Activity 1.2.6

Maximizing Motor Power – VEX V5

Distance Learning Support

If you are doing this activity away from the classroom, jump to the flexible path **DL: Activity 1.2.6 Maximizing Motor Power**.

INTRODUCTION

An engineer often must design a system to get the most out of limited resources. For example, to design a laptop or smartphone, an engineering team works to make the battery last as long as possible. In another example, a vibrating smartphone uses a motor with an off-center load, and it needs to be designed with a gear train that delivers the most **power** or highest **efficiency** .

In this activity, you will learn how to make measurements of a motor and create characteristic curves that can be used to select a motor that delivers maximum power or maximum efficiency for a given task.

Figure 1. Laptop and Smartphone

EQUIPMENT

- POE Gearbox Motor Winch from Activity 1.2.5
- Tape
- Timing device to measure time to 0.01 s precision
- Vernier® Go Direct® Force and Acceleration Sensor
- Vernier® Graphical Analysis 4™

> **Note:** Your teacher may direct you to use this alternative equipment:
> - Vernier® LabQuest® Mini or Vernier Go!Link®
> - Vernier® Dual-Range Force Sensor

RESOURCES

- POE Gearbox Motor Winch Construction Guide
- Motor Power Spreadsheet
- Maximizing Motor Power at Constant Voltage
- Graphical Analysis 4

Procedure

To develop specifications, for a motor four measurements are needed: power, efficiency, current, and speed. These four measurements describe the most important properties of a particular motor at a given **voltage** and help an engineer develop and analyze the curves that characterize, or describe the technical specifications of, a motor like the one shown in Figure 2.

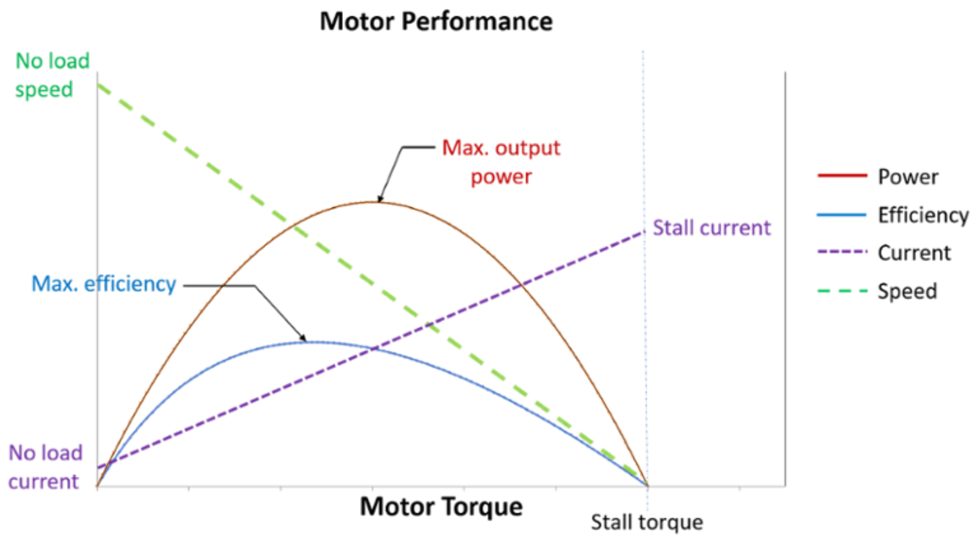


Figure 2. Motor Characteristics Curves

No Load Performance

1. Add a Vernier® Go Direct® Force and Acceleration Sensor to the POE Gearbox Motor Winch from Activity 1.2.5 as shown in Figure 3.

