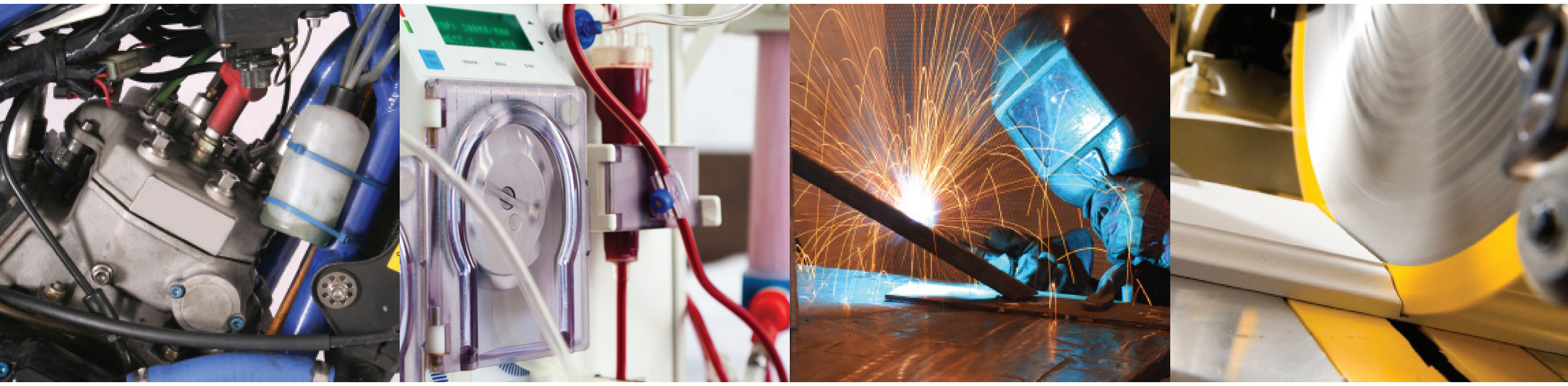
WHITEPAPER

Choosing the Right Permanent Magnet Motor for Your Application



Specialty Motors
SOLUTIONS IN MOTION

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Introduction

Choosing the right electric motor for a new product application can be a difficult problem with many conflicting requirements. Balancing and prioritizing power, torque, size, operating temperature and price is a very complex and often confusing puzzle. We sometimes joke that our typical customer wants a motor that requires no power to run, develops infinite torque, takes up no space and generates cold. Since motors that meet all these requirements are very difficult to produce, it's helpful to understand the key characteristics that drive motor design and how they relate to each other in terms of performance and cost.

An electric motor is simply a conversion device that changes electrical power to mechanical power. The byproduct of this conversion process is heat due to power loss which must be dissipated from the motor to keep it from burning up. In terms of an equation think of it as:

$$P_{in} = P_{loss} + P_{out}$$

Inspection of this equation brings us to the first basic concept of motor design which is that you'll never have a motor that generates more power out than you put into it or reaches 100% efficiency. In short, there's no free lunch and power out is always less than power in.

In order to focus the discussion, this paper will primarily address fractional horsepower permanent magnet motors with ratings of 1/10 HP to 2 HP. PMDC motors in this size range make up the vast majority of electrical motors sold in the multi-billion dollar electric motor industry. Many of the basic principles discussed here are universal but some may vary with motors that are much larger or much smaller than this size range.

Horsepower Isn't Enough

Many, if not most, of our customers make their first inquiry with a horsepower rating in mind for the motor they need. These may be based on motors they've seen in other applications or by engineer's intuition. The fact is, however, that horsepower alone isn't enough to define the operating requirements for a motor in a given application. A motor of a given horsepower rating may perform well under some load and speed conditions but fail on a grand scale under different circumstances that may appear very similar. For example, a motor that meets a sustained horsepower requirement at 2500 rpm may burn up and fail when trying to produce the same horsepower at 250 rpm. Four major factors define a motor design. These are: torque, power, rotational speed and thermal efficiency. In order to understand the relationship between these factors it's good to start with some basic concepts.

Torque

Torque is defined as the turning moment about a fixed point. It is most easily understood by looking at a simple lever.

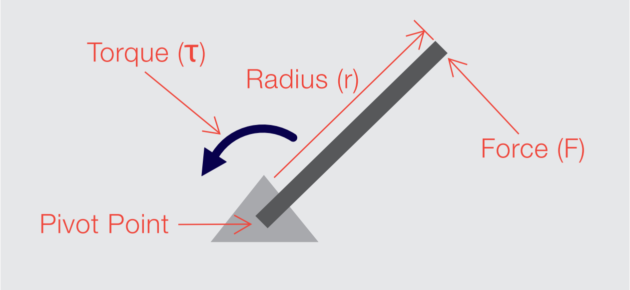

Figure 1 – Applying force to a lever produces torque

In this case torque is defined as the product of force multiplied by radius or:

$$\tau = F*r$$

Where τ *= torque, F = force and r = radius or moment arm*

Torque is usually expressed in terms of ounce-inches (oz-in) or Newton meters (Nm).

