

Technical Note 12-01

Random-wound vs. Form-wound Stator Coils

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Overview

There has been significant debate, mis-understanding, and perhaps mis-information circulating and propagating throughout the industrial induction motor marketplace among suppliers and customers surrounding the advantages and disadvantages of random-wound (mush-wound) stator windings and form-wound stator windings. It is important for clients and suppliers to understand the technical differences and clearly identify market mis-perceptions so that rational decisions about motor selection can be made. The intent of this technical note is to address this issue.

Background Research

- The following clause is excerpted from the Introduction section of Reference E:
*The approval of electrical insulation systems for use in rotating electrical machines driven from voltage converters is set out in two Technical Specifications. They separate the systems into those which are **not** expected to experience partial discharge activity within specified conditions in their service lives (Type I) and those which **are** expected to withstand partial discharge activity in any part of the insulation system throughout their service lives (Type II).*
- Reference D is specifically applicable to Type I insulation systems “...typically used in rotating electrical machines rated at less than 700 V r.m.s and tend to have random-wound stators...”
- Reference E is specifically applicable to Type II insulation systems “...generally used in rotating machines and tend to have form-wound coils, mostly rated above 700 V r.m.s.”
- Reference F, Sections 12.60.1 & 12.60.2 provide specifications for “...600 volts or less (random-wound)...” and “...medium voltage, 5000 volts or less (form-wound)...”

Technical Discussion

There are three fundamental technical areas of concern when evaluating the performance of a coil in an induction motor; insulation break-down, electro-magnetic performance, and thermal effects. What follows is a summary discussion on each of these fundamental areas of concern.

Insulation Break-Down

The current perception among some suppliers and customers is that form-wound motors are superior to random-wound motors; there have been numerous publications to support and even propagate this perception¹. At the time of the writing of Ref A and Ref B (both of Kato Engineering; now a subsidiary of Emerson Industrial Automation), Pulse-Width-Modulation (PWM) based motor drives and voltage converters were relatively new to the market. As a result of the fast switching of these highly efficient drives, voltage spikes and circulating currents at higher harmonic frequencies were induced in conductors that resulted in excess heating and eventual insulation material failure; these failures would not be witnessed in a ‘pure sine wave’ driven motor as the rate of change of voltage and peak voltages would be well within insulation break-down limits. However, in recent years, winding insulation materials have improved dramatically and Global Vacuum Pressure Impregnation (GVPI) processes have also improved. Additionally, the IEC² has established standards for testing of winding insulation in motors that are intended to be used with PWM type voltage converters³; manufacturers have responded with ‘Inverter Duty’ motors and transformers that utilize more durable conductor enamel with specialized coating that are resistant to voltage spikes.

If a cursory review is conducted of the references, it becomes clear that form-wound stators are generally viewed as applicable to medium voltage motors while low voltage (< 690 V) motors are generally assumed to be random-wound.

¹ Refer to references A and B

² International Electro-Technical Commission

³ Refer to references D and E

These standards and specifications do not preclude a low voltage motor from having a form-wound construction however, but do seem to indicate (and Ref C suggests) that for low voltage motors, form-wound construction is not required. However, for medium voltage motors, the risk of partial discharge/corona effect is more prevalent; as a result, designers typically employ *only* form-wound coils in the construction and design of medium voltage motors instead of using a random-wound coil topology.

