

Motor Control For Designers (Part 9): Motor Design Parameters

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In power-converter electronics, overall design optimization occurs when both power circuits and magnetics design are understood and optimized together. This also applies to motion control whenever both motor-drive and motor are optimized together. Consequently, the motor-drive designer benefits from some understanding of how motor parameters affect motor performance and how the motor can be optimized with the drive for an overall optimized solution to the motion-control problem.

The earlier parts of this series^[1-8] introduced and explained the theory of motor operation. Those articles covered how motors develop torque, and underlying electromagnetic principles including the torque vs. current relationship. They also discussed configurations of rotors, pole-pairs and phase windings, their induced voltage waveforms, and drive sequences. A key takeaway from these discussions was the development of electro-mechanical PMS motor models—dynamic and quasistatic.

With this theory in hand, the next parts will explore motor design to enlighten the motor drive designer. The three aspects of motor design are electrical, field (magnetic), and mechanical. Electrical design involves the windings, with considerations of wire size, resistance, insulation voltage breakdown, number of turns, and number of motor pole-pairs and phase-windings.

The magnetic aspect involves stator shape, dimensions, and winding configuration, permanent-magnet design, magnetic field distribution in the magnetic path, and air gap width. The mechanical design involves material strength and stresses, bearing runout, loading and life, thermal design, and mechanical dynamics of inertia, aerodynamic drag, and vibration (torque ripple).

These three aspects of motor design interact. More specifically, motor design and motor-drive design interact because optimization of the interface between motor-drive electronics and motor windings involves all three of these aspects. How? As we saw previously in the motor model, the induced-voltage source v_ω on the electrical side of the motor is a portal to what is on the mechanical side, and also is affected by the motor magnetic field. Consequently, both motor and motor-drive are optimized as a system.

This article begins with a review of the previously introduced torque vs. speed graph, but this time analyzing the influence of motor parameters on the slopes and intercepts of the curves. In the subsequent sections, we delve further into these relationships in examining the influence of winding resistance, and factors influencing winding resistance (such as winding area (affected by motor geometry)) and turns number, on the torque vs. speed curves.

The impact of magnet property B_r , which is itself affected by magnet volume, on the torque vs. speed curves is also analyzed. A table helps to summarize and explain the connections between motor size and geometry and the winding and magnet properties that influence the torque vs. speed curves. Finally, we explore influence of these same motor winding and magnet parameters on motor performance figures of merit such as torque density and mechanical power density.

How $T(\omega_{me})$ Is Affected by Motor Parameters

The most basic view for the electronics engineer of the mechanics of the motor is from the graph or equation of the PMS motor torque-speed family of plots with winding voltage-source amplitude V_g as parameter. To reiterate, $T(\omega_{me})$ is plotted in Fig. 1.

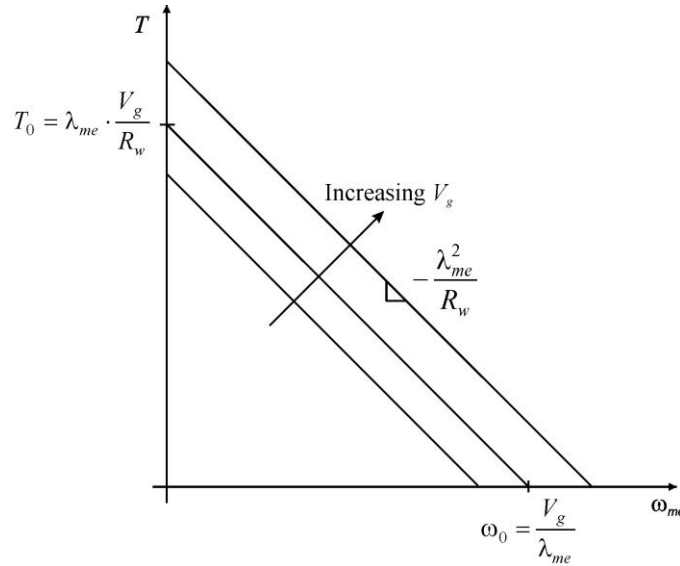


Fig. 1. Quasistatic torque-speed graph of a linear PMS motor with drive voltage amplitude V_g as a parameter.