The torque rating of an electric motor torque is described as the maximum turning movent the motor can produce at its output shaft without overheating. The useful torque of a motor for a given application can vary over a broad range depending on a large number of complex variables including cooling, ambient temperature and the duty cycle. For this reason you will see peak torque ratings and continuous torque ratings which take some of these variables into account. The force that produces the torque in a permanent magnet (PM) motor is proportional to three factors including: total magnetic field strength, amount of current going into the motor and the windings (where the number of turns affects motor torque and wire diameter affects heat and efficiency).

Torque is a Major Cost Driver

Increasing torque (and what designer doesn't want more torque?) is a major cost driver in a motor's design because it is determined by three of the most expensive parts of the motor: magnets, frame size and copper magnet wire. Increasing magnetic field strength may lead to larger magnets or require more expensive magnets. Increasing the volume of copper windings may require a larger winding area which can also increase cost. Significantly increasing current requires larger diameter wire which can also require a larger motor or result in higher operating temperatures which can cause other design issues that increase cost. We'll address those issues in a later section.

Power

The definition of power starts with the concept of work. In linear terms work is simply force times distance or $W = Fd$. In the rotating world of electric motors work is defined as torque acting through angular displacement, represented by the symbol θ. Therefore $W = \tau\theta$. To return to the lever for a moment:

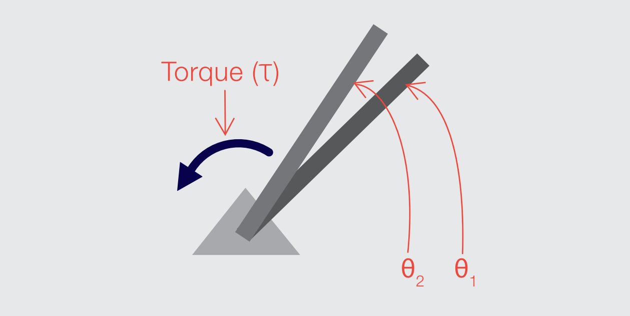

Figure 2 – Work is proportional to torque and displacement

It’s pretty easy to grasp the concept that more work is done by rotating through angle θ2 than angle θ1. Now that we have work nailed down we can turn to power which is defined as the rate at which work is done. In terms of an equation it is expressed as:

$$P = W/t \text{ (or) } P = \tau * \theta / t \text{ (or) } P = \tau * \omega$$

Where τ = torque, θ = angular displacement,
t = time and ω = angular velocity or θ/t

Given this relationship of torque, angular displacement and time it may be seen that the ultimate performance of a motor depends on the load it must move, the distance it moves the load and the time over which it moves through the angular displacement. It is also useful to note that torque is proportional to current and angular velocity is proportional to voltage so the power supply available will have a big impact on the ultimate motor design. For example, a motor may be perfectly capable of performing a desired task but if the controller is current limited it will not allow the motor to reach the desired torque of which it is capable.

Another issue that makes sizing a motor more difficult is that power, torque and rotational velocity are often expressed in different units that must be converted to a common basis. Power is typically defined as Horsepower (HP) or watts (W) but torque values can be expressed as *ft-lb*, *in-lb*, *oz-in* or Newton-meters. The basic equation $P = \tau * \omega$ defines power in watts as a function of, torque (τ) in Newton-meters and ω in radians per second. This equation works fine in the European world of metric units but in the real world a conversion factor (K) is necessary to convert to common units. This yields the following equation:

$$P_{out} = \tau * \omega * K$$

The following table provides a set of constants that can be used to make this calculation. For these values of K, ω is expressed in revolutions per minute in all cases. If you want to use these constants and have ω in radians per second you’ll have to do another conversion. If you’ve read this far you’re smart enough to figure that one out yourself.

Torque (τ) Units	K to Calculate Power in Watts (W)	K to Calculate Power in Horsepower (HP)
Oz-in	.0007395	9.913 x10^{-7}
N-m	.1047	1.404 x10^{-4}
Lb-in	.01183	1.586 x10^{-5}
Lb-ft	.1420	1.903 x10^{-4}

Example:

A motor that runs at 3500 RPM with 2.0 N-m of torque applied will be producing the following Power at the shaft.

