

Characterization of Small DC Brushed and Brushless Motors

by Aaron M. Harrington and Christopher Kroninger

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14. ABSTRACT <p>Micro brushed and brushless motors of the size typically used on micro-ground vehicles and micro-air vehicles have been found to have very low efficiencies. This lack of efficiency not only stems from low manufacturing tolerances, but is also because motors at these scales are generally operated over a large range of loading conditions causing them to operate off design point. This technical report: (1) provides a basis for a simple motor analysis, comparing analysis with actual motor test data, (2) examines the efficiencies of many of the off-the-shelf brushed and brushless motors used in micro vehicle applications, and (3) provides a methodology for proper motor selection, emphasizing the importance in ensuring motor loading conditions are matched to the motor design in order to maximize power efficiency.</p>					
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1. Introduction

With the ever increasing popularity of mobile robotic platforms in the form of unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs), there is the desire to decrease their size, weight, power, and cost. At larger scales (larger than $6 \times 6 \times 6$ in volume), these vehicles use a wide variety of actuators that include, but are not limited to, servos, linear actuators, and brushed and brushless motors. As the size of these vehicles decrease, the size and complexity of servos and linear actuators prohibits their use and most vehicles only use brushed and brushless motors. Motors applied at the vehicle scale of interest suffer from low efficiency relative to larger motors. Motors of 100s of grams, for example, can achieve efficiencies greater than 85% (1). As the size of motors is reduced, so is their maximum operating efficiency. Figure 1 shows a representative sample of brushed and brushless motors commonly used for robotic applications, ranging from 0.46 to 151 grams (g). As size decreases, efficiency quickly drops. As the need for actuation in robotics spans this range of scale, it is important for users to understand the impact of scale on their system efficiency.

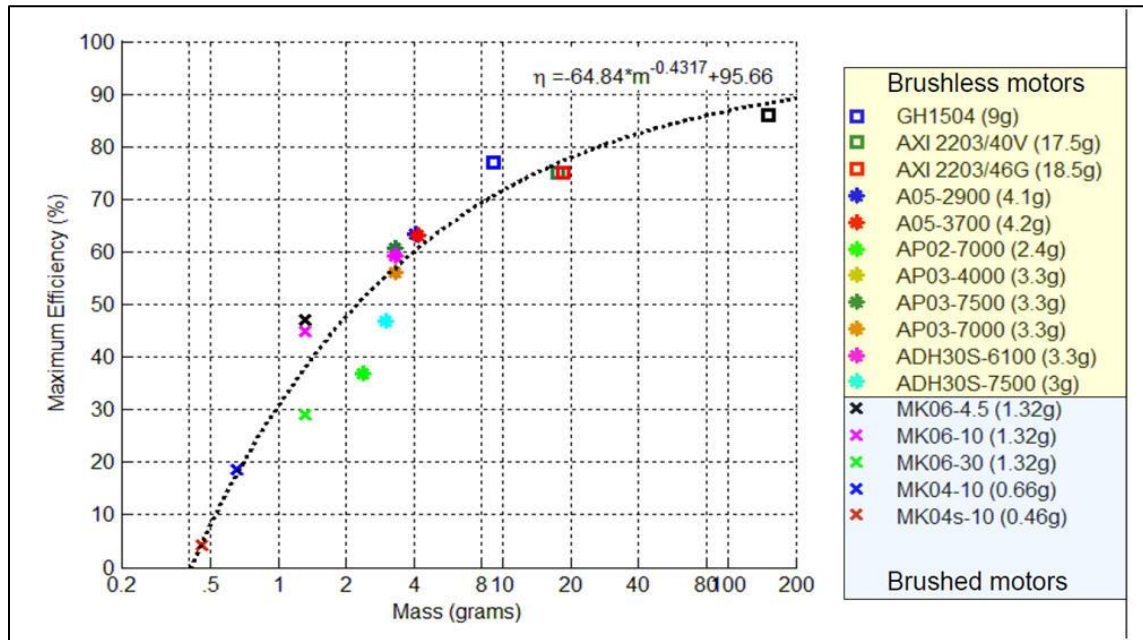


Figure 1. Maximum efficiency vs. mass for a representative sample of motors.

When considering motor selection as a designer, the specifics about efficiency and power output over the entire envelope of torque and RPM are desired. Many commercial off-the-shelf (COTS) motors at this scale are manufactured for hobbyists and do not include extensive data sheets, and many do not have performance information at all. Most motors only come with information on general characteristics such as their size, weight, operating voltage and current,

and “KV” rating. The KV rating is generally the user’s only indication of motor performance and is an incomplete performance metric that describes the no-load rotation rate per the input voltage. Experiments described in this report have shown that these values do not correlate to actual operational performance under load, and thus, it is difficult for the user to properly choose the best motor for a particular application. Efficiency is a more straight forward metric and is generally only provided by the manufacturers of motors greater than 4.2 g. These values are only given at a single operating point, and the revolutions per minute (RPM) and torque for this operating condition are generally not provided.

This technical report provides an understanding of motor design and operation, and is a guide to motor selection and implementation for robotics applications. This report includes an introduction to basic brushed and brushless motor design and their operation. Brushed and brushless motor operation under load is examined and the relation of efficiency against torque, RPM, voltage, and throttle setting (for brushless motors) is presented. This technical report also provides detailed information that is not provided by the manufacturers for a selection of the most widely used small motors, that include 12 brushed direct current (DC) motors and 8 brushless motors—provided in the appendix. The characteristic size of the motors in this study have a diameter of 15 millimeters (mm) or less and weigh <5 g.

1.1 Motor Theory

The purpose of motors is to convert electrical power to mechanical power in the form of rotary motion. This electromechanical system is characterized by a few specific parameters that, if known, can help one predict the performance of the motor in a system. These parameters include the no-load and stall speed, torque, current, and voltages, as well as the power factor, and can be obtained using a power analyzer and a dynamometer. No load describes the free rotor speed of the motor when there is no torque applied. Similarly, stall describes the motor’s point of maximum torque where RPM, by definition, is zero. These two extremes are not realized in practice but are not necessary as the motor would not be operated at these conditions in a practical application. The following is an example analytic model based on theoretical motor performance, developed for a DC brushless motor based on the values obtained through measurement on a micro dynamometer.

These previously mentioned parameters must be measured in order to predict the performance of a DC motor. However, most of these values cannot be measured directly as they cannot be achieved and must be extrapolated from attainable experimental data. Each of the three parameters, RPM, voltage, and current, have a linear relationship with torque and therefore, three important relationships can be derived—the motor’s torque-RPM slope, the torque-current slope, as shown in figure 2, and the torque-voltage slope, which is also linear (not shown).

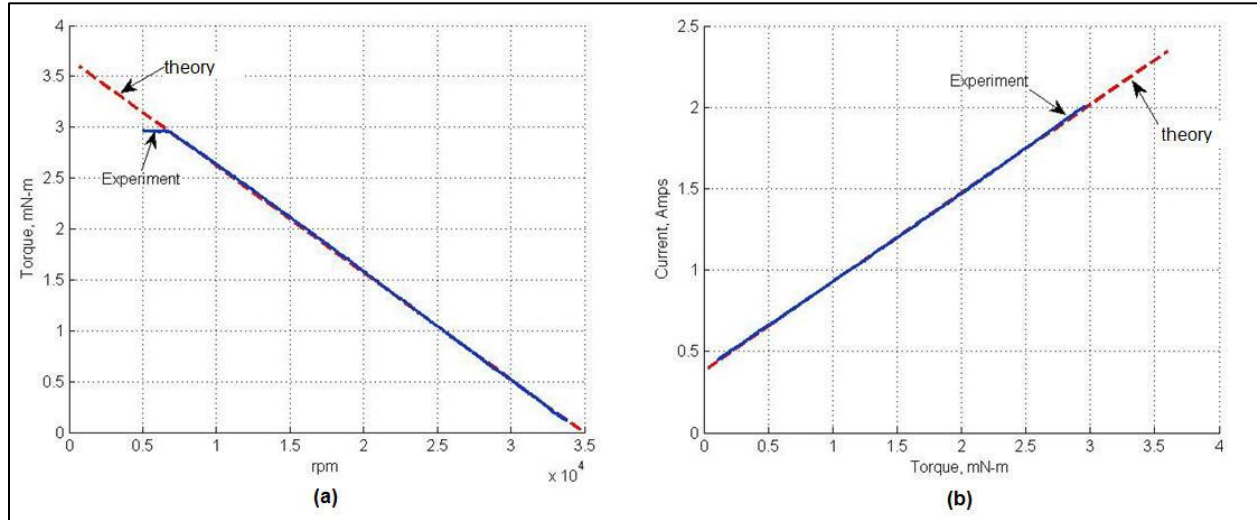


Figure 2. (a) Torque vs. RPM and (b) current vs. torque comparing theory and experiment for an AP03-7000 brushless motor.

The final value, known as the power factor, relates the apparent power vs. the active power of the motor. This active power is the actual power delivered to the motor that it uses to create a torque at a specific RPM and the apparent power is the mean voltage times mean current. Thus, the ratio of active power to apparent power is called the power factor (λ). This power factor accounts for voltage and current signals that are not necessarily in phase with each other, and therefore, the power input is not simply the product of the mean current and voltage. The current will either lead or lag the voltage by a phase angle with the relationship $\phi = \cos^{-1}(\lambda)$ and corresponds to the reactive portion of the impedance in the motor. Thus, a positive phase angle would indicate a strong inductive load on the motor. The output power of the motor is measured as the product of the torque and RPM. The relationship between output power and torque is shown in figure 3 with the theoretical curve forming a parabola, the product of the linear relationship displayed in figure 2. The motor's inability to achieve stall and no load is evident. Actual motor performance deviates though not significantly.

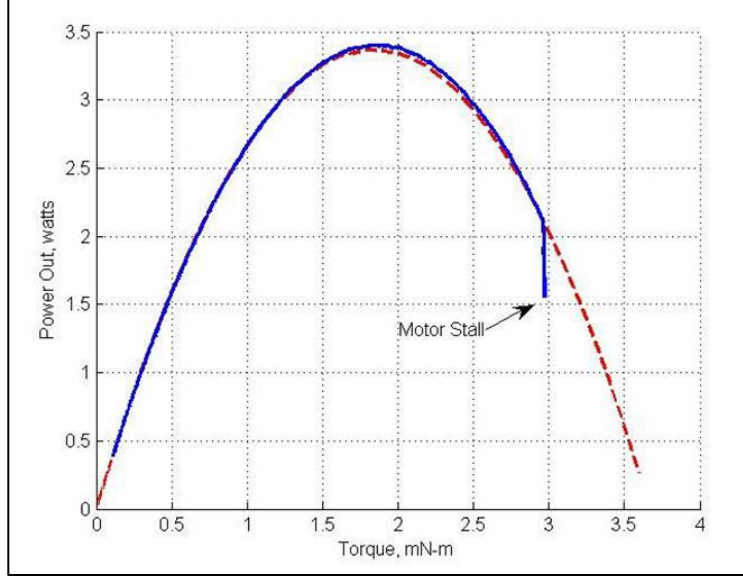


Figure 3. Measured power out vs. torque for an AP03-7000 brushless motor.

In order to calculate the salient characteristics of the motor, the voltage and current across each phase of the motor is measured, which is generally given as an RMS value. The voltage is an RMS value measured at the output of the speed controller and not the applied voltage, which would be the input to the speed controller. The voltage (V) and current (I) sum of the motor is then determined as the average of the three voltages and currents measured across each motor's winding phase as shown in equations 1 and 2.

$$V_{avg} = \frac{V_1 + V_2 + V_3}{3} . \quad (1)$$

$$I_{avg} = \frac{I_1 + I_2 + I_3}{3} . \quad (2)$$

Because the three waveforms are 120° apart from one another, the apparent power of the motor (S) is given as the relationship of the average of each winding phase's power with a multiplication factor to account for when two waveforms overlap, which occurs every 60°.

$$S = \frac{\sqrt{3}}{3} (V_1 I_1 + V_2 I_2 + V_3 I_3) . \quad (3)$$

In general, the voltage and current sum of the motor can be measured, but the voltages and currents across each individual winding phase may not be known. In this case, it can be assumed that each winding phase will have similar values of voltage and current because of the inherent symmetry in the motor; therefore, the voltage and current sums, which are just the average of these three values, are also similar. This simplifies the equation for apparent power.

$$V_{avg} \cong V_1 \cong V_2 \cong V_3 . \quad (4)$$

$$I_{avg} \cong I_1 \cong I_2 \cong I_3 . \quad (5)$$

$$S = \frac{\sqrt{3}}{3} (V_1 I_1 + V_2 I_2 + V_3 I_3) = \frac{\sqrt{3}}{3} (3(V_{avg} I_{avg})) . \quad (6)$$

$$S = \sqrt{3} (V_{avg} I_{avg}) . \quad (7)$$

From the derivation of the apparent power, the power factor can be applied and the active power can be determined. In practicality, it might be difficult to measure or obtain a value for the power factor without a power analyzer or oscilloscope capable of also measuring current.

$$P_{in} = \lambda S = \lambda \sqrt{3} (V_{sum} I_{sum}) . \quad (8)$$

The motor's output power is then just the product of the torque (τ) and RPM (ω). It is important to note that for brushed motors, since there is only one winding phase, the load on a brushed motor does not fluctuate with rotation, and the power is simply the product of voltage and current. By dividing the output power by the input power, an estimate of the motor's efficiency (η) can be obtained.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\tau \omega}{\eta \sqrt{3} (V_{avg} I_{avg})} . \quad (9)$$

$$\eta = \frac{\tau \omega}{\eta \sqrt{3} (V_{avg} I_{avg})} . \quad (10)$$

One might expect power factor to change with RPM as the impedance of the motor is changing, but for the purposes of analysis, power factor can be assumed constant as the actual change in power factor with RPM is very small. A comparison of the motor theory with experiment for efficiency vs. RPM and output power are shown in figure 4.

