



Slot Fill and Design for Manufacturability

For more than 50 years, **WINDINGS** has provided engineered electromagnetic solutions for critical applications in Aerospace, Defense, Automotive and Oil & Gas industries. As a full-service provider, Windings is a leader in the design, test, manufacture and support of custom electric motors, generators and related components including rotors, stators, lamination stacks and insulation systems.

Basic Principle

Electric motors convert electrical energy into mechanical energy in the form of torque. Current flowing through copper wire coils wrapped around an iron core (stator) creates an electro-magnetic field that either opposes or attracts the magnetic field provided by permanent magnets mounted to a drive shaft (rotor). The interaction of the electro-magnetic field with the permanent magnet field is what produces torque. The motor's torque output is determined by the voltage applied to the wire, the density of the wire, and the number of coils. The motor's maximum speed is determined by the amount of current flowing through the coils. The application requirements for which the motor will be applied, therefore, largely determines the coil winding requirements—creating a design challenge for engineers.

As its name suggests, a stator does not move, but it provides the force that drives the rotor. In general, a stator has an outer frame typically made from stacks of aluminum or steel laminations. Within the frame is a magnetic core for creating and containing a magnetic path. The stator is laminated to minimize eddy current losses in the form of heat and is divided into multiple slots. Insulated electrical coils of copper wire are inserted into the slots and arranged so that current passing through them creates an electro-magnetic field. The size and number of slots determine how much wire can be contained in each coil, and the wire diameter determines the amount of current that can pass through the coil.

Stators and Slots

Because stators are cylindrical, the slots are shaped like wedges. The number of slots depends on how many phases of power are provided to the coil windings. A basic single-phase motor usually has four slots that contain two pairs of windings, each offset by 90 degrees; a basic three-phase motor has six slots with three pairs of windings, each pair offset by 120 degrees. To complicate matters, multiples of pole pairs can be utilized to increase the corresponding number of slots.

Some of the greatest challenges for a custom stator manufacturer are related to maximizing the amount of copper wire inserted into each slot (commonly referred to as "slot fill") to maximize torque output. Stator manufacturing is based on relatively simple principles but stators are inherently difficult to build. Beyond the physical design limits and the question of how much slot fill is appropriate for the application, engineers have to account for manufacturability. To balance these requirements, engineers must rely on proven design practices and custom manufacturing techniques.

Slot Fill Factor

Slot fill factor is the ratio of the cross-sectional area occupied by copper wire inside the stator slot to the total amount of available space in the bare slot. In practical terms, 100% slot fill would theoretically result in the maximum possible output torque of the motor, but such a design would be impossible to build. Slot fill ratio, therefore, will always be less than one; insulating slot liners, wedges, and phase separators within the slot use some of the available space; insulation on the wire reduces the amount of cross-sectional area that is conductive material; and round wire, commonly used in coil windings, leaves gaps no matter how efficiently arranged.

On average, copper wire accounts for 65 percent of total slot fill. For applications where power density is critical higher slot fills are possible, but with increasing slot fill comes increased manufacturing complexity which drives cost up and increases the risk of quality issues.

Calculating Slot Fill

Design engineers must account for every component that will occupy the limited space of a stator slot. That means measuring the cross-section area of each item, multiplying that area by the number of times that item is placed in the slot (such as the number of copper coil windings), adding the total area of all items, and dividing that result by the available area in the slot. The formula can be expressed like this:

$$SF_{Total} = \frac{A_{Total\ Wire} + A_{Materials}}{A_{Slot}}$$

Total slot fill includes the cross-sectional area of all materials going into the slot: wire, liners, wedges, etc. To calculate total slot fill, an engineer will start by determining the total area of the bare slot. A CAD model of the lamination or slot geometry can sometimes provide this measurement.

To define the maximum full level for the slot, the engineer must decide where to close off the slot opening. This is often the point where the tooth foot starts to extend from the tooth itself. Area of the actual slot opening is not usually included; this is where a wedge will span the opening. The wedge is held in place by the foot of the tooth to keep the wire in the slot.

