

Motor Control For Designers (Part 12): Wire Size In Motor Design

by Dennis Feucht, Innovatia Laboratories, Cayo, Belize

Recent articles in this motor control series^[1-11] have discussed magnet operation and sizing of motor magnets. This motor design article is solely about winding design. Some of the basic winding design formulas are offered, some are derived, and relationships such as packing factor with wire size are graphed. However, to begin, we review the dimensional definitions underlying the AWG wire sizes as these values will be used in some of the derived equations.

Understanding AWG

Enamel coated "magnet wire" is commonly used to wind motors. Its insulation is typically single, double ("heavy"), or triple insulated. Heavy insulation has a typical voltage breakdown of around 750 V. The American Wire Gage (AWG) is still commonly used in North America for wire sizing, though metric sizes are slowly displacing it globally. But given the current prevalence of AWG, we'll want to define the equations we develop to define wire size in motor design in terms of the AWG standard. It is a logarithmic gage with a conductor radius gaged as

$$AWG = -20 \cdot \log_{10} \left(\frac{r}{r_0} \right) \approx -6 \cdot \log_2 \left(\frac{r}{r_0} \right), r_0 = r(AWG = 0) = 4.126 \text{ mm}$$

Then the difference between two AWG wire sizes is

$$AWG_2 - AWG_1 = -6 \cdot \log_2(r_2/r_1) = -3 \cdot \log_2(A_2/A_1)$$

The difference in radii between two AWG numbers is

$$r_2 = r_1 \cdot 2^{\left(\frac{AWG_1 - AWG_2}{6} \right)} = r_1 \cdot 2^{\frac{AWG_1}{6}} \cdot (2^{\frac{1}{6}})^{-AWG_2}, 2^{1/6} \approx 1.12246$$

Thus, wire radius and conductive cross-sectional area from AWG are

$$r = r_0 \cdot (2^{1/6})^{-AWG} \approx (4.126 \text{ mm}) \cdot (1.123)^{-AWG}$$

$$A_c(AWG) = \pi \cdot r_c^2 = \pi \cdot r_0^2 \cdot 2^{-AWG/3} \approx (53.48 \text{ mm}^2) \cdot (1.260)^{-AWG}$$

The Japanese standard (JIS) wire size is in mm. Square wire is specified in dimensions. Note that AWG is not a unit and is not even a scale factor but is a numerical scaling indicator or *gage*.

Lengths Of Winding Turns

Winding turn lengths are of interest in design for calculating winding resistance and specifying the length of wire needed for motor builds. The length of winding is $N \cdot l_c$ where l_c = turn length. Motor winding loops vary depending on motor geometry.

Motors with stators for which length $l \approx 2 \cdot r$ where r is the stator tooth radius, have wire loops between round and square in shape. For a round winding window, $l_c = 2 \cdot \pi \cdot r$; r from r_i to r_o where the average window width is $\Delta r = r_o - r_i$. Note that the r_o here for outer radius is distinct from the r_0 used above for 0 gauge wire. Fig. 7 part 11, which is repeated here as Fig. 1, illustrates how these radius terms define the winding window.

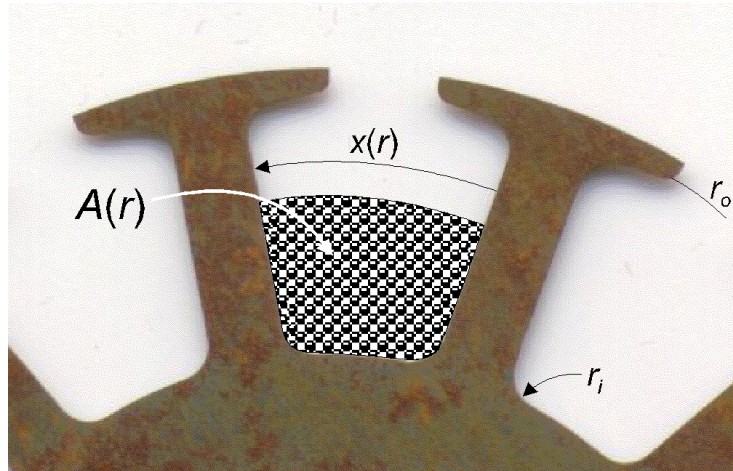


Fig. 1. Photo of an inner-stator lamination with dimensions depicting a winding window with r_i and r_o terms identified.