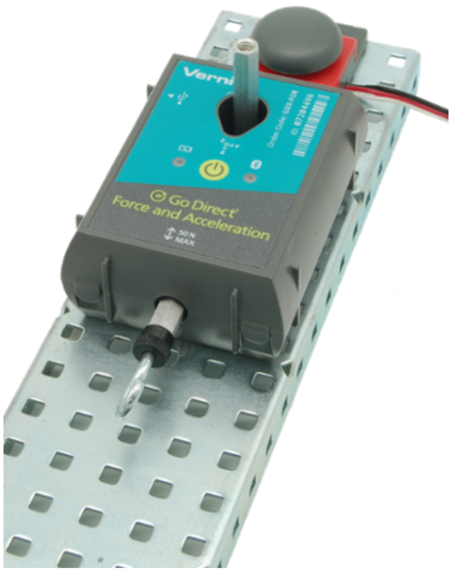


Figure 3. Force and Acceleration Sensor

2 Prepare the winch cable to make measurements:

a. Unspool the winch cable.

b. Pass the loop at the end of the cable through the spokes of the 4-inch wheel as shown in Figure 4.

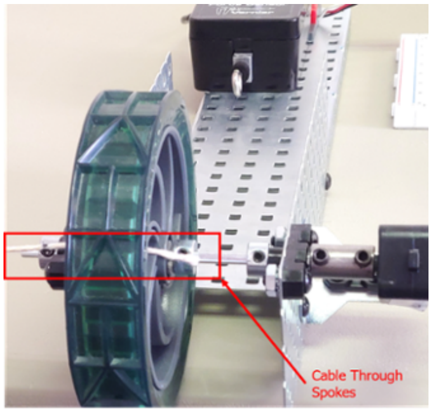


Figure 4. Cable Passed Through Spokes

c. Loop the cable back through the end that is attached to the winch drum as shown in Figure 5. The cable loop must be in the center of the wheel circumference.

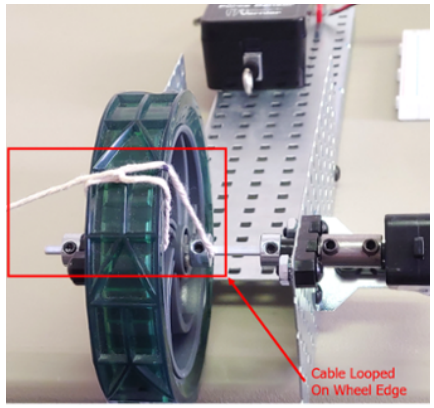


Figure 5. Cable Looped on Wheel Edge

d. Refer to Figure 6. Secure the end of the cable onto the wheel to avoid interference with the wheel movement:
   i. Hold light tension on the end of the cable as you turn the top of the wheel toward the force sensor.
   ii. Adjust the cable alignment so that the cable is wound around the center of the wheel circumference.
   iii. Tape the end of the cable onto the face of the wheel.

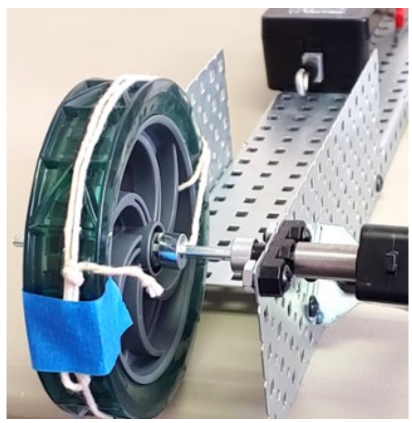


Figure 6. Cable End Secured

> **Note**: Blue tape is shown in Figure 6 to improve visibility for the image. Any tape can be used to secure the end of the cable.

e. Add a doubled-over piece of tape to the edge of the wheel as shown in figure 7. This will slap your finger as the wheel turns to help you count the number of revolutions.

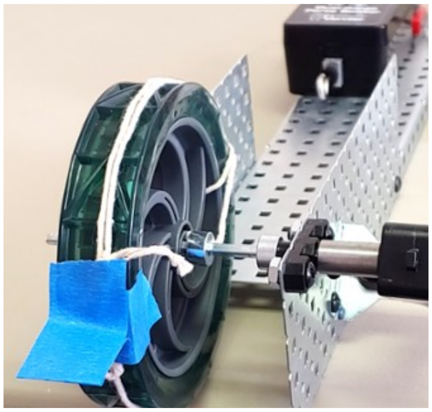


Figure 7. Finger Striker

3 Measure the no-load speed of the motor:

a. Turn on the power supply.
b. Turn the Current knob fully clockwise.
c. Adjust the voltage knob until the display shows: 4.5 V +/– 0.2 V
d. Position your finger so that the doubled-over tape strikes your finger each time the wheel turns to help you count the number of revolutions.
e. Press the bumper switch to start the winch turning.
f. Start the stopwatch when you see the tape reach and slap your finger.
g. Record the voltage and current displayed on the variable power supply.
h. Stop the stopwatch after the winch turns 20 times.
i. Repeat steps b–h two more times.
j. Turn off the power supply.

