Insulation Comparison – VPI produced versus Resin Rich

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Introduction

Over time, various methods for producing stator insulation for large rotating machines have evolved. Within the industry there are basically two types of insulation production methods. One method is referred to as VPI (Vacuum Pressure Impregnation) technology. This method uses dry mica tapes, typically made of mica paper and reinforcing layers bonded with a relatively small amount of epoxy based adhesive [3],[5]. The stator bars and coils are wrapped with the dry mica tapes. After completing the wrapping the coils and bars undergo a vacuum cycle which removes volatiles and humidity, then resin is introduced and pressurized, driving the resin into the insulation. After undergoing the Vacuum Pressure Impregnation process, the resin penetrated, final product is cured afterwards in an oven.

Fig 1 -Impregnation mold lifting out of the VAT

Fig 2 -Example of development VPI facility

The second manufacturing method is referred to as Resin Rich technology. This method involves applying tapes, that are also constructed from mica paper and reinforcing layers [3],[5] that are pre-wetted with a semi-cured epoxy resin (B-staged), that are applied and then later heated and compressed (either by dedicated press or autoclave) causing the resin to flow and cure the layers together.

Few companies are using both manufacturing technologies as Andritz Hydro does. For us we have well-grounded experience using both methods for decades, so we feel we are in a good position to provide an objective comparison for people in the industry.

Fig 3 - Resin Rich Insulation Press

Discussion

All modern insulation systems used for stator windings for rotating machine stators operating above about 4kV are comprised, in general, of the following basic materials;

- Strand insulation, Dacron (1) glass, mica tape or enamel, or combinations of these.
- Turn insulation, if used, of mica paper tape (multi-turn coils only).
- Internal potential grading for stator bars, using a semi-conductive tape (to achieve onerous requirements).
- Groundwall insulation made of mica paper, glass backers (strength), sometimes film such as polyester (may also be used in fleece form), and a binding resin (either polyester or epoxy).
- Semi Conducting slot armour, using semi-conductive (glass fabric or polyester fleece based).
- End grading made of silicon carbide loaded tapes or paints.

Inherently, since the basic materials are similar, a reasonable technician would believe that all systems should be capable of similar performance.

In fact when comparing test results, life characteristics in service, machine performance, etc., this seems to be true, but this is based on the caveat that the system designer has done the correct homework and that the manufacturing processes used (whether VPI or Resin Rich) is stable and well controlled.

When the systems are adequately designed and manufactured using proper quality control both methods produce bars and coils that meet the most onerous customer requirements, for different operation regimes (run of river, and stop/start duty) and fulfill the following expectations;

- Class F capability (thermal class 155°C).
- Dimensional stability.
- Elimination of significant voids in groundwall insulation*.
- Excellent DF and Tip-Up.
- Low partial discharge levels.
- Thermal cycle stability.
- Good voltage endurance life.
- High puncture strength.
- Excellent grading system performance during testing and operation (no corona).
- Consistent slot armour resistance in proper range.
- Excellent insulation quality even in end winding area.

* Some micro voids always exist with all manufacturing methods.

What is fundamentally different about the two systems is the areas that manufacturing and quality people need to focus their attention on to make sure things go well , so this is the main area to concentrate on. It should be noted in advance that the issues described are manageable to those with the proper expertise and experience.

VPI Issues

The main potential issues that manufacturers face when making VPI systems are;

1. Making sure that the resin penetrates and fully wets through all layers of mica tape in the insulation all the way down to the copper. This can be extremely challenging particularly as the geometry of the bar and insulation builds (different rated voltages) vary widely among generator designs. Stator windings with thick insulation build (higher voltages) or bars for machines with long stacks, pose the most significant challenges. [1]

Fig 4 – Cross section of VPI'd bar

2. Making sure that during impregnation in the VPI tank the resin gelation is progressed to such an extent that very little resin runs back out of the insulation, when moving bars from the VPI tank to the oven, as this could affect the performance of the finished insulation.