The previously-derived torque-speed equation from the quasistatic model is

$$T(\omega_{me}) = -\left(\frac{\lambda_{me}^2}{R_w}\right) \cdot \omega_{me} + \lambda_{me} \cdot \left(\frac{V_g}{R_w}\right) = T_0 \cdot \left(1 - \frac{\omega_{me}}{\omega_0}\right)$$

R_w = winding resistance per phase-winding, in Ω and λ_{me} = electromechanical flux in units of $V \cdot s \equiv N \cdot m/A$. Useful units conversions for motors are

$$V/krpm = (60/2 \cdot \pi) \cdot mV \cdot s \approx 9.55 \cdot mV \cdot s$$

$$V/Hz \text{ me} = (100/6) \cdot V/krpm \approx 16.67 \cdot V/krpm$$

Consequently λ_{me} , the conversion parameter that relates winding to field to mechanics and has units of circuit flux $V \cdot s = V/s^{-1}$ or voltage per speed or $N \cdot m/A$ of torque per current, can also be converted to alternative units of $V/krpm$. This is typically how motor manufacturers present λ_{me} in motor specifications and call it K_v or the “voltage constant”.

To confuse matters, they also list it again as K_T , a “torque constant,” but in units of $N \cdot m/A$. Do not be fooled; $K_v \equiv K_T$; they are not independent parameters though the two are expressed in different units. This might be convenient for motor users but for those trying to understand motors, it creates a conceptual conundrum.

The parameters affecting $T(\omega_{me})$ are λ_{me} and R_w —both motor parameters—and V_g , a motor-drive variable. The PMS motor model has two equations bilaterally relating the electrical and mechanical sides of the motor:

$$T = \lambda_{me} \cdot i_s \quad v_\omega = \lambda_{me} \cdot \omega_{me}$$

These equations are both linear and the transfer of power between the two sides is linear for the model. For well-designed motors it is approximately linear because large departures from linearity such as magnetic saturation or winding loss are often accompanied by suboptimal performance.

The T and ω_{me} axis intercept points on the $T(\omega_{me})$ graph are the range extremes of motor operation (see Fig. 1 repeated below). The first is

$$\text{Stall torque} = T_0 = \lambda_{me} \cdot \left(\frac{V_g}{R_w} \right) = \lambda_{me} \cdot I_0$$

T_0 occurs at zero speed $\omega_{me} = 0 \text{ s}^{-1}$ and $v_\omega = 0 \text{ V}$; full V_g is applied across R_w resulting in

$$\text{Stall current} = I_0 = \frac{V_g}{R_w}$$

Typically I_0 exceeds what is desired; that much sustained current overheats windings or saturates the magnetic path and results in $T \ll \lambda_{me} \cdot I_0$. Drive sources of windings are often controlled as current, not voltage, sources and have a maximum current range. The motor model given here is driven by a voltage source v_g but later, that will change to a current source. Yet $T(\omega_{me})$ is still valid for the motor, which is not changed by the source that drives it.

At the other extremes of motor speed and torque ranges is the *base speed* or

$$\text{No-load speed} = \omega_0 = \frac{V_g}{\lambda_{me}}$$

At this speed, the amplitude of $v_\omega = V_g$, leaving no voltage drop across R_w . Consequently $i_s = 0 \text{ A}$, and torque is zero. All this assumes field-oriented phase control. Faster speeds can be obtained by increasing the torque angle to $\delta > \pi/2 = 90^\circ$, entering the constant-power region of operation—a more advanced topic in motor-drive design.

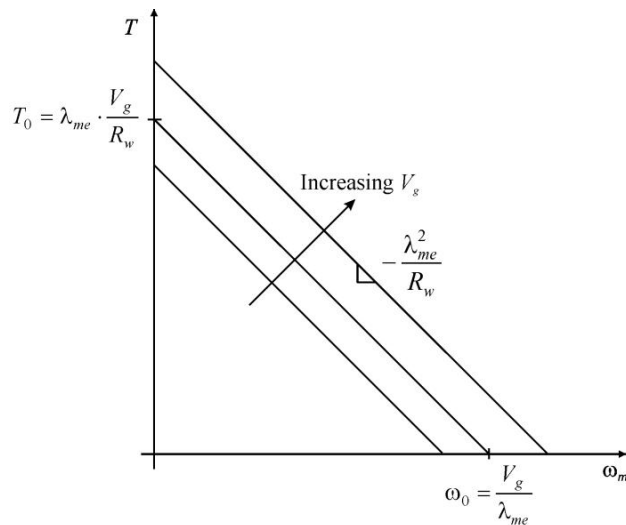


Fig. 1 again. Quasistatic torque-speed graph of a linear PMS motor.

