DESIGN CONSIDERATIONS TO OPTIMIZE STATOR MANUFACTURING

In the past, lamination design was primarily an electro-mechanical consideration. Today, improved performance and efficiency is increasingly important; however, so is reliable, minimal cost stator assembly. Two major factors influence the ability to automatically assemble a stator: lamination and winding design.

The most significant single factor to be considered in automatic stator assembly is the lamination design. The lamination itself cannot be altered without paying a very large penalty in modifications to tooling and/or complete new and expensive die. The second most important consideration is winding specifications (wire size, turns, and winding configuration or pole configuration). Unlike, the lamination design, winding specifications can be readily changed without a major penalty.

In order to optimize lamination/stator design for manufacturing, there are three major areas involved with lamination design which should be considered (Outside Diameter Shape, Inner Diameter/Slot Shape and Winding Specifications):

OUTSIDE DIAMETER SHAPE
The O.D. shape of the lamination is always important from the standpoint of material savings, particularly when pressing laminations from stripped material. When designing the O.D., it should be considered to add a location notch. The location notch is often referenced when placing the stator into forming and lacing tooling. In addition, a location notch is very important if the stator is to be assembled by a fully automated system.

The shape of the cleating notch can be an important consideration in that the cleating slot should be standardized for all laminations (regardless of stator size). When building stator cores with a great variation in O.D.’s, the same cleat material can be used for all of the different lamination sizes. The only difference between the different laminations will be the number of cleats (which is programmable). Location of the cleat notches is also important from the standpoint that it should be located directly behind a tooth in the stator to optimize back iron and provide the best possible magnetics. If possible, cleating notches should be equally spaced about the periphery of the stator so that the forces are opposed by the cleating action on the opposite end. This becomes much more important in larger stators where the number of cleats required increases.

Some generators and servo motors require stators which are skewed. When automatically assembling, these stators can be stacked, insulated and inserted with wire prior to skewing. Skewing is then done by a hydraulically actuated device, which skews the stator either by a slot on the O.D. or by a protrusion from the O.D. There is no “rule” for the dimension of this slot since its depth and width is determined by the size of the stator and the skew angle of the minimum stack. Stators that have been skewed can be bonded (glued), which is time consuming. Welding the stator is a much faster process. It is recommended that when welding a skewed stator, the welding path follow the skew and remain directly behind a stator tooth to optimize back iron.
INSIDE DIAMETER,SLOT SHAPE

- Slot Opening

From a manufacturing standpoint, it is always desirable to have the largest possible slot opening in a lamination (See Figure 1). From a performance standpoint, a large slot opening can decrease motor efficiency and increase noise. Hence, final selection of slot opening is a compromise between the desired design parameters and the restrictions imposed on the manufacturing process.

When automatically injecting coils into a stator, the coils are guided into the stator core (and protected from the stator core) by the injection blades. Since the blade fits around the stator tooth, the stator tooth dimensions directly affect the blade design. The two major dimensions that determine the ease of injection and the longevity of the injection blades are the length and thickness of the blade fins.

From an insertion tooling design point of view, careful consideration needs to be paid to the thickness of the insertion blade fins and the resulting Blade Gap (Figure 2). This Blade Gap needs to allow for insertion of the coils in a “Precision Wind” range or the “Level Wind” range. In between the two is the “Locking Wire” range. This condition will occur when the wire staggers within the blade gap and can not proceed in either the precision or level manner. The resulting side ways forces will lock the wires within the blade gap. Referring to a Blade Gap Chart when designing both the stator lamination and the respective injection tooling can prevent this condition.
In order to maximize the strength of the blade lip, the lip should not exceed three times its thickness. If the stator tooth exceeds this dimension, the blade fin will have to be increased in order to protect the wire from the stator core during insertion. Exceeding a 3:1 ratio could compromise the lips integrity and lifetime.