> **Note**: A recommended practice is to measure multiple trials, then calculate the average for each measurement. If any of your time measurements seem drastically different from the others, consider it an **outlier** and do not include it in the mean.

Measurement	Trial 1	Trial 2	Trial 3	Average
n (0.0) Number of rotations				
t (0.00 s) Time for *n* rotations				
$V_{no\text{-}load}$ (0.0 V)				
$I_{no\text{-}load}$ (0.00 A)				

5 Calculate the no-load speed, which is the fastest a motor will spin at a voltage. Use the formula shown in the table.

Formulas	Substitute / Solve	Final Answer (0.000)
No Load Speed (0.00 rotations / s) $\omega_{\text{no-load}} = \frac{\text{number of rotations}}{\text{time}}$		
No Load Speed (0.00 radians / s) Convert to no-load speed in radians per second where 2π radians = 1 rotation		

Stall Performance

6 Remove the tape that secured the cable to the winch wheel.

7 Hold light tension on the end of the cable as you hook the loop onto the force sensor hook as shown in Figure 8.

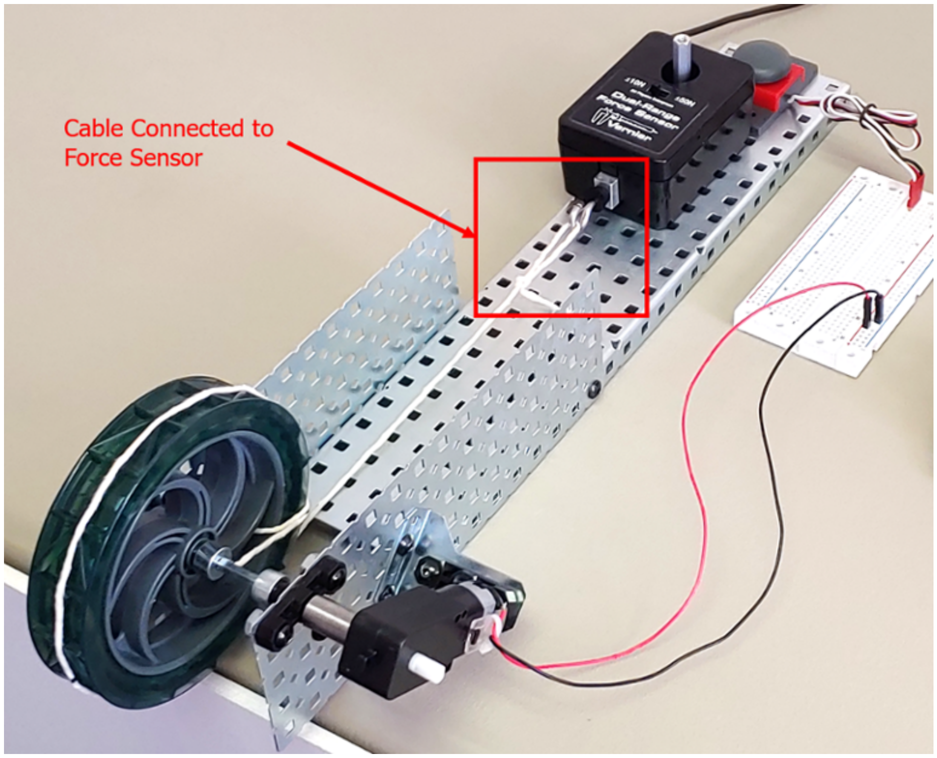


Figure 8. Stall Measurement Configuration. This setup shows Dual-Range Force Sensor; set up is the same for the Go Direct Force and Acceleration Sensor.