From the graph of Fig. 1, another feature of $T(\omega_{me})$ is its slope, which affects both T_0 and ω_0 ;

$$\text{Slope of } T(\omega_{me}) = -\frac{\lambda_{me}^2}{R_w}$$

Changing either λ_{me} or R_w rotates the $T(\omega_{me})$ line; increasing R_w reduces slope magnitude, causing T_0 to decrease and ω_0 to increase. Increasing λ_{me} results in a steeper slope, with larger T_0 and less ω_0 . Hence both torque and speed ranges can be fit to the mechanical requirements of the problem by adjusting these two motor parameters.

Motor Design Parameters

How do motor geometry and windings affect R_w and λ_{me} ? We already have the basic theory we need to determine this. For a given total winding window (slot) area A_w between the stator teeth, and with pole windings connected in series, the equation for resistance, $R_w = \rho \cdot l / A_c = l / \sigma \cdot A_c$, is applied to the resulting multi-pole winding:

$$R_w = \frac{p \cdot N \cdot l_c}{\sigma \cdot A_c} = \frac{p \cdot N \cdot 2 \cdot l / k_l}{\sigma \cdot k_p \cdot A_w / 2 \cdot p \cdot N} = (2 \cdot p \cdot N)^2 \cdot \left(\frac{l}{\sigma \cdot k_p \cdot k_l \cdot A_w} \right) = \frac{(2 \cdot p \cdot N)^2}{\sigma \cdot \pi \cdot k_w \cdot k_p \cdot k_l} \cdot \frac{l}{r^2}$$

p = pole-pairs = 2 poles of a winding loop

$\sigma = 1/\rho$ = conductivity, $1/\Omega \cdot m$

N = number of turns per pole-pair

l_c = per-turn conductor length = $2 \cdot l + 4 \cdot r$, $2 \cdot r$ = winding end-turn length = stator diameter

A_c = wire conductor area = $k_p \cdot A_w / 2 \cdot p \cdot N$

l = wire torque-producing length

k_l = turn utilization fraction = $2 \cdot l / l_c$

k_p = conductor packing factor = $2 \cdot p \cdot N \cdot A_c / A_w$

A_w = total winding area in windows

$k_w = A_w / \pi \cdot r^2$ = winding fraction of stator area

We previously derived a geometric expression for λ_{me} :

$$\lambda_{me} = p \cdot N \cdot (2 \cdot r \cdot l) \cdot B_r$$

The torque-producing loop has two poles, one on each side of the loop at radius r , with pole-pair area $A = 2 \cdot r \cdot l$; the rotor field-flux per pole-pair is $\phi_r = B_r \cdot A$; and the circuit-referred flux is $\lambda = (p \cdot N) \cdot \phi_r$.

How do motor geometry and windings affect $T(\omega_{me})$? Total winding area A_w (all windows of winding) relates to the $T(\omega_{me})$ slope along with motor geometry r and l , to magnets as B_r (rotor magnetic flux density), to winding geometric factors k_l and k_p , and to conductivity σ . Then given the cylindrical stator volume $V = \pi \cdot r^2 \cdot l$, the $T(\omega_{me})$ slope magnitude is

$$\frac{\lambda_{me}^2}{R_w} = \sigma \cdot k_p \cdot k_l \cdot B_r^2 \cdot l \cdot r^2 \cdot A_w = \sigma \cdot \pi \cdot k_p \cdot k_l \cdot k_w \cdot B_r^2 \cdot l \cdot r^4 = \sigma \cdot k_p \cdot k_l \cdot k_w \cdot B_r^2 \cdot r^2 \cdot V$$

Turns N does not affect the slope. The $T(\omega_{me})$ slope appears constant with N because N is within $k_p \cdot A_w$ but N is not in the per-turn wire conductor area $A_c = k_p \cdot A_w / 2 \cdot p \cdot N$; the denominator N is cancelled by the N in A_w . In contrast, the slope is highly dependent on motor radius r .

