turbine on top of the rail and connect the small cables to the module
4. Fix the wind machine to the rail at the 5 cm position.
5. Connect the voltage sensor parallel to the wind turbine.
6. Connect the current sensor in series to the wind turbine and the potentiometer so that the circuit is closed.

MultiLab Setup

1. Launch MultiLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the current sensor to I/O-1 port of the NOVA LINK.
4. Connect the voltage sensor to I/O-2 port of the NOVA LINK.
5. Click ⚙.
6. Click **Next**.
7. Set **Select rate** to **25 Samples per second**.
8. Set **Select recording mode** to **Add**.
9. Click **Next**.
10. Set **by samples** to **Continuous**.
11. Click **Finish**.

Experimental Procedure

1. Attach the 2-blade rotor to the wind turbine.
2. Connect the power supply to the wind machine.
3. Set the knob of the 1kΩ-potentiometer to its minimum.
4. Set the knob of the 100Ω-potentiometer to its maximum.
5. Wait until the wind machine and the wind turbine have maximum speed.
6. Click ▶.
7. Turn the knob of the 100Ω-potentiometer anti-clockwise continuously.
8. At the end click ⏹.
9. Disconnect the wind machine.
10. Exchange the 2-blade rotor with the 3-blade rotor and repeat steps 3 to 9 again.
11. Exchange the 3-blade rotor with the 4-blade rotor and repeat steps 3 to 9 again.

Data Analysis

1. Click 〜 and set the cursor to the first voltage point which is at the beginning of the decreasing part of the graph.
2. Click 〜 and set the second cursor to a point on the graph where the voltage has saturated.
3. Go to the Menu **Graph** and click **Crop**.
4. Click f_x.
5. Click **Functions**.
6. Set **Functions** to **Multiply**.
7. Select the cropped voltage and current datasets as **G1** and **G2**, respectively.
8. Click **Ok**.
9. Click ▦.
10. Add the column of the calculated power function.
11. Click Ok.
12. Click 📊.
13. Repeat all analysis steps for the 3- and 4-blade rotor.

Graph

1. Click ⌐ʸₓ.
2. Set **X-axis** to the cropped **voltage** (2 blade rotor).
3. Set **Y-axis** to the cropped **current** (2 blade rotor).
4. Set the **Graph title** to "**IV-2 Blade Rotor**".
5. Click **Ok**.
6. Click 📊.
7. Click ⌐ʸₓ.
8. Set **X-axis** to **voltage** (2 blade rotor).
9. Set **Y-axis** to the **calculated power** (2 blade rotor).
10. Set the **Graph title** to "**Power - V – Rotor Blade Bependence**".
11. Click Ok.
12. Click 📊.
13. Repeat all analysis steps for the 3- and 4-blade rotor.

IV-characteristic of wind turbine

IV-characteristic of wind turbine

IV-characteristic of wind turbine
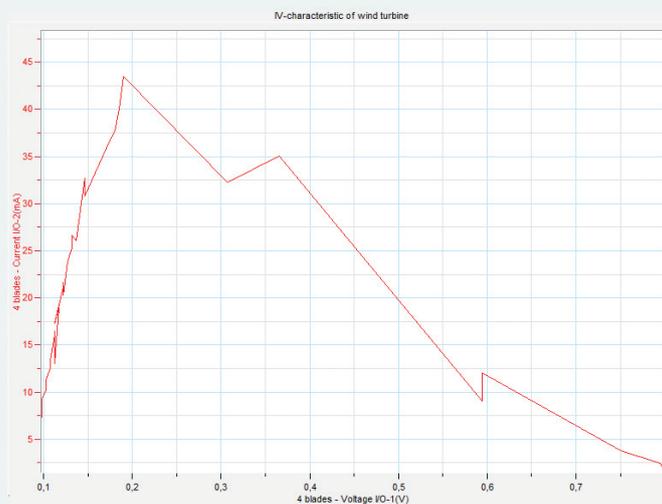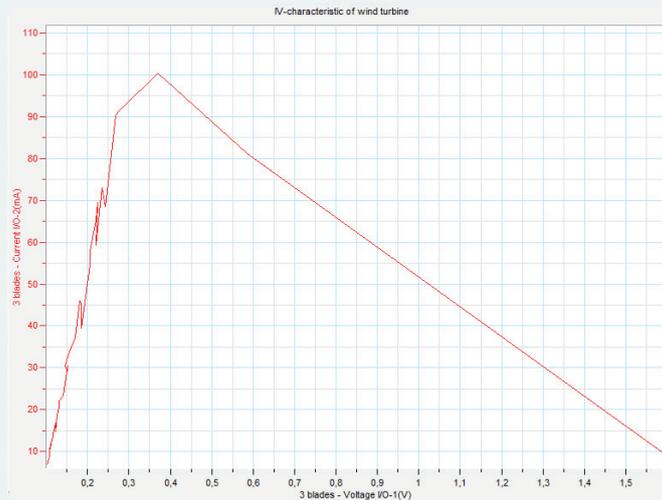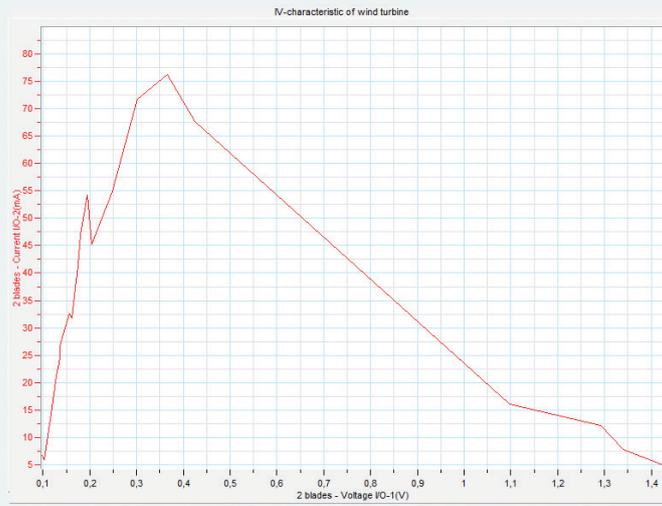
1. Read the following characteristic values from your measurement using using the first cursor 〜 :

	Umax / V	Imax / mA	Pmax / mW	Ropt / Ω
2 blade rotor				
3 blade rotor				
4 blade rotor				

Ropt means the optimal resistance value, where the output power is maximal.

2. According to the experiment, what is the optimal number of blades for a wind turbine?

Answers

1.