- Cross-sectional area of bare slot: A_{Slot}

Once the bare slot area is known, the engineer determines the area of all insulating materials by adding the cross-sectional area of each piece of material. For insulators such as Nomex or Nomex Kapton laminates, this can be calculated from the length and nominal thickness of the material. For powder coat insulation, a manufacturer's thickness measurements can be used. This can vary depending on lam geometry, coating material, and part size.

Because exact sizes are difficult to measure, manufacturers tend to make conservative estimates. For example, when estimating phase separator size in custom motor manufacturing, engineers want to ensure that the phase separator completely separates the two phases that share the same slot—but placement of the border between the coils will depend on the lay of the wire. If the material is oversized to ensure complete coverage, it also uses more slot area.

- Cross-sectional area of all insulating materials: $A_{Materials}$

The last thing to be measured is magnet wire area. That includes the thickness of wire insulation, which means total magnet wire area will be greater than the area of copper wire. Also, the calculations will need to account for the gaps left between windings of round wire.

Starting with the area of one wire with insulation, which may be available from a magnet wire catalog or handbook, an engineer will multiply the area of that wire by the number of wires in parallel and the number of coil turns to get the total area of the coil.

Assuming the coil area is round (which is unlikely because of non-uniform layering), the engineer may square the diameter for a more conservative estimated coil area. If applicable, that estimated coil area is then multiplied by the number of coils per slot.

Total area of magnet wire:

- Calculate area of one wire, including insulation

$$A_{wire} = (\pi r_{wire}^2)$$

- Multiply the wire area by the number of wires in parallel and the number of turns per coil to get the total coil area

$$A_{coil} = A_{wire} * N_{parallel} * TPC$$

- Convert total coil area to a diameter

$$D_{coil} = 2 * \sqrt{A_{coil}/\pi}$$

- Square the diameter to get estimated coil area

$$A_{Est} = D_{coil}^2$$

- Multiply the estimated coil area by the total number of coils per slot

$$A_{Total\ wire} = A_{Est} * \#coils/slot$$

Area of magnet wire: $A_{Total\ Wire}$

Factors in Manufacturability

Each of these components has its own characteristics. To meet the requirements of a given application, engineers must find a balance within the range of options for each component, and an optimal combination among all materials. No single feature is always best; every design is the result of tradeoffs. Greater need for motor optimization often

leads to custom motor designs where the emphasis is on performance over cost and manufacturability; as production volumes increase, cost and manufacturability generally become more important.

As slot fill percentages increase, so do time and labor costs. Among manufacturers, a percentage of 60 to 70 is considered standard. Stators with slot fill percentages of 70 to 80 percent are more challenging to build and may require specialized tooling. Above 80 percent is very difficult; inserting all the components without damaging the wire or its insulation requires custom tools and fixtures, and may take up to three times as long or longer to manufacture than lower slot fill designs. Here are some of the choices and tradeoffs engineers make for manufacturability.

Stack Aspect Ratio

This represents the relationship of stack length to outside diameter (OD). As stack length increases while OD remains constant or declines, the maximum possible slot fill factor decreases while the difficulty of manufacturing increases.

In principle, the higher the aspect ratio, the more difficult the design becomes to build. It is more difficult to get the wire to compress in the middle of the stack length on longer parts as leverage is reduced. For example, a part with an aspect ratio of about 3.25 will be more difficult to build than one with the same OD but a ratio of 2.5 because of the effort required for insertion.

Practice bears this out. There is a direct correlation between aspect ratio and manufacturability. A custom builder may achieve slot fills up to 65 percent on a stack with an aspect ratio of 10, while a slot fill percentage of 70 requires an aspect ratio closer to 3. Slot fill percentages of 80 or more may be possible if the aspect ratio is less than 1.

Aspect ratio is a product of design, driven by application requirements. To achieve higher slot fills, manufacturers look to develop unique solutions such as new compression methods to fit the wire into the slots.

