The Efficiency in Fractional HP Motors and Gearmotors

A Groschopp, Inc. White Paper

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I. INTRODUCTION

Efficiency can be a tricky topic for designers because it is very subjective. What is considered “energy efficient” for a particular designer may not be considered efficient by another designer. By examining motor and gearmotor efficiency from several different angles, it becomes clear that efficiency concerns affect, and are affected by, the many characteristics of an application. Because energy efficiency lies in the complete motion system rather than one specific component it’s important to explore the efficiencies and operating characteristics of various motors, gearboxes and controls and properly size the components to work optimally within the application. The variability in gearmotor components causes some designers to assume that the higher the efficiency the better suited a motor is for an application. As a general rule, energy efficient motors are an excellent choice but it is important to consider the trade- offs of efficiency as well. With several simple formulas designers can easily evaluate system and operating costs while ensuring efficiency and design requirements are met. A deeper look at the effects of efficiency will assist designers in evaluating efficiency requirements and trade offs of an application.

II. IMPORTANCE OF EFFICIENCY

When discussing efficiency as it relates to fractional horsepower motors and gearmotors most engineers primarily think about how it relates to cost. While this relationship is important, efficiency is also closely tied with many other critical design considerations.

A. Costs

Many designers do not stop to consider the whole picture when it comes to purchase cost and efficiency. Often efficiency is only thought of in terms of energy use but efficiency also affects the purchase cost. Furthermore, there is an increased system cost related to powering a low efficiency motor. Almost every component of an electrical system must be sized based on current draw. Higher current requires the use of heavier wire gage, larger relays and other tradeoffs.

Step	Purpose	Equation
1	Calculate *input power*	Output Power ÷ Efficiency
2	Calculate annual *energy usage*	Hours per year X Input Power
3	Calculate annual *operating cost*	Electrical Rate X Energy Usage

Table 1: Three Steps to Determine Operating Costs

There are three major steps to determine operating costs (Table 1). First, use system efficiency and required output power to calculate input power. Next, multiply the hours per year and input power to establish the energy usage. Finally, the energy usage and electrical rate are used to calculate the annual operating cost. For example, consider a ½ hp motor (373 W) that is 70% efficient. This would require an input power of 533 W. If this motor were to be run 8 hours a day, 7 days a week, the total run time would equal 2,912 hrs. The annual energy usage at this duty cycle would be 1,552 kWh. At an electrical rate of 12 cents/kWh, the annual operating cost would be $186.24 (Table 2).

Step	Purpose	Equation
1	Calculate *input power*	$\frac{373}{.7} \approx 533\text{W}$
2	Calculate annual *energy usage*	533 X 2,912 = 1,552kWh
3	Calculate annual *operating cost*	1,552kWh X $0.12 = $186.24

Table 2: An example Using Three Steps to Determine Operating Costs

Typically, when designing an application the motor's output power is based on what is needed in terms of application output requirements. Unfortunately, many designers fail to take the next step, which is to calculate the electrical power needed to drive the motor. This is required to ensure that the power supply is sufficient for the application. This will also give an idea of the efficiency needed for the motor. In an application that has current output limitations; pay special attention to the motor's efficiency to ensure a successful project.

B. General Design

It is important to review all aspects of the system that are affected by the efficiency of the components, because efficiency is related to all the parts. For example, efficiency can be affected by the size and weight of the motor. One of the primary factors driving motor size is heat dissipation. A motor's ability to dissipate enough heat is dependent in part on its surface area. Since heat is the primary form of energy loss in motors, increasing efficiency will decrease heat dissipation and therefore may allow the use of a smaller motor.

C. Environment

The final factor to take into account with motor efficiency is the environmental perspective. Frequently, only the environmental impact of the energy the motor uses is considered, however, the energy required to manufacture the motor should be assessed as well. In terms of energy usage, there are not many regulations that pertain directly to fractional horsepower motors. However, there are many regulations, such as the 1992 Energy Policy Act (EPAct) and Energy Independence and Security Act of 2007 (EISA), that apply to various end products in which fractional horsepower motors are used. Thus, efficiency must be accounted for in order to meet end product regulations.

III. COMPONENT EFFICIENCY

When analyzing the efficiency of a fractional horsepower motor, the efficiency of each component needs to be examined; from the input power source to the motor and the gearbox. One inefficient component will negatively impact the efficiency of the entire system.