Since the injection tooling occupies part of the slot opening (as shown in Figure 2), the resulting slot opening must be larger than the thickest wire to be injected into the lamination. For small and medium frame stators up to NEMA 320 frame (IEC 200), the stator slot opening should be 0.03 inches (0.8mm) larger than the maximum wire size. For stators larger than this, the slot opening should be 0.06 inches (1.6mm) larger than the maximum wire size.

- Wedge Entry Area

Wedge entry area (wedge seat) is very important to assure that the bore closure wedge stays in position after injection. If the wedge seat area in minimized, the wedge could turn during or after injection. Not only will this require additional handwork to straighten the wedge; but it could cause wires to be caught between the closure wedge and the slot liner.

For automatic insertion of the closure wedge, there is a very definite configuration that is desirable. Figure 1 outlines this configuration for the bottom of the slot, and gives a few basic dimensions defining the desirable shape.

- Slot Depth to Width Ratio

Referring to Figure 1, the depth of the slot, is defined as the length from the bottom of the slot to the back of the slot. The width is defined as the width at the bottom of the slot prior to converging toward the slot opening. For ideal conditions to inject wire, a slot should be extremely narrow in width and very long in depth. From a practical standpoint it has been found that a practical value for this ratio should be 4:1. As in all general rules, the number 4 is not final; however, it is a practical rule in which any lamination design having a ratio in the area of 4 or greater can be expected to result in relatively problem free insertion. A lamination having a ratio of 3 or less (particularly when the ratio approaches 1), begins to present problems in process which are non-existent in the higher ratio design. Most of these problems are related to the wedge such as wire behind the wedge, wedge dislocation or wedge falling out of the slot.

- Shape of the Back of The Slot

It is generally found in two basic configurations: square bottom or a round bottom. The round bottom is the preferred shape. During injection, the wire will come through the blade gap and toward the back of the slot. With a round back slot, the wire has a tendency to fill the back of the slot and “roll” into the corners (keeping the blade gap clear for the entry of additional wire and injection of the wedge). With a square back slot, the wire has a greater tendency to hit the back of the slot and stay there. Not only does this impede the wire from entering the blade gap; but, the wire will usually not fill the corners of the slot (thus minimizing maximum potential slot fill).

The present basic practice in lamination design is to consider what is the best
lamination design in order to obtain the desired electrical characteristics and performance of the motor. From an electromechanical standpoint, there are some areas that must differ within a family of laminations to maximize the performance of the motor. One example is a 24 slot lamination design for a 2-pole fractional and 36 slot lamination design for a 4 or 6 pole.

Although the number of slots may differ, there are areas that can be standardized within a family of laminations (i.e. I.D., slot opening, wedge seat, end turn dimensions). Usually these small variations can be eliminated with no significant effect on the electrical performance of the motor. By standardizing on these dimensions, manufacturers can use identical toolings, even though the laminations are not identical in all other respects.

Winding Specifications (wire size, turns and pole configurations) are the second most critical criteria for automatic stator processing. Compatibility of the selected tooling blade gap (which is dependent on the slot opening) and the wire size to be used is essential. However, (unlike lamination changes) wire sizes and number of turns can be varied to a certain degree without incurring penalties of product performance or decreased machine utilization from changeover. As mentioned in the previous section the larger the slot opening the greater the versatility of wire size selections.

When designing the winding specification, consideration needs to be paid to five major areas:

**WINDING SPECIFICATIONS**

- **Wire Sizes and Number in Parallel**

When stators were hand wound, the maximum wire size was limited to 18AWG (1.00mm). This was because such a wire size was easy to form and insert into the stator by hand. With the advent of form winders, the maximum size was increased to 16AWG (1.25mm); however, the flexibility of these machines was limited by their ability to control the windings and the numbers of wires that could be wound in parallel.