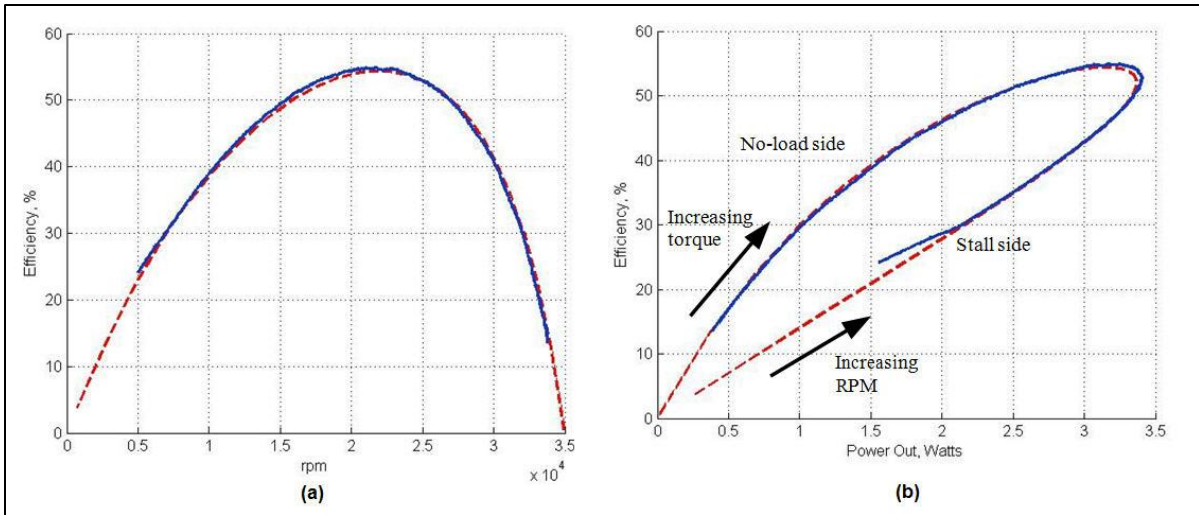


Figure 4. (a) Efficiency vs. RPM and (b) efficiency vs. power out showing the comparison between theory (red) and experiment (blue) for an AP03-7000 brushless motor.

Here it can be seen that the efficiency vs. output power forms a loop. This is due to the same output power being achieved at two pairs of torque and RPM occurring on either side of the peak power torque and RPM. These two sides of the loop are the stall side and no-load side. The stall side of the motor is the high torque and low RPM combination that corresponds to the lower efficiency, whereas, the low torque and high RPM or no-load side will have a higher efficiency for the same output power. For example, 2.6 millinewton-meters (mN-m) of torque at 10,000 RPM would be the same output power as 1 mN-m at 26,000 RPM, but the efficiency values are different, 39% and 51%, respectively. It is also interesting to note that in the experiment, the motor does not fully come back to zero power for reasons discussed earlier. This may be a characteristic of the speed controller not being able to properly regulate the speed of the motor when it is under a high loading condition and, therefore, the motor stalls.

Although the theory requires measured values as input variables, it shows good agreement with the experiment. The theory allows extrapolation of performance characteristics near the stall and no-load boundaries where the actual motors cannot be operated. Despite this limitation, motors are not typically operated very near to a stall or no-load condition.

2. Experimental Setup

In order to characterize the brushed and brushless motors, precise measurement of the torque, RPM, voltage, and current must be obtained simultaneously. To measure the torque and RPM, a Magtrol MicroDyne hysteresis dynamometer was used. The dynamometer is specifically designed for small motors and uses a magnetic brake to apply a torque load to the motor of up to 4 mN-m and allows rotational speeds up to 100,000 RPM. To obtain a power curve, a motor is installed into the dynamometer and the shafts connected. The motor is set at a specific input voltage and, for brushless motors, the input power is regulated by a speed controller. The no-load speed and torque are then recorded. Although no load is applied, there is a relatively small torque required to spin the rotor casing and optical encoder needed to measure the speed. Once the RPM reaches a steady state no-load speed, a magnetic brake is applied and the load on the motor is progressively increased, thus increasing the torque and decreasing the RPM of the motor. Once the RPM reaches a preset minimum value (to prevent the motor from stalling), the brake slowly releases the load on the motor until it had reached its free speed again. This ramp up/down method then allowed the dynamometer software to average the effects of hysteresis from dynamic loading during the two loading phases caused by angular acceleration on the motor. The load due to angular acceleration is seen when applying a load to the motor; the inertia of the rotor applies a slight resistive force countering the speed decrease. The opposite occurs when the resistive force is released and the rotor speed appears to “lag” behind as the rotor RPM increases.

Thus, a slight hysteresis is seen between the two loading phases. The magnitude of this hysteresis can be reduced by applying and releasing the braking force more slowly; however, the tests can become impractically long and running the motors under load for an extended period of time will cause them to heat up.

Measuring the voltage and current input to the brushed motors is straight forward as there is only a DC current. However, the brushless motors are driven by a three-phase power circuit from a motor controller and measuring the voltage and current requires relatively unique equipment. A Yokogawa WT-3000 precision three-phase power analyzer was used to measure the power from the speed controller going into the brushless motor. The power analyzer is an in-line pass through device that independently measures the voltage and current for up to three phases. The product of the voltage and current is the power for each phase at any instance, and the overall power going into the motor is the sum of the three phases as previously described. To regulate the power going into the speed controller a BK Precision programmable power supply was used and the current was limited to 2-A input in order to prevent the motors from drawing too much current and burning out.

The dynamometer has the ability to measure rotational speeds as high as 100,000 RPM and torques up to 4 mN-m with a torque measurement resolution better than 0.04 mN-m and a rotation rate measurement accuracy of 0.02% of the reading. The power analyzer's power measurement accuracy is 0.02% of full scale. Calibration of the power analyzer is performed internally. Known masses are hung at a prescribed moment arm to calibrate the dynamometer's integrated torque cell.

3. Brushed Motors

As already alluded to, there are two main classes of motors—brushed and brushless. Brushed motors use an internal electrical commutator (brushes) that reverse the polarity of the active wire coils as they pass magnets of a fixed polarity. Therefore, the electronics are contained in the rotor. Speed is simply controlled via DC voltage change, which is a great advantage relative to brushless motors that require a three-phase speed controller. Another advantage to brushed motors is that they have a low cost of construction. Furthermore, they can easily be made very small (<1 g).

3.1 Design and Operation

There are three main parts that can be found in any brushed motor—the stator, rotor, and commutator/brushes. The general construction of a brushed motor is illustrated in figure 5. The stator portion of the motor contains the permanent magnets. In larger brushed motors, the stator portion might have shunt, series, or compound coil wound stators. However, in small brushed motors permanent magnets are used because it is difficult to retain a high-strength magnetic field

with coils. This, coupled with the availability of high-field permanent magnets (e.g., neodymium magnets) has made permanent magnet stators the preferred choice for small motors (2). These magnets are arranged in polar pairs of alternating north-south configuration. Thus, there must always be an even number of magnets in any brushed motor with half having their south pole facing inward and the other half with an inward facing north pole. The rotor contains an armature wound with copper coils. When energized, one-half of the armature will have an electrically induced magnetic north pole that will attract to the south poled permanent magnet while the southern pole of the armature will attract to the north poled permanent magnet. This will cause the armature and connected axle to rotate toward equilibrium. As the armature approaches its magnetic equilibrium position, the wire coils' magnetic polarity is reversed via the electrical commutator and the rotor's inertia will carry it through toward a new equilibrium position.

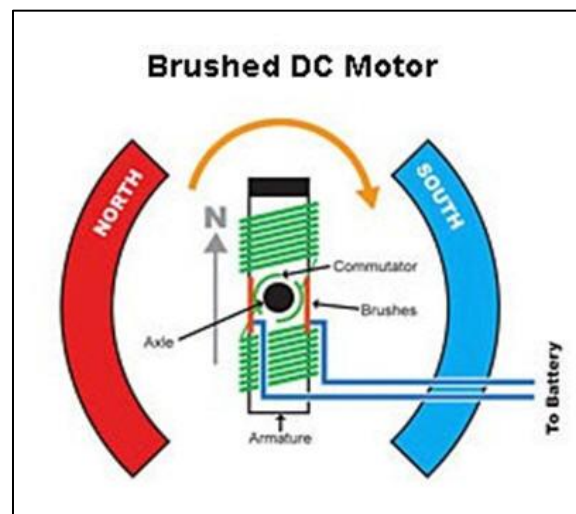


Figure 5. Diagram of a DC brushed motor (3).

There are, however, disadvantages to the brushed motor design that are primarily related to the use of brushes and commutator within the motor. Brushes will experience wear over time and eventually either the brushes or entire motor will need to be replaced (4). In addition to heat generated by the current flowing through the coils, brush arcing augments heat production. Not only does this brush arcing create heat, but it generates a high amount of electrical noise and electromagnetic interference (EMI). This can cause major problems for robotic applications that require radio communications or have sensitive electronic sensors on board as the electrical and EMI noise can interfere with both. Lastly, the contact friction associated with the brushes introduces motor torque load. This inefficiency grows with motor RPM, and the maximum angular velocity of the motor is limited by the increased friction of the brushes and commutator. Despite their disadvantages, brushed motors continue to be popular for UAV and UGV robotics applications.

3.2 Performance Characteristics

Brushed motors generally have a characteristically linear torque vs. RPM curve ideally with constant slope across all input voltages. Input voltage is the primary method for throttling the motor. An example torque and RPM curve for a brushed motor is shown in figure 6. Each line shows a motor input voltage with the lower right hand side representing the motor's "no-load" speed and the upper left hand side representing torque at max current draw. The jagged portion of the curves near zero RPM occurs as the motor approaches its stall torque. The no-load speed on these plots represents a non-braked value where the motor is only turning an optical shaft encoder and its own rotor and shaft, thus, torque is not truly zero. Some of this no-load torque also comes from the brushes inside the motor as the friction of the brushes and commutator increases with increasing speed. The limiting factor for these motors in terms of the attainable torque and RPM relates to the input power because only so much current can be pushed through the coils before the insulation burns off the wires and the coils short circuit. This is true of brushless motors as well.

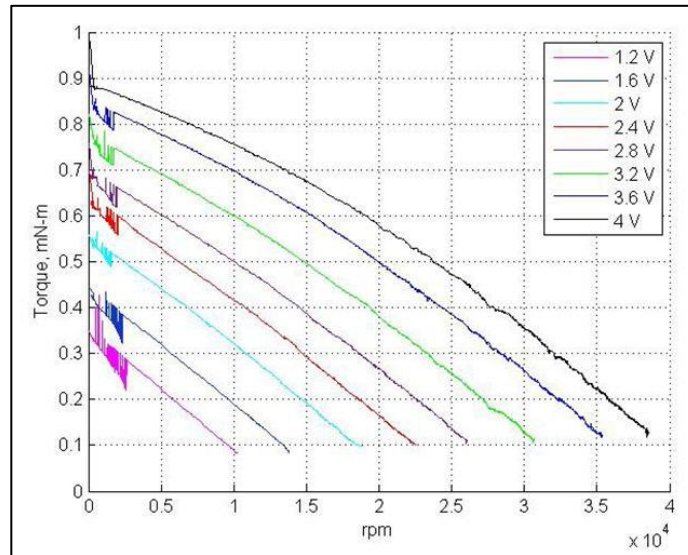


Figure 6. Torque vs. RPM for a SS7-1.7-1 brushed motor.

Figure 7 shows that as voltage increases the resulting output power increases. The overall power and efficiency of the motor, at a given voltage input, varies with position on the torque/RPM curve. The maximum efficiency does not occur at maximum power. The maximum power occurs at a low RPM, higher torque condition than the maximum efficiency.

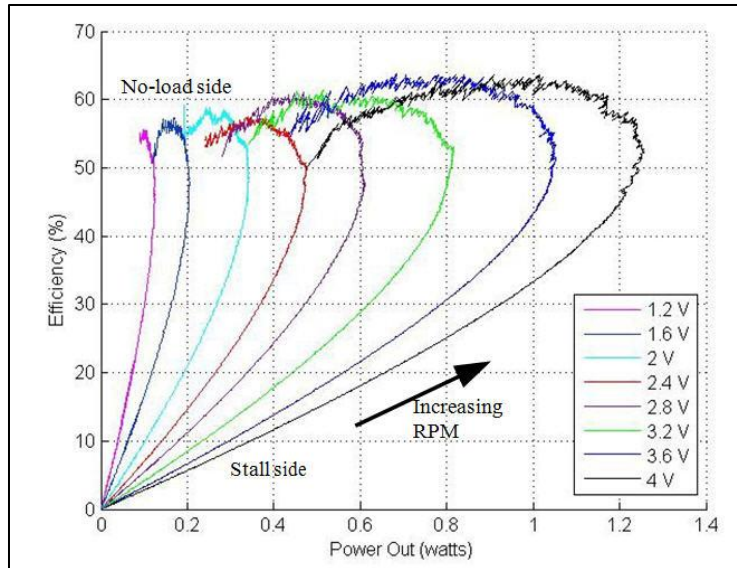


Figure 7. Efficiency vs. motor power output for SS7-1.7-1 brushed motor.