> **Note**: The cable should contact the wheel at the bottom of the circumference, not the top.

8 Set up the force sensor using the following steps:

> **Vernier Sensors and GA4:** Refer to the **Graphical Analysis 4** and **Sensors and Probes** resources as needed for more details and videos about connecting sensors and collecting, saving, and printing data.

a. Launch GA4 and select Sensor Data Collection.
b. Connect the Force and Acceleration Sensor (Figure 9) to your device using a computer via Bluetooth or the USB connection.

Figure 9. Go Direct Force and Acceleration Sensor with USB Cord

9. Measure the stall performance of the motor:
   a. Turn on the power supply.
   b. Turn the Current knob fully clockwise.
   c. Adjust the voltage knob until the display shows 5.5 V +/– 0.2 V.

> **Caution**: Before you proceed to the next step, read this warning. The Gearbox Motor has no overcurrent protection, so it can be damaged by too much current. The current heats up the motor coils and melts the insulation, short-circuiting coils to each other. It is good practice to make this measurement quickly and then turn off the power to the motor. Let the Gearbox Motor cool for about 10 seconds and measure again.

   d. Prepare GA4 to record force data.
      i. With the Go Direct Force and Acceleration Sensor connected to GA4, you should have a graph displayed ready to collect data, as shown in Figure 10.

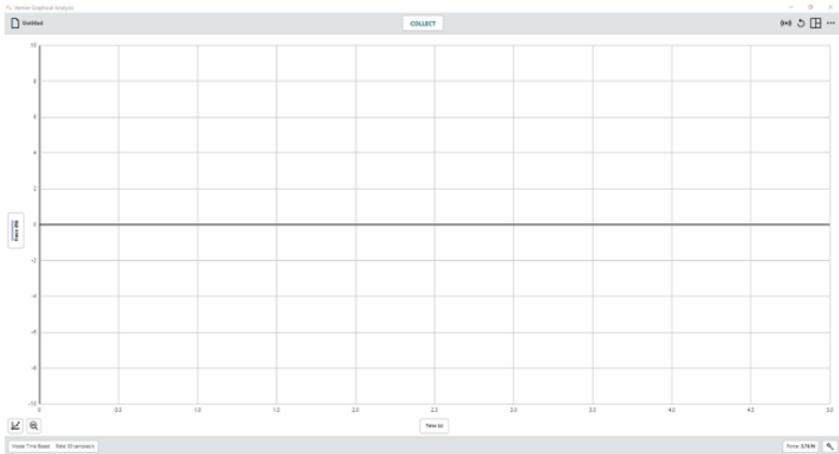


Figure 10. Graphical Analysis Window with Go Direct Force and Acceleration Sensor Connected

ii. If your sensor value is not 0.0 N (zero Newtons) you will need to zero your sensor, select the force reading, and then select Zero from the menu.