With modern shed winders, maximum wire size can go up to 13 AWG (1.8mm). In addition, shed winders designed for mid and large frame stators exceeding NEMA 180 frame (IEC 112 frame) are capable of winding up to (12) twelve 18AWG (1.00mm) wires in parallel.

- **Winding Configuration**

Although the coil insertion process today uses almost 100% concentric type windings, hand inserted lap windings have been preferred by many motor designers (since the lap design is usually slightly more efficient than the concentric design). In addition, the lap winding results in slightly shorter end turns since the coils are hand placed and not automatically inserted (allowing the overall motor package to be reduced).

The major problem with the lap design is that it can not be automatically inserted. When hand inserting, the start of the first coil is left hanging for placement of the last coil underneath it. When automatically inserting, all of the coils are inserted at the
same time. It should be noted that lap windings could be inserted if they are modified. A “modified lap” requires the last coil to go from the top of its starting slot to top of its finishing slot (instead of top to bottom with a hand placed coil).

Although it is possible to insert modified lap windings, it is almost impossible to achieve slot fills and production rates of equivalent concentric windings. This is because concentric designs have most of their coils nested within a pole. This design allows for much faster winding times by eliminating unnecessary wire handling. In addition, concentric wound coils eliminate a great deal of post insertion labor since many interpole connections can be automatically maintained.

The vast majority of the single phase motors produced today follow a standard 2, 4, 6 or 8 pole configuration varying only in the number of concentric coils per pole (which is limited) and slot fill. Three phase motors present a much greater opportunity for variation in pole configuration. The most popular is the three layer, concentric design. Such a design can share or not share slots between phases (depending on the pole configuration and the number of slots).

The 4-pole 3-phase motors present a high degree of variation. One fairly popular design today is the consequent pole design. The main reason is the two-layer (3-coils per layer) configuration usually does not share any slots. This allows for simultaneous insertion of all the coils or (worst case) two insertions. Winding time is less for the consequent design since only six coils for a complete motor need to be wound (rather than 12 coils for the 4 pole, 3 layer concentric design).

However there are some disadvantages to the 2 layer consequent.
1. Usually considered being a less efficient motor.
2. More interpole or lead connections.
3. Has been known to require more copper than the three layer design.
4. Can only be used on small to medium size motors.

- Slot Fill

This is usually given as a percentage figure and expresses the amount of wire in a slot in relation to the total slot area. Although there are several methods of calculating slot fill, many do not take into account the size or thickness of the insulation (slot liner, interphase wedge and closure wedge) or the air gaps between the wires. The following describes a slot fill calculation method that accounts for all of these factors.

For purposes of this paper the term “slot fill” (abbreviated S.F.) will be calculated as follows:

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S.F. = \frac{(\text{Wire Diameter})^2 \times (\text{Number of Turns})}{\text{Available Slot Area}}
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Wire diameter must include insulation thickness.

Available slot area (Figure 3) is the slot area calculated from the lamination subtracting the insulation occupying area and the area between the base of the wedge and the bore of the slot. This results in a true available slot area within which wire can be inserted.
Today's trends and desires are to maximize slot fill. By maximizing slot fill, the resulting motor maximizes performance efficiency while minimizing material cost and motor package. For manufacturers, this has become a necessity. Not only to compete in the marketplace; but, to meet with governmental efficiency regulations.

A few years ago a slot fills of 50 to 65% was acceptable and manufacturing efforts were concentrated on reducing labor. Today, slot fills of 75 to 80% are fairly common and produced in volume with relatively few production problems. In some cases slot fills up to 85% have been achieved. This can only be accomplished through optimizing the lamination/stator design as well as the manufacturing process.

Typically, stators which have all of their coils inserted simultaneously can not achieve a slot fill exceeding 75%. If higher slot fills are required, manufacturers will insert the stator in multiple passes (layers). Once the first layer is inserted, the coils must be drifted. This operation involves pressing the coils to the back of the slot. This will allow for subsequent insertions to be easier since the slot area has been maximized. Usually, implementing the drifting process will permit for slot fills of 80% to be achieved.