	Umax / V	Imax / mA	Pmax / mW	Ropt / Ω
2 blade rotor	0,37	76	28,1	4,8
3 blade rotor	0,37	100,5	37,2	3,7
4 blade rotor	0,4	80	32	5

2. There is little difference in the utilisation of wind energy between three and four blade rotors. A two-blade rotor can only generate low output power and only starts at high wind speeds. Moreover, less material is needed for a three-blade rotor than for a four-blade rotor. This is why mainly three-blade rotors are used for the utilisation of wind power (also compare experiment 4).

8) IV Characteristics depending on wind velocity

Introduction

In Experiment 3 we have seen that the output power of a wind turbine strongly depend on wind velocity. But there only the output power for a fixed load was measured. The correct way is to measure the IV-characteristics and analyze the behavior of the maximum output. This should be done in this experiment.

Learning Objects

Record the current-voltage characteristics of the wind rotor at different distances. Also determine the load resistance at which the maximum output is achieved.

Concepts

Electrical circuits
Wind speed (experiment 3

Time Frame

2 lesson

Equipment

1. Main board
2. Wind generator module with rail and power supply (12V)
3. Wind turbine module (with three rotor blades)
4. Potentiometer module
5. Voltage sensor
6. Current sensor
7. NOVA LINK

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!)
2. Fix the rail to the wind turbine module
3. Mount the wind turbine on top of the rail and connect the small cables to the module
4. Fix the wind machine to the rail at the 5 cm position
5. Plug the potentiometer module onto the second place of the main board
6. Turn the knob of the 1kΩ potentiometer to Rmin and the knob of the 100 Ω potentiometer to Rmax.

MultiLab Setup

1. Launch MultiLab
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the current sensor to I/O-1 port of the NOVA LINK
4. Connect the voltage sensor to I/O-2 port of the NOVA LINK
5. Click ⚙.
6. Click **Next**.
7. Set **Select rate** to **Manual**.
8. Set **Select recording mode** to **Add**.
9. Click **Next**.
10. Set **by samples** to **50**.
11. Click **Finish**.

Experimental Procedure

1. Connect the power supply to the wind generator.
2. Wait until the wind machine and the wind turbine have maximum speed.
3. Click ▶.
4. Turn the knob of the 100Ω-potentiometer anti-clockwise continuous and not to slow.
5. At the end click ⬛.
6. Repeat step 2 to 5 with 10 cm, 15 cm, 20 cm and 25 cm distance between wind turbine and wind machine.
7. click Save 💾 to save your data.

Data Analysis

**Cropping data and calculating power**

1. Click 〜 and set the cursor to the first voltage point which is at the beginning of the decreasing part of the graph.
2. Click 〜 and set the second cursor to a point on the graph where the voltage has saturated.
3. Go to the Menu **Graph** and click **Crop**.
4. Click f_x .
5. Click **Functions**.
6. Set **Functions** to **Multiply**.
7. Select the cropped voltage and current datasets as **G1** and **G2**, respectively.
8. Click **Ok**.
9. **Repeat these steps all distance measurements!**
10. Click ▦.
11. Add the column of the calculated power function for 5 cm distance.
12. Click Ok.
13. Click 🖿.
14. Repeat these steps for the other distances.

Graph

1. Click ⌐ᵧₓ.
2. Set **X-axis** to be the cropped **voltage** data of the 5 cm distance.
3. Set **Y-axis** to be the cropped **currents** data of the 5 cm distance.
4. Set the **Graph title** to "**IV-Curves of 5cm Distance**".
5. Click **Ok**.
6. Click 🖿.
7. Click ⌐ᵧₓ.
8. Set **X-axis** to the cropped **voltage** data of the 5 cm distance.
9. Set **Y-axis** to the **calculated power** of the 5 cm distance measurement.
10. Set the **Graph title** to "**Power – Voltage Curve**".
11. Click Ok.
12. Click ⌐ᵧₓ.
13. **Repeat these steps for the other distances.**