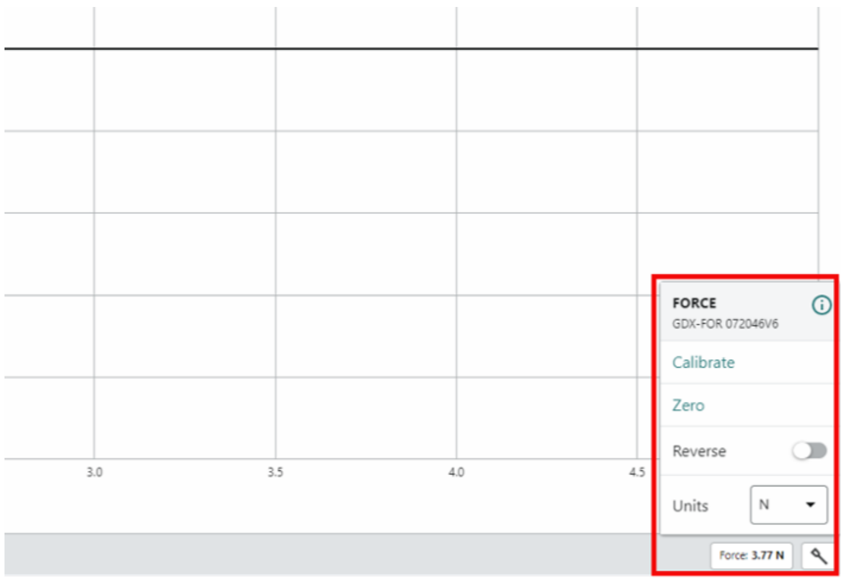


Figure 11. GA4 Window Selecting the Force Reading to Zero the Sensor

iii. Add the Data Table and Window feature to more closely view your readings

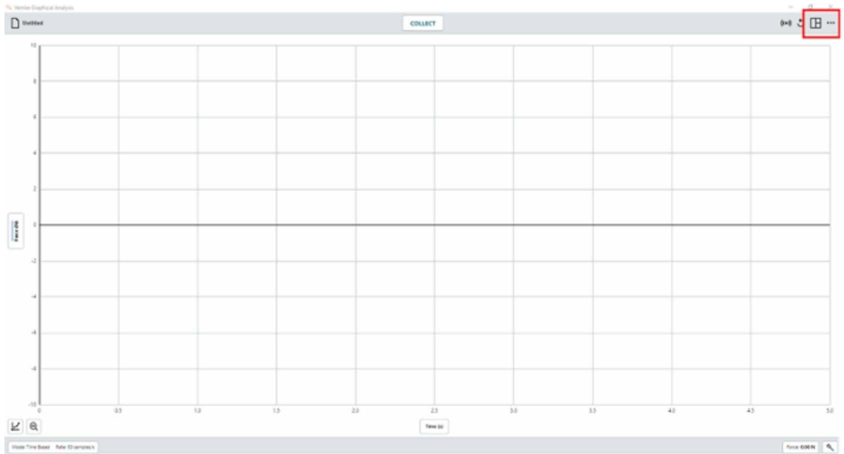


Figure 12. GA 4 Window Selecting the Windows Option Icon

iv. Toggle the Data Table and Meters on

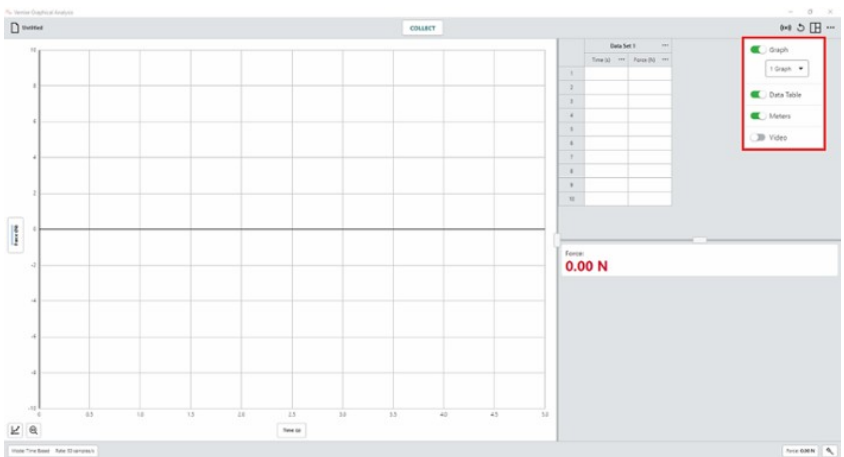


Figure 13. GA 4 Window Toggling On the Data Table and Meter Windows

v. Adjust the collection time by selecting the Mode button

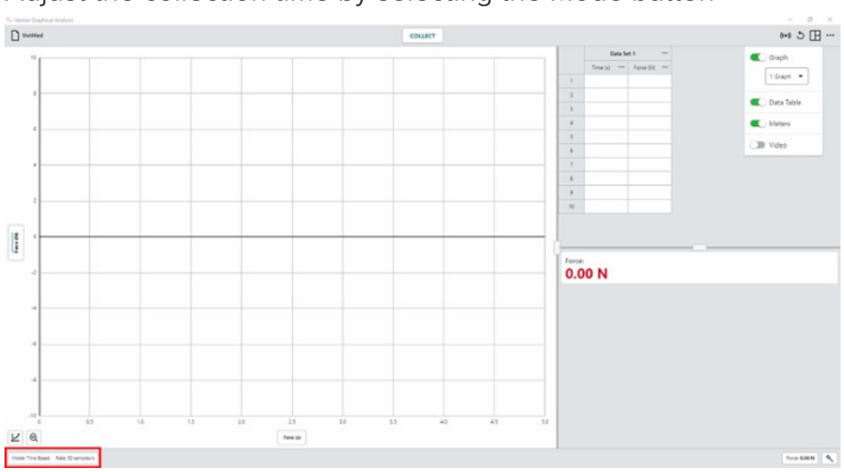


Figure 14. GA 4 Window Selecting the Mode Icon to Access Data Collection Settings

vi. In the Data Collection Settings window adjust the End Collection time to after 10 s duration.

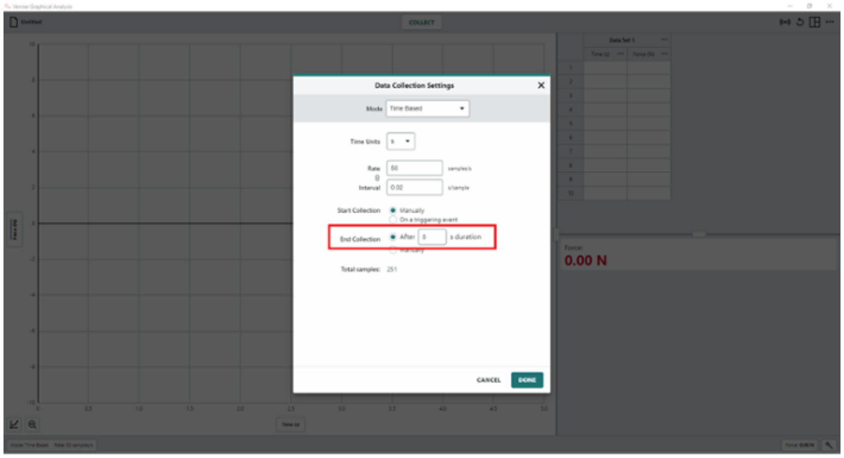


Figure 15. GA 4 Data Collection Window Adjusting End Duration to 10 Seconds

e. Press the COLLECT button.
f. Press the bumper switch to start the winch turning.
g. Record the voltage and current displayed on the variable power supply.
h. Record the force applied to the force sensor.
i. Turn off the power supply.

d (distance from the axis of rotation to point where force is applied where wheel diameter is 4 inches) = _____ inches (0.0)

