Technical Note 13-01

Calculation Method - Withstand Voltage in AC Induction Motors

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Overview

When considering the construction of a 3-phase AC Induction Motor (ACIM), a designer is presented with competing constraints: maximizing performance and efficiency by maximizing electrical and magnetic materials (copper, aluminum, and electrical steel) while observing requirements for economically available materials and manufacturing processes. A paramount part of this complex problem is driven by the requirement to ensure electrical isolation of the electrically conductive windings from each other and from the frame of the motor. In order to determine the level of insulation needed, the designer must consider worst case conditions in intended use and select materials that will provide suitable protection under the prescribed environmental conditions over the intended life of the motor and do so economically. This technical note sets out to identify a useful method and guidelines for determining the maximum safe withstand voltage of a given winding/insulation arrangement and sets out safety factors to be considered.

Background Research

NEMA MG-1 and MW-1000 (Ref. A and B) provide standards for motor construction, insulation, and detail the capabilities, practices, and tests for motors and magnet wire. Additionally, ASTM D149 and ASTM D2307 provide methods for testing the dielectric strength and thermal endurance of any of material and are often cited for electrical insulation materials. UL and IEC offer guidance for creepage and clearance distances for any non-insulated electrical conductor within a device.

Materials utilized for electrical insulation will possess intrinsic properties (both electrical and mechanical). These properties are guaranteed by the material manufacturer or delineated by industry standards for that material. The materials are manufactured to standard thicknesses and all material properties are made available on datasheets for that material. For example, 2mil (0.002”) polyimide film (DuPont™ Kapton® HN) has a reported dielectric strength of 6100 V/mil which would provide a voltage withstand capability of about 12,200 V @ 23C. Typically, insulating materials will lose some of the withstand capability with higher temperatures and with age.

Technical Discussion

Inside of a large induction machine, nearly all exposed conductors are dutifully insulated during manufacture to preclude electrical shorting from any potential source. Additional insulating materials are often provided in the slot to protect the windings from the steel lamination. For dual layer windings (most common type in large machines), in many slots, two windings of different phases will be located in the same slot. This proximity is continued on both ends of the coil in what is commonly referred to as the ‘end winding’. Most will recognize that a direct phase-to-phase short in any 3-phase system could be catastrophic so extra care is exercised when insulating between coils.