For $d = \text{wire diameter} = 2 \cdot r$, the distance from the center of a turn at $r_i + d/2$ to $r_o - d/2 =$

$$\left(r_o - \frac{d}{2}\right) - \left(r_i + \frac{d}{2}\right) = (r_o - r_i) - d$$

Let $r = i \cdot d - d/2$, $i = 1, \dots$, and $(r_o - r_i)/d = \# \text{ of layers}$. Then the average length of a turn is

$$\bar{l}_c = \frac{\sum_{i=1}^{\frac{r_o - r_i}{d}} 2 \cdot \pi \cdot \left([i \cdot d - \frac{d}{2}] + r_i\right)}{\frac{r_o - r_i}{d}} = 2 \cdot \pi \cdot \left(\frac{r_o + r_i}{2}\right) = 2 \cdot \pi \cdot \bar{r}$$

It is more common for motor windings to be wound with end-turns on two sides and torque-producing lengths on the other two sides. Fig. 6 from part 2, repeated here as Fig. 2, offers an example view of end turns. This forms a rectangular winding window with rounded corners, shown as a square winding in Fig. 3.

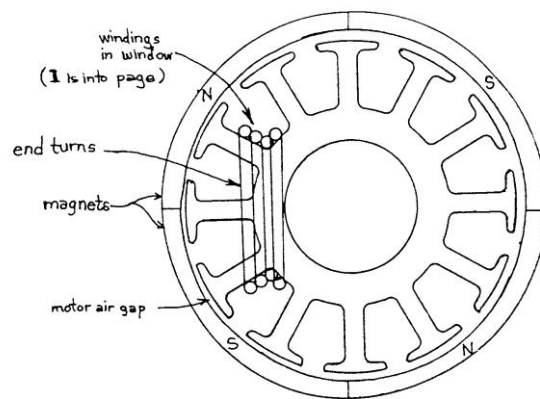


Fig. 2. End-turns of a winding spanning three stator teeth of a PMS motor.