Slot Opening

Slot opening design is affected by the size of the chosen magnet wire. During insertion, coils of wire need to pass from the inside diameter (ID) of the stack into the slots. The larger the opening, the easier it is to insert the wire, but a larger slot opening can have a negative impact on flux path. Also, if the slot opening is too small for the wire to pass through, the wire must be wound into the slots turn by turn. This increases the difficulty of inserting and compressing the wire and reduces the maximum possible slot fill due to limited space for tooling.

Coil Bundle Size

Coil bundle size refers to the number of turns per coil and the number of wires in parallel. In random wound coils, more turns and more wire in parallel leads to a large coil bundle with many wires crossing each other without a set pattern. Twisting and crossing wires during the winding and inserting process creates extra dead space between individual strands of wire. This reduces the available slot area and can increase the difficulty of insertion. In addition, a large bundle coupled with a small slot opening will increase the difficulty of assembly as the wires may need to be passed through the slot one by one.

Wire Gauge

The gauge (diameter) of magnet wire influences design in two ways. One is total diameter, which has a direct relationship to potential slot fill; the other is actual conductor area—the amount of total diameter that is wire, not insulation—which helps determine how much current can flow through the coil.

One way to increase conductor area is to use a larger gauge of conductor to get more copper with less insulation. But as wire size increases, it becomes stiffer and more difficult to handle. Stiff wire is less likely to conform to the slot shape and to other wire in the slot. Using smaller gauge wire will improve ease of handling but will increase the ratio of insulation to conductor. Smaller gauge wires can also result in more turns or parallel wires which increases the risk of wire damage during insertion.

For smaller stators up to 12” in diameter, the most common wire gauges are between 22 and 28 AWG. This size range provides a good copper to insulation ratio, is durable and easily formed, and is small enough to be readily worked.

Design and Performance Decisions

Beginning with the intended application, engineers adjust the specifications of all these factors to design a motor that meets performance requirements and can be manufactured economically. The design process involves decisions about slot opening, slot shape, and winding and insertion methods.

Slot Opening

As mentioned above, a slot opening must allow wire to pass through during insertion and accommodate some manufacturing aids that protect the wire from the edges of the steel teeth, especially when slot liners are the primary means of insulation. The insertion aid is typically a thin piece of protective plastic that helps guide the wire into the slot; however it reduces the opening space by a small amount and should be accounted for in the design

To allow the wire to fit through the opening and leave some space for the guides, the minimum opening should be approximately two times the wire diameter. Larger coil bundle sizes can make insertion more difficult. This increases the opening size requirement; an opening dimension of three or four times the wire diameter is common.

Slot Shape

The amount of material that will fit in a slot depends on the shape of the slot as well as the area and shape of the stator components. The goal in designing slot shape is to maximize capacity for copper and other components while minimizing impact to magnetic flux or manufacturability.

Most distributed coil stators with random winding use one of two slot shapes: flat bottom slots with squared or rounded corners, or rounded slots with a radius along the bottom—a kind of teardrop shape. At first glance, the flat bottom slot appears to have higher capacity, but its corners can create challenges.

For example, if a slot liner is used to insulate the stack, it will seldom conform perfectly to the slot and fill in the corners, creating dead space. Even if the liners fit perfectly in the slots, round magnet wire will still not conform to the flat bottom and corners. This also happens in stacks with powder coating: Sharp corners typically lead to buildup of excess powder coating and create similar dead spaces in the slot that cannot be used by the wire.

Rounded bottom slot shapes resolve both problems. A rounded bottom slot provides a consistent surface to which the slot liners conform. The radius can be optimized to allow the wire to fill in more space around the slot edges. Rounded slots can increase maximum slot fill by 5–10 percent.

One manufacturer had a calculated fill factor of about 93 percent in a design with a flat bottom slot shape. During insertion, the first prototype would not allow all the wire to fit. Engineers considered increasing the slot size, but instead tried changing the slot shape to a rounded bottom. This allowed the insulation and wire to better conform to the shape. The revised design held the same amount of copper fill and made the stator manufacturable without changing the winding.