Convert to _____ meters (m) (0.000)

F⊥ (force to stall the motor) = _____ N (0.00)

τ_{stall} (stall torque) = d × F⊥ = _____ N-m (0.00)

Stall voltage _____ volts (V) (0.0)

Stall current _____ amps (A) (0.00)

10 Congratulations! You have measured everything you need to characterize your motor. You have the most important design parameters that describe the motor's performance for operation at 5.5 V. Let's put them together, creating a specification sheet, or "spec sheet" as it is commonly called. Create the following specification with your measured and calculated values in your PLTW Engineering Notebook.

Specification Sheet

Motor model: ____________

For operation at 5.5 V:

No-load current: _________

Stall current: _________

No-load speed: _________

Stall torque: _________

Motor Power

Engineers make many design decisions by calculating important results from these specifications. For example, an engineer may need to know how much torque is applied when a motor is operated at maximum power.

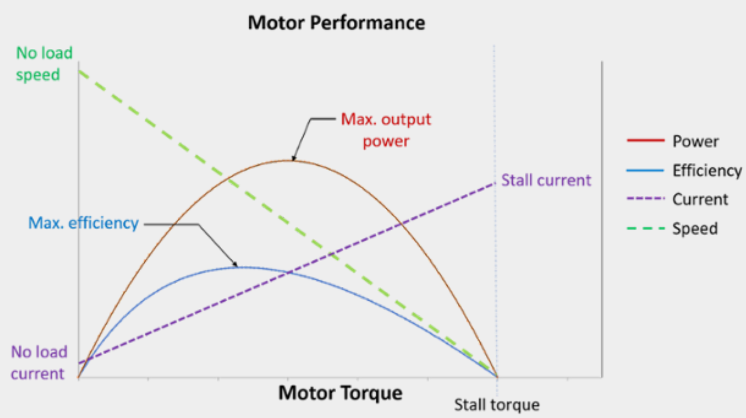
10 View the **Maximizing Motor Power at Constant Voltage** presentation.