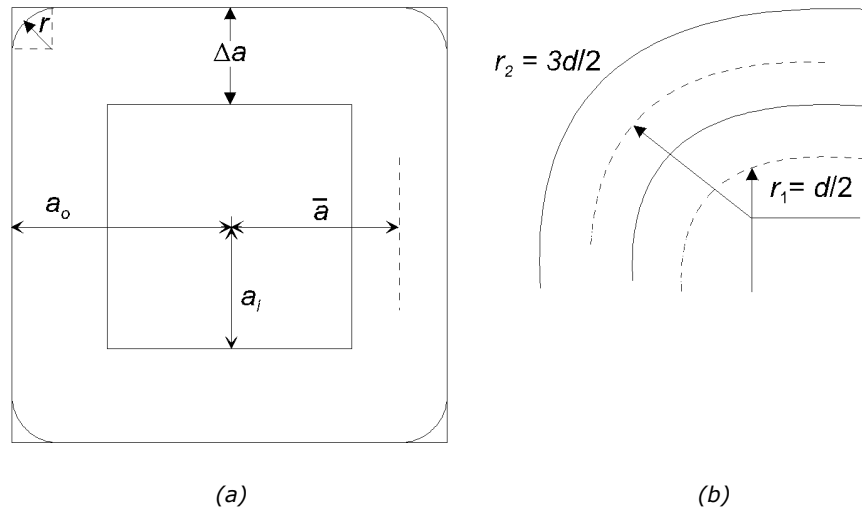
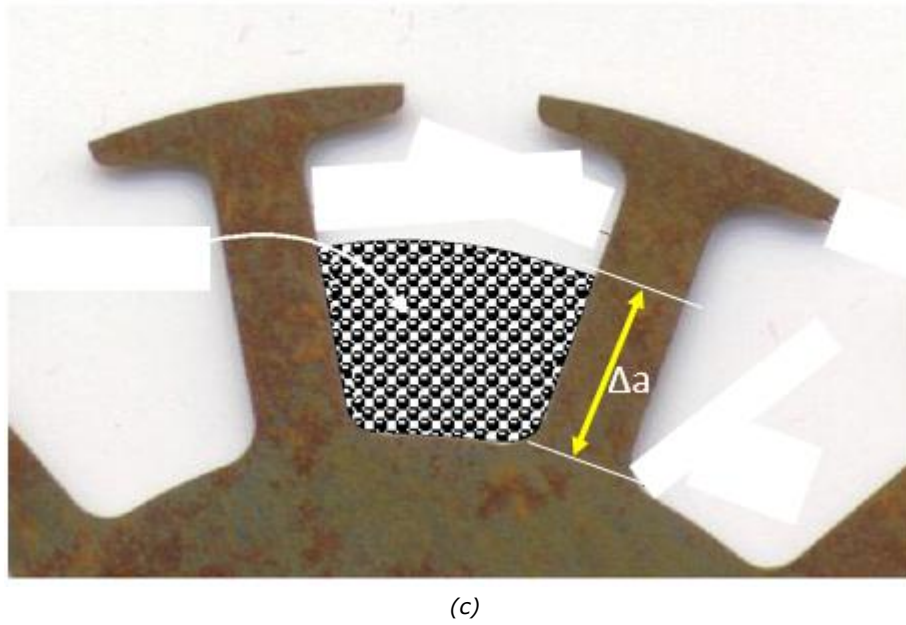


Fig. 3. Square winding window (a) and corner detail (b) of two turn layers with dotted wire centers. The height Δa of the square window shown in part (a) corresponds to the view from the stator tooth looking into the windings in part (c). Although not labeled in part c, the radius r would be the curve of these windings as they bend around the stator tooth.

Working through the geometry to obtain average turn length, wire layers = $\Delta a/d$ where

$$\Delta a = a_o - a_i$$

Turn length = $l_c = (2 \cdot \bar{a}) \cdot 4 = 8 \cdot \bar{a}$. Average turn length =

$$\bar{l}_c = 8 \cdot \bar{a} = 8 \cdot \left(\frac{a_i + a_o}{2} \right) = 4 \cdot (a_i + a_o)$$

For square turns with radius r at corners, the corner arc length = $(\pi/2) \cdot r$ and turn length =

$$\begin{aligned} l_c &= 8 \cdot (a - r) + 4 \cdot \left(\frac{\pi}{2} \right) \cdot r = 8 \cdot (a - r) + 2 \cdot \pi \cdot r \\ &= 8 \cdot a - 2 \cdot (4 - \pi) \cdot r \approx 8 \cdot a - 1.72 \cdot r \end{aligned}$$

n = layer 1 to $\Delta a/d$. In the corner,

$$r_n = (n - \frac{1}{2}) \cdot d; \quad a_n = a_i + r_n = a_i + (n - \frac{1}{2}) \cdot d$$

$$\bar{a} = \frac{1}{\frac{\Delta a}{d}} \cdot \sum_{n=1}^{\frac{\Delta a}{d}} a_n = a_i + \frac{\Delta a}{2} = a_i + \bar{r}$$

Length of turn of layer n =

$$l_n = 8 \cdot a_n - 2 \cdot (4 - \pi) \cdot r_n = 8 \cdot a_i + 2 \cdot \pi \cdot r_n$$