A. Input Power Source

Although input power is not a true component, it is an important factor that affects the efficiency of a motor. Input power sources need to be considered in terms of limits on voltage and current. There are several possible input power sources to consider including line power, battery power, solar power, and motor controls. Line power needs to be evaluated for the current limit and provisions taken that adequate current can be supplied without tripping the breaker. Applications that use a battery for input power may be limited by the capacity of the battery (Amp-hours). Similarly, if solar panels are used for input power then the current is limited by the size and number of panels. Choosing a more efficient motor could allow a designer to reduce the number of panels required. Motor controls or drives should not be neglected in the evaluation of the system as their efficiency changes based on control type. In DC motors the key to a highly efficient control is the process by which the DC buss is generated. The rectification stage on the control will mean the difference between 85% efficient control and one running at 98% efficiency or higher.

B. Motor

There is a misconception that motor efficiency is simple; however, it is more complex than most designers realize. Contrary to the majority of published ratings, a motor's efficiency is not static, instead it varies with load. By definition, efficiency starts at zero with no load, ends with zero at its stall point and reaches a peak somewhere in the middle. Since efficiency is not constant through the operating range, there are tradeoffs when using a motor that is under-sized or over-sized. The following efficiency curve (Figure 1) demonstrates the variability of efficiency with load.

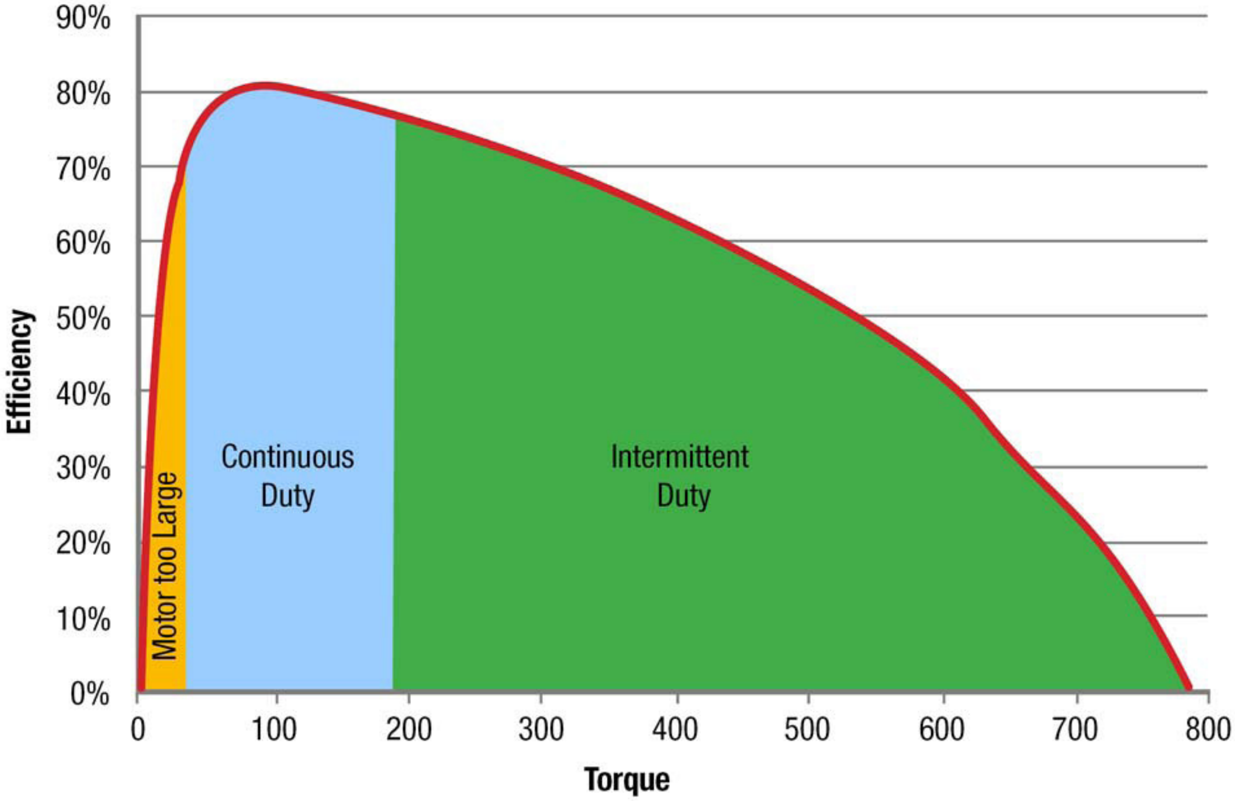


Figure 1: Variability of Efficiency with Load

In a well-designed motor the continuous duty rating should occur at or near peak efficiency, as indicated in blue. Most motors are designed to operate in the continuous duty area and published nameplate data is based on the specifications within this region. As shown on the curve, the motor's efficiency tails off gradually as the motor is overloaded and drops off sharply when the motor is under-loaded.