No-load speed ω_0 varies inversely with N ;

$$\omega_0 = \frac{V_g}{\lambda_{me}} = \frac{V_g}{p \cdot N \cdot 2 \cdot r \cdot l \cdot B_r}$$

Stall torque T_0 also varies inversely with N . As N increases, $T(\omega_{me})$ shifts toward the origin and the slope remains constant;

$$T_0 = \lambda_{me} \cdot \left(\frac{V_g}{R_w} \right) = \frac{V_g \cdot \sigma \cdot k_p \cdot k_l \cdot B_r \cdot r \cdot A_w}{2 \cdot p \cdot N} = \sigma \cdot k_l \cdot B_r \cdot A_c \cdot r \cdot V_g$$

T_0 decreases with increasing turns, totaling $2 \cdot p \cdot N$. As wire size (measured in A_c , wire conductive area) decreases while holding winding area A_w constant, then N must increase and $T(\omega_{me})$ shifts towards the origin while the slope remains constant.

Effects Of Magnets On $T(\omega_{me})$ Parameters

The only magnet parameter we have considered is rotor $B = B_r$ and this term has an influence on the torque vs. speed curves as suggested above. To understand the role of B_r we start by noting that magnet characteristics are usually plotted on a $B(H)$ graph with B -axis intercept at B_m and second-quadrant H -axis intercept at $-H_m$.

For a rounded-square $B(H)$ function, the maximum energy-density point on the plot is at $B_m \cdot H_m$ at the knee of the $B(H)$ curve. The $B_m \cdot H_m$ product is a factor in magnet volume,

$$\text{Magnet volume} = V_m = \frac{B_g^2 \cdot V_{gap}}{\mu_g \cdot (B_m \cdot H_m)}$$

V_{gap} is the magnetic-circuit air-gap volume, B_g = magnetic-field density in gap, and μ_g = gap permeability.

B_r doesn't appear in the above equation, but there's a relationship between magnet volume and B_r , which we'll explain below. But first, let's see how B_r and other factors discussed above vary with motor design parameters. The table shows the effects of varying motor design parameters on performance parameters.

Table. The effects of motor parameter variation. Key: ↑ increase; ↓ decrease; – no change.

Modification	N	A_w	R_w	P_{max}	B_r	λ_{me}	λ_{me}^2/R_w	T_0	ω_0	I	r
Decrease wire size (diameter)	↑	–	↑	↓	–	↑	–	↓	↓	–	–
Increase wire window, same wire size	↑	↑	↑	↓	–	↑	↑	–	↓	–	–
Increase wire and window size; same N	–	↑	↓	↑	–	–	↑	↑	–	–	–
Increase motor radius and wire size	–	↑	↓	↑	–	↑	↑	↑	↓	–	↑
Lengthen stator and magnets	–	–	↑	↓	↑	↑	↑	↑	↓	↑	–
Shorten stator and magnets; increase radius	–	–	↓	↑	↓	↓	–	↑	–	↓	↑

A more graphical demonstration of the effects of motor parameter variations on $T(\omega_{me})$ is given in Fig. 2.

Magnet B_r value varies (Fig. 2 top-right) with the square-root of the magnet volume, or $B_r \sim \sqrt{V_m}$. Lengthening the stator and magnets also increases winding length and resistance, but λ_{me}^2 dominates over R_w , steepening the $T(\omega_{me})$ slope.

In the first row of the table and bottom-right of Fig. 2, motor geometry changes from a long, tubular-shaped motor to a short, pancake-shaped motor. With winding length l decreasing and radius r increasing, more stall torque is produced. This motor is sometimes referred to as a “torque motor”—high-torque at low speed.