Expected Results
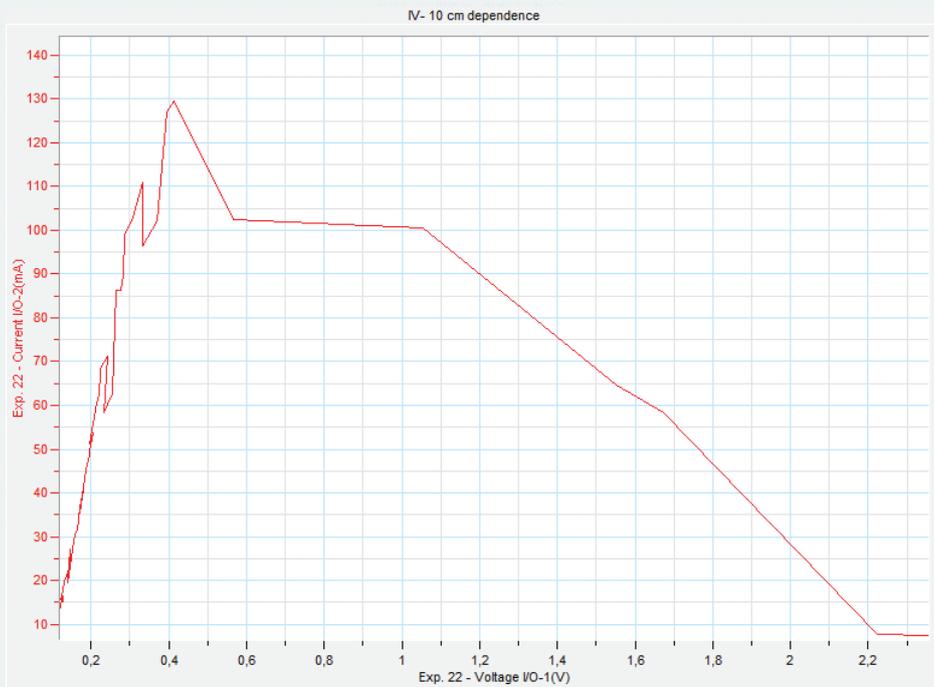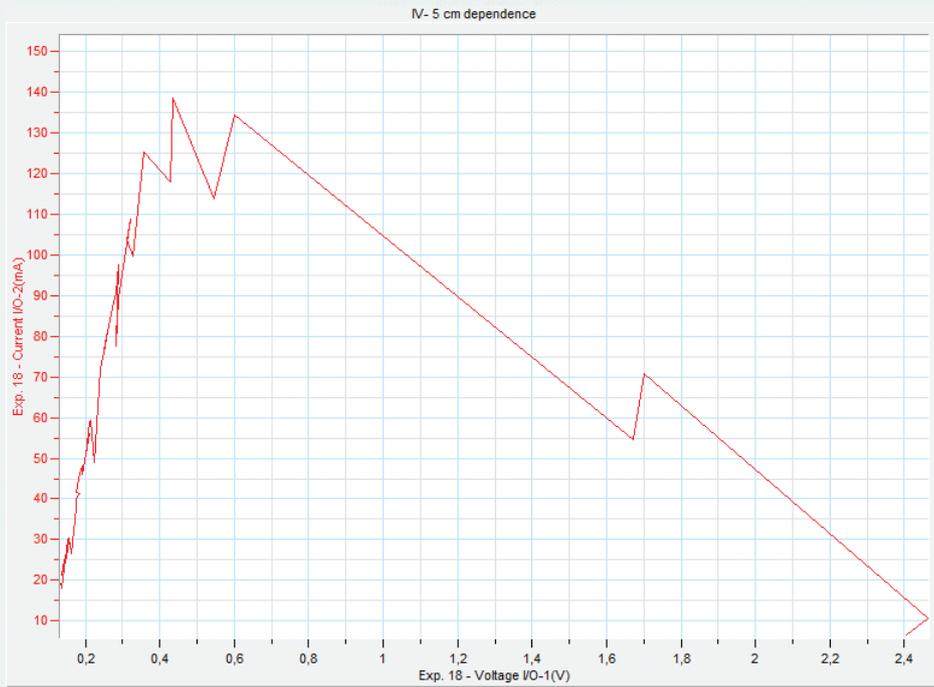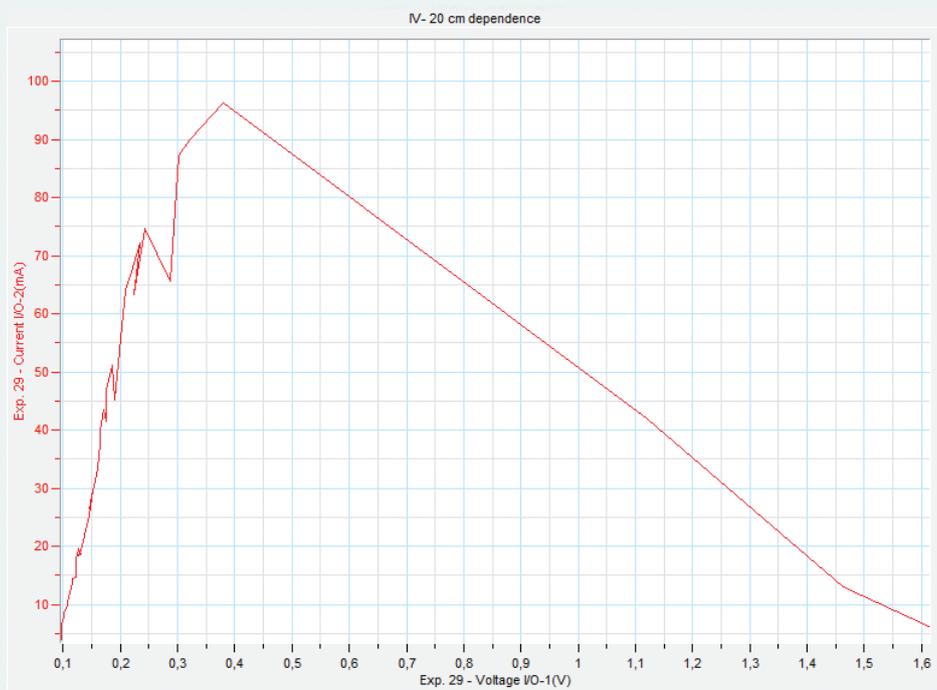