3. If the tapes used for manufacture contain the resin catalyst, control of taping is more important to minimize separation of the tape layers as large "pools" of resin, e.g. caused by significant wrinkles may not cure properly if separated too far from the catalyst. [4]

Resin penetration as discussed in point 1, is complex and many strategies are used to make sure resin is fully penetrated, as if the impregnation process is not well suited to the particular geometry being produced (challenge for long bars and those with heavy insulation builds) dry mica layers, and/or lack of impregnation resin may occur which are typically near the copper.

This issue is compounded, if non-porous film such as polyester (Mylar (1)) is used on the mica tape as a backer, since this in conjunction with the mica being non-porous inhibits resin flow within the system. [8]

Well designed, VPI based insulation systems utilize non-calcined mica papers or splittings, and porous glass fabric tape backers since these materials absorb resin freely and lead to good penetration and high quality insulation as a result [8],[6].

Systems that are well designed and manufactured, typically avoid resin penetration issues by monitoring the viscosity and the reactivity of the resin, having regular resin changes to the VPI storage tank (ageing can affect resin viscosity and reactivity and in consequence, the penetration ability of the resin) and either monitoring the penetration by using capacitance monitoring or "tank coils" where prior to baking the insulation is cut from a surplus coil to make sure all tape layers are wetted. [7]

In some systems depending on tape flexibility the first layers of tape are purposely applied to achieve, small channels to facilitate resin to penetrate axially down the length of the bar to help ensure wetting. This measure can amongst others help to make sure that the impregnating resin is fully penetrated into the insulation but it has to be done carefully so that the wrinkles are not so large that pools of resin occur as discussed in point 3.

Fig 5 - Taping a VPI bar on a modern 6-Axis taping machine

Depending on the tapes and resins used, the mica contents of both systems may vary. Lower viscosity resins, and tapes with better, wetting may result in higher mica loading within VPI systems but this is not universally true. To the extent possible system designers work to maximize the mica content of the systems they provide.

Generally, if increased mica loading is possible, the result is excellent performance, provided, the system is well designed, and is subject to excellent performance [1].

As discussed in point 2, the issues that may occur due to resin run out during transport between the VPI tank and the oven can be avoided by having a well-coordinated manufacturing process. If the catalyst is in the mica tape the un-catalyzed impregnation resin within the insulation starts to gel already in the VPI tank (early gelation phase). Therefore the amount of resin running back out can be minimized, even when heating in the oven starts and the resin viscosity reduces prior to gelation.

A deep understanding of the resin viscosity as well as the gelling process at impregnation temperature and through the curing process is important to ensure that no resin is running out. If a significant amount of resin runs out of the bar or coil, the result would be air filled voids within the insulation leading to elevated partial discharge levels and reduced insulation quality.

Fig 6 - Typical bar fixture (impregnation mold) for VPI

Often, the shelf life of the VPI impregnating resin is increased by using an un-catalyzed, impregnation resin for the VPI process. The catalyst needed to initiate resin gelling and curing is place in the mica tape itself. For most

VPI systems the presence of catalyst in the mica tape is indicated by the mica tape colour. Tapes with catalyst used most often for VPI process is "pink" in colour.

Fig 7 - VPI mica tape roll with catalyst (pink catalyst)

Catalyzed resins start cross linking each time they are exposed to temperature. Most often the vacuum process requires that you heat the stator bars/coils or complete stator to remove humidity and volatiles. Each time the resin is introduced, the resin has energy to start the cross linking process. Therefore the resin's ability to penetrate the mica tapes decreases over time, when the catalyst is in the resin itself.

When the catalyst (Issue 3) is in the mica tape, resin gelling and curing occurs fast for the resin that is in immediate contact with or very close to the catalyst in the mica tape. If there is a significant separation in the mica tape, the resin that fills that area, may not cure fully during post baking if the catalyst is at very low concentration levels or zero. (Good process control helps avoid this risk) This is also depending on the used VPI tape (solubility of the catalyst in the resin and distribution of the catalyst within the tape) and technology regarding resin flow during the impregnation process.