It is interesting to note that for brushed motors, near-peak efficiency occurs only over a very small range of RPM and then drops rather significantly at lower rotational rates shown in figure 8. These lower RPM values correspond to increasing values of torque. For direct drive applications, this suggests that brushed motors would be a good choice for use in high speed, low torque applications. This also suggests the system efficiency will suffer for operation off the design point. Of course an appropriate transmission can allow efficient motor operation while achieving a different desired torque and RPM combination for the required application.

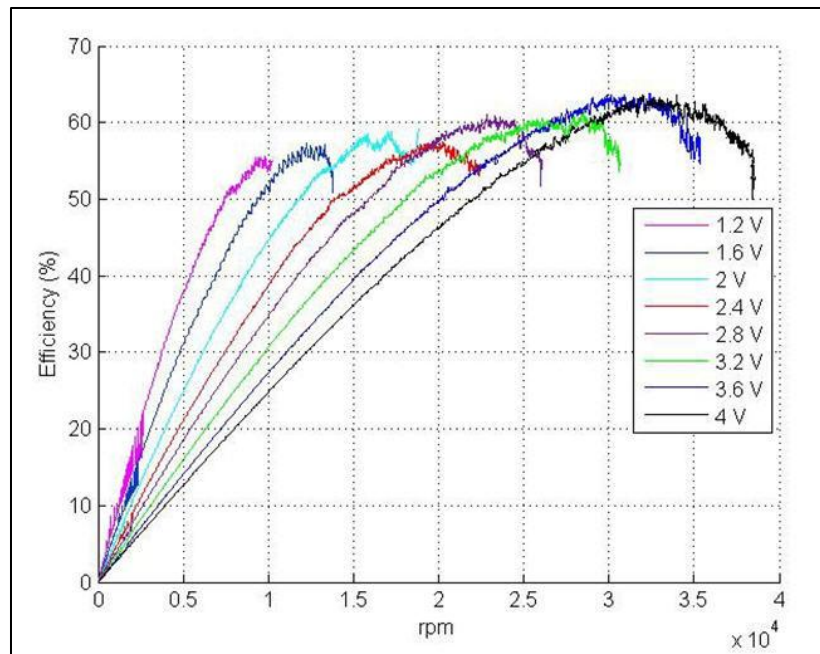


Figure 8. Efficiency vs. RPM for SS7-1.7-1 brushed motor.

4. Brushless DC Motors

The other main class of motors that are fast becoming the preferred choice among robotics designers is the DC brushless motor. These motors eliminate the need for a commutator and brushes and the electronic portion of the motor is now contained in the stator. This results in different advantages and disadvantages for brushless motors. Efficiency can be increased because there is no longer a voltage drop across the brushes and during commutation. Due to no brushes being present, internal friction is reduced and higher speeds can be attained. Lower electrical noise and reduced EMI are also added benefits. However, brushless motors are not without their disadvantages. The main disadvantage is the higher cost of control because a separate speed controller with much more complex electronics is needed. These speed controllers can often be as heavy and expensive as the motors themselves, which can be prohibitive for micro-air vehicle applications where weight is at a premium. They are also a secondary source of inefficiency that will be discussed later on in this report.

4.1 Design and Operation

Unlike brushed motors, brushless designs cannot simply be controlled via a DC voltage input. Due to lack of brushes, a circuit must control polarity switching. As with the brushed, there is a rotor and stator. However, the rotor, in this case, contains the permanent magnets and the stator the electromagnetic coils.

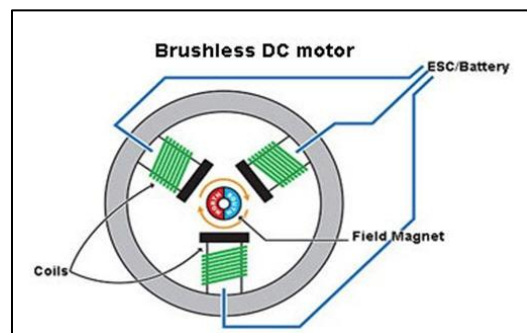


Figure 9. Diagram of a DC brushless motor (3).

For a three-phase design, the number of stators must always be multiples of three (5). To prevent achieving magnetic equilibrium, which would result in a motor that would not self-start, there are an even number of poles (permanent magnets) that cannot be a multiple of the number of stators. Further increasing the complexity is that there are a variety of winding styles. Two main circuits exist—the delta and star (wye) winding. The wye style generally provides higher torques and is easier to manufacture (5). This ease of manufacture is especially important for motors at this scale because most are hand wound and assembled unlike large motors that are precision wound by machines.

4.2 Brushless Speed Control

Due to their lack of commutator, brushless motors require dedicated speed control electronics. These speed controllers take a DC power source input as well as a pulse width modulated (PWM) signal and in turn, electrically phase the voltage and current going to each winding phase of the motor accordingly to regulate speed. A brushless motor operates through the application of a voltage over two of the three phases of the motor at any given time. This causes the stators associated with that phase to create an electric field. The permanent magnets then cause the rotor to move as the magnets are attracted to the electromagnetic coils just as with a brushed motor. This electronic phase shifting occurs over and over again with the rotor progressively “chasing” the magnetic field created by the sequentially active stators. The movement of the magnets over the coils also creates a back electromotive force (EMF) on the unenergized stator, which is sensed by the speed controller to monitor rotation rate. The current results, ideally, as sequential square waves. On top of the square wave, the back EMF creates a trapezoid pattern, shown in figure 10. The speed controller measures this back EMF and uses it to determine the speed of the motor. Thus, if the motor slows down due to an applied torque, the speed controller will adjust the phasing and magnitude of the voltage and provide the motor more power resulting in more current and power, so the rotor portion of the motor can still “chase” the signal. The back EMF and the speed are closely related through a value “KV,” a measure commonly provided by manufacturers that is the back EMF per rotational speed of the motor at no load. This is a constant for a particular motor and can be used to give an indication of the motor’s no-load RPM for a given input voltage. Some larger brushless motors have dedicated hall-effect sensors or shaft encoders for speed feedback. These sensors provide more precise measures of angular velocity than measuring back EMF; however, they require more hardware and increase the complexity of the speed controller itself and are, therefore, generally not used for small brushless motors.

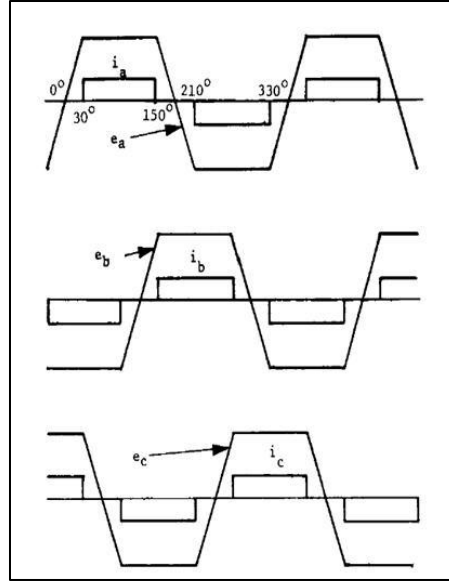


Figure 10. Phased current input and back EMF signals for a brushless motor (6).

4.3 Performance Characteristics

Unlike brushed motors, brushless motors have an additional control parameter that affects their performance, the PWM signal which throttles the motor. Therefore, both voltage and throttle setting have effects on the motor's power output. As was seen with brushed motors, torque vs. RPM curves are linear and parallel with applied voltage, which is how brushed motors are throttled. RPM on a brushless motor is traditionally controlled via PWM, and we can see that the torque vs. RPM curves are also nearly linear in figure 12. However, these lines are not parallel with throttle as was seen with variable voltage. This would suggest that operating at one half the throttle setting for a given voltage is not equivalent to operating at full throttle at one half the voltage. The impact of this will be discussed later in the report.

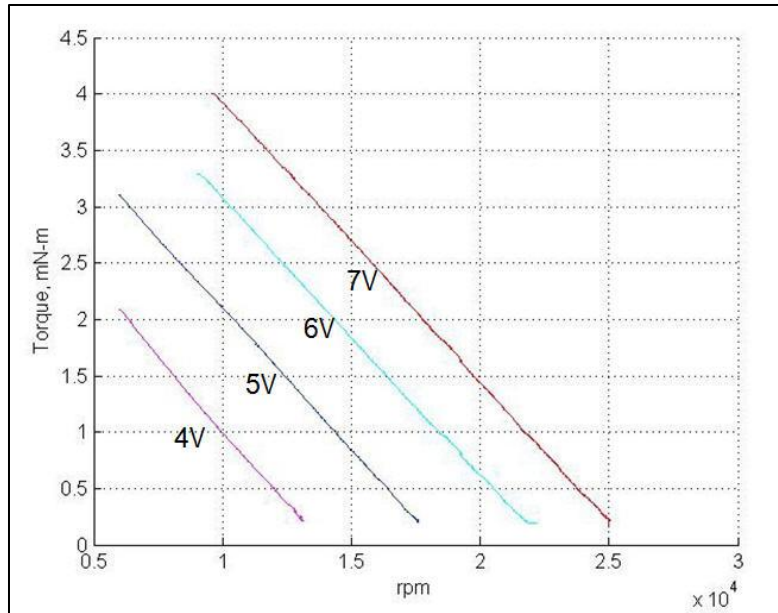


Figure 11. Torque vs. RPM at various voltages, 100% throttle for an A05-3700 brushless motor.

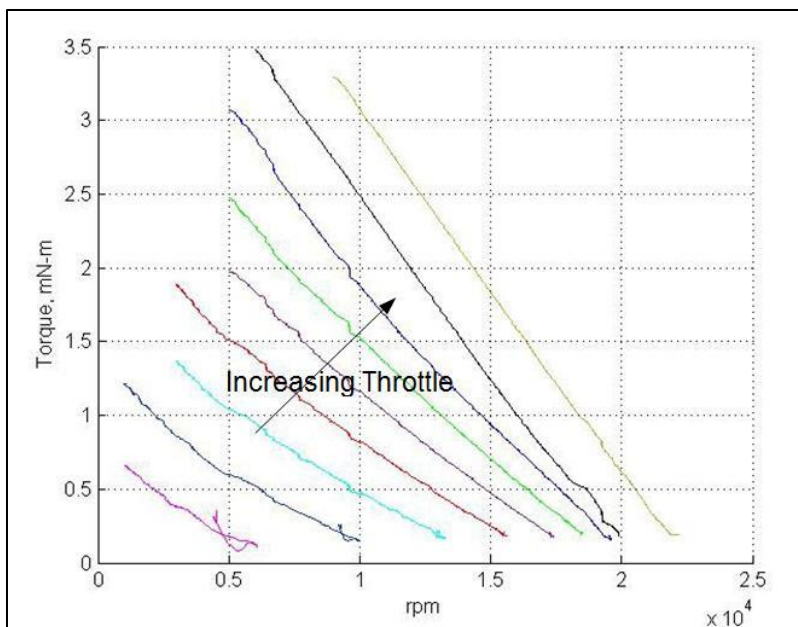


Figure 12. Torque vs. RPM at various throttle settings at 6 V input for an A05-3700 brushless motor.

Examining the efficiency vs. motor power out, it can also be seen that the brushless motor behaves differently than its brushed counterpart. Brushless motors can achieve higher rotational speeds than brushed motors due to their reduced friction (no brushes), but they cannot reach the true stall boundary. The brushless motors show a gentler drop from peak efficiency as compared

to their brushed counterparts. Fundamental behavior between brushed and brushless motors, however, is the same.

If the points of maximum efficiency for each of the different voltages at a constant throttle in figure 13a are connected, then the maximum efficiency remains relatively constant as shown in figure 14 for this and several other motors. In comparison, the points of maximum efficiency for a constant voltage at varying throttle settings are shown in figure 13b. These results show that in order to get the best efficiency from a brushless motor is to maintain 100% throttle and vary the voltage. Nearly all brushless motors show a gentle increase in overall efficiency with an increase in power output as a result of increasing input voltage; however, the relative changes are small, indicating that increasing the voltage further would not result in a substantial gain in efficiency.