Coil Winding and Insertion

Beyond slot design, coil winding and insertion techniques can affect manufacturability and slot fill. Two relatively coil designs allow engineers to break down coil size without changing the number of parallel wires or turns in the coil. One is often called a “double-back coil”; the other is known as “2-coils-make-1”.

- The double-back coil uses half as many turns and same number of wires in parallel but twice as many coils, which increases the overall length of the wound coil set. Assemblers insert two coils back to back for each slot; this allows them to break down the coil into half the size which is more manageable while still inserting the same amount of wire per slot.
- In the 2-coils-make-1 method, each set has the same number of coils. Each coil has half as many turns and wires in parallel but twice

the total number of coil sets. Assemblers insert one coil from each coil set at the same time. The coil sets will be connected in parallel once inserted to achieve the same number of wires in parallel. This is similar to the double-back method in that the coil bundle is half the size, but 2-coils-make-1 does not double the overall length of the coil.

Techniques and Tradeoffs

To further improve slot fill, some additional manufacturing techniques can be implemented in place of—or in addition to—good design. These methods are usually specialized to the individual case, but frequently involve an advanced compression system that increases the amount of force on the wire during insertion without damaging the stack or wire. The downside to some of these techniques is that they require additional time and materials for designing the specific tooling and manufacturing processes to implement them on a part.

Lamination Variation

Stacks are made of individual laminations which vary from one to the next depending how they were manufactured. In addition, depending on the manufacturing process and how they are being held, laminations can shift as they are stacked. This can lead to slots that are not 100 percent straight, potentially affecting overall slot fill of the whole stack.

Random Winding

Coils with random winding can cross over each other and will not be consistently layered in the slots. This variation is difficult to anticipate in the design phase. One way to reduce variation in coil layering is to use precision wound coils that are either hand inserted or machine inserted. This can reduce wire crossover, but the additional tooling required to place the wires precisely in the slots can reduce overall slot fill.

Segmented Winding

With segmented winding, the stator is broken up into multiple individual segments based on the number of teeth in the design. Those individual segments are then wound as a concentrated pole

where the wire is either wound separately and installed to the tooth or the wire is wound directly onto the tooth without any interference from the neighboring tooth. Once the teeth are wound they can then be assembled together to form the full stator assembly. This method can allow for higher slot fill since the tooling is all external to the stator and you do not need to have the wire pass through a slot. The difficulty in this assembly is the design of how the teeth come together and are restrained to ensure that electromagnetic path is closed.

Prototyping Methods

To identify and offset some of these technical challenges, advanced manufacturers are working with dummy stacks that are 3D printed out of plastic or made from steel using electrical discharge machining (EDM). These simulations allow manufacturing teams to try a slot fill, define tooling, and provide better feedback to designers earlier on in the design cycle of new product development.

Conclusion

In electric motor design, manufacturers can choose between machine assembly and hand building. In doing so, they also choose between manufacturability and high slot fill factors. Despite advances in automation, stator coil windings made by machine are still limited to lower slot fill factors. To achieve consistent slot fill factors higher than 80 percent, hand building remains the industry standard.

About the Author

Blaine Alderks is the Sales Application Engineering Manager at Windings, Inc. He has extensive experience in manufacturing and design for manufacturing. Alderks works closely with customers to understand and define their needs and collaborates with them to solve their unique problems.

About Windings

Windings is a privately held company headquartered in New Ulm, Minnesota. The company, founded in 1965, engineers electromagnetic solutions for critical applications in several industries: aerospace, defense, automotive, medical, oil and gas, and general factory automation.



With more than 165 years of combined experience, the Windings engineering team partners closely with clients from project inception to ensure an optimized outcome that meets or exceeds client expectations. Windings offers design analysis and

simulation, including electromagnetic, thermal and mechanical modeling, with the goal of providing the optimal solution design based on unique application requirements.

For further information, please contact us!

@ <https://www.windings.com/oil-and-gas-industry/>

📞 1-800-795-8533

🌐 sales@windings.com