12 Detailed Design

This chapter gathers many of the details that are spread throughout the rest of the text. In doing so, it forms a basis for design guidelines as well as for analyzing numerous designs using the tools and techniques presented in this text.

12.1 Design Guidelines

When faced with creating a new motor, there are many choices to be made. While some choices are relatively straightforward to make, others are not at all that clear. Moreover, the relative importance of many choices varies with the intended application. The following sections identify basic choices.

Rotor Type

The most fundamental consideration in the design of a brushless permanent magnet motor is rotor type, *i.e.*, surface permanent magnet or interior permanent magnet. Of these types, surface permanent magnet motors are more popular. Surface permanent magnet rotors have minimal reluctance torque and therefore have a much more linear torque versus current relationship. Moreover, the lack of reluctance torque generally leads to less torque ripple. On the other hand, surface permanent magnet rotors typically require magnets having an arc shaped cross section, which makes them more expensive. In addition, as diameter and speed increase, some means of retaining the magnets on the rotor must be employed, such as a nonmagnetic and nonconductive sleeve or wrap. In those cases where an electrically conductive sleeve is used, additional eddy current losses are induced in the sleeve, leading to diminished efficiency. Surface permanent magnet rotors are very commonly used in positioning applications.

Interior permanent magnet rotors provide a complement to surface permanent magnet rotors. They are typically mechanically robust since the magnets are buried within a rigid rotor structure. They inherently accept magnets having a rectangular cross section. They can exhibit significant reluctance torque, which can increase torque, but also add torque ripple and reduce torque linearity with respect to current. Interior permanent magnet rotors are more commonly used in velocity controlled applications and seldom used in positioning applications.

Number of Magnet Poles

The number of magnet poles N_m must be an even number so that the rotor has equal number of North and South poles facing the air gap. The number of magnet poles determines the fundamental electrical frequency according to (1.7)

$$f_e = \frac{N_m}{120} S \tag{1.7}$$

where S is the motor speed in rpm. The fundamental electrical frequency is the fundamental frequency of the motor back EMF and it is the frequency at which motor current must be generated. Therefore, as the number of magnet poles increases, the faster the motor must be commutated or driven for a given motor speed. Among other things, the higher the fundamental electrical frequency, the higher the core losses will be.

Since the PWM frequency used by power electronics to create motor currents must be significantly greater than the fundamental electric frequency, the number of magnet poles is often limited by power electronic switching capabilities and switching losses. Generally speaking, the higher the speed, the lower the number of magnet poles.

Secondarily, the number of magnet poles is limited by the rotor geometry and topology. As the number of magnet poles increases, the circumferential width available for each magnet decreases, leading to narrow magnets. Magnet narrowing increases the relative amount of magnet flux that leaks from magnet to magnet rather crossing into the stator to produce torque. This flux leakage is particularly apparent in interior permanent magnet rotors where there is less room for magnets than in surface permanent magnet motors.

Number of Stator Slots

Given the number of magnet poles, the number of stator slots N_s can be chosen from a wide selection of possibilities. Most fundamentally, the number of stator slots must support a balanced three phase winding, which dictates that the number of slots is a factor of three for two layer windings and a factor of six for single layer windings. Moreover, the choice must support an integer slot offset between phases as given by (8.6) for double layer windings and (8.13) for single layer windings

$$K_o = \frac{2N_s}{3N_m}(1+3q) \tag{8.6}$$

$$K_o = \frac{2N_s}{3N_m}(1+3q) \quad K_o \neq S \tag{8.13}$$

where q is any positive integer and S is the chosen coil span.

The number of stator slots determines the index of the first cogging torque harmonic through (11.46)

$$n_{cog} = \frac{\operatorname{lcm}(N_s, N_m)}{N_m} \tag{11.46}$$

Generally speaking, the lower n_{cog} is, the worse the cogging torque will be. Moreover, the higher n_{cog} is, the less skew is required to minimize cogging. The best possible choice is when N_s and N_m share no common factor. Since N_m must be even, the best choice always occurs when N_s is odd.

The number of stator slots also determines the index of the first static radial force harmonic as given by (11.56) when the number of stator slots is odd

$$n_{rad} = \min\left(\frac{(2q-1)N_s \pm 1}{N_m}\right) \tag{11.56}$$

When the number of slots is even, symmetry exists between the rotor and stator around the air gap and the motor ideally exhibits no static unbalanced magnetic pull. Generally speaking, the greater n_{rad} is, the lower the static radial force between the rotor and stator.