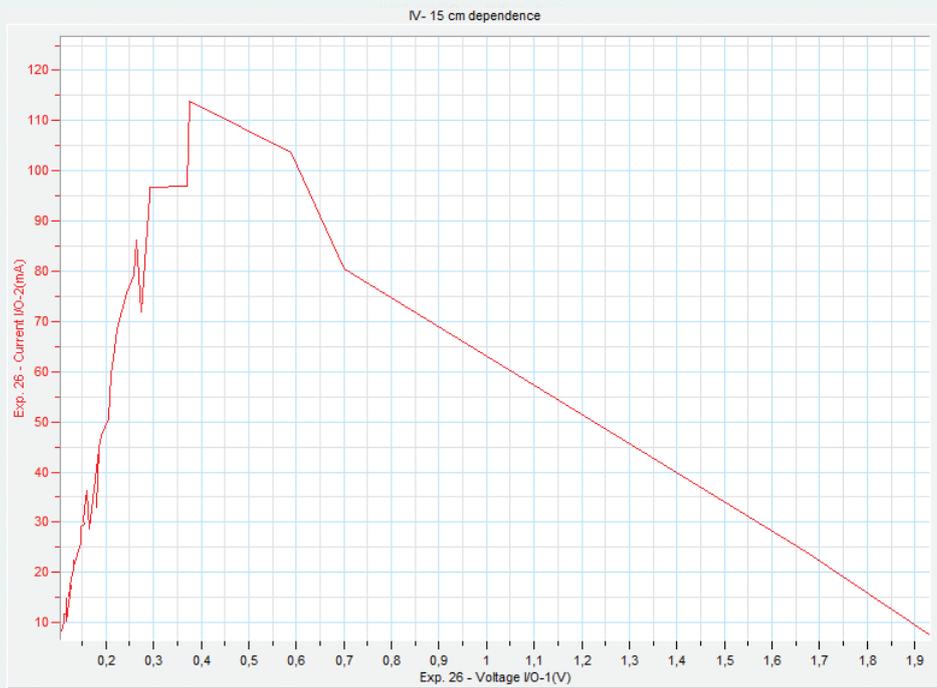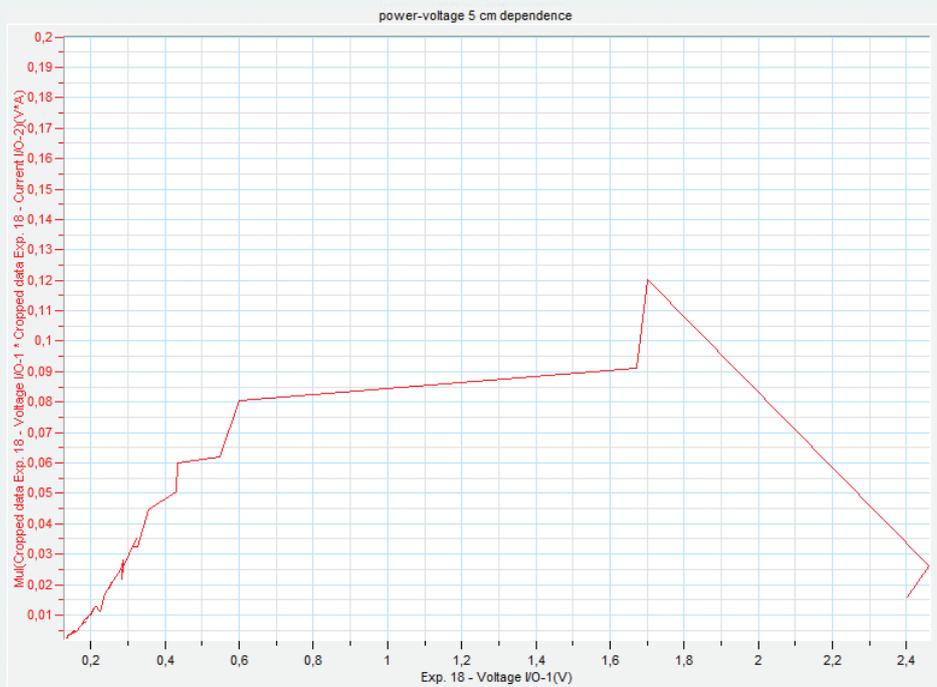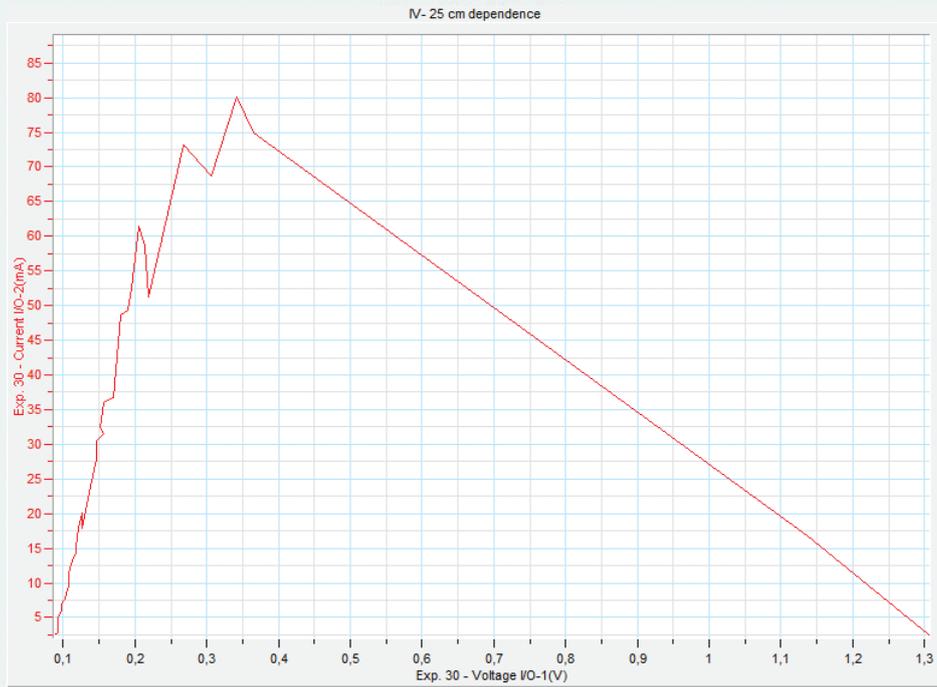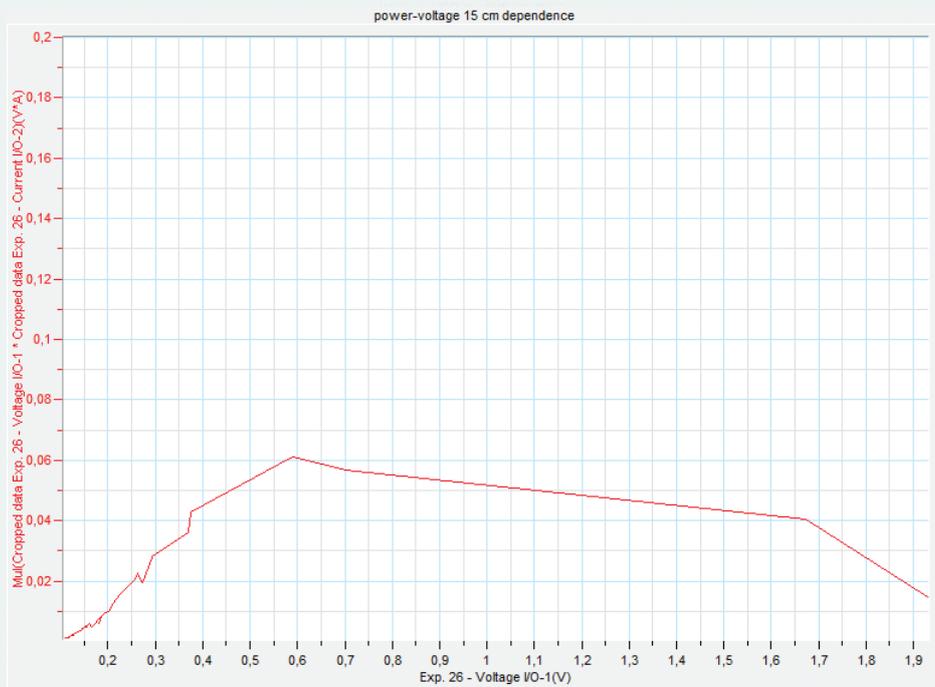