Motors can be run in the overloaded condition if the duty cycle is adjusted, as shown in green. For an application that runs periodically instead of continually this can be advantageous because it may allow for the use of a smaller motor. The loss of efficiency can be a concern but the shorter duty cycle often means that the total energy cost is minimal.

Though an intermittent duty cycle allows for the use of a smaller motor while maintaining good efficiency and temperature, such is not the case with an oversized motor or under-loaded motor, indicated in orange (Figure 1). Efficiency drops quickly as the load decreases and operating in this region should be avoided whenever possible. Not only is the efficiency reduced and energy cost increased, the motor is also larger than it needs to be. However, for applications with a variable load it may not be possible to avoid this condition during part of the cycle. When an application has a variable load, care must be taken to ensure that the motor does not overheat, as some types of motors will draw more current at a light load than at full load.

Because efficiency is not constant through the operating range, there are tradeoffs when using a motor that is under-sized or over-sized. To illustrate this point, Table 3 compares three 90 VDC permanent magnet motors of different sizes. Both the efficiency and purchase price increase as the motor size increases. If these motors are used in an application where the load closely matches the motor's nameplate ratings the motor will run at the rated speed with the appropriate voltage applied.

If all three motors are used in an application suited for the 3-inch diameter motor it would mean the 2-inch motor would be undersized, and the 4-inch motor would be oversized. Both the largest and smallest motors would no longer operate at their peak efficiency. In fact, the smallest motor would burn up if operated continuously at this load. However, if the duty cycle is intermittent, the smaller motor could be more cost effective due to its small size even though it is less efficient than the 3-inch motor.

Size	Motor Weight	Nameplate Efficiency	Price	Amps	Application Load Efficiency
2" OD	4 lbs.	62%	$200	0.9	61%
3" OD	7 lbs.	75%	$275	0.7	75%
4" OD	17 lbs.	81%	$450	1.0	54%

Table 3: Motor Size Influences Purchase Price and Efficiency

On the surface it appears there is no reason to use the 4-inch motor in this application. The motor is larger, more expensive and less efficient than the appropriately sized 3-inch motor. However, the "bigger is better" concept is a common trap for designers. Many designers do not fully realize how much overall system performance is sacrificed when using an oversized motor. However, there are a few instances where it is justified. For example, there may be a need to have a "margin of safety" in the design, for an application that has occasional spikes in the load. Or if the required motor rating does not exist, a designer may need to choose the next available size. Because an undersized motor may overheat and fail, sometimes the only choice is to use the next larger size. Finally, if the motor will be running at high ambient operational temperatures (greater than 40°C) a larger motor should be used to create adequate surface area for heat dissipation. Designers need to be aware of these tradeoffs when choosing an oversized or undersized motor.

An additional rating to consider is the current draw of the motor. When comparing the current draw of each motor in Table 3, keep in mind all three motors are producing the same power, so the difference in amp draw highlights the impact of efficiency.

Ideally, a motor should run at its nameplate “rated” load, but occasionally there are good reasons to use an undersized or oversized motor. For those applications, designers need to look beyond the nameplate efficiency and be aware of the tradeoffs because efficiency changes with load. At first glance, by looking at nameplate efficiency it appears as though the four-inch motor in Table 3 costs an extra $175 for a motor that is 6% more efficient in comparison to the three-inch motor. However, by looking at the efficiency at the application load, it’s clear the 3-inch motor is more efficient and cost-effective.