If slot fills exceeding 80% are required, additional intermediate forming is required. This includes using expanding drift fins, expanding I.D. forming and even collapsing O.D. forming. By optimizing coil position, subsequent insertions require less force; thus permitting for slot fills up to 85% to be achieved.

- **Coil End Turns**

Since the coil end turns do not contribute to motor performance, it is often desired to have them minimized. Not only does this save on space; but minimizing end turn length will minimize wire usage (thus reducing motor cost). End turn length can be minimized a variety of ways.

The primary attribute effecting end turn height is winding pole configuration. A two
pole stator will typically have longer end turns than a 4 pole or 6 pole coil. This is because the fewer the number of poles, the greater the span of the coils. A 2 pole coil spans 180° of the stator where a 4 pole coil only spans 90°. In order to insert the two pole, the coil length must be increased so that the coils can “wrap around” the stator. This results in an increased end turn height.

One of the easiest ways to minimize end turn height is by inserting in multiple layers using “grated coils”. With the “grated coil” method, the first layer of coils is inserted and drifted. The coils of the second layer are then wound slightly shorter than the first. This is accomplished by automatically bringing the coilforms closer together on the winder. The third layer is then wound and inserted with coils shorter than the second layer. By shortening the coil between subsequent layers, the amount of wire inserted into the stator is minimized; thereby, minimizing the stator end turns.

- Phase Insulation

This is perhaps one of the most difficult, time consuming, and expensive (from a labor and material standpoint) areas within a stator. Some motor manufacturers have eliminated phase insulation by using the new Corona Resistant wire enamels. Originally designed to minimize corona discharges for variable frequency and servo motors, these new wire enamels are very effective at eliminating phase insulation in single phase and low voltage three phase applications.

Due to running voltages, temperature classification or operating environment, some stator designs can not eliminate phase insulation. For such applications, phase insulation can be applied in several different methods.

One of the most popular is the H-paper type insulation that must be installed during the process of winding the stator in between the layers or phases of windings. This involves winding one layer of the stator and hand inserting the H-paper type insulation over the inserted coils. The next layers of coils are then inserted over the first layer and its H-paper. The H-paper can be automatically inserted into the stator. It should be noted that optimization of this process involves a great deal of experimentation of the H-paper shape.

A second method is to insert the first layer and proceed then by hand to add an adhesive tape to the end turns, which acts as a phase insulation. This is also a labor intensive operation and requires special materials which sometimes are not compatible with the products being manufactured, i.e. the adhesive tape.

The third method, is an operation in which all three layers (3 phase) or two layers (single phase) of the motor are inserted in a continuing flow operation without interruption for phase insulation. A variable wedge length device is included on the equipment for notching wedges, which in the end result constitutes a part of the phase insulation. After completion of the winding of the stator, phase insulation is then added into and between the end turns of the wire as required. This material can be of the same polyester type as used in the "H" paper; however, it is merely a strip of material in which scrap is virtually eliminated except for the rounding of the corners of the insulator.
There are several advantages using this method:
1. The non-interruption of the winder operation.
2. The equipment is not idle during phase insulation and stator handling is minimized.
3. The elimination of polyester scrap is an obvious cost saving.
4. The time required to insert the phase insulation is substantially less than either of the above methods.

CONCLUSION
A compromise between motor performance and ease of manufacturing can be achieved as long as both are considered from the start of motor design. Many design attributes effect the ease of manufacturing and performance. The primary of these is the lamination slot design. A stator with a poor slot design may be able to be manufactured; however its potential maximum slot fill will be minimal and scrap rate could be unacceptably high. Secondary considerations include coil configuration, wire size/turn count, end turn dimensions and insulation materials. Sometimes, these can be changed with minimal effect on manufacturing; however, great care needs to be taken to insure this.