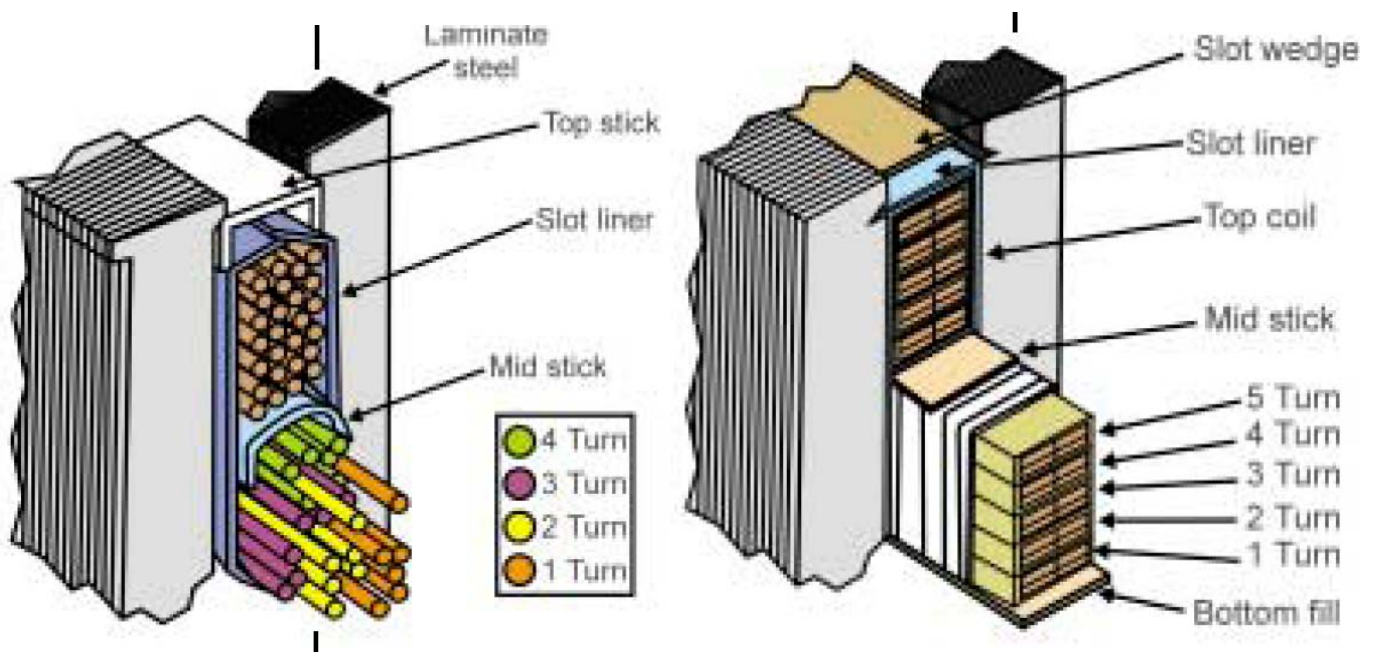
Electro-Magnetic Performance

Similar in nature to the perceptions regarding insulation break-down of random-wound coils vs. form-wound coils, there seems to be some disagreement regarding which style of coil will provide superior rotating machine performance.

In general, there are only a few criteria that govern the performance of one design over another when limiting the evaluation to differences in coil designs –

- Ratio of slot copper cross-section to stator lamination steel (slot fill)
- Slot gap width
- Skin Effect and Proximity Effect in conductors

Due to the distinct advantage of maximizing slot fill (thereby minimizing air pockets in stator slots) in both random-wound and form-wound designs, effects from the skin effect and proximity effect are effectively equal or the differences are negligible. One could perhaps argue that a form-wound coil will be easier to analyze and evaluate due to the ordered structure of the conductors within the slot but unless the simplification of analysis produces a performance enhancement, there is little practical value to the end user.



In a random-wound stator, the slot profile is typically bulbous in shape with a small opening near the rotor air gap; this opening is provided to insert the random-wound coils during assembly, a few conductors at a time. The slot area is carefully selected to ensure that slot fill is maximized based on the number of strands of wire, number of coil turns, and insulation materials required. If the motor designer fails to understand these intricacies, it is conceivable that excess slot area would be designed-in to preclude economic risk during prototyping. This extra slot area will often not be addressed after production starts due to the cost of changing tooling. To the contrary, a form-wound coil is manufactured from rectangular copper strip that is formed into shape and then inserted into a rectangular slot in the

stator. The slot is designed up-front to accommodate the rectangular shape of the formed coil, the dimensions of which are quite predictable. As such, it is easier for a designer to feel confident that a form-wound coil and stator will have good slot fill during prototyping without requiring further geometric analysis or calculation and precluding the risk of re-tooling after prototyping. For this reason, many form-wound motors are viewed as having better slot fill and slots that fit tighter on the windings; however, a well-designed random-wound motor will easily out-perform a poorly designed form-wound motor.

Additionally, analysis programs and equations developed to predict the performance of induction machines generally don't make distinctions between form-wound or random-wound coils explicitly. Instead, focus is paid to the stator slot geometry; purely rectangular slots that are required to accommodate form-wound coils incur a performance penalty. Regarding slot fill, analysis of total cross-section of the conductors in the slot is used and the specific arrangement of the conductors in the slot is typically ignored during performance prediction and analysis⁴.

A larger stator slot gap results in higher magnitude EMF⁵ harmonics and higher slot leakage reactance that tend to degrade performance, result in torque ripple, or cause excess radiated electro-magnetic and acoustic noise. For some applications (for example, military applications aboard submarines), a random-wound stator is preferred to minimize radiated acoustic noise and torque ripple (which, depending on the application, would result in radiated or structure borne noise). In some commercial applications, these criteria are not as important so the systems engineer is open to select either a random-wound or form-wound motor or make decisions based on other criteria. For comparable slot fill of copper in a given slot, a random-wound motor will have less leakage inductance due to the smaller gap opening which in-turn will allow for a more efficient, better performing motor. Additionally, a random-wound stator will allow the motor designer more geometric flexibility with slot shape since there is no constraint to make the slot rectangular; this will allow for a more efficient handling of magnetic flux during the optimization stages of design.