What happens when more turns are added but to keep winding resistance constant, wire size and window area are increased? The $T(\omega_{me})$ graph on Fig. 2 second-row right shows the effect; the plot rotates CW, with increasing T_0 and decreasing ω_0 . The motion-systems designer now has the capability of adjusting motor parameters to fit the $T(\omega_{me})$ function to the mechanical system to optimize the motor for the application.

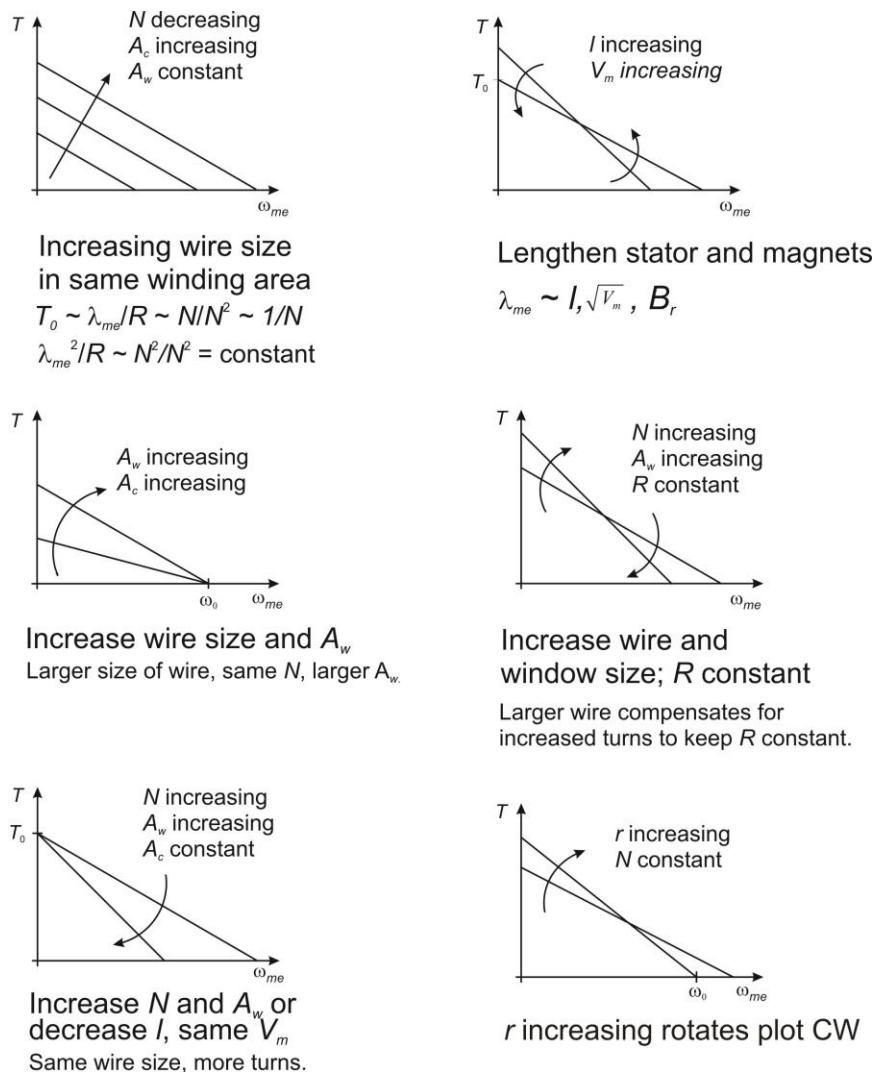


Fig. 2. How variations in motor parameters affect the torque-speed plots.

Motor Design Figures Of Merit

A unitless motor design parameter is the winding area fraction k_w , the fraction of stator window area A_w that is winding-filled slots: $k_w = A_w / \pi \cdot r^2$. Conductor current density $J_c = i_s / A_c$; then stator current is

$$i_s = J_c \cdot A_c = \frac{J_c \cdot k_p \cdot A_w}{2 \cdot p \cdot N} = \frac{J_c \cdot k_p \cdot (\pi \cdot r^2 \cdot k_w)}{2 \cdot p \cdot N}$$

From this equation, we can see which parameters affect the stator current. Wire current density J_c is limited thermally, k_w varies with the stator geometric design, wire packing factor of the winding k_p decreases with decreasing wire size, and the total turns $2 \cdot p \cdot N$ per pole-pair p of N turns per pole of a single winding loop increases resistance and decreases allowable i_s .