The average length of a square turn with corner radius r is

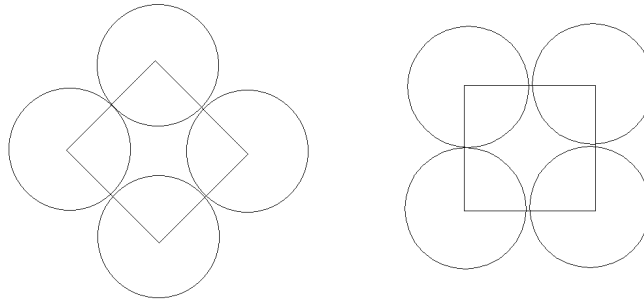
$$\begin{aligned} \bar{l}_c &= \frac{1}{\frac{\Delta a}{d}} \cdot \sum_{n=1}^{\frac{\Delta a}{d}} l_n = 8 \cdot a_i + \pi \cdot \Delta a \\ &= 8 \cdot \bar{a} - 2 \cdot (4 - \pi) \cdot \underbrace{\frac{\Delta \cdot a}{2}}_{\bar{r}} = 8 \cdot a_i + 2 \cdot \pi \cdot \left(\frac{\Delta \cdot a}{2} \right) \\ &= \underbrace{(8 - \pi)}_{4.86} \cdot a_i + \pi \cdot a_o \end{aligned}$$

Wire Packing Factor

The parameter that is the ratio of conductive cross-sectional area A_c of wire in a winding to the total winding area A_w is the *packing factor* $k_p = N \cdot A_c / A_w$ where N is the number of turns in A_w . Packing factor can be decomposed into *porosity* k_{pw} , which accounts for spacing between wires, usually because of insulation, and *fill factor* k_{pf} caused by gaps between wires.

Square or hexagonally-shaped wires would pack without any wasted space between them, but round wires have a fill factor of $\pi/4$. Whether round wires are geometrically configured as diamond or square, as shown in Fig. 4, makes no difference because a diamond packing is a square packing rotated by 45° .

Minimum k_p



Maximum k_p

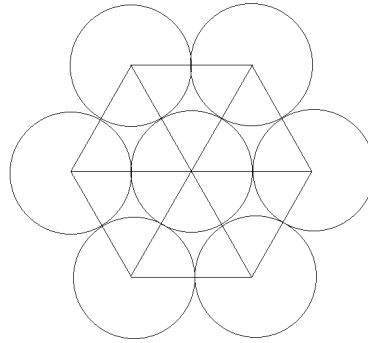


Fig. 4. Packing factor k_p of round wire when wires are aligned (above) or alternative layers offset (below) to fit into the grooves of the adjacent layers.

The most compact configuration for multiple layers of round wires is shown in Fig. 4 as having the maximum k_p . These are layers that are offset to fit into the grooves of adjacent layers. For insulated wire radius = r and conductor radius = r_c , then the minimum k_p configurations with square and diamond packing have

$$A_{sq} = (2 \cdot r)^2 = 4 \cdot r^2$$

The area of wire within the square =

$$A_{wsq} = 4 \cdot \left(\frac{1}{4} \cdot \pi \cdot r^2\right) = \pi \cdot r^2$$

Then the packing factor is

$$k_{pwsq} = \frac{A_{wsq}}{A_{sq}} = \frac{\pi}{4} \approx 0.785$$

The more compact configuration of *hexagonal packing* is shown in Fig. 5 with hexagons (Fig. 4) decomposed into six equilateral triangles drawn between adjacent wire centers, each having area

$$A_{tri} = \frac{1}{2} \cdot b \cdot h = \frac{1}{2} \cdot (2 \cdot r) \cdot (\sqrt{3} \cdot r)$$

$$= \sqrt{3} \cdot r^2$$

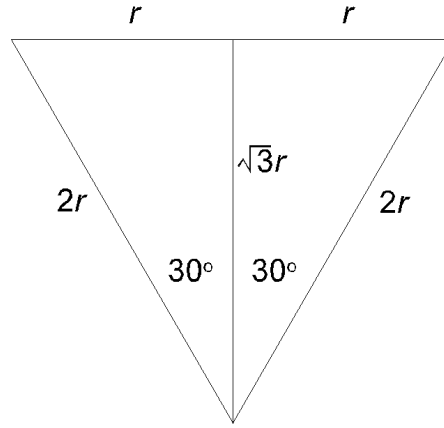


Fig. 5. Hexagonal packing of round wire in multiple offset layers with line segments drawn between adjacent wire centers forms hexagons used to derive k_p . One side of a hexagon of $2 \cdot r$ length is shown here.