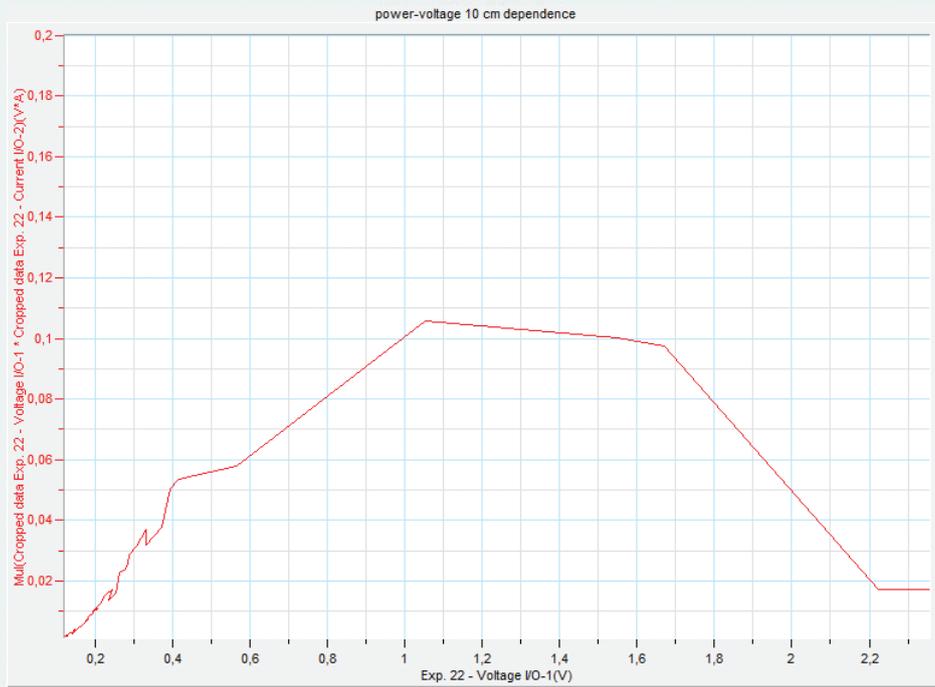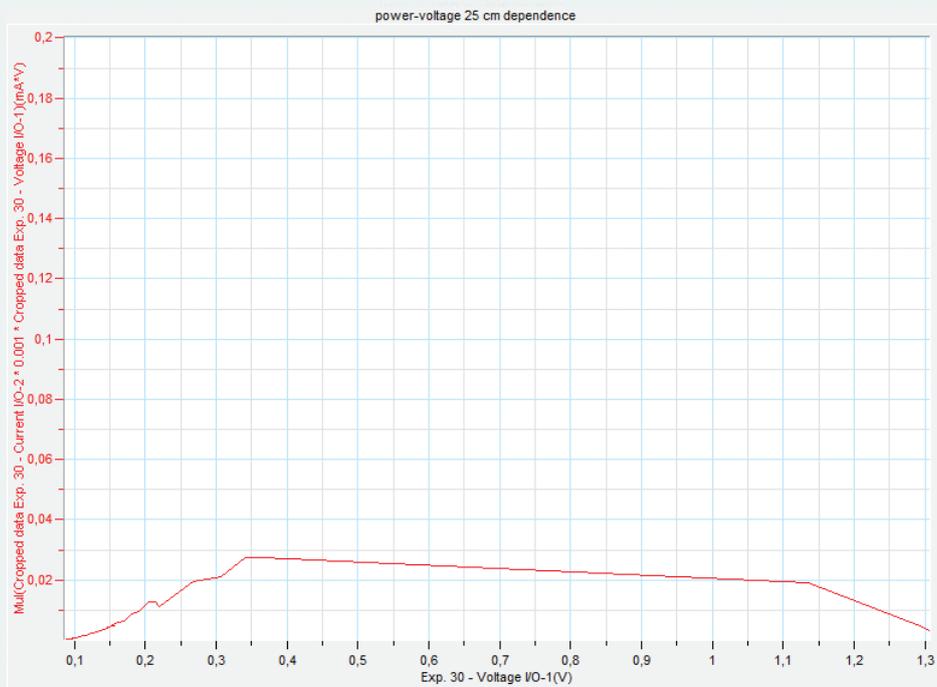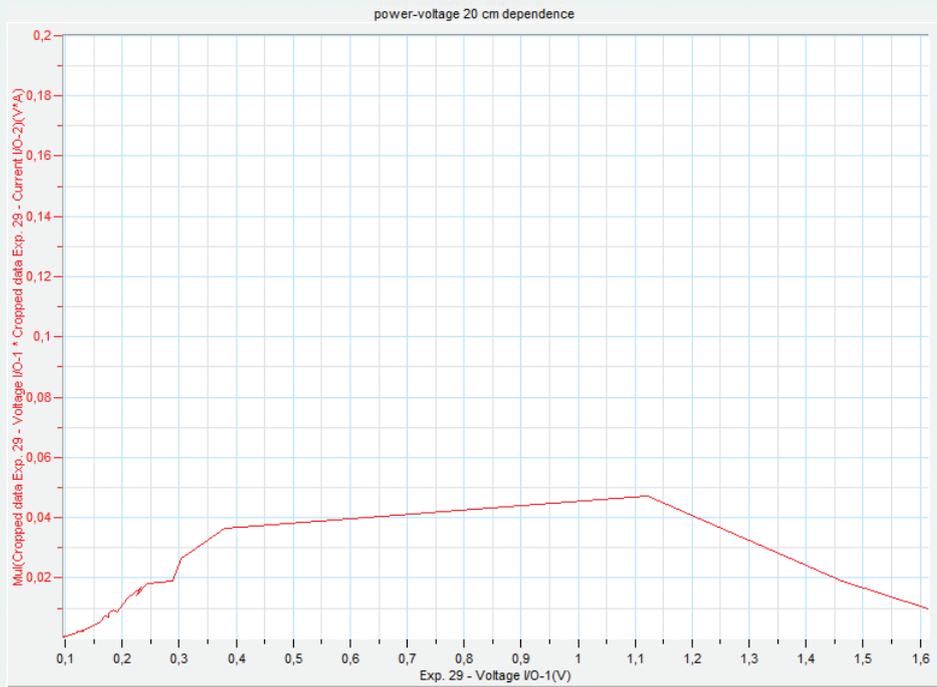
IV- 5 cm dependence