P_{out} resulting in Watts:

$$P_{out} = (2.0 \text{ N-m}) * (3500 \text{ RPM}) * (.1047)$$

= 733 Watts

P_{out} resulting in Hp:

$$P_{out} = (2.0 \text{ N-m}) * (3500 \text{ RPM}) * (1.404 \text{ x10-4})$$

= .983 HP

Another handy conversion factor is: 1 HP = 746 W.

Heat Dissipation

As we discussed at the beginning, a DC motor is a device that converts electrical power into mechanical power. No converter is 100% efficient however and that's where the issue of heat comes in. The relationship between power in, power out and power losses can be seen in the following figure.

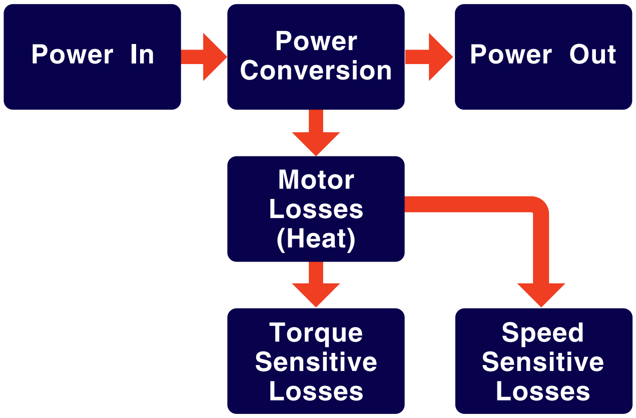

Figure 3 – Motor losses generate heat

Motor losses are a byproduct of the power conversion process. These losses are dissipated as heat in the motor and they come in two types. The first is proportional to torque and the second is related to speed. Torque losses are primarily caused by the resistance of the motor and are equal to I^2_aR where I is current and R is the terminal resistance of the motor. This relationship highlights the fact that heat losses are extremely sensitive to any increase in current. Speed sensitive losses are complex and interrelated and include such things as eddy currents, hysteresis, bearing friction and brush contacts. We won't analyze each of these phenomena but will simply make the point that they all vary with changing speeds and also depend on whether the motor is accelerating, decelerating or running steady state.

While these losses cause a temperature rise in the coils and brushes, the heat must be dissipated through the housing if the motor is to operate for a significant time without burning up which is why the operating environment must be carefully considered. The main question is: How much will the motor's environment or duty cycle help or hinder the heat dissipation process? For example, as a rule of thumb, a fan cooled motor will dissipate as much as four times the heat of a non-fan cooled motor which means a smaller motor can be used for the same application.

Some other factors to consider include:

- Heat sinking, such as mounting the motor to a large aluminum plate or machine frame improves thermal efficiency.
- Larger motors with more surface area will radiate more heat than a smaller motor.
- High ambient temperatures will reduce motor thermal efficiency and operating in cold environments will improve it.
- Motors mounted in enclosed spaces will be less efficient than motors used in areas with free air circulation or forced air flow.
- Intermittent duty, which allows cool-down time between operating cycles, will require a smaller motor.
- Dirty motors radiate less heat than clean motors. Dirt acts as an insulator and prevents heat dissipation.

Conclusion

In our culture electric motors are so common it's easy to think of them as an off-the-shelf commodity. It would seem that one motor with a given power rating should perform just as well as another in any given application. Given the actual complexity of the task even an experienced motor designer must frequently rely on intuition and experience when making design decisions. Variables can be extremely complex and are often in conflict with each other. Our purpose with this paper has been to make the reader aware of some of the factors and complexities that can affect motor size and cost. Taking these factors into account early in the design process will remove a lot of guess work, trial and error and result in a smoother design process with better performance, greater reliabilityand lower cost.

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About Specialty Motors

Specialty Motors (SMI) was established in 1971 to provide armature and field sets to leading companies such as KitchenAid and Whirlpool. Motor design and manufacturing followed shortly after, as SMI began producing several product lines for the U.S. military, as well as serving other industrial and commercial markets. In the early 1980's, in order to meet customer demand, larger scale motor manufacturing became the focus of SMI.

Today, Specialty Motors designs and manufactures custom fractional horsepower motors that are used in a wide range of applications including: pitching machines, treadmills, peristaltic medical pumps, buffers, polishers, grinders, and more. The company maintains an experienced and sophisticated engineering design and support team to serve its customers using AutoCAD design with electronic interface and rapid prototyping supported by a complete in house machine shop.

As a US manufacturer with a focus on short lead times and smaller volume runs, Specialty Motors also serves as the ideal inventory solution for its customers enabling them to carry less inventory than typically required with overseas vendors.

SMI has been a MIL I and MIL Q certified supplier for over twenty years.

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