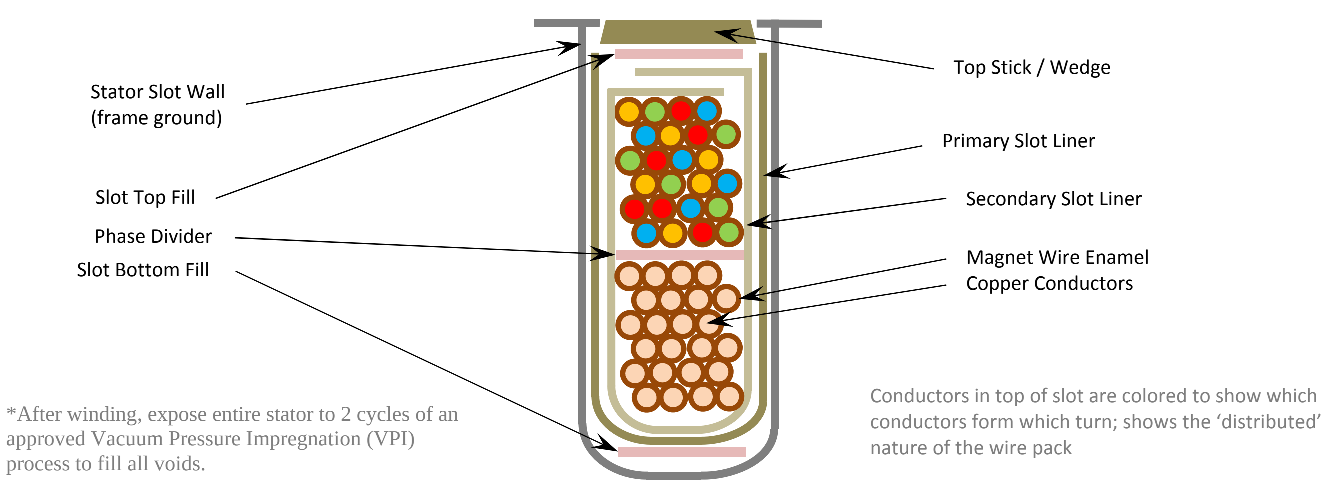

Figure 1 - Example of Wound Coil Slot Insulation

Figure 1 shows a cross-section of a typical slot packing and insulation arrangement for a severe duty 'mush' wound stator slot. In this image, the coil specification might indicate 6 strands (6-in-hand), 4 turns per coil. For our purposes, we will assume that the top coil and bottom coil belong to different phases.

Sources of Electrical Shorts

- **Turn to Turn Short** :: As can be seen in Figure 1, within a given coil the first turn of the coil (colored red) and the last turn of the coil (colored green) could be located adjacent to each other in one or more places; further, any turn could be adjacent to any other turn at one or multiple locations along the length of the slot. When selecting enamel for the coil conductors, it is imperative that the designer consider this worst case slot fill to ensure that the electrical insulating properties of the enamel will withstand the voltages expected within a given coil. Within a given coil, if two conductors (perhaps one from the first turn and one from the last turn) were to become shorted, the net result would be that the coil in question would become completely ineffective at generating torque and would lower the impedance of that electrical branch. This would result in instability, electrical imbalance, and perhaps localized heating.
- **Phase to Phase Short** :: A phase to phase short would result if a conductor from the top of the slot were to make electrical contact with a conductor in the bottom of the slot; in a worst case scenario, this could result in a direct phase-to-phase short. If not detected quickly enough, significant electrical damage due to arcing and localized heating would result. To mitigate this possibility, a dedicated phase separator is implemented to ensure that phase to phase shorts do not occur.
- **Phase to Ground Short** :: If the copper of a conductor were to come into contact with any portion of the grounded motor frame, a low impedance path to earth ground would result and could cause excessive currents, localized heating, and/or arcing. If the frame of the motor was not properly grounded, the frame of the machine could become energized with very high electrical potentials capable of injuring or killing an unsuspecting worker. In this example, several layers of electrical insulation and mechanical reinforcement have been implemented to minimize the danger of electrical shorts by relying on the conductor enamel, primary and secondary slot liners, and dual VPI treatments.

Root Causes of Shorts and Mitigation Strategies

- **Overheating** :: Insulation materials have a maximum temperature specification, above which, the ability of the material to withstand voltage diminishes rapidly. This effect can occur even though there is little or no discoloration of the affected insulating material. There are several potential reasons that a motor may over-heat;
    - Over-load – operating the motor above the design full power load for the given voltage and speed
    - Under/Over Voltage – An induction motor will generate more heat if the applied voltage is only a few percent too high or too low.
    - Excessive ambient temperature – the waste heat generated from an induction motor must be removed to keep temperatures within limits. If nearby equipment is exhausting hot air/gas or the ambient temperature is above the nameplate rated value, the motor is likely to overheat.
    - Improper cooling air flow – in order to operate an induction motor at the rated power output for the given speed, it is imperative that the air flow stated on the nameplate be supplied to the motor. It is common for supply fan curves to be mis-interpreted or for ventilation restrictions (e.g. auxiliary hydraulic oil radiators) to be placed in the design flow path. Any restriction added to the cooling air flow path will increase the back pressure on the cooling fan which will result in reduced cooling flow to the motor.
    - Poor design – Any of the above conditions could result from poor machine design. Poor magnetic design will result in lower efficiencies, higher currents, and more heat generation. Over-specifying the power capabilities of the machine to satisfy company desires will invariably over-load the motor beyond its intended operating power level and result in excessive heating. Cost saving strategies my result in more

stringent specification copper mass in the windings which will directly affect total heat production. Poor fluid analysis and internal flow path design will result in unbalanced or insufficient cooling flows which will result in higher bulk or localized temperatures. Poor thermal design would result if effective strategies for heat conduction to the cooling medium are not effectively employed. A motor designer that fails to consider all facets of motor operation will produce a motor with excessive heating.