IV- 10 cm dependence

IV- 15 cm dependence

IV- 20 cm dependence

IV- 25 cm dependence

power-voltage 5 cm dependence

power-voltage 10 cm dependence

power-voltage 15 cm dependence

power-voltage 20 cm dependence

power-voltage 25 cm dependence

1. Read the following characteristic values from your measurement using using the first cursor 〜 :

distance	Wind speed / m/s	Umax / V	Imax / mA	Pmax / mW	Ropt / Ω
5 cm	7,4				
10 cm	6,3				
15 cm	6,2				
20 cm	6				
25 cm	5,7				

Ropt means the optimal resistance value, where the output power is maximal.

Write the values in table in MultiLab and plot Pmax over the wind speed.

2. Compare the results to experiment 3.

Answers

1. Read the following characteristic values from your measurement using using the first cursor :

distance	Wind speed / m/s	Umax / V	Imax / mA	Pmax / mW	Ropt / Ω
5 cm	7,4	0,43	138	59,3	3,1
10 cm	6,3	0,41	129	52,9	3,2
15 cm	6,2	0,38	114	43,4	3.3
20 cm	6	0,38	96	36,5	4
25 cm	5,7	0,34	80	27,2	4,3
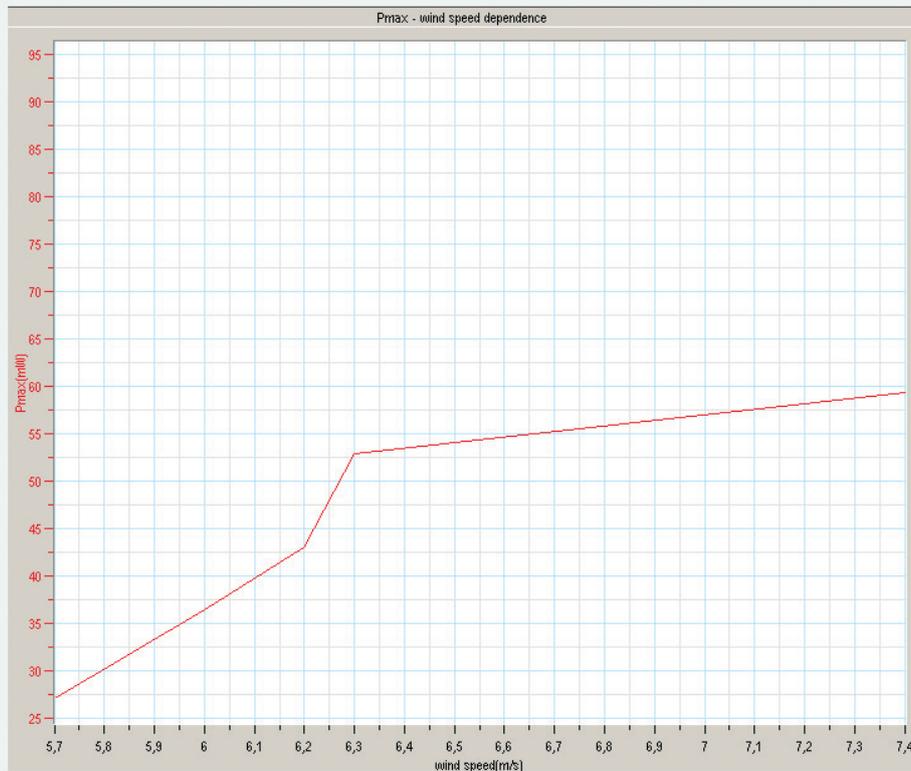
2. The qualitative trend of the curves is the same. There is a strong increase of power for wind speeds up to 6 m/s before the power goes into saturation for higher wind speeds. The absolute values differ because in experiment 3 each measurement was on a random point of the IV-characteristics but not at Pmax.

9) Start-up characteristics of different rotor blades

Introduction

In the previous experiments we have seen that the 3-blade rotor has advantages compared to 2 - or 4 - blade rotors – especially the output power is higher for this configuration. But how fast can the maximum output be reached when wind hits the turbine? This question should be observed in this experiment.

Learning Objects

Measure the start-up behaviour of wind rotors with different number of blades and compare the behaviour.

Concepts

Electrical circuits

Time Frame

1 lesson

Equipment

1. Main board
2. Wind generator module with rail and power supply (12V)
3. Wind turbine module (with 2, 3 and 4 rotor blades)
4. Voltage sensor
5. NOVA LINK

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!).
2. Fix the rail to the wind turbine module.
3. Mount the wind turbine on top of the rail and connect the small cables to the module.
4. Fix the wind machine to the rail at the 10 cm position.
5. Connect the voltage sensor parallel to the wind turbine.

MultiLab Setup

1. Launch MultiLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the voltage sensor to I/O-1 port of the NOVA LINK.
4. Click ⚙.
5. Click **Next**.
6. Set **Select rate** to **25 per second**.
7. Set **Select recording mode** to **Add**.
8. Click **Next**.
9. Set **by samples** to **continuous**.
10. Click **Finish**.

Experimental Procedure

1. Attach the two-blade rotor to the wind turbine.
2. Hold one hand between the wind generator and the wind turbine module, so that the rotor blades do not rotate.
3. Connect the power supply to the wind generator.
4. Wait until the wind machine has maximum speed.
5. Click ▶ and take your hand away (If the rotor does not start on its own give it a small impulse).
6. When the rotor reached maximum speed click ⏹.
7. Turn the wind machine off.
8. Replace the 2 blade rotor with the 3 - and 4 - blade rotor
9. Repeat step 2 to 7.
10. Click 💾 to save your data.

Data Analysis

1. Click Table in the menu and select **Add manual column**.
2. Set Column name to # of blades.
3. Click Ok.
4. Go to **Table** > **Add manual column**.
5. Set Column name to "**Time**".
6. Set units to s.
7. Click Ok.
8. Click ^Y_X .
9. Set X-axis to voltage.
10. Set Y-axis to measured current of the 2 blades.
11. Set the Graph title to IV-curve 2 blades.
12. Click Ok.
13. Click .
14. Repeat all these steps for the 3- and 4-rotor blade rotor.

Evaluate the start-up time

1. Activate the graph for the 2 blade rotor.
2. Click .
3. Click . Now you can see two arrows.
4. Move the first arrow to the beginning of the voltage curve and the second arrow to the point where the voltage curve reaches a plateau.
5. Read the time difference of the two points and fill it in the prepared table.
6. Repeat these steps for the other measurements.