Residuals of not fully cured "pools" of resin can cause issues with test parameters such as DF, and Tip-Up.

Insulation system designers have found that using catalyst systems that dissolve in the VPI resin can virtually eliminate un-cured resin pools. When the catalyst dissolves in the resin, it is transported throughout the entire applied insulation giving improved and more even cure levels.

Resin Rich Issues

The challenges associated with the two methods don't result in a strong disadvantage for one technology over the other, they are simply a different set that also can be controlled with proper knowledge and due diligence;

1. Resin rich systems start by having all the resin they need to fully bond all layers together, but it is possible to cure them without giving sufficient time to allow the voids to be eliminated by resin flowing. This is known as pre-gelation. Pre-gelation, if it occurs, results in trapped voids particularly near the areas where the resin carrying the trapped void content exits the slot portion (end grading). [1]

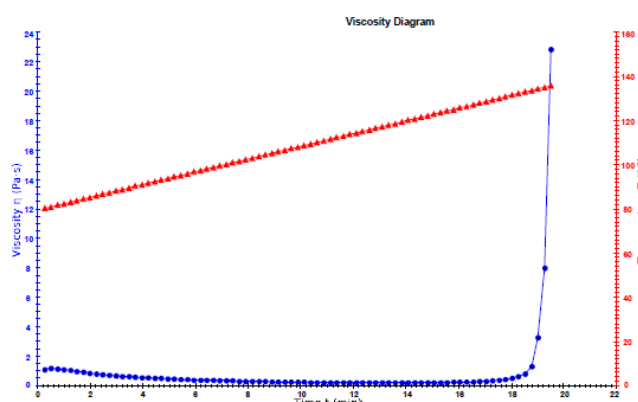

Fig 8- Rheometer plot showing resin viscosity drop and then gelation occurs.

2. Control of tape input (quantity of tape) and tension during winding of the bar, is important since, at least for resin rich coils and bars made in presses, the presses will close to their stops, and too little tape input results in voids and under-compaction. Too much tape input will result in over-squeezing the insulation resulting in insufficient resin content and resin poor areas. Also, having extra tape input may make closing the press challenging and therefore oversized bars and coils may result.

Fig 9 -Operator checking tape tension

3. For resin rich systems tapes compress and the "excess" must go somewhere, so the system typically is subject to wrinkles near the surface of the insulation. Mica tapes are typically applied at the maximum consistent tape tension that the tape can withstand without breaking but even this does not fully eliminate wrinkling [6] particularly near the bend area where taping buildup is larger.

Fig 10- Excess wrinkles resulting from lack of tape tension

When pressing a resin rich system, the full slot portion of the bar or coil is sealed into sacrifice material to prevent the finished product from sticking to the tooling, this helps to control the outside condition of the finished product, but it

Fig 11- Stator Bar Ready to enter press with sacrifice tape applied

Also, means that any air or volatile material must exit from the ends of the slot portion. To do this well, requires that the resin is heated, softened, and pressed while the resin maintains a low viscosity permitting the "voids" (air bubbles)to exit entrained in the excess resin being squeezed, without advancing the resin to the state of gelation. The press cycle is of huge importance to achieving this result. Well controlled resin rich systems have processes for monitoring the press cycle and have incoming tape tests where resin reactivity is monitored such as a Differential Scanning Calorimeter and Rheometer, to allow small "tweaks" to the pressing cycle to account for resin batches that may be slightly different than each other. Contrary to popular belief, taking a vat and mixing the same resin components together in a controlled way does not always achieve identical reactivity results. A well monitored shop is ready to account for the small variation that should be expected.

Tape quantity and tension is extremely important as for each system. There is an ideal compaction range where the resin quantity of the finished insulation is sufficient to bond and fill voids, but not excessive.

Well controlled processes have manufacturing routines for monitoring and controlling tape tension and have a tape input feedback process (based on measurement of physical compressed thickness of tape or based on tape density), that helps yield the correct amount of tape quantity to the product in-spite of the tape dimensions and tape constituents varying.