Each circular sector within a hexagon has area

$$A_{\text{sect}} = \frac{\theta}{2} \cdot r^2 = \frac{\pi}{6} \cdot r^2$$

The packing factor is thus

$$k_{pf}(\text{hex}) = \frac{3 \cdot A_{\text{sect}}}{A_{tri}} = \frac{3 \cdot \left(\frac{\pi}{6}\right) \cdot r^2}{\sqrt{3} \cdot r^2} = \frac{\pi}{2 \cdot \sqrt{3}} \approx 0.907$$

where k_{pf} is the insulated wire fill factor. For the conductor, the total packing factor is

$$k_p = k_{pw} \cdot k_{pf} = \left(\frac{r_c}{r}\right)^2 \cdot k_{pf}$$

For heavy (double) insulated wire, insulation thickness is $r - r_c$, and

$$\left(\frac{r_c}{r}\right)^2 = \frac{r_c}{r_c + \sqrt{a \cdot r_c}} = \frac{1}{1 + \sqrt{\frac{a}{r_c}}}, a \approx 392 \cdot 10^{-6} \text{ cm};$$

$$r_c = (0.41264 \text{ cm}) \cdot (1.123)^{-AWG}$$

The packing factor range of the two-layer configurations is between minimum and maximum:

$$k_p \in \left\{ \left(\frac{r_c}{r} \right)^2 \cdot \frac{\pi}{2 \cdot \sqrt{3}}, \left(\frac{r_c}{r} \right)^2 \cdot \left(\frac{\pi}{4} \right) \right\}$$

Then the average packing factor =

$$\bar{k}_p = \left(\frac{r_c}{r} \right)^2 \cdot \underbrace{\left(\frac{(\sqrt{3} + 2) \cdot \pi}{8 \cdot \sqrt{3}} \right)}_{0.846}$$

The winding window also affects k_p as end-effects caused by the limited dimensions of the window that constrains the number of wires in a layer to an integer fit (Fig. 4).

$$k_p = \frac{\pi \cdot r^2}{(2 \cdot r)^2} = \frac{\pi}{4} \approx 0.785$$

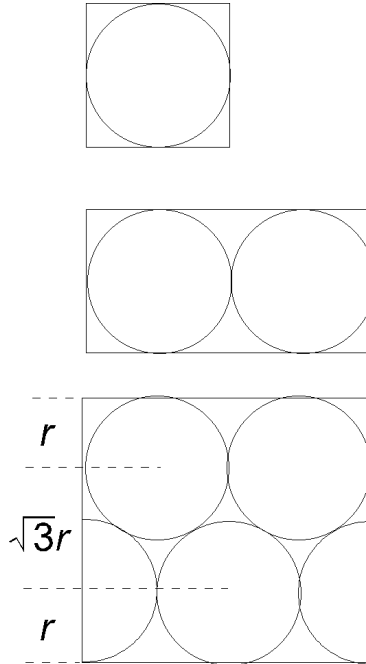


Fig. 4. Window dimensions limit wire packing as end-effects in both dimensions: number of turns per layer and number of layers must both have window dimensions that are integer multiples of wire diameters for a perfect fit.

$$k_p = \frac{2 \cdot \pi \cdot r^2}{(2 \cdot r) \cdot (4 \cdot r)} = \frac{\pi}{4} \approx 0.785$$

The hex configuration has max k_p , and for a rectangular window m wires wide $\times n$ layers, the window area =

$$A_{wndw} = (2 \cdot m \cdot r) \cdot [(2 + \sqrt{3} \cdot (n-1)) \cdot r]$$

Total wire area within window =

$$A_{wire} = \begin{cases} m \cdot n \cdot \pi \cdot r^2, & \text{full occupancy : no missing center wires} \\ \left(\frac{3}{2} \cdot m\right) \cdot \left(\frac{n}{2}\right) \cdot \pi \cdot r^2, & \text{missing center wires from hex configuration} \end{cases}$$