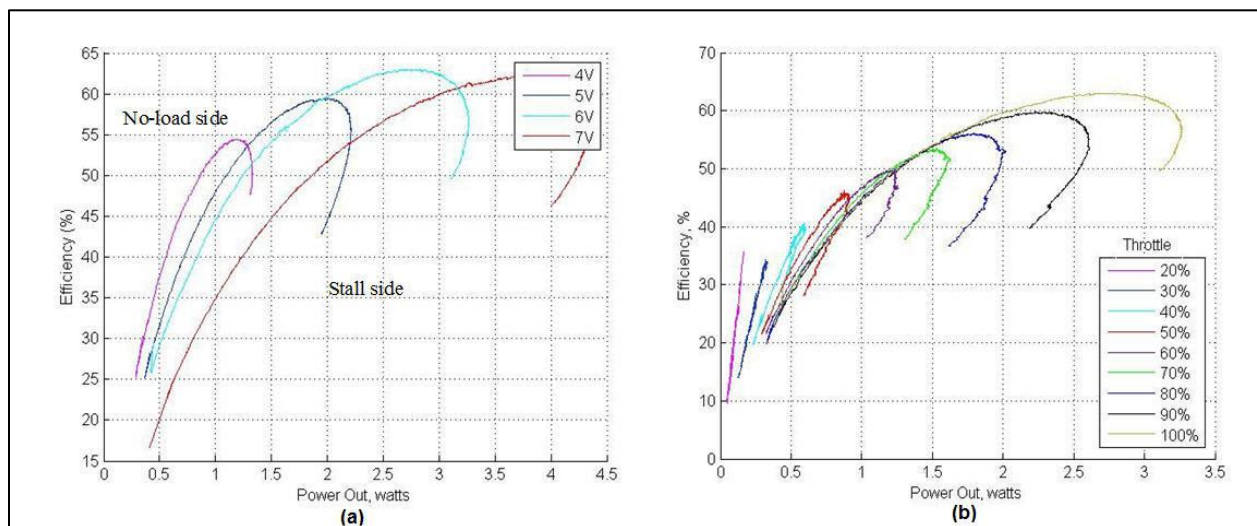


Figure 13. Efficiency vs. power out for A05-3700 at (a) 100% throttle and varying voltage and (b) constant voltage and varying throttle.

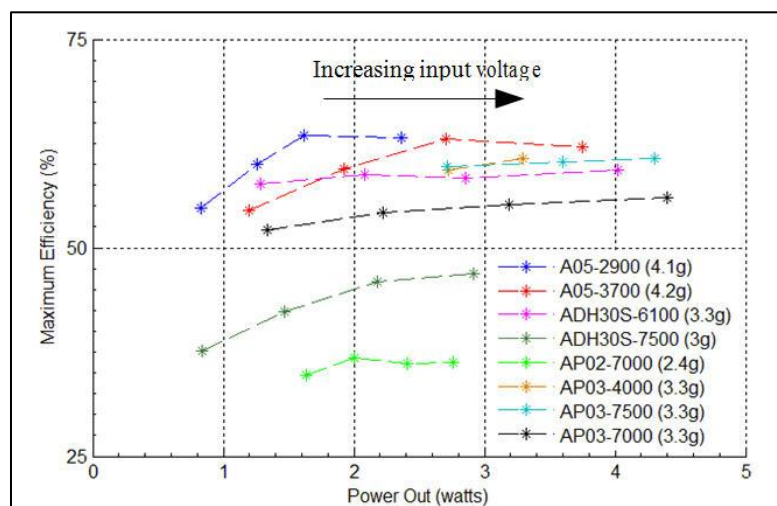


Figure 14. Maximum achievable efficiency vs. power out for various brushless motors.

By examining how the efficiency changes with RPM at different throttle settings, points of constant torque can be connected between the throttle setting variable RPM vs. torque curves. This is shown by the representative example in figure 15. This is particularly useful as a design tool that will be discussed later.

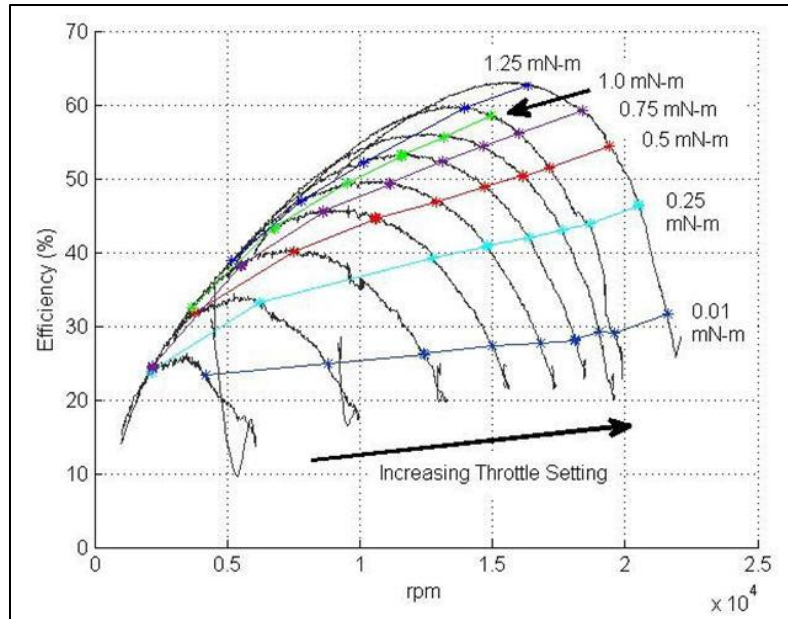


Figure 15. Efficiency vs. RPM with lines of constant torque for varying throttle at 6-V input voltage.

It can be seen that for a particular RPM, a higher torque results in increased efficiency. This is also true for a particular torque, where a higher RPM leads to increased efficiency. The peaks of the black parabolic curves constitute the maximum torque attainable at that particular RPM. If torque is increased further, RPM will decrease.

Referring back to figure 1, which shows the peak efficiency vs. power output for the representative set of brushless motors with their corresponding weights, it shows that there is a wide range of efficiencies and power outputs for the various brushless motors. Maximum efficiencies range from 37 to 63% with maximum power output ranging from 2.1 to 3.9 W. This wide range of efficiencies indicates that there is some sort of variability in the design of the motor that causes them to be less efficient. The parameters that most greatly affect efficiency still require extensive study.

5. Brushless Speed Controller Efficiency

Because the brushless motor requires the addition of a speed controller for operation, the speed controller becomes another source of loss. The speed controller's main purpose is to convert a

DC voltage into three-phase power for the motor. To do this, the speed controller uses a series of Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) and diodes to commutate the signal (5). This power switching between phases results in electrical circuit losses in the form of heat and, thus, the efficiency of the system is decreased. To obtain an estimate for the efficiency of the speed controller, experiments were performed where the efficiency was analyzed between the power input to the speed controller and the mechanical output power of the motor. These results were then compared to the efficiency of the stand alone motor and the remaining contribution was assumed to be efficiency of the speed controller. In all brushless motor tests, a Castle Creations Phoenix 6 speed controller was used. Figure 16 shows the comparison between the efficiency of the brushless motor itself, the combined efficiency of the motor and speed controller, and the resulting controller efficiency. The black line, which is the quotient of the combined efficiency (blue) and stand alone motor efficiency (red), represents the speed controller's efficiency.

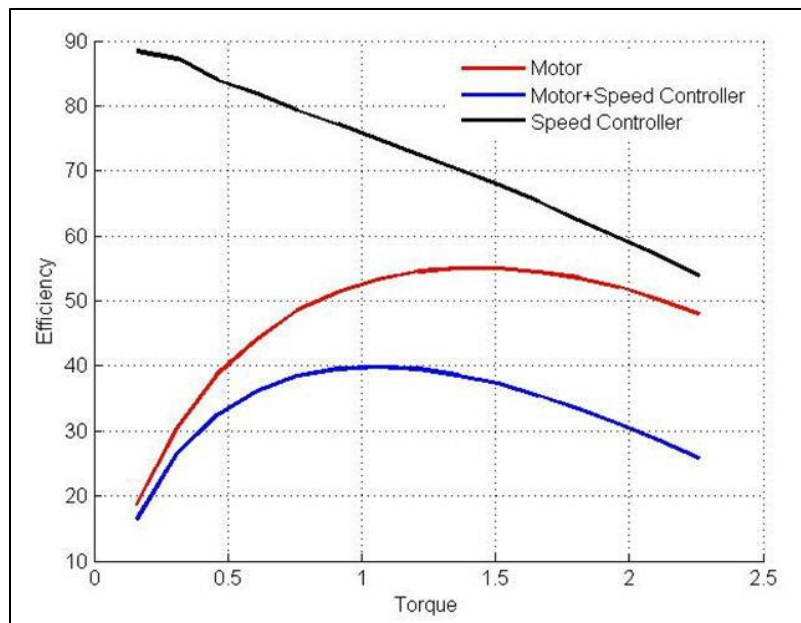


Figure 16. Comparison of efficiency values for an ADH30S-6100 brushless motor with a Castle Creations Phoenix 6 speed controller.

In order to identify the exact causal relationship resulting in the linear decay in efficiency, an extensive study on the design and performance of brushless speed controllers would need to be performed. It should also be noted that a brushed motor does not suffer from this extra loss in efficiency if a commutating speed controller is not used.

The speed controller exhibits a decrease in efficiency from nearly 90% efficient at the motor's no-load RPM, decreasing linearly to around 55% efficient at the maximum applied torque. To verify that these results were not an artifact of the chosen motor, the tests were repeated for a different motor made by a different manufacturer. Figure 17 shows similar results for an

ADH30S-6100 brushless motor and the same Castle Creations Phoenix 6 speed controller. This indicates that the linear decay in efficiency is roughly consistent across different motors. For these two motors, the addition of the speed controller efficiency shows the significant decrease in overall efficiency as shown in figure 18. Here it can be seen that this drop is significantly below the trend and that the entire trend would be shifted down for all the motors if their corresponding speed controller efficiencies were included. Other speed controllers may behave differently and, therefore, generalization about speed controller performance cannot be made. An independent study of speed controller efficiency will need to be carried out.

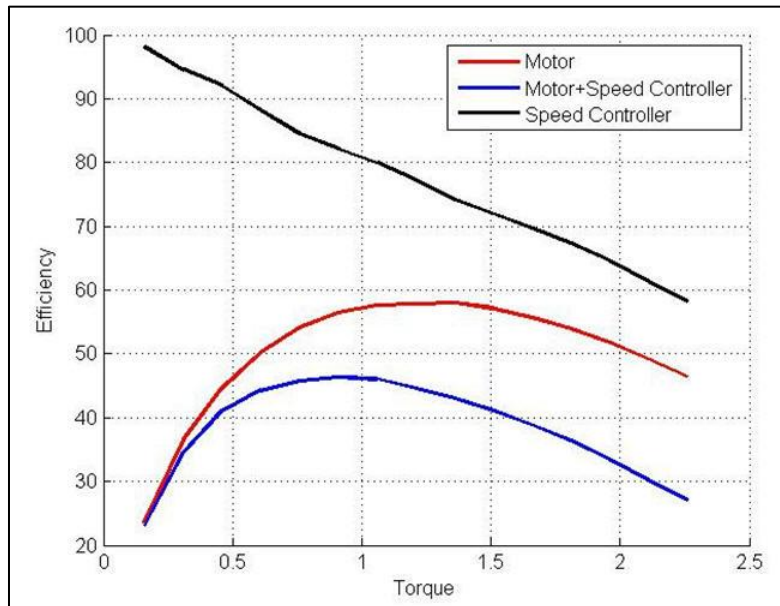


Figure 17. Comparison of efficiency values for an AP03-7000 brushless motor with a Castle Creations Phoenix 6 speed controller.

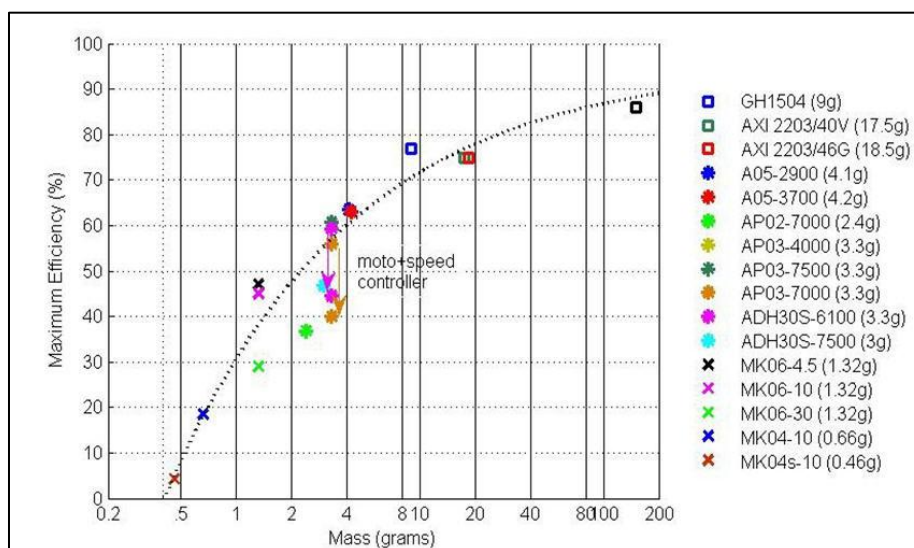


Figure 18. Motor efficiency with size showing effect of speed controller efficiency.

6. Motor Applications for Propulsion Systems

When designing a vehicle, whether it is a ground vehicle with a transmission system and wheels or tracks, or an aerial vehicle with a gearbox, rotors or a propeller, it is important to know the operating conditions of the propulsion system. Knowledge of the power required, power available, and the required torque and RPM are imperative for proper motor selection. In practice, most robotics engineers and designers tend to choose the motors that are most readily available. Often acquiring the highest KV is the adopted selection criteria because manufacturers will specify a KV. The KV indicates the expected rotational speed for a given input voltage under no-load conditions. This gives the designer no indication regarding the expected rotational speed and power expected or efficiency when the motor is under load. In this section, a process for selecting a motor is presented for a UAV application where thrust from a rotor is varied via RPM as is the case for a propeller.