C. Gearboxes (Speed Reducers)

Like motors, gearbox efficiency changes with the load but also with input speed. At low speeds, for example 50 RPM, lubricants can be pressed away from the gear face causing higher friction due to metal on metal contact. At high speeds, typically 5,000 RPM and up, some of the gearbox power is consumed to stir the lubricant, thus reducing efficiency. This is most commonly the case when using oil as the lubricant. Another factor affecting gearbox efficiency is the reducer ratio. Generally, as the ratio increases, the efficiency decreases. This is especially true when adding a gear stage, because there are more contact surfaces. Finally, gear type plays a significant role in determining the efficiency of the gearbox. Gear type often depends on the reducer configuration. For example, most right angle reducers use a worm type gear, which is much less efficient than the spur type gear that is used in most parallel shaft and planetary reducers.

There is a connection between gearbox efficiency, load, and gear life. A Gearbox Efficiency Curve (Figure 2) shows efficiency versus torque at a fixed speed and gives a clear picture of the relationship between efficiency, load, and gear life.

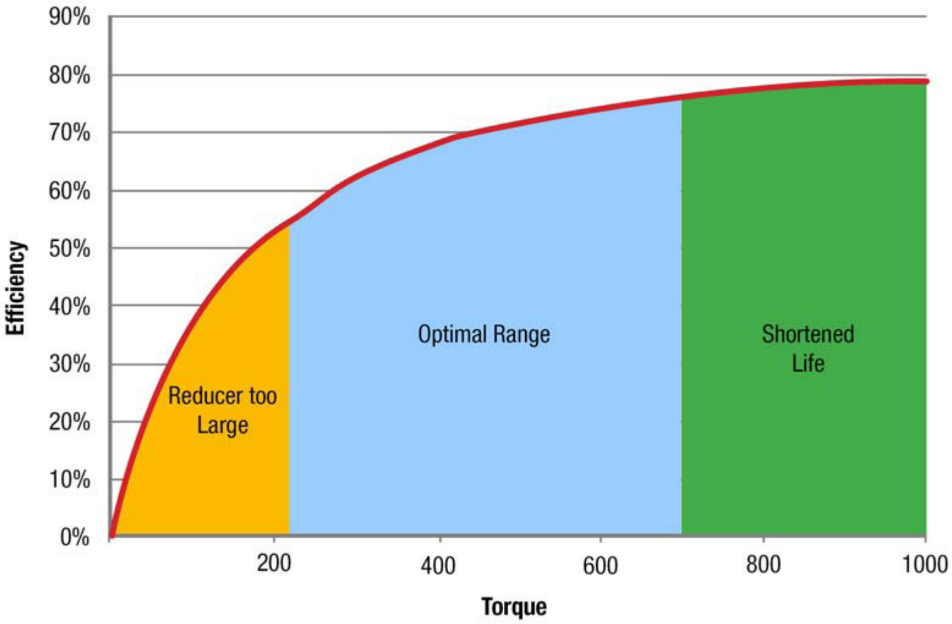


Figure 2: Gearbox Efficiency Curve

In the “Reducer Too Large” range (highlighted in orange), it is obvious that the efficiency of the gearbox falls off as the load decreases. An oversized reducer may be considered for some applications that see occasional spikes in load. However, over-sizing the gearbox could require an oversized motor to supply adequate input power. Thus, over-sizing a gearbox and working in the inefficient part of the curve is not a good approach.

Another portion of the curve to note is the “Shortened Life” range indicted in green. Interestingly, this is the region where the gearbox reaches its highest efficiency. Yet it is not the efficiency that prevents usage in this part of the curve, but the life of the gearbox. The gearbox will keep gaining efficiency as the load is increased, right up until the gear teeth break off. Operating in this area can be acceptable, provided care is taken to ensure the gearbox life will meet the life required for the application.

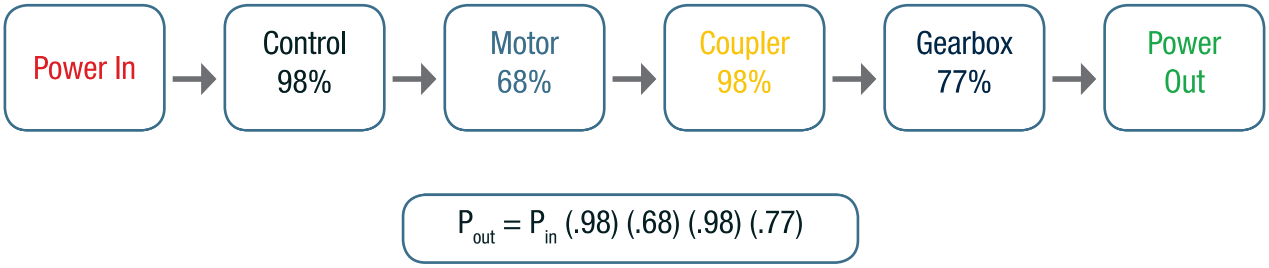
The region of the curve emphasized in blue is the “Optimal Range,” it balances efficiency with gear life. For most applications, this is where the reducer should run.