11 Calculate the torque at which the motor delivers maximum power.
τ (Motor torque for maximum power) = ½ stall torque =
[ ] N·m

12 An engineer may need to select a component based on a value calculated from the motor specifications. For example, an engineer requires a smartphone vibration motor with at least 200 mW of power. Calculate the maximum output power of your motor in watts and horsepower to determine whether the motor you characterized.

Note: The speed of the motor at half the stall torque is half the no-load speed. It is common for motor output power to be reported in horsepower (hp). The Engineering Formula sheet has a conversion factor.

Speed versus Power: Remember from the Maximizing Motor Power presentation that the speed versus power relationship (green line in the graph) is linear, and the motor speed is 0 at the stall torque.



Justify that the motor speed at maximum power is half of the no-load speed.

What is the motor speed when the torque is 25% of the stall torque?

Hint

ω (Motor speed at maximum power) = ½ no-load speed =

rad/s

P_{out} (Motor output power at maximum power) τ × ω =

W

P_{out} (Motor output power at maximum power) x

[ ] (conversion factor) =

[ ] hp

13 Research the power output of a power tool or air compressor. Create a specification sheet for the equipment you researched. Compare that tool to your motor.

14 What gear ratio is needed for your motor to deliver its maximum power to the driveshaft?

> **Note**: Recall the formula for gear ratio:
>
> $$GR = \frac{\tau_{out}}{\tau_{in}}$$

Additional Information: The characterization you completed for your motor can be the foundation of engineering design decisions. Consider a design challenge to drive a robot. The robot requires 10 N·m of torque to be applied on the drive axle through a gear train to transfer power from a motor to the drive axle. This means the motor will be the input torque applied on the gear train, and the output torque from the great train must be 10 N·m.

GR = [ ] (unitless)

15 How much electrical power is supplied to the motor when the motor is exerting half of its stall torque (maximum output power)?

Additional Information: The specifications for the motor you measured and calculated are the foundation for you to predict how much electrical power it will consume.

Voltage = ________ V

Current halfway between the stall current and no-load current = ________ A

$P_{in} = I \cdot V =$ ________ = ________ W

Motor Efficiency

An engineer may need to design a device that operates as efficiently as possible instead of designing it to be powerful.

16 Calculate the efficiency of your motor when it is operating at maximum power.

Note: For the purpose of calculating efficiency, P_{in} is the electrical power to the motor, and P_{out} is the mechanical power produced by the motor. Some energy is lost in the system. Recall the equation for efficiency:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

efficiency = ________ %

17 With a partner discuss and develop an algorithm to calculate the maximum efficiency at any torque.

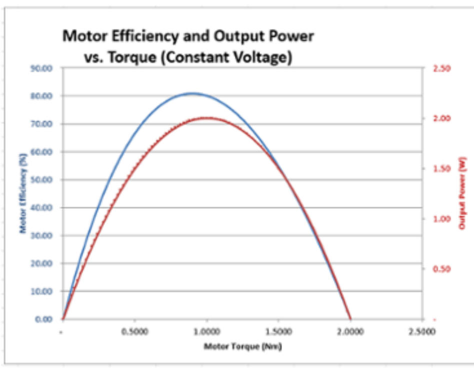
Additional Information: The calculation of torque at which the motor would deliver maximum power was rather simple (step 11). More complex was the calculation of the torque at which the motor will deliver power at maximum efficiency. There is a procedure to follow which is known as an **algorithm** . Steps 12, 15, and 16 guided you through the algorithm to calculate the efficiency for a given torque (half the stall torque in this example). You can generalize the process to develop an algorithm to calculate the maximum efficiency at any torque.