The 2 of $2 \cdot p \cdot N$ represents the torque-producing lengths l for each pole of the winding loop. Thus each *pole* is a half-loop (minus end-turn loop segments), and each loop has a pair of poles. A single winding can have multiple pole-pairs with one loop in series per pole-pair. *Phase-windings* each have their own pole-pairs and winding loops.

Another performance indicator is

$$\text{Torque density} = \frac{T}{V} = \frac{(p \cdot N \cdot (2 \cdot r) \cdot l \cdot B_r) \cdot i_s}{\pi \cdot r^2 \cdot l} = r \cdot B_r \cdot k_w \cdot k_p \cdot J_c$$

The different factors in this expression are *not* independent. If $k_w = 1$, $B_r = 0$ (all winding area, no flux area). The motor design requires a tradeoff among parameters to achieve an overall optimum.

Maximum mechanical power, $\max P_{me} = P_{\max}$, for a given V_g occurs at midscale torque and speed:

$$P_{\max} = \left(\frac{T_0}{2} \right) \cdot \left(\frac{\omega_0}{2} \right) = \left(\frac{1}{2} \cdot \lambda_{me} \cdot \frac{V_g}{R_w} \right) \cdot \left(\frac{1}{2} \cdot \frac{V_g}{\lambda_{me}} \right) = \frac{(V_g / 2)^2}{R_w}$$

Then the maximum *power density* = $P_{\max} / V$ is

$$\text{Power density} = \frac{P_{\max}}{V} = \frac{(V_g / 2)^2}{R_w \cdot V} = \left(\frac{V_g}{2} \right)^2 \cdot \frac{\sigma \cdot k_w \cdot k_p \cdot k_l}{(2 \cdot p \cdot N)^2 \cdot l^2}$$

The design factors k_w , k_p , and k_l are unitless fractions that ideally (that is, optimally, without opposing design constraints) have a value of one. Ideally, all of the stator cross-sectional area is winding window ($k_w = 1$), all of the area within windows is conductor ($k_p = 1$), and all turn segments of windings produce torque ($k_l = 1$). Yet at $k_w = 1$ there is no area for the stator to support the magnetic field; at $k_p = 1$ there is no area for wire insulation or spatial gaps between round wires, and at $k_l = 1$, there is no winding length wasted as “end-turns”.

These shortcomings in design parameter values direct design toward optimal wire sizes, stator calibers ($2 \cdot r / l$), and for $k_l \rightarrow 1$, the motor must have $l \gg r$ though that constrains $T(\omega_{me})$ to a high-speed, low-torque design.

As power-transfer density increases, so does winding (electrical) power loss. Another performance parameter is the winding (electrical) *power-loss density* = $P_w / V = i_s^2 \cdot R_w / V = (J_c \cdot A_c)^2 \cdot R_w / V$ or

$$\text{power-loss density} = \frac{P_w}{V} = \frac{J_c^2 \cdot k_w \cdot k_p}{\sigma \cdot k_l} = \left(\frac{J_c}{\sigma} \right) \cdot \left(\frac{k_w \cdot k_p}{k_l} \right) = \left(\frac{J_c / \sigma}{r \cdot B_r \cdot k_l} \right) \cdot \left(\frac{T}{V} \right), V_g \text{ constant}$$

The first factor in the expression on the right is wire-dependent and the second is design-dependent. Factors $J_c \sim \sigma \sim k_w$ and are not entirely independent. By applying the maximum power-transfer theorem to the motor

model, maximum power is converted when electrical loss is equal to mechanical loss. However, loss in the magnetic path of stator and rotor causes the theorem to be approximate.

Recall from the previous part 6 that $T(\omega_{me})$ as given above is the torque *per phase-winding*. Total torque depends on the v_ω waveshape and how the phase-windings are driven. Total torque is the sum of the phase-winding contributions so that for Q phase-windings, torque is Q times the torque per phase-winding.

References

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About The Author



Dennis Feucht has been involved in power electronics for 40 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

For further reading on motors and motor drives, see "[A Practical Primer On Motor Drives](#)".