IV. SYSTEM EFFICIENCY

Once the efficiency of the motor and gearbox has been analyzed, the entire system needs to be examined by calculating system efficiency. Once the total system efficiency has been calculated each component must be evaluated to optimize cost.

A. Calculating System Efficiency

System efficiency is a simple calculation once the efficiency of each component is known (Figure 3). Every component needs to be included, not just the major ones. For example, even a coupler between a motor and reducer will have some component of loss and needs to be included in the calculation.



$$P_{out} = P_{in} (.98) (.68) (.98) (.77)$$

Figure 3: Calculating System Efficiency

System efficiency is a product of the individual component efficiencies. Calculating system efficiency is relatively simple, but obtaining the efficiency values is not always straightforward. This is further complicated by the fact that if the components are running at different load points than their ratings, the actual efficiency changes. In addition, some applications have multiple load points and consequently have multiple system efficiencies with which to be concerned. It may be important to calculate system efficiencies for a number of different operating conditions. For a given application, once system efficiency has been calculated, the design constraints can be revisited to determine if the system efficiency meets the application requirements.

B. Selecting the Best Motor and Gearbox Combination

One of the most important pieces of maximizing system efficiency is selecting the optimum motor-gearbox combination. While many designers choose standard, individual components and then mate them to make a gearmotor, an alternative option would be simply selecting a pre-engineered gearmotor. Previously it was noted that the most difficult part of determining system efficiency can be obtaining the efficiencies of the individual components, especially when they are not operating at their rated loads. Choosing a pre-engineered gearmotor can eliminate this problem. Not only have the manufacturer's engineers already determined the motor and reducer are well matched, they typically calculate and publish system efficiency. Second, pre-engineered gearmotors usually have a built-in interface between the components that already takes coupler efficiency losses into consideration when calculating the system efficiency.

Finally, it's important to ensure that motor and gearbox efficiencies are in a similar range to avoid mating an expensive, high efficiency motor with an inexpensive, poor efficiency reducer.

$$\text{Output Speed} = \frac{\text{Motor Speed}}{\text{Gearbox Ratio}}$$

Equation 1: Output Speed Calculation

Again, it is imperative to consider how the characteristics of one component in the system can affect the efficiency of another component. For example, if a designer is selecting a gearmotor and trying to meet a certain output speed, there are many combinations of motor speeds and reducer ratios that will accomplish the goal. Reducer efficiency goes up as the ratio goes down and affects the motor efficiency correspondingly. In contrast, gearmotor speed goes down as reducer ratio increases, this is a simple calculation because it does not include efficiency (Equation). If a low ratio gearbox is selected, a slow running motor will need to be matched with that gearbox. This motor will need to be larger in order to produce the torque needed, but may also be more efficient than a smaller, faster motor. Of course the larger motor will also be more expensive, so it comes back to evaluating efficiency versus cost.

V. GEARMOTOR COST

Designers need to be aware of how the efficiency of each component in a system affects the size and cost of the rest of the components. Table 4 illustrates this point, by evaluating whether a more efficient system is worth the cost. In some cases, the utility cost can justify upgrading to a more efficient system. *

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* For purposes of explanation, relative market prices for the gearmotors were used. Actual prices will vary depending on options, volume, and other application details.

1 HP						System Efficiency	Annual Operating Costs	
Motor	**Motor Efficiency**	**Reducer**	**Reducer Efficiency**	**Weight**	**Price**	**System Efficiency**	**100 hrs/ year**	**2000 hrs/ year**
PMDC	68%	RA	57%	25 lbs.	$300	38%	$18	$353
PMDC	73%	PS	80%	22 lbs.	$400	58%	$12	$232
BLDC	83%	RP	76%	19 lbs.	$600	63%	$11	$213

Table 4: The Relationship between Efficiency and Annual Operating Costs - 1 HP Gearmotor

Consider an application for a 1 hp right angle gearmotor. The top row shows the typical solution, a simple PMDC motor with a low cost right angle worm (RA) gearbox. While the efficiency of the individual components is acceptable, the system efficiency is relatively poor.