6.1 Understanding the Power Requirements

Estimating the power requirements for a rotor is relatively straight forward because much work has been done to develop various analysis techniques for determining how torque and thrust change with RPM. Some of the most comprehensive techniques include computational fluid dynamic (CFD) studies or free wake analysis, but blade element momentum theory (BEMT) techniques show relatively good correlation with experiments (7, 8). A rotor's torque varies with the square of the RPM and the power varies with the cube. Using this information, we can gauge how the torque and power requirements change if the RPM is changed. An example rotor torque vs. RPM curve is plotted on an example motor curve in figure 19.

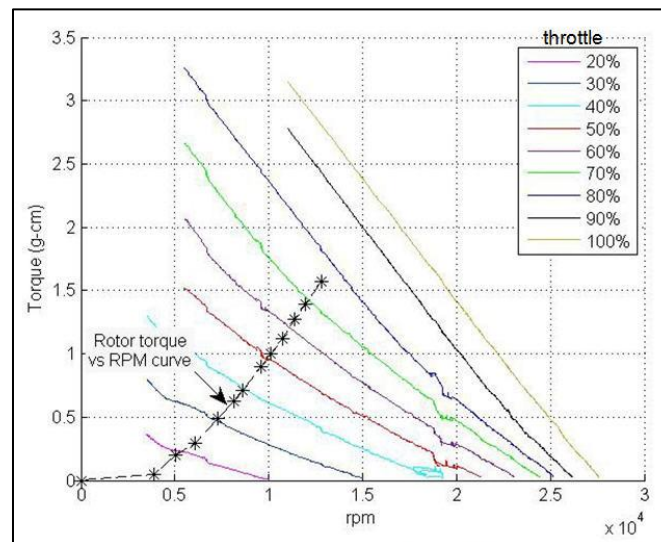


Figure 19. Torque vs. RPM curves plotted for an example motor with rotor data overlaid.

This plot is useful in determining if a particular motor is capable of spinning the rotor at a particular RPM, and also indicates at which throttle setting an RPM will be reached. However, this graph does not provide information on the efficiency of the motor at the various torques and rotational speeds. If the operating conditions are known, for example during hover 0.8 mN-m of torque at 10,000 RPM is required, then that point is known and can be plotted on the motor efficiency chart as shown in figure 20. This shows the efficiency of the motor at the rotor's operating point as it relates to the overall efficiency of the motor. In this example, the motor is an AP03-7500 KV motor and is running around 38% efficient. This is very poor relative to the possible 58% efficiency the motor is capable of reaching. When motor efficiency (38%) is combined with the efficiencies in the rotor (65%), speed controller (70%), and associated electronics (90%+), the overall system efficiency may be lower than 20%.

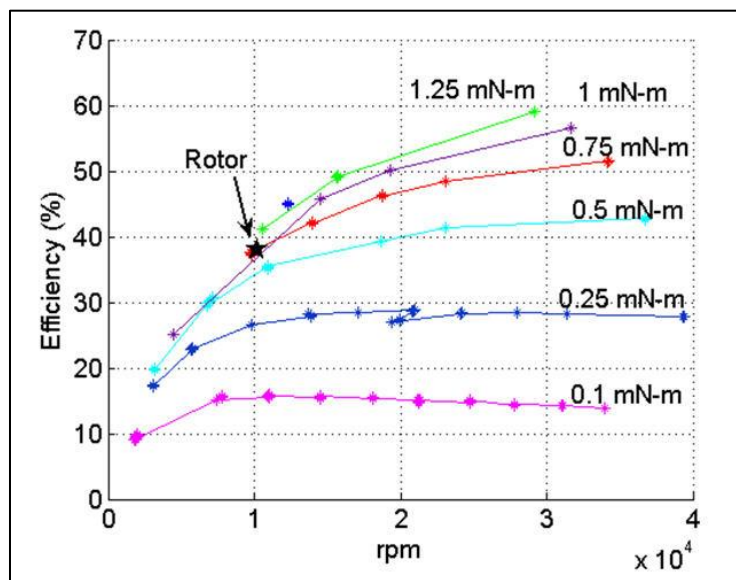


Figure 20. AP03-7500 KV efficiency vs. RPM chart with lines of constant torque.

Clearly the motor is capable of reaching much higher efficiencies, as high as 58%. However, for a rotor application, it may not be suitable to design a rotor to operate within that portion of the motor's capability as the highest efficiencies only occur at maximum throttle for brushless motors. Therefore, it may be beneficial to choose a different motor and attempt to move to a higher efficiency at the current rotor operating conditions. To illustrate this, if the same rotor as shown in figure 20 was used on an AP03-4000 KV motor, the motor would operate at around 45% efficiency shown in figure 21.

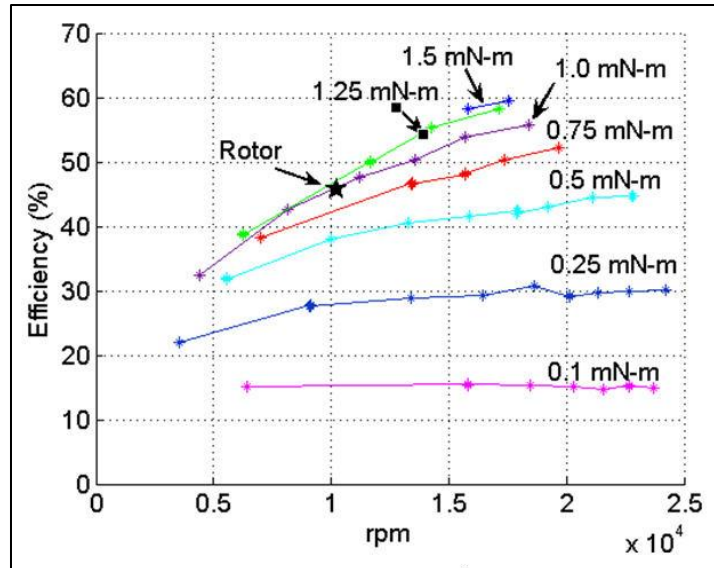


Figure 21. AP03-4000 KV efficiency vs. RPM chart with lines of constant torque.

By switching to a different motor, of the same size and weight of the same manufacturer, there is an 18% increase in efficiency. To the user, the only distinguishing characteristic is the manufacturer specified KV value, which in this case, is lower than the motor tested in the previous example. By testing the other brushless motors available, one can determine if there is another motor that may be even better suited for this particular application and attempt to increase efficiency further. In figure 22, it was found that a different model of motor is an even better choice. By using the A05-2900, a 45% increase in efficiency is predicted over the original. All of this is without changing any of the associated electronics or the rotor, which suggests that the efficiency could be increased even further.

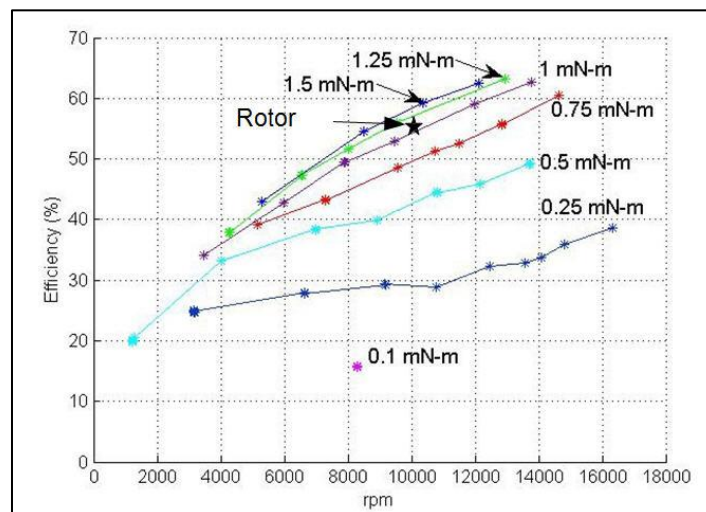


Figure 22. A05-2900 KV efficiency vs. RPM chart with lines of constant torque.

7. Conclusions and Future Work

Brushed and brushless motors are currently the preferred option for propulsion systems for micro-robotics applications. This technical report examined a representative sample of both brushed and brushless motors weighing <5 g. It was shown that motors at this scale have a wide range of efficiencies that are relatively low and efficiency decreases significantly with size. It is therefore important to properly analyze the particular propulsion system of interest by determining the operating torque and RPM, and correspondingly choosing the proper motor. By doing this, overall propulsion system efficiency can be increased so that the system's operating conditions are ideally matched to that of the motor. However, the electromechanical parameters that have an effect on efficiency have not been systematically varied and tested to date and should be an area of future study, nor have theoretical limits on performance been considered. It was also determined that operation of brushless motors at other than 100% throttle results in decreased efficiency and that throttling the motor by varying the voltage is a preferred method. Therefore, development of new types of speed controllers that operate at max PWM and vary the voltage instead may increase overall system efficiency. Lastly, it was found that brushless motor speed controllers are a significant source of inefficiency. Their efficiency drops linearly with increased motor load. Further analysis of other types of speed controllers should be performed in the future to determine if this is a phenomenon seen in all brushless speed controllers. In conclusion, by ideally matching motor loading conditions, using variable voltage speed control, and studying speed controller efficiencies, the endurance of vehicles can be increased, making them more mission capable and increasing their practicality.

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Appendix. Brushed and Brushless Motor Data

A.1 Brushed Motor Data

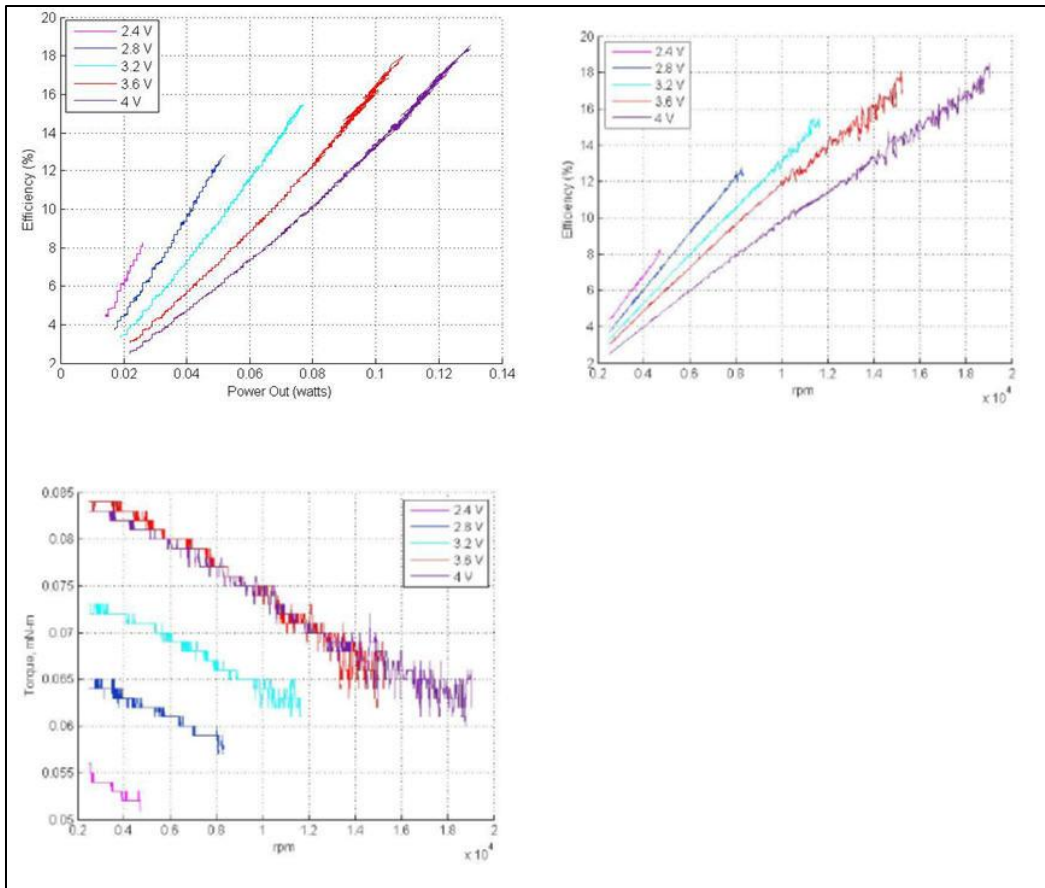


Figure A-1. MK04-10-1 (0.66 g).