IV- 5 cm dependence

IV- 5 cm dependence

IV- 5 cm dependence


start up time - # of rotor dependence
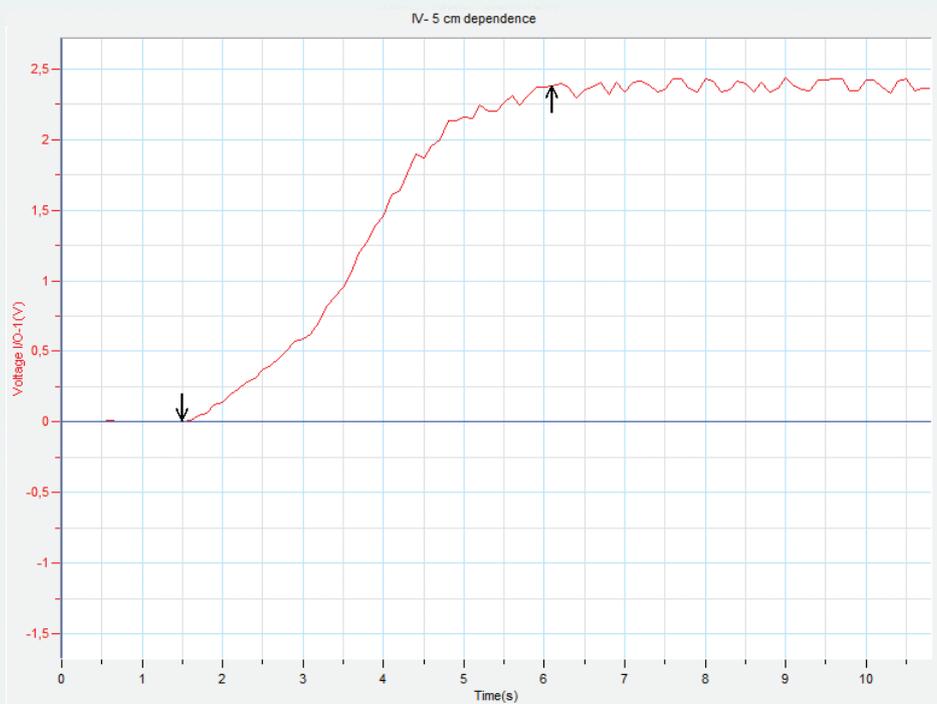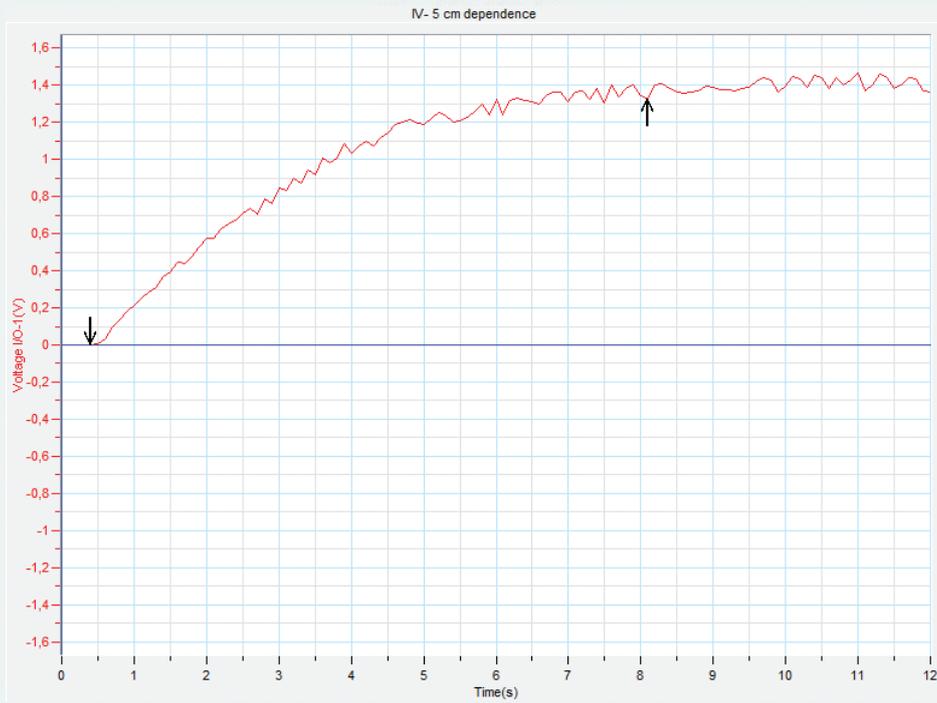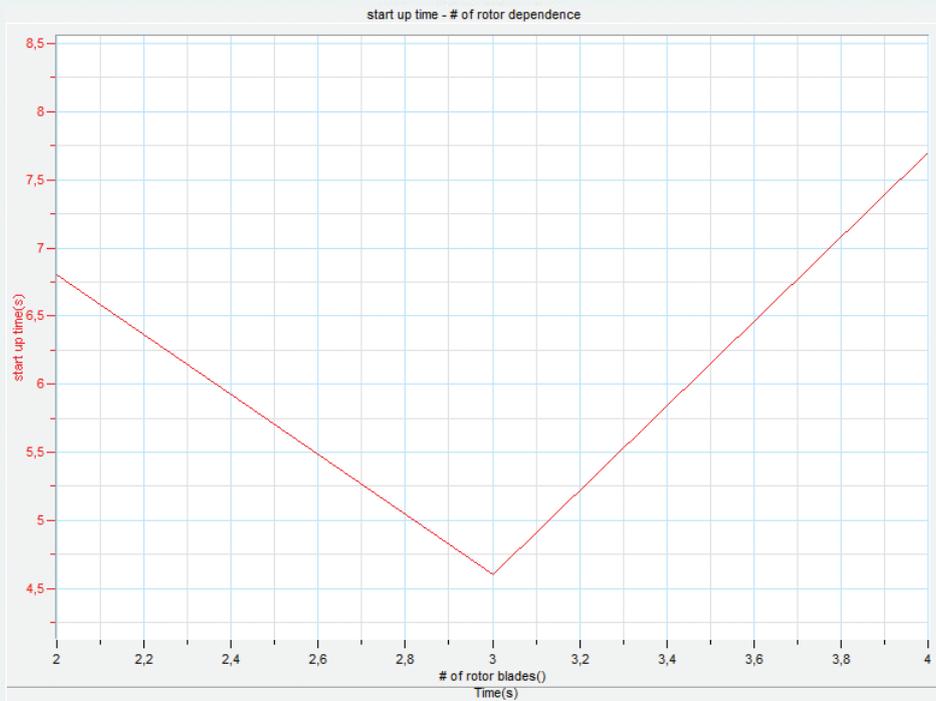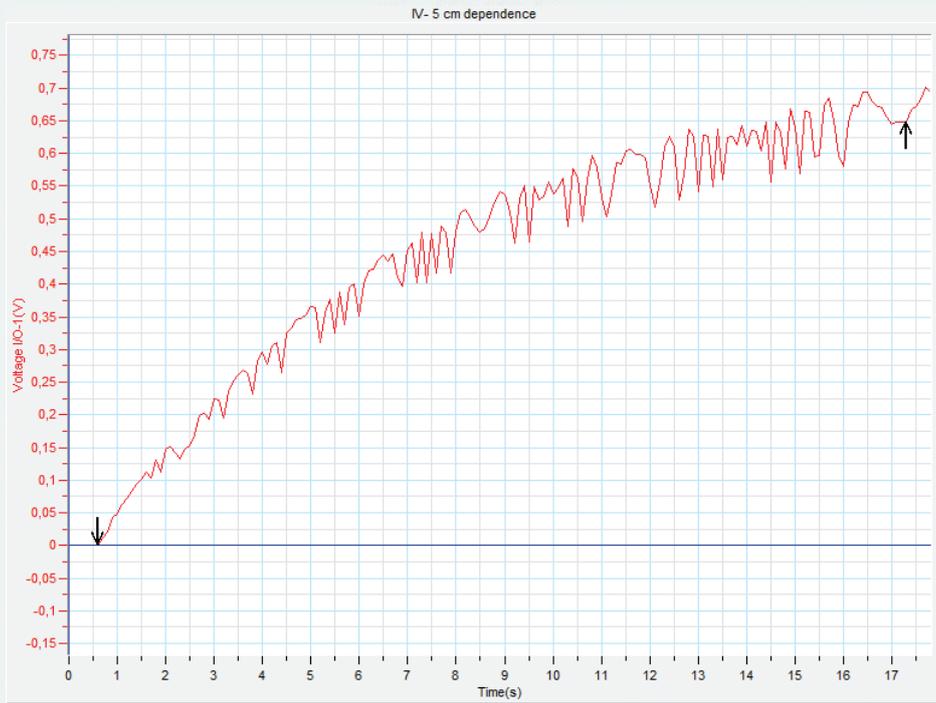
Questions

1. What is the reason for the start-up time - Why the wind turbines do not start faster?
2. Which effects could also influence the start-up time?