Perhaps more than anything else, the number of stator slots defines the winding layout, which largely determines the harmonic content of the back EMF as well as the extent existence and extent of dynamic radial forces. Integral slot motors where N_s/N_m is an integer generally have the greatest back EMF harmonic content, whereas fractional slot motors, where N_s/N_m is not an integer, have more sinusoidal back EMFs.

Diameter versus Length

The stator radius or diameter and the motor axial length play a significant role in motor performance. Generally speaking, motor performance is proportional to rotor volume as given by (1.10)

$$T = k D^2 L \tag{1.10}$$

where D is the rotor diameter, L is the motor axial length, and k is a constant that depends on all the details of motor construction.

For the most part, mechanical constraints determine the diameter and length of a motor. In many cases, dimensional constraints arising from the intended application dictate limiting values for the diameter or length. For example, the spindle motor in a hard disk drive has clear dimensional constraints.

In other cases, torque or speed specifications provide dimensional constraints. For example, as speed increases, the rotor diameter must be limited so that it maintains its structural integrity, *i.e.*, it doesn't break apart under the stresses that come from rotating at high speeds. Therefore, as speed increases maximum diameter generally decreases. When the torque requirement increases, the diameter squared factor in (1.10) plays a more dominant role than axial length because of the squared factor. Therefore, high torque motors generally have larger diameters. This guideline is particularly true for low speed motors where maintaining structural integrity is generally not a significant issue.

Generally speaking, most common motors have an outer diameter and axial length that are approximately equal. The difference between these two dimensions generally increases as application constraints dictate them to do so.

Rotor Outside Radius

For a specified outside stator radius R_{so}, the rotor outside radius R_{ro} can take on a wide range of values. As the rotor outside radius increases, there is less and less space available for windings, but there is more space for magnets and the radius at which torque is produced increases. The opposite is true when the rotor outside radius decreases. Examples of these two constructions are shown in Fig. 11-2.

Using simplifying assumptions, (11.19) gives the optimum ratio R_{ro}/R_{so} that maximizes the motor constant (4.46). The outside rotor radius value predicted by this equation represents a good starting point for design. However, because of the assumptions necessary to permit an analytic solution, the true optimum value can differ significantly from that predicted by (11.19). Equation (11.19) ignores the influence of stator slots on the air gap flux density and associate flux passing into the stator teeth as described in sections 7.1 and 7.2. It also ignores the impact of skew as described in section 7.4. Perhaps most importantly, (11.19) ignores the saturation of the rotor and stator ferromagnetic material as described in section 7.5. Saturation of the stator teeth in particular acts to diminish the air gap flux that links to the stator windings to produce torque.

Not only is the flux density in the stator teeth (7.16) important, but the length of the stator teeth plays a role that is of equal or greater significance. As the stator teeth length increases, the tooth MMF F_t, as illustrated in Fig. 7-11 and appearing in (7.40) increases. This effect occurs because MMF is linearly related to length for a given flux as shown by the substitution of (2.7) into (2.8). The increase in tooth MMF diminishes the permanent magnet flux that contributes to torque as demonstrated by (7.41). For this reason, the optimum rotor radius is often greater than that predicted by (11.19), because increasing the outside rotor radius while keeping the outside stator radius fixed decreases the stator tooth length.

Number of Turns

The number of turns per coil N determines the back EMF constant and the torque constant of a motor. The back EMF constant and the torque constant are linearly proportional to the number of turns per coil. Depending on the number of coil groups (8.14), a winding may or may not support combining individual phase winding coils in parallel. For a chosen combination of coils in parallel, the number of turns per coil is most commonly chosen so that the peak back EMF per phase at rated speed is somewhat less than the power supply voltage used to drive the motor. This guideline is required so that the power electronics can control the motor current as demonstrated by (11.81). The difference between the power supply voltage and the peak back EMF at rated speed can be thought of as the headroom available to the power electronics. How large the headroom must be depends on many factors including personal preference.

The number of turns per coil does not affect many aspects of the motor performance as long as the percentage of the slot cross-sectional area occupied by windings remains fixed. For example, the power dissipated by the windings in the slots remains constant as given by (4.44)

$$P_{slot} = \rho J^2 V_{wb} \tag{4.44}$$

where ρ is the winding resistivity, J is the current density, and V_{wb} is the bare wire volume in a slot. In addition, since both the resistance (4.42) and inductance (3.4) of a winding are proportional to N^2, the electrical time constant of a winding is not a function of N. Perhaps most important, the motor constant is independent of the number of turns as illustrated by (4.47)

$$K_m = \frac{B_g R_{ro}}{\sqrt{\rho}} \sqrt{V_{wb}} \tag{4.47}$$

The choice of number of turns also does not allow one to increase motor torque while keeping current constant. When slot cross-sectional area is fixed and the percentage of that space occupied by windings is fixed, the product Ni is fixed as given by (4.45)

$$N i = K_{wb} A_{sl} J \tag{4.45}$$

where K_{wb} is the bare wire slot fill (4.39), A_{sl} is the slot cross-sectional area and J is the RMS current density. Since the right hand side of this equation is fixed by geometry and heat dissipation capability, any increase in number of turns must coincide with an equal decrease in current i. When the number of turns increases, the wire diameter must decrease so that the turns still fit into the slot. This decrease in wire diameter forces the current i to decrease so that the current density J and the power dissipated in the slot resistance (4.44) remains the same.