- **Mechanical Abrasion of Insulating Materials** :: There are several potential sources of mechanical abrasion; if sufficient attention is not paid to potential abrasion sources, end-turn conductor insulation could be damaged or abraded without directly cutting the underlying conductor. If the damage is not noticed and corrected, then debris or water intrusion (mist, humidity, dust, etc) may cause a short when a short may not have occurred before the abrasion.
    - During routine maintenance, it becomes likely that workers will remove machine covers to perform inspections or replace consumable/worn parts (e.g. bearings). To mitigate this effect, the manufacturer may use abrasion resistant materials, multiple layers of insulation and the end user can exercise extreme caution when working internal to a large AC machine.
    - Motors are subjected to vibration during operation, shipping, and due to other external influences during use (top drive vibration). This will serve to apply inertial forces on the end-windings, connection rings (if any), and connection cables. Additional forces are exerted on the end-turns and cables due to the relatively high currents in the cables and coils creating interacting magnetic fields and resultant forces. These vibrational forces will displace the electrical components very slightly over a broad band frequency range (magnetic at motor current frequency, mechanical at vibrational frequency). The mechanical rigidity and compliance of the insulation materials as well as abrasion resistance will determine if these vibrations will result in stress cracks of the insulation material of choice. Methods of mitigation would be to employ different insulation materials of different thicknesses and use of a preferred VPI resin with good thermal stability and mechanical properties. The VPI resin process should be tightly controlled for temperature and pressure; additionally, by subjecting the motor windings to VPI twice consecutively, a thicker layer of varnish will be created and larger void volumes will be filled…preventing possible sources of abrasion even further. Other methods include employing surge ropes wrapped tightly around the end windings, tightly wrapping/insulating the entire end-winding mass into a unified mechanical structure, and securing all current carrying conductors internal to the motor frame.
- **Aging** :: Most insulation materials will lose some fraction of their mechanical and electrical properties over time. Using thicker materials, more material, or higher quality materials will extend the expected life but all insulation materials will wear out at some point in time and require re-winding.
- **Chemical Attack** :: Most insulating materials are resistant to common atomized chemicals that may enter the motor internals. Some materials used by some manufacturers may possess a susceptibility to certain compounds which may prevent the insulation materials from adhering/curing properly (contamination at manufacture) or would rapidly degrade the insulation materials much quicker than expected. The designer must consider the application and intended environment of use when selecting insulating materials. Additionally, the manufacturer must employ quality and cleanliness controls during insulation/taping and during the critical VPI process to ensure the full mechanical strength and endurance of the VPI resin is developed.

Concluding Remarks

- Ward Leonard conducts detailed analysis of voltage withstand for all motor designs; extra focus is devoted when the motor design will be used in harsh environments or will be submitted for certification (i.e. Military, ATEX drilling motors, etc.).
- Ward Leonard manufacturing processes enforce practices that significantly reduce the likelihood of insulation failure:
    - Every coil is placed and insulated by hand and only by trained and skilled craftsmen.
    - In process, high voltage testing is employed to catch any insulation issues early.
    - Ward Leonard processes don't allow for a single VPI cycle; 2 or more VPI cycles are employed on every motor manufactured at Ward Leonard.
- Only the highest quality insulating materials from reputable manufacturers are used for winding and slot insulation (DuPont, 3M, VonRoll, Superior Essex, Dolphs, etc)
- Proper and complete certification of AC Drilling Motors by international and independent certifying bodies (i.e. Sira, Intertek, etc) ensure that Ward Leonard designs are compliant with ATEX, CE, CSA, and IEC requirements for potentially explosive atmospheres; other manufactures simply 'comply with' these standards but fail to obtain official certification. Ward Leonard provides copies of certificates upon request.

References

A. NEMA MG-1
B. NEMA MW-1000
C. Technical Note 12-01. Ward Leonard CT LLC, dated 6/5/212, D. Cook; http://www.wardleonard.com/ward-leonard-application-notes.php