Lastly, no matter how well applied the mica tape is over the coil by the taping machine, there is friction associated with taping due to the resin in the tape, and additionally, tape is applied by round taping heads over a "basically" rectangular bar or coil. Tapes compress more naturally, at the corners, tensions are then second greatest on the narrow edges of the bar or coil, and finally at a lower tension level is the taping on the longer sides. This means that the applied insulation in cross section looks more "pillow" profiled than rectangular during taping.

From there, the insulation is heated and compacted into a truly rectangular profile, with tapes tending to wrinkle midway down the long flat sides of the bar or coil. Wrinkle control is based on control of tape quantity, but also taping tensions when insulating the bar. Overall tensions when taping tend to be higher for resin rich coils and bars than are needed to achieve a good result for VPI based systems.

Fig 12 - Taped coil showing the "pillow" effect

Insulation system design is ultimately important to reduce the effects of the potential issues but also good design practice and testing provides superior life and performance for both systems. Having an insulation product that provides long term service depends on the amount of “homework” the design team and manufacturing team has done to perfect the insulation product.

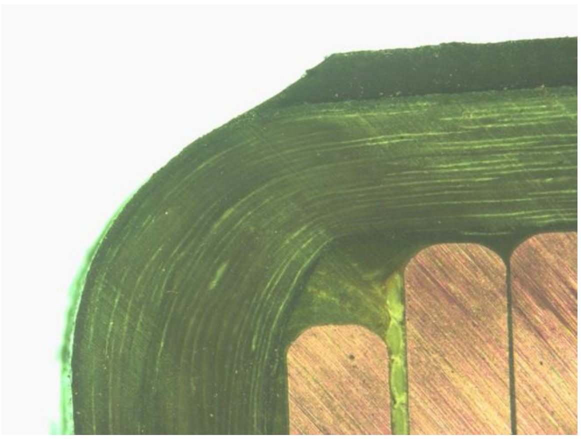

Fig 13 – Cross section of Resin Rich Bar with silicone side packing applied

In addition to the inherent manufacturing challenges, there are also many other aspects to the production of long lasting, high reliability insulation systems. Many customers have strong opinions regarding which basic insulation process is used, collectively there seems to be a strong bias – even among experts - towards which materials can comprise a system.

There seems to be two different schools of thought about material families. The “European view” of good materials for making systems are, in some respects, different than what North Americans, typically put in specifications. Imagine having a vendor’s bid proposing with the following construction;

- Enameled strand insulation with no Dacron (1) glass.
- Coils with no turn tape but rather either simply enameled strands doing double duty or the use of mica based (film backed) tape insulation.
- Proposing measuring PD levels only, instead of DF and Tip-up.

These systems with the appropriate amount of design and experience also work very well. In general, enameled strands have higher dielectric strength and lower incidence rates for strand shorts. The resin system in the ground wall is based on chemistry where excellent bonding to the strand package is assured.

Most users outside North America have been accepting mica based strand insulation instead of dedicated mica based turn insulation (in multi-turn coils), for some time, and their experience is satisfactory. While for coils, the surges associated with variable speed drives still warrants the use of mica as a turn insulator.

Several manufacturers in Europe have stopped the routine practice of doing DF and Tip-up on 100% of production in favor of testing PD for their internal quality control. Today most voids in production are very small, so PD likely is a much more meaningful result than the older DF and Tip-up numbers.

Conclusions

Based on experience, the risks to the user are less about what manufacturing technology is used, but rather more related to dealing with suppliers that have done the right testing, using excellent knowledge, experience and technology. Dealing with suppliers offering fully vetted systems provides the user with the lowest risk for long term operation.

R&D work in the insulation technology is key for providing insulation systems to users that are reliable and will continue to meet future specification needs. What inhibits development, often is customer specifications that rely in “old thinking” and are not current with the technology that is available.

You do get what you pay for, in the insulation world.

(*1) Registered trademark of EI Dupont.

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