Then wire packing factor is

$$k_{pw} = \frac{A_{wire}}{A_{wndw}} = \begin{cases} \frac{\left(\frac{n}{2}\right) \cdot \pi}{2 + \sqrt{3} \cdot (n-1)}, & \text{full occupancy} \\ \frac{3}{4} \cdot \frac{\left(\frac{n}{2}\right) \cdot \pi}{2 + \sqrt{3} \cdot (n-1)}, & \text{missing centers} \end{cases}$$

For layer $n \rightarrow \infty$,

$$k_{pw}(n \rightarrow \infty) = \begin{cases} \frac{\pi}{2 \cdot \sqrt{3}} \cong 0.907 \\ \frac{3}{4} \cdot \frac{\pi}{2 \cdot \sqrt{3}} \cong 0.680 \end{cases}$$

Average k_{pw} =

$$\bar{k}_{pw} = \frac{7}{8} \cdot \frac{\left(\frac{n}{2}\right) \cdot \pi}{2 + \sqrt{3} \cdot (n-1)} \xrightarrow{n \rightarrow \infty} \frac{7}{8} \cdot \frac{\pi}{2 \cdot \sqrt{3}} \cong 0.765$$

A graph of k_p (AWG) is given in Fig. 6 based on the following equations:

Conductor radius:

$$r_c(\text{avg}) := (4.10\text{mm}) \cdot 2^{-\frac{\text{avg}}{6}}$$

Insulated wire radius:

$$r(\text{avg}) := r_c(\text{avg}) + \sqrt{(1.568 \cdot 10^{-3} \cdot \text{cm}) \cdot r_c(\text{avg})} \quad (\text{triple insulation})$$

Wire packing factor = $A_{\text{conductor}}/A_w = k_p$.

$$k_p(\text{avg}) := \frac{7}{8} \cdot \left(\frac{\pi}{2 \cdot \sqrt{3}} \right) \cdot \left(\frac{1}{1 + \sqrt{\frac{1.568 \cdot 10^{-3} \cdot \text{cm}}{r_c(\text{avg})}}} \right)^2$$

$$\text{AWG}(r) := -19.93 \log\left(\frac{r}{4.10 \text{mm}}\right) \quad \text{AWG}_A(\text{Area}) := -9.97 \log\left(\frac{\text{Area}}{53.48 \text{mm}^2}\right) \quad \text{Gage} = 5 \text{ to } 40$$