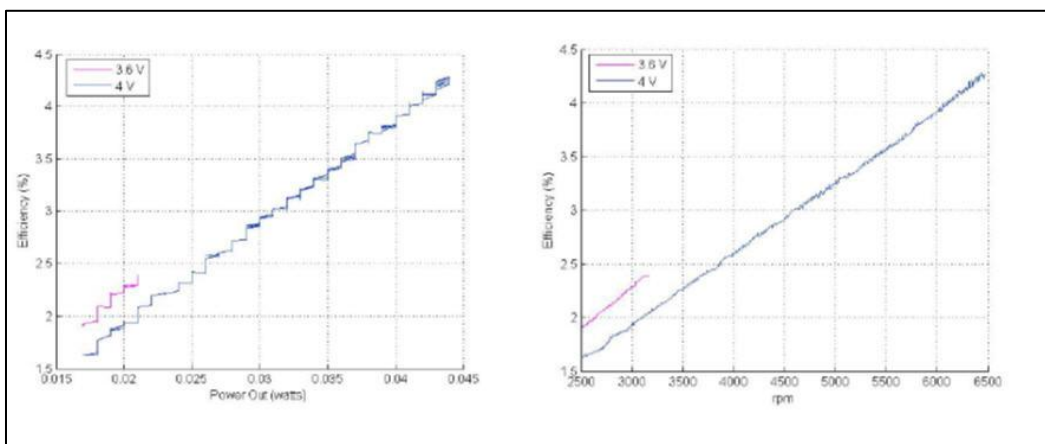


Figure A-2. MK04S-10-1 (0.46 g).

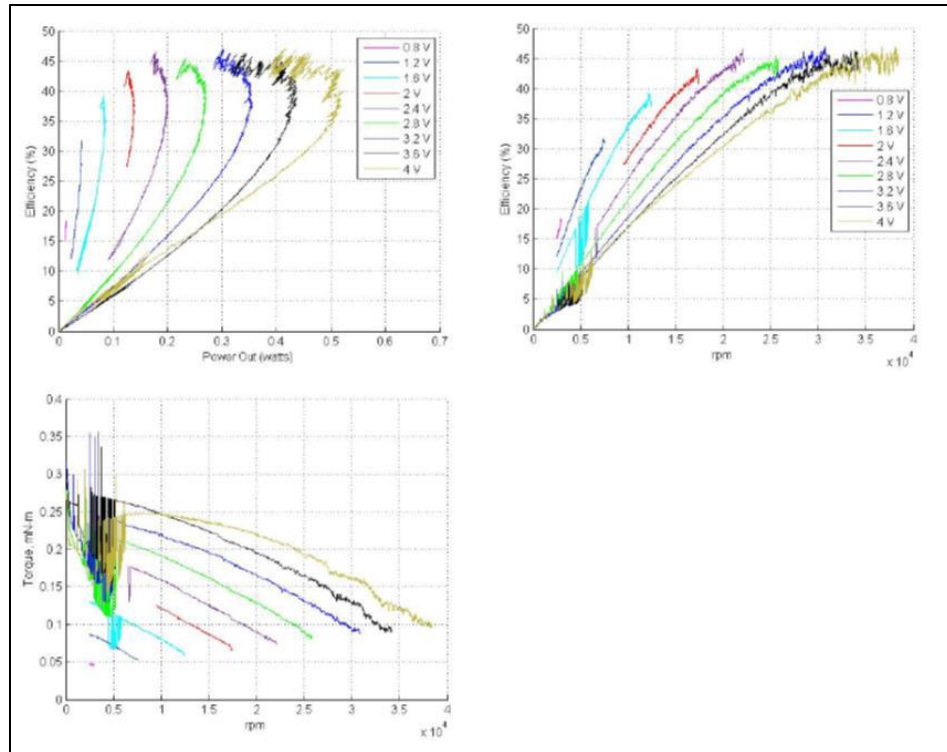


Figure A-3. MK06-4.5-1 (1.32 g).

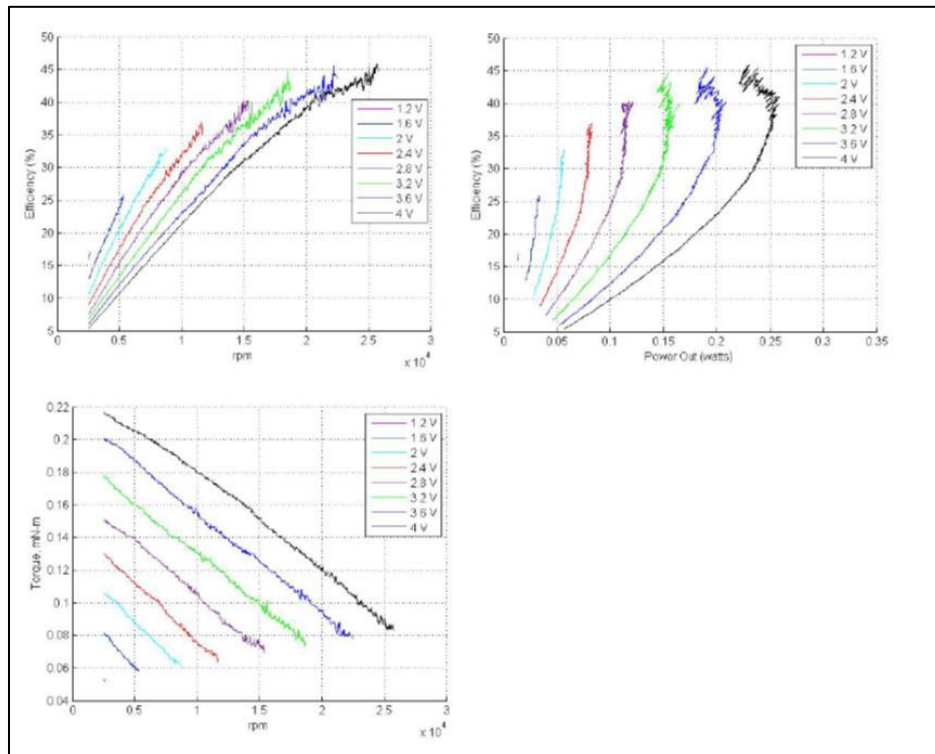


Figure A-4. MK06-10-1 (1.32 g).

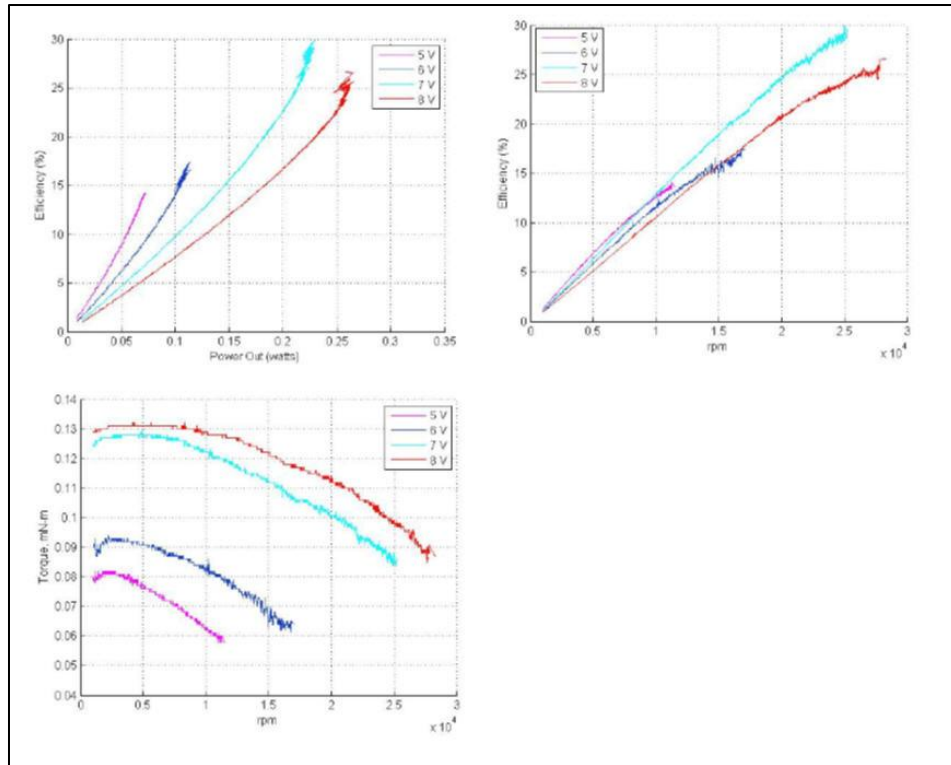


Figure A-5. MK06-30-1 (1.32 g).

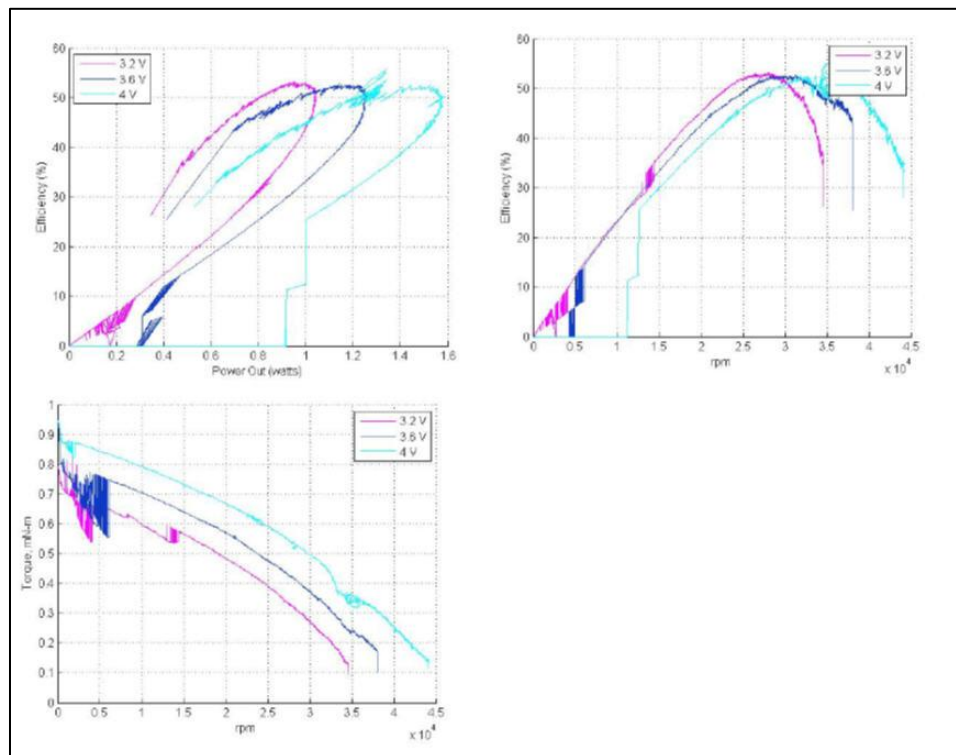


Figure A-6. SS7-1.1-1

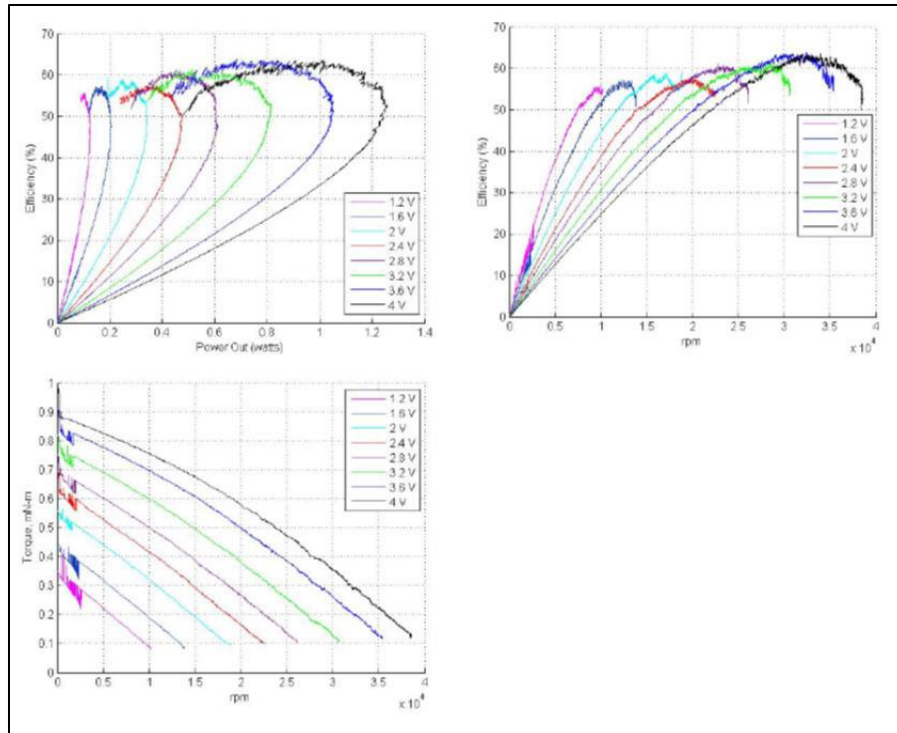


Figure A-7. SS7-1.7-1.