Thermal Performance

A critical source of heat (and source of inefficiency) in an induction motor is the windings; specifically Joule heating due to current flow through the conductors. Fundamental heat transfer analysis tells us that for a given quantity of heat flowing across a surface boundary, the difference in temperature required is inversely proportional to the thermal conductivity of the material between the thermal source and thermal sink.

$$Q = kA \frac{\Delta T}{d}$$

Large induction motors are typically cooled by forced convection by a separately attached blower/motor assembly which forces air through the operating motor to remove heat and reject that heat by exhausting to the surrounding environment. The copper winding is covered with various layers of insulation and resins and retained in a slot made from silicon steel; ambient air is blown through vent openings in the steel to remove heat. If we consider the heat flow at a given point in the coil, heat is generated in the copper material and increases the temperature. The heat is forced to flow across the insulating material, through the steel laminations, and then transfer to the flowing air. Copper has a very high thermal conductivity relative to the insulation and the dimension of the copper windings is relatively small so it is safe to assume that the temperature across a copper conductor is quite uniform. Steel laminations are a relatively good conductor of heat as well though there may be several inches of steel between the heat source and the flowing air;

⁴ For example, RMxprt tools coupled with Maxwell (formerly owned by Ansoft) model a winding as a 'stranded conductor' which imposes an artificial constraint on the conductor of uniform current density across the entire winding cross-section, the winding is modeled as a solid mass and that mass is assumed to be placed in the slot. The exact location of each conductor in the slot is ignored as any effects due to individual conductor placement are deemed to be negligible.

⁵ Electromotive Force as described by Farady's Law of Induction

a temperature gradient will form across this distance as heat flows from the winding to the air. The largest temperature drop by far, though, is the insulation material itself; most electrical insulating materials have a rather poor thermal conductivity.

In a random-wound motor, the winding wires or strands are intended to be 'packed-in' quite tightly but having small gaps between individual conductors is unavoidable. Each conductor is also coated with enamel which decreases the effective copper for a given cross-section (generating more heat for a given current) and enamel is a poor thermal conductor. Further, a slot liner (typically of a thin, durable insulating material) is inserted into the slot prior to inserting the conductors, effectively blocking good heat transfer from the coils to the steel. This construction is necessary for electrical insulation but detrimental for heat transfer. Further, a random-wound motor typically has tightly packed end-turn windings that preclude air flow through the end-turn mass resulting in higher than expected temperatures in the internals of the end-winding.

In contrast, form-wound windings, while still being wrapped in insulating materials and being subject to poor cooling construction within a slot, are quite open and well ventilated on the end-turns. This allows circulating air around the end-turns of form-wound coils and assists in heat removal. Additionally, form-wound coils are typically constructed from 1 strand of a large conductor with enamel coating while a random-wound coil is typically constructed from several strands of a given wire gauge; each strand is likely to be coated in enamel thereby taking up more space for the same cross-section of copper. Additionally, round wires have a characteristic 'packing ratio' which accounts for the inevitable spaces left between several circular objects packed as efficiently as possible.

In comparison, a form-wound coil of equivalent copper content, efficiency, power rating, and cooling air geometry as a random-wound should run cooler; however, by providing for more effective cooling of random-wound windings and/or increasing cooling air flow, a random-wound motor could run cooler than a similar form-wound motor. Additionally, a random-wound motor of similar ratings can be more efficient than a form-wound motor due to the smaller slot gap; higher efficiency means less waste heat which in-turn means lower temperatures.

Concluding Remarks

Ward Leonard manufactures a broad spectrum of induction motors from fractional horsepower to > 1500HP incorporating both random-wound and form-wound stator coils in the construction. In all cases (independent of size or coil type), the stator assembly is subjected to a 'double-dip' GVPI process with rigorous in-process controls. Further, the rated voltage of Ward Leonard motors for military applications is 480V while motors for commercial applications are currently limited to 690V; at the time of this writing, all Ward Leonard motors are Low Voltage Motors. Un-biased research has shown that there is minimal technical benefit to a form-wound coil over a random-wound coil in low voltage applications with regard to insulation break-down. Depending on the internal construction of the stator lamination and particular motor geometry, one style of coil may exhibit better thermal characteristics over the other but generally speaking, sweeping classifications with regard to coil type are difficult to characterize. Additionally, for some geometries, a random-wound coil may be more economical while for a different motor geometry, a form-wound coil will provide more savings in manufacturing costs (again, difficult to characterize).

Generally speaking, as-is true for any highly complex engineered product, there are advantages and dis-advantages associated with each design choice. Nearly every design choice has associated trade-offs; selecting between form-wound vs random-wound coils for low voltage induction motors is no different. It is up to the designer to understand these differences and apply the appropriate technologies to best suit the needs of the end-user and end-application.

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