Answers

1. The reason for the retarded start-up is the inertia of the rotor and the blades. The rotor has to be accelerated for a while to reach its maximum number of rotations.
2. Buoyancy effects at the rotor blades play an essential role for the rotor's movement. Therefore, the blade profiles are optimized to achieve the largest possible buoyancy. But this optimization is only valid for a certain number of rotations of the rotor. That is why the rotor has a lower efficiency at lower number of rotations. This is also the reason for the slower increase of voltage at the beginning of the curve.

Further Suggestions

Also measure the behavior of the voltage when the rotor stops because of a sudden absence of wind.

10) Efficiency of the wind turbine

Introduction

It is of great interest to harvest the energy of the wind as efficient as possible because with a higher efficiency of a wind turbine the costs per khW will decrease. In this experiment the efficiency calculation of the model wind turbine from the experiment kit should be calculated.

Learning Objects

Examine the energy balance of the wind turbine when it is loaded by a fixed resistance and calculate the efficiency.

Concepts

Electrical circuits
Efficiency

Time Frame

1 lesson

Equipment

1. Main board
2. Wind generator module with rail and power supply (12V)
3. Wind turbine module (with three rotor blades)
4. Potentiometer module
5. Voltage sensor
6. Current sensor
7. Temperature sensor
8. NOVA LINK

Equipment Setup Procedure

1. Plug the wind turbine module onto the main board without the generator part (Important: do not plug the module onto the main board in wrong direction – see the picture for reference!)
2. Fix the rail to the wind turbine module
3. Mount the wind turbine on top of the rail and connect the small cables to the module
4. Fix the wind machine to the rail at the 20 cm position
5. Plug the potentiometer module onto the second place of the main board
6. Turn the knob of the 1kΩ potentiometer to Rmin and the knob of the 100Ω potentiometer ca. a third turn from Rmin to Rmax.
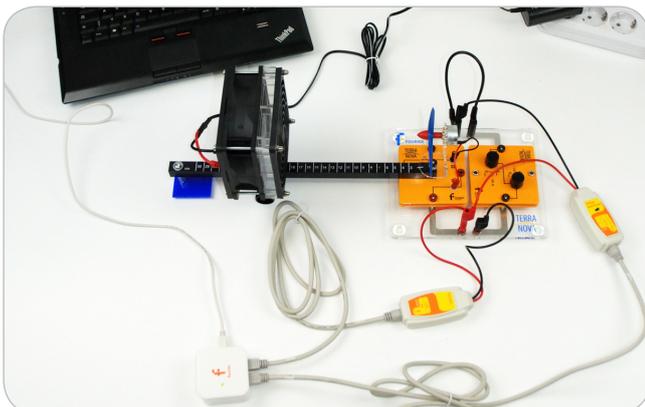
MultiLab Setup

1. Launch MultiLab.
2. Connect the NOVA LINK to the USB port on the computer. The green LED will turn on when the NOVA LINK is successfully connected to the computer.
3. Connect the current sensor to I/O-1 port of the NOVA LINK.
4. Connect the voltage sensor to I/O-2 port of the NOVA LINK.
5. Connect the temperature sensor to I/O-3 port of the NOVA LINK.
6. Click ⚙.
7. Click **Next**.
8. Set **Select rate** to **Manual**.
9. Set **Select recording mode** to **Add**.
10. Click **Next**.
11. Set **by samples** to **50**.
12. Click **Finish**.

Notes

The energy balance represents a comparison of the kinetic energy of the air (wind energy) in front of the rotor to that of the energy used by the wind turbine. For this purpose the quotient from the actually converted output by the wind turbine and the output of the wind in front of the rotor is considered. We call this quotient ε.

$$\varepsilon = \frac{P_n}{P_{Wind}}$$

This figure makes a assertion about how much wind energy the wind turbine can actually convert into electrical energy. Thus ε is comparable to the efficiency of a wind turbine, which however is calculated differently in wind energy technology.

Experimental Procedure

1. Put the wind generator to the 20 cm mark on the rail.
2. Connect the power supply to the wind generator.
3. Wait until the wind generator and the wind turbine have maximum speed.
4. Click ▶.
5. At the end click ⬛.

Data Analysis

1. Click f_x.
2. Click on Functions.
3. Set Functions to Multiply.
4. Set G1 and G2 to the voltage and current measurement data.
5. Click Ok.
6. Click 📖.
7. Add the columns of the calculated power function.
8. Press Ok.
9. Click .
10. Measure the **temperature** and read the respective value for the density ρ of the air from the plot at the beginning of the manual.
11. Read the respective wind speed for the used distance from the plot at the beginning of the manual.

12. Measure the diameter of the rotor blade.
13. Calculate the power of the wind speed.

$$P_{Wind} = \frac{1}{2} \rho A v^3_{Wind} \qquad A = \frac{\pi}{4} d^2$$

14. Calculate the power of the rated output $P = IV$.
15. Calculate the efficiency:

$$\varepsilon = \frac{P_n}{P_{Wind}}$$

Expected Results

$\theta = 22\,°C \rightarrow \rho = 1.195\ \text{kg/m}^3$

$V_{wind} = 5.3\ \text{m/s}$

$d = 10\ \text{cm}$

$U = 1.8\ \text{V} \qquad I = 46\ \text{mA}$

Target surface:

$A = \dfrac{\pi}{4}\,d^2 = 0.00785\ \text{m}^2$

Wind energy:

$P_{Wind} = \dfrac{1}{2}\,\rho\ A\,v^3_{Wind} = 0.070\ \text{W}$

Rated output:

$P = U \cdot I = 0.083\ \text{W}$

Energy balance:

$\varepsilon = \dfrac{P_n}{P_{Wind}} = 0.1185 = 11.85\ \%$

? Questions

1. The wind energy is not fully converted at the wind turbine. Why does depreciation take place and consequently "loss" of energy? Into which forms of energy is the wind energy converted?
2. Find out about the efficiency of real wind turbines and compare your results with the real values. Name possible reasons for the differences.

✓ Answers

1. Wind energy is not fully converted due to frictional losses on the rotor blades and turbulence behind the wind rotor. Besides, frictional losses on the axis, the gearbox and in the turbine occur.
2. The aerodynamic efficiency (only related to wind rotor) is typically 70-85%. The Efficiency based on the complete system with turbine, gearbox and transformer is typically approx. 30%.
   Possible reasons for deviation between real wind turbines and the model are: not optimal wing shape, not enough laminar flow, much smaller components (other flow phenomena).