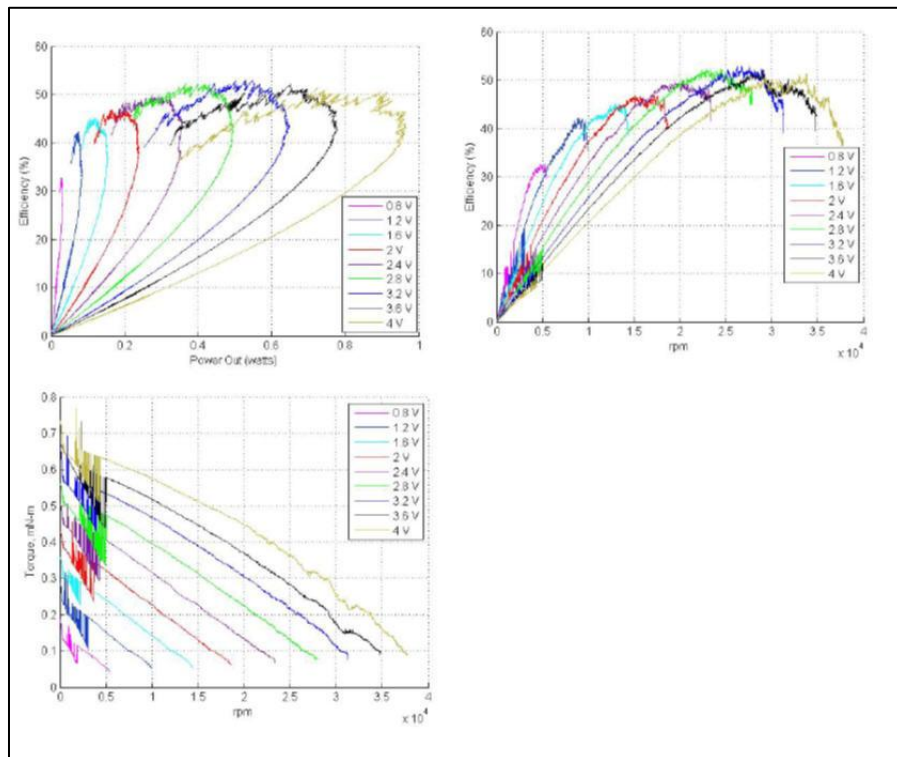


Figure A-8. SS7-2.3-1.

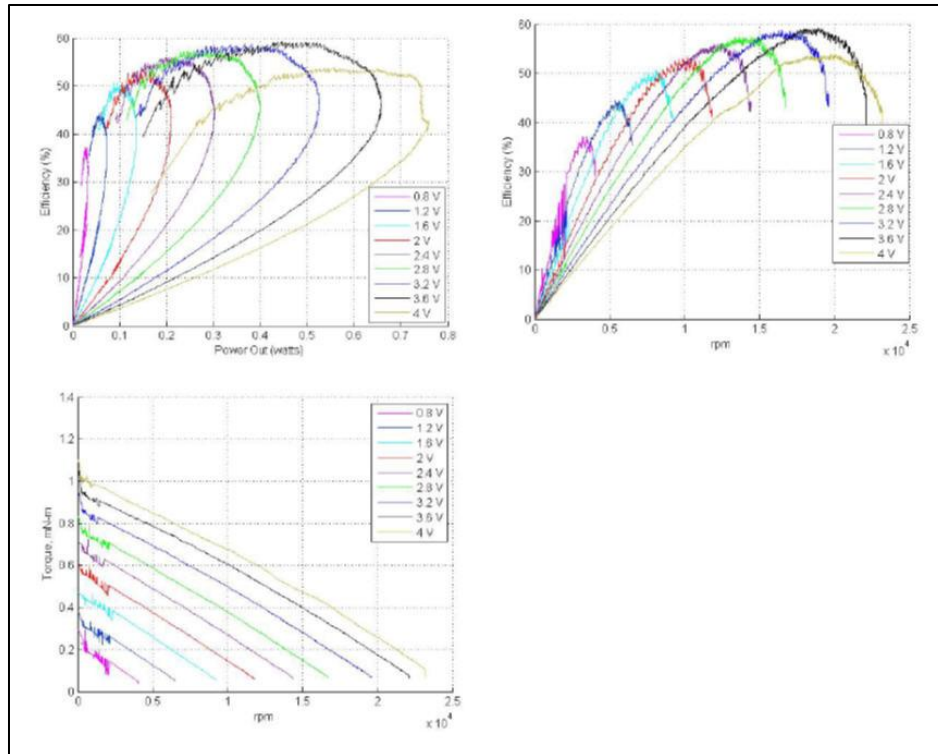


Figure A-9. SS7-3.3-1.

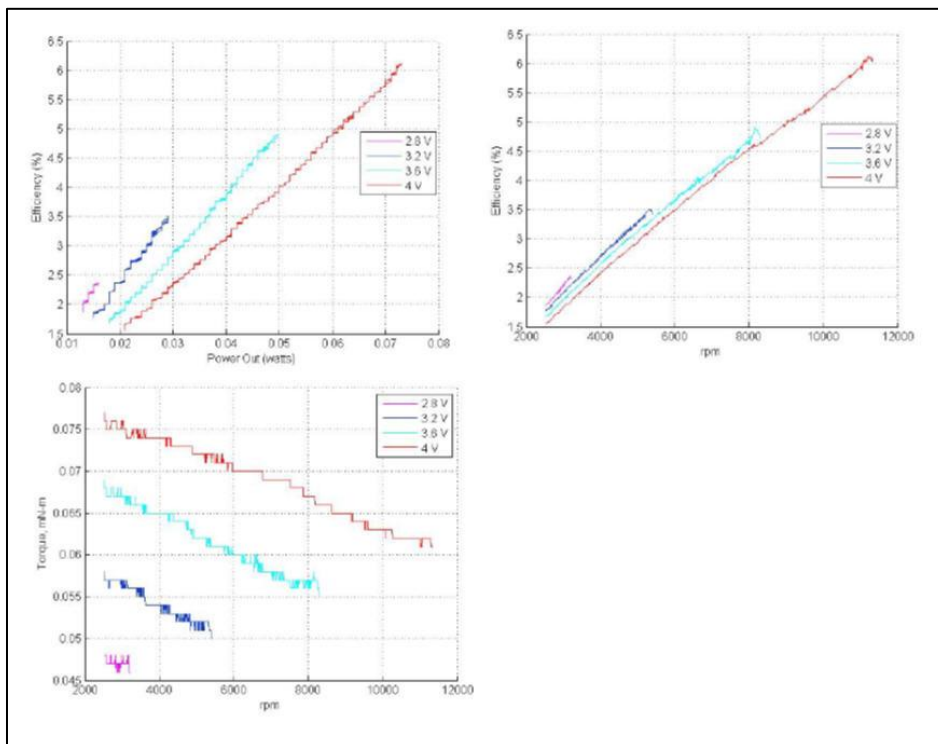


Figure A-10. Stan-1.

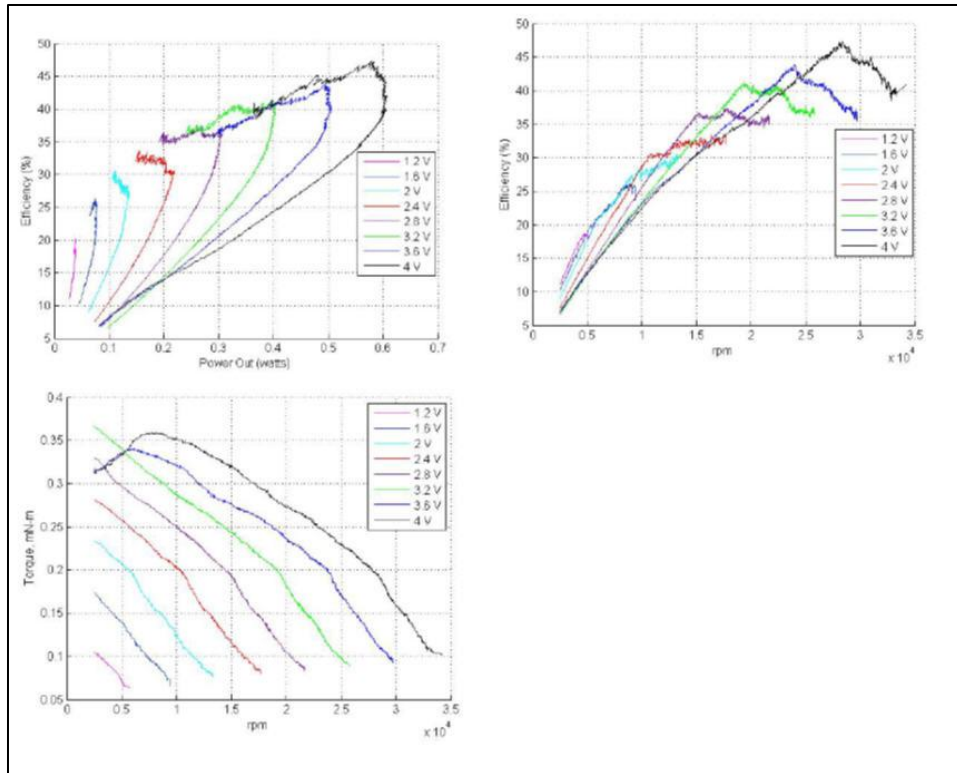


Figure A-11. VAMP-1.

A.2 Brushless Motor Data

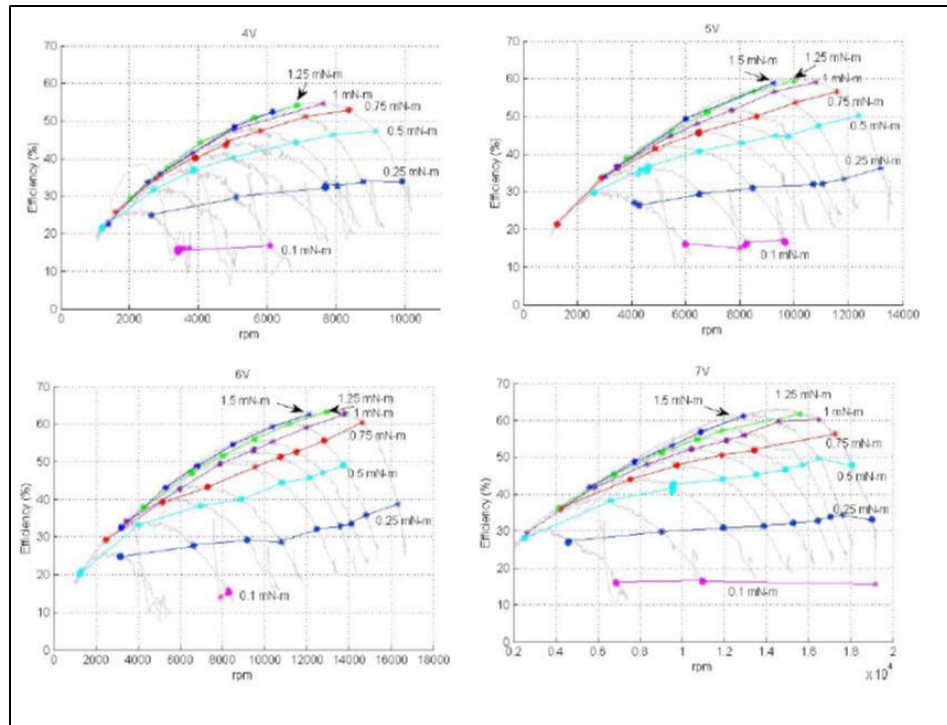


Figure A-12. A05-2900 (4.1 g).

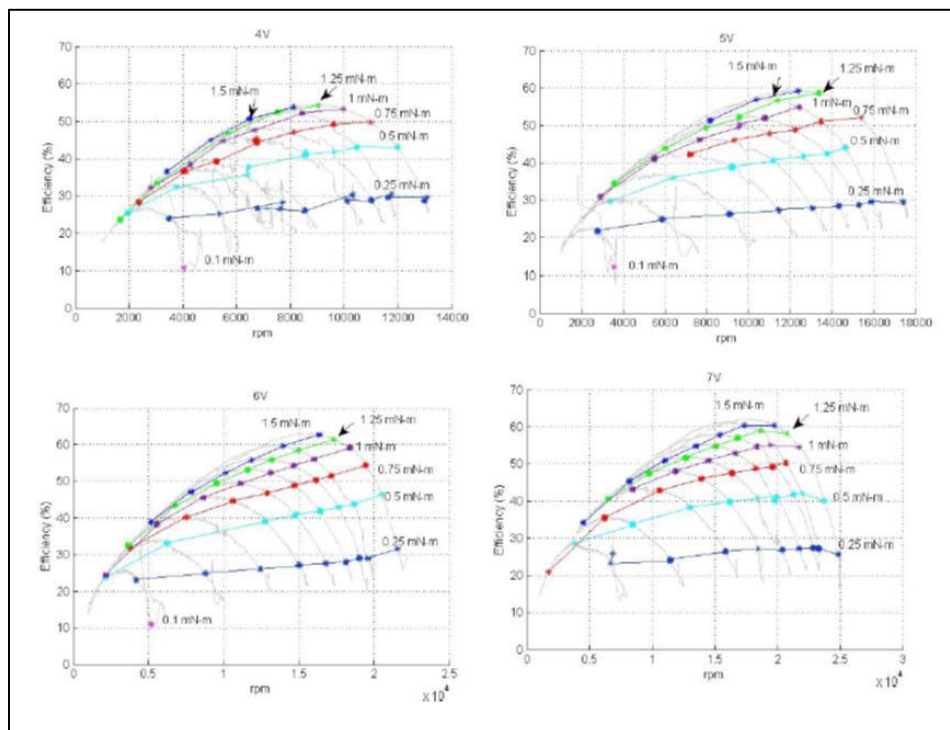


Figure A-13. A05-3700 (4.2 g).