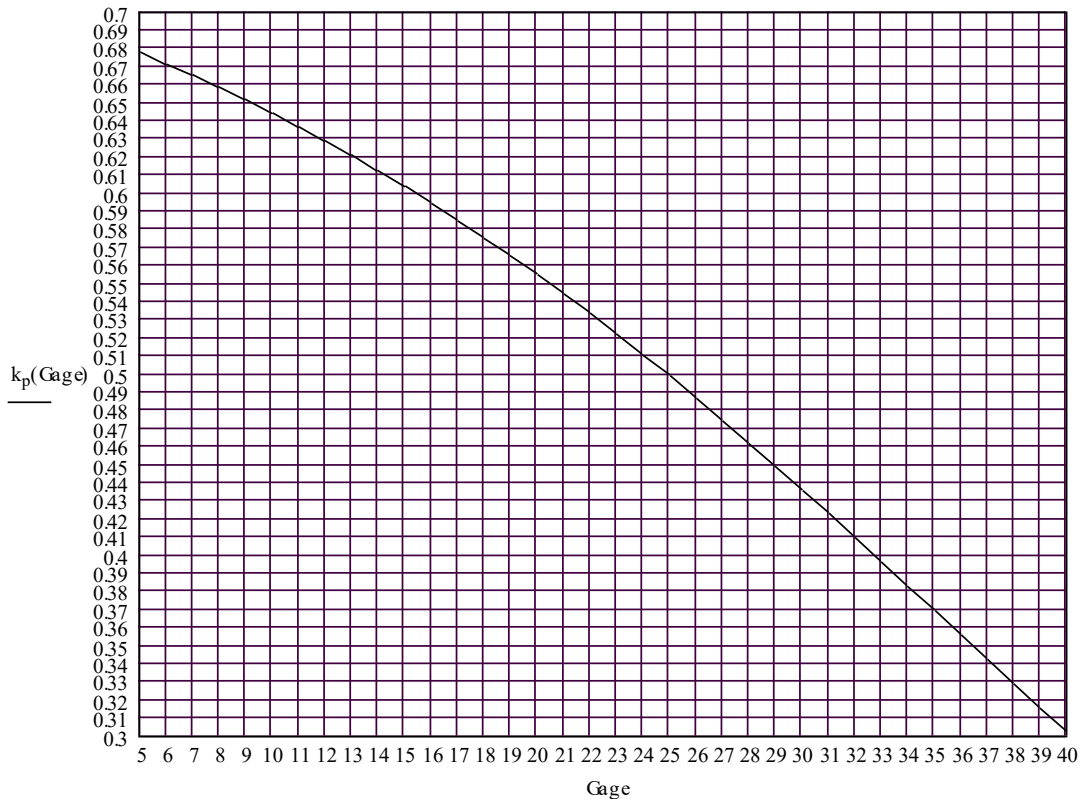


Fig. 6. Winding packing (fill) factor vs American Wire Gage based on equations given above.

Larger wire leaves less nonconducting space between wires because the fraction of the wire radius that is insulation is less. Insulation thickness is relatively independent of wire size.

These design formulas for packing factor guide its maximization and are applied to the motor windings with wire filling the windows between teeth. In previous parts, design tradeoffs for winding area and magnetic path area through the teeth depended on winding resistance, which is reduced by greater winding window area A_w . However, this decreases tooth width which increases magnetic saturation and magnetic loss.

The optimization between them is essentially the same as in transformer design, and the *H2P* section on magnetic design has multiple articles on this substantial topic.^[12] Unlike transductor optimization, the specified $T(\omega_{me})$ in motor design places additional constraints on winding and magnetic-path design.^[9]

References

1. "[Motor Control For Designers \(Part 1\): Basic Principles Of Motor Theory](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, July 2025.
2. "[Motor Control For Designers \(Part 2\): Electromagnetic Force Production In Motors](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, August 2025.
3. "[Motor Control For Designers \(Part 3\): Torque-Current Relationship](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, October 2025.
4. "[Motor Control For Designers \(Part 4\): PMS Motor Electrical Model](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, November 2025.
5. "[Motor Control For Designers \(Part 5\): Deriving Force Production From Magnetic Energy](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, January 2026.
6. "[Motor Control For Designers \(Part 6\): Three-Phase Motor Waveforms](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, April 2026.
7. "[Motor Control For Designers \(Part 7\): Quasistatic And Dynamic PMS Motor Models](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, May 2026.
8. "[Motor Control For Designers \(Part 8\): Step-Motor \$V_g\$ Range And Efficiency](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, June 2026.
9. "[Motor Control For Designers \(Part 9\): Motor Design Parameters](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, July 2026.
10. "[Motor Control For Designers \(Part 10\): Motor Magnetics Optimization](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, July 2026.
11. "[Motor Control For Designers \(Part 11\): Optimal Gap Sizing And Leakage Inductance In Motor Design](#)" by Dennis Feucht, Innovatia Laboratories, How2Power Today, September 2026.
12. How2Power's [Design Guide](#) is a searchable database of free articles and other source materials on a range of topics in power electronics design. You'll find links to magnetics articles there (See "Design Area, Magnetics") or click [here](#) to access those articles directly. You'll also find a link to these articles in the [Power Magnetics section](#) under "designing magnetic components".

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](#)".