The second option shows the benefits that can be obtained using a parallel shaft (PS) gearbox instead of the right angle worm. While this is not always possible due to package or mounting restraints, the difference in efficiency shows that it is an option worth considering.

If the application specifications are such that only a right angle gearmotor will work, there are higher efficiency right angle options. The more expensive brushless motor (BLDC) coupled to a right angle planetary (RP) gearbox has highly attractive system efficiency, but with higher efficiency comes the highest initial cost. It is also important to note that the brushless motor would require a control, which is not included in this cost.

One of the most important factors related to the cost and efficiency of a motor or gearmotor is the expected annual operating cost. This cost may not be considered in the total cost evaluation of the design. Notice the final two columns in Table 4 include the annual operating cost and compare two cases, an intermittent duty application at 100 hours per year and a continuous application, running 8 hours per day, at 2,000 hours per year.

Duty cycle is the single most important factor in considering efficiency requirements. In applications with short duty cycles the power cost is minimal, reducing the effects of energy use. In those cases the initial cost of the motor is a much larger factor. Table 4 is a strong illustration of duty cycle relevancy. In the first case, at 100 hours per year there is simply no economic way to justify the more expensive gearmotors. But there may be other reasons to choose the higher efficiency design beyond cost. For example, instead of using a PMDC motor with the worm gearbox a designer could switch to a brushless motor with the planetary gearbox, thereby reducing gearmotor weight by 24%. Even though the current draw will be proportionally less with the higher efficiency motor, from an energy and operating cost perspective it is not necessarily the best choice to purchase the more expensive gearmotor.

This picture changes when evaluating these options for a continuous duty application running at 2,000 hours per year. Looking at the first two options in Table 4, there is a potential electricity costs savings of $121 per year by spending an extra $100 up front. It is not always easy for a designer to propose a more expensive motor to save energy but there are reasons for considering a more expensive, higher efficiency motor. For example, looking only at the energy savings, a brushless motor would not be chosen. However, the brushless motor will last two to three times as long as the PMDC and require less maintenance, which may create a more attractive, cost efficient option.

This argument falls apart if a smaller ¼ hp motor or gearmotor is used (Table 6). With a smaller motor the difference in energy cost is significantly less than the difference in purchase price, making energy cost a very small factor in the evaluation. As the motor gets smaller or as the running time gets shorter, the energy usage cost becomes much less important in selecting the gearmotor.

1/4 HP				System Efficiency	Annual Operating Costs	
Motor	**Reducer**	**Weight**	**Price**	**System**	**100 hrs/ year**	**2000 hrs/ year**
PMDC	RA	25 lbs.	$150	38%	$4	$88
PMDC	PS	22 lbs.	$200	58%	$3	$58
BLDC	RP	19 lbs.	$600	63%	$11	$213
BLDC	RA	20 lbs.	$250	48%	$3	$69

Table 6: The Relationship between Efficiency and Annual Operating Costs- 1/4 HP Gearmotor

Care must be taken in evaluating energy usage costs to ensure that efficiency needs are met. Designers need to evaluate how the efficiency of one component affects the size and cost of other components and avoid an efficiency mismatch by selecting components with similar efficiencies and costs.

VI. CONCLUSION

It is clear that energy efficiency is intertwined with nearly every characteristic of a system. The traits of one component in the system can affect the efficiency of other components. Careful consideration needs to be made regarding the way each component's efficiency affects the size and cost of the rest of the components in the system. The importance of efficiency varies with individual applications and the designer must evaluate the importance of efficiency in each new design project.

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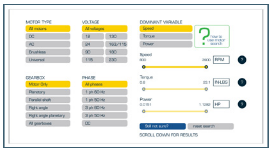

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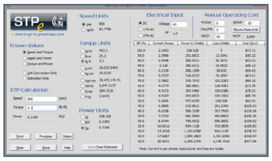

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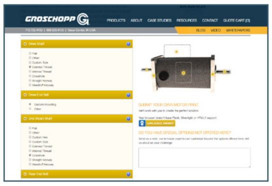

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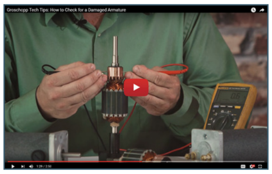

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