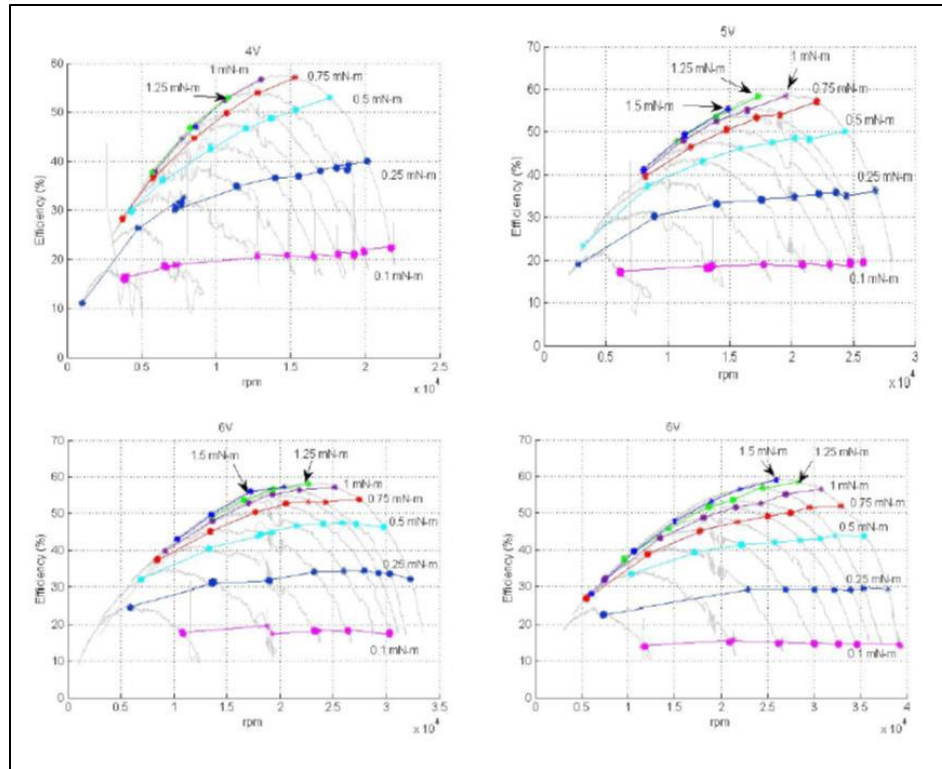


Figure A-14. ADH30S-6100 (3.3 g).

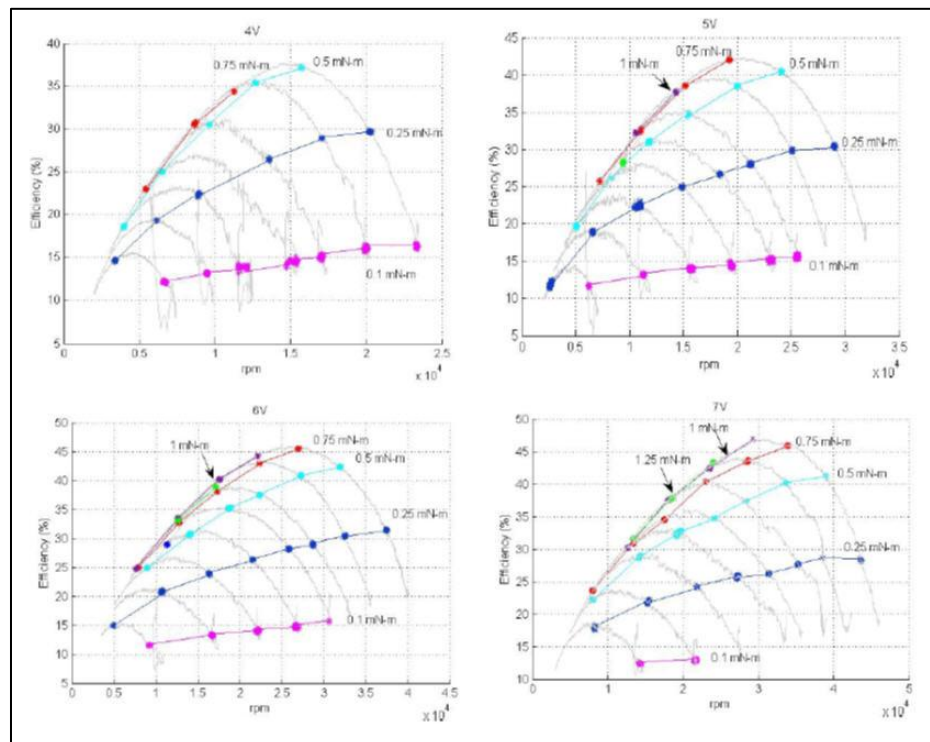


Figure A-15. ADH30S-7500 (3 g).

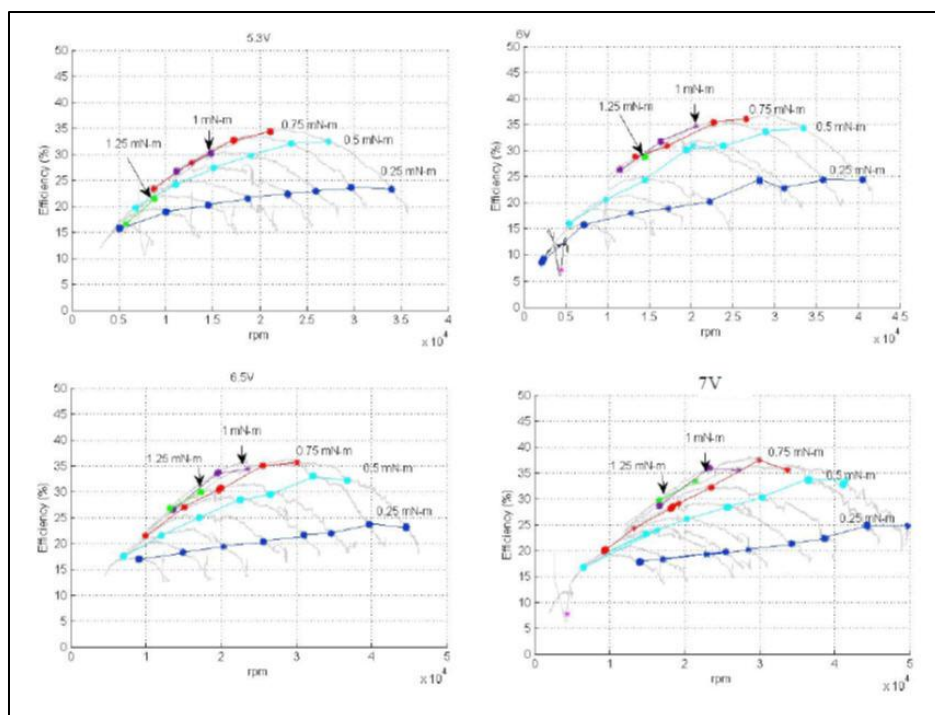


Figure A-16. AP02-7000 (2.4 g).

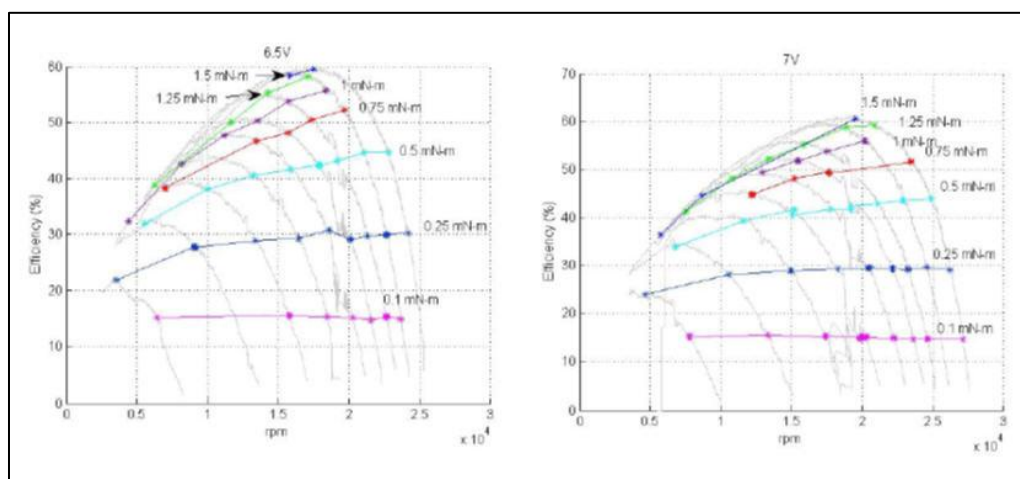


Figure A-17. AP03-4000 (3.3 g).

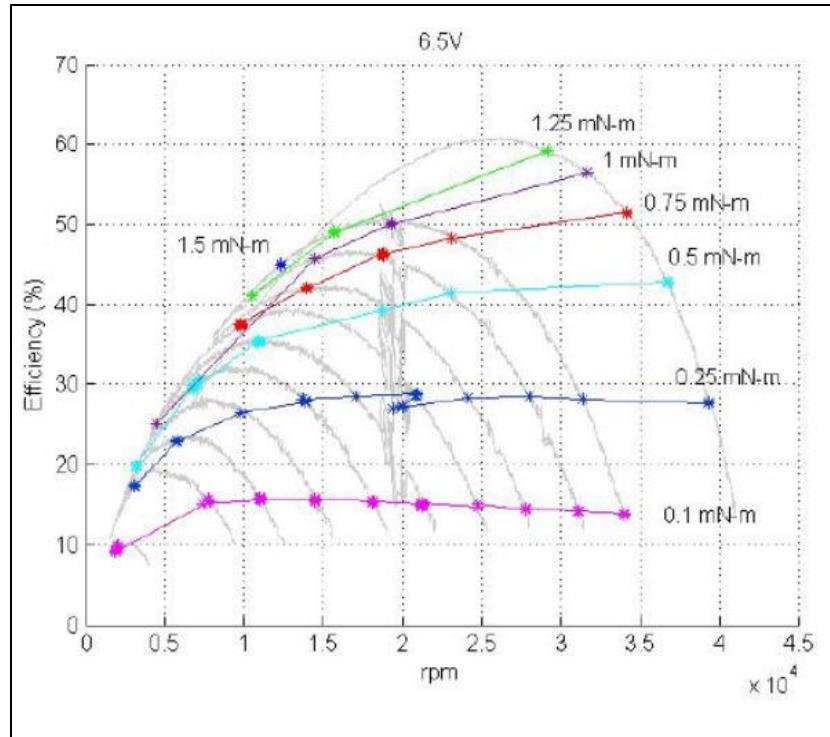


Figure A-18. AP03-7000 (3.3 g).

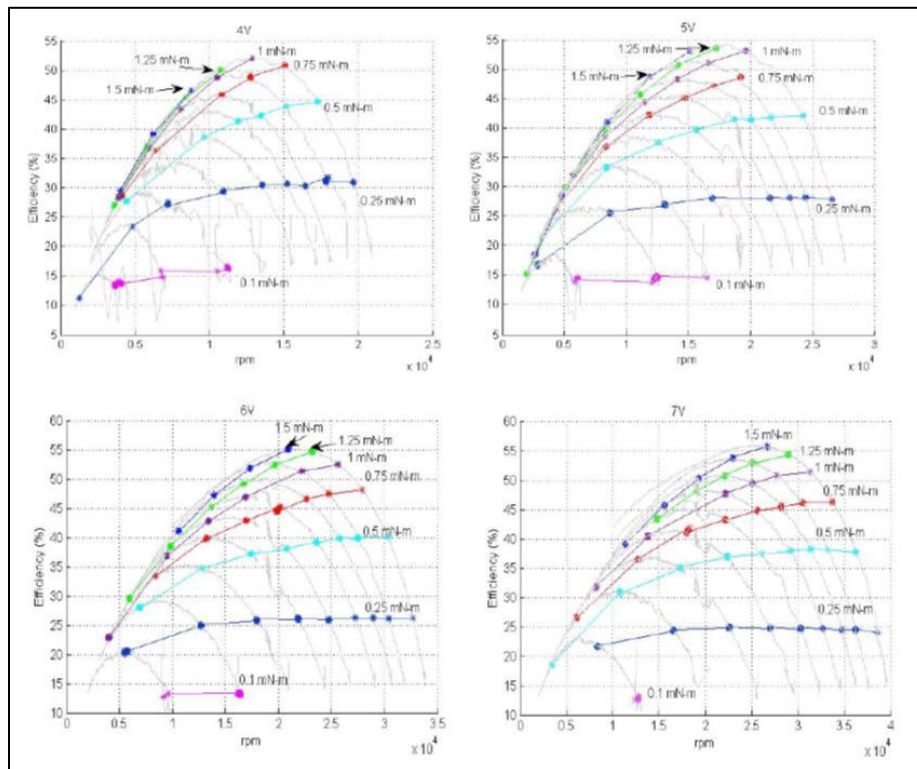


Figure A-19. AP03-7500 (3.3 g).

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List of Symbols, Abbreviations, and Acronyms

(η)	efficiency
(λ)	power factor
(τ)	torque
(ω)	rotational velocity
BEMT	blade element momentum theory
CFD	computational fluid dynamic
COTS	commercial off-the-shelf
DC	direct current
EMF	electromotive force
EMI	electromagnetic interference
g	gram
I	current
mm	millimeter
mN-m	millinewton-meter
MOSFETs	Metal-Oxide-Semiconductor Field-Effect Transistors
P	power
PWM	pulse width modulated
RMP	revolutions per minute
S	apparent power
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle
V	voltage

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