Magnet and Air Gap Dimensions

The air gap flux density is largely determined by the magnet operating point, which is defined by the permeance coefficient (2.33)

$$P_c = \frac{l_m}{g} \frac{1}{C_\phi} \tag{2.33}$$

where l_m is the magnet length in the direction of magnetization, g is the radial air gap length, and C_ϕ is the flux concentration factor (2.30). In a motor, the permeance coefficient determines the amount of the magnet remanence B_r that is directed across the air gap as the air gap flux density B_g as illustrated in Fig. 4-4. This figure demonstrates that a permeance coefficient between 4 and 6 represents a good compromise between the volume of permanent magnet material required and the resulting air gap flux density.

The minimum air gap length g required for a motor generally depends on mechanical tolerances. The air gap length should be chosen so that its variation around the air gap is minimal given manufacturing tolerances. Any variation in air gap length around the air gap will lead to spurious cogging torque and radial force harmonics. For surface permanent magnet motors, the air gap length must accommodate magnet retention material added to the outer rotor surface.

While minimizing the air gap length minimizes the amount of permanent magnet material required to achieve a desired air gap flux density, increasing the air gap length is beneficial. Increasing the air gap length g and associated magnet length l_m, decreases the air gap inductance component since both terms appear in the denominator of (4.22). Perhaps more importantly, increasing the air gap length decreases the cogging torque because the variation in the air gap reluctance due to slotting decreases with increasing air gap. This decrease in cogging torque occurs because the added air gap length over the slots is a smaller percentage of the total air gap length as g increases. Given that reluctance R is directly proportional to length (2.7), the effect of air gap length on cogging torque is given simply by (4.50)

$$T_{cog} = \frac{-1}{2} \phi_m^2 \frac{dR}{d\theta} \tag{4.50}$$

where ϕ_m is the magnet flux crossing into the air gap and R is the air gap reluctance as a function of position θ.

General Design Process

With all the above guidelines in mind, the process for analyzing a motor design can follow the steps outlined below:

- Start with knowledge of all pertinent dimensions.
- Find the ideal air gap flux density distribution for the given rotor type chosen.

- Compute the tooth, rotor yoke, and stator yoke fluxes and flux densities taking into account the slot openings.
- Determine the saturation affect on these fluxes and flux densities due to the ferromagnetic regions of the motor.
- Take skew into account.
- Find the slot cross-sectional area available for windings.
- Determine the winding layout.
- Find the back EMF, number of turns per coil, and the wire diameter.
- Compute the phase resistance, inductance, and mutual inductance.
- Compute the torque for a given current or current for a given torque, the motor constant, efficiency, and other performance measures.
- Make changes and iterate this process.

12.2 Detailed Examples

Because there are so many design possibilities, this section focuses extensively on a ten pole, twelve slot motor and on a 44 pole, 48 slot motor. Other pole and slot counts are considered, but not in detail.

Default Characteristics

To facilitate the following discussion, unless noted otherwise, all motor designs considered in this chapter have the following characteristics:

- The stator outside radius is R_{so} = 50 mm.
- The rotor outside radius is R_{ro} = 28 mm.
- The motor axial length is L_{st} = 100 mm.
- The air gap length is g = 1 mm.
- The radial magnet length is $l_m = 4g$ = 4 mm.
- The angular magnet width is set to 144 °E, which gives a magnet fraction of α_m = 144/180 = 0.8.
- The stator tooth body width w_{tb}, stator yoke width w_{sy}, and the rotor yoke width w_{ry} are adjusted to keep the peak flux density in these regions at 1.2 T due to the magnetic field created by the permanent magnets.
- The slot openings are set at 7.5 % of the slot pitch.
- Neither the magnets nor the stator slots are skewed.
- The ferromagnetic portions of the motor are constructed using common, high quality electrical steel.
- The permanent magnets are radially magnetized and operate at a remanence of B_r = 1.24 T and relative recoil permeability of μ_R = 1.055.