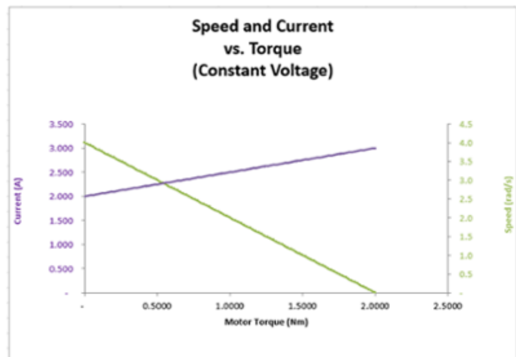
Automating the Motor Efficiency Calculation

To find the maximum efficiency, you can calculate the efficiency at many different torques and pick the highest efficiency. That requires many iterations of the algorithm. Computers are very good at automating that work so a spreadsheet application is provided to you to create the characteristic curves of a motor at a constant voltage.

How the spreadsheet works: This spreadsheet is automated to calculate efficiencies for 100 torque values between 0 N·m and the stall torque you enter. It automatically updates the graphs to specify how four design parameters for your motor are dependent on the torque the motor delivers. The first graph shows efficiency (in blue) and motor output power (in red).

1.00	= V = Voltage (V)
2.000	= I_free = No-load current (A)
3.000	= I_stall = Stall current (A)
4.00	= omega_no-load = No-load Speed (rad/s)
2.00	= tau_stall = Stall torque (Nm)





18 Open the **Motor Power Spreadsheet** spreadsheet and enter the specifications of your motor. Save images of your graphs.

19 Discuss these graphs with your partner including what the x- and y-axes for each curve represent.

Note: Notice two y-axes on each graph

Color	y-variable	vs.	x-variable
blue:		vs.	
red:	motor output power	vs.	motor torque
green:		vs.	
purple:		vs.	

20 Find the point on the Efficiency graph that identifies the maximum efficiency. Indicate this spot on the graph that you saved into the spreadsheet in the previous step.

> **Note**: To find the coordinates of the point of maximum efficiency, you can use mathematical representation, the data table, or the graph.

21 Based on your graphs, what is the maximum efficiency?

η_{max} = ______ %

22 At what torque does the maximum efficiency occur?

$\tau_{max\ efficiency}$ = ______ N·m

23 Using the torque from step 21 as the x-coordinate on the second graph, find the current that your motor uses when it is operating at maximum efficiency. Circle this point on your second graph.

$I_{max\ efficiency}$ = ______ A

24 How much electrical power does the motor use when it is operating at maximum efficiency?

$P_{electrical} = I \cdot V =$ ______ =

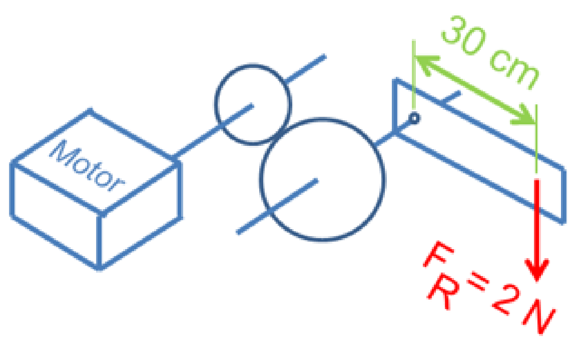
______ W

25 The efficiency indicates the percentage of electrical energy transformed into mechanical energy. The rest of the energy is converted into thermal energy, increasing the temperature of the motor. Given that power is the rate at which energy is transformed, at what rate is thermal energy transferred to the motor when it is operating most efficiently?

$P_{heat} = (1 - \eta_{max})\ P_{elec} =$ ______

CONCLUSION

1. Summarize what it means to “characterize” an electrical component in a system.
2. What are the advantages of using math and science in engineering design? What are the advantages of trial and error?
3. Explain how efficiency is related to electrical energy, mechanical energy, and heat energy.
4. The motor in the design shown at left has the specifications shown at right. What gear ratio should be used for maximum power?



For operation at:	9 V
No-load current:	100 mA
Stall current:	3 A
No-load speed:	20 rad/s
Stall torque:	60 N·m

Proceed to next lesson