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DETERMINING CURE OF A VARNISH/RESIN AFTER IMPREGNATION OF AN ELECTRIC MOTOR STATOR OR TRANSFORMERS

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Abstract: Research has been undertaken recently using a sensitive Megohmeter to monitor the leakage current (LC) during a stator or transformer's curing process. The stator or transformers leads are twisted together and attached to the positive megger lead, and the negative megger lead was attached to the lamination stack. Lead wire can be used to extend the distance practical between the megger by many feet. This allows us to monitor the LC of the stator or transformer, after the resin has been applied, and the test sample, after the device has been put in the process oven. A megger is a standard test instrument used to determine the insulation resistance of all kinds of high voltage devices. Usually when the insulation resistance (IR) of a device is lower than expected one possible solution is to place the stator or transformer back into the processing oven to try to finish the curing of the resin. Once cooled it will be tested again and if the IR has increased the resin would have finished curing.

This test procedure would allow a manufacturer to evaluate processes against each other for purposes of optimization. It is not unknown for a manufacturer to partially cure a unit and allow it to cure in application. With this technique, that manufacturer can determine what it takes to cure the unit in application. This procedure will be found to be valuable to manufacturers of electric motors and transformer and could be used by companies that produce other high voltage devices whose IR can be tested.

I. INTRODUCTION

A question that is constantly asked is "What is the degree of cure of the resin that is used to bond magnet wire together on a stator or transformer?" Many stators and transformers, because of their application, must be well-cured. Vendors of those resins provide guidelines on how to cure the resins they sell. Most of the cure times that manufacturers set for these resins are determined by past experience or by a trial and error, combined with some electrical testing to evaluate whether processing is successful. No one has been able to determine the degree of cure using the unit as the test cell.

A Differential Scanning Calorimeter[1] (DSC) is one instrument that is used to determine when and at what speed a resin cures in the laboratory. This is one method that resin vendors use to determine the guidelines to cure their products. A DSC measures the exothermic heat from the chemical reaction that a resin undergoes as the sample heated at a programmed rate. Once the heat is measured, a computer will calculate the kinetic (speed of the reaction) information, which will provide the time to 100% cure at a particular temperature. The tests are run in small pans that are placed in the DSC test chamber. Testing cannot be done while the resin is in the stator or transformer.

Some resin suppliers may use a Rheometer[2], which is a sophisticated instrument that will determine the viscoelastic properties of fluids. It can be used to determine the rate of a chemical reaction of a thermosetting resin by monitoring how the storage modulus (stiffness) increases and eventually stabilizes at a constant temperature. As a polymer cures it becomes stiffer until it reaches it maximum stiffness or storage modulus at the elevated temperature. The Rheometer test chamber consists of two oscillating or rotating disks in a cup with the resin filling the volume between the disks so there is contact of the fluids on both disk surfaces. As the resin is heated to the desired process temperature or temperatures, the resin begins to gel and cure. The time to 100% cure can be measured and this will give a resin vendor information for curing guidelines for their customers to use when processing their products. A Rheometer is a laboratory instrument and can only determine guidelines for applications in cure processing.

A Dielectrometer or Dielectric Analyzer (DEA) can determine properties in some applications by using a remote sensor. This remote sensor is a small microchip with an entwined electrode on the chip surface. Molders of Thermosetting plastic compounds have been successful in placing these remote sensors in the molding compound and measuring properties as the compound cures. Some vendors of DEA have remote sensors that can be installed in the surface of a mold and measure their electrical properties as the compound cures. One of these remote sensors would not be practical for measuring electrical properties in a stator or transformer as the resin cures.

The interesting property that we would like to measure would be the ionic viscosity[3,4]. This is the log of the conductivity as the resin cures at a constant temperature versus time. The conductivity measured would have a frequency component and therefore would be alternating current (Vac)-like and not direct current (Vdc)-like. None of the above methods to determine when a resin is cured, can use the stator or transformer as the test cell. Since stators and transformers are electrical devices, it would be convenient if an electrical property could be measured that would be affected by the degree of cure that it could possibly give us some curing information.

One possible method would be to measure the insulation resistance (IR) or the leakage current of the stator or transformer using a highly sensitive megohmmeter. This instrument applies a direct current voltage. The IR will increase if the stator or transformer is measured at a partial cure and again after full cure. The LC will decrease since the IR is inversely proportional to the leakage current.

$$V = I\,(R) \qquad (1)$$

The symbol I is the leakage current and R is the Insulation Resistance. The standard voltage for the type of stators and transformers is 500 Volts dc. If leakage current will stabilize at an elevated temperature then perhaps it will give us some information on the degree of cure.

II. EXPERIMENTAL

The instrumentation used was a QuadTech™ 1865 Megohmmeter capable of measuring down to at least the picoamp range and a Stanford Research Systems™ SR720 LCR meter to measure capacitance at 1 volt and frequency of 1kHz. All leads of a stator or transformer were tied together in some manner, and a lead wire connected to the internal leads. Tapping or clipping into the stack, and to the lead wire, served to attach the lamination stack electrically to the external diagnostics. The end of the lead was attached to the positive Kelvin clip of either instrument and the lamination stack lead was attached to the negative Kelvin clip. The LCR meter was used to monitor the resin filling the stator or transformer while the unit was in a dip, vacuum or other kind of tank to determine how quickly the unit filled. The stator or transformer was hooked to the megohmmeter by running the lead extensions out of the oven and attaching the stator or transformer leads to the positive megohmmeter lead and the lamination stack to the negative lead of the megohmmeter. The leakage current was measured after the dip and before the unit was placed in the oven. The units were charge for 30 seconds at 500 Vdc and the leakage current was read. The leakage current value was measured at timed intervals throughout the expected cure time of the unit and this data was analyzed using KaleidaGraph™ curve-fitting software.

III. RESULTS

The cures on a number of production units have been carefully monitored with this technique to determine the cure times of resins. The processes and curing temperatures, for different resins, were compared to determine if this new monitoring technology offers any advantage both in cost and performance enhancement. The figure 1 shows a trickled stator that had 24 grams of a polyester resin applied to it. The stator is on a 12-station turret that spins during the trickle process and continues until the stator is removed from the turret. By the time the stator can be hooked to the megohmmeter, Contents | Print | Text Search

the resin has gelled but remains tacky. Figure 1 shows the leakage current change over 22 hours of monitoring. Figure 2 is the same part number stator with 64 grams of the same resin applied to the stator. This stator was "tacky" when removed from the turret but within 4 or 5 hours the "tackiness" was gone and, as can be seen, the leakage current stabilized by this time indicating that the cure was approaching 100%. This points out two differences between figures 1 and 2: the stator represented by figure 1 had less resin, which developed a lower exotherm and took longer to cure; and the leakage current in figure 1 starts much higher than figure 2, which should indicate better fill of the stator in figure 2.

Some Lighting Ballasts are large transformers, which are called High Intensity Discharge [HID] ballasts. There was a need to characterize the curing process with HID ballast. The process is a vacuum process to which this new technique was applied, beginning by measuring the capacitance of the ballast in the vacuum chamber. A feed-through connector was used though the lid, so the capacitance of a ballast could be measured as the ballast was filled with resin. Interesting observations were made when one of the ballast was underfilled. When the vacuum was broken and the tank was brought back to atmospheric pressure, this pressure seemed to push resin into the windings that were dry. This can be seen in figure 3.

The ballast was then attached to the megohmmeter and the leakage current was measured just before the ballast was placed in the oven. Again the leakage current was measured at timed intervals, then the data was analyzed in the same fashion as for the trickled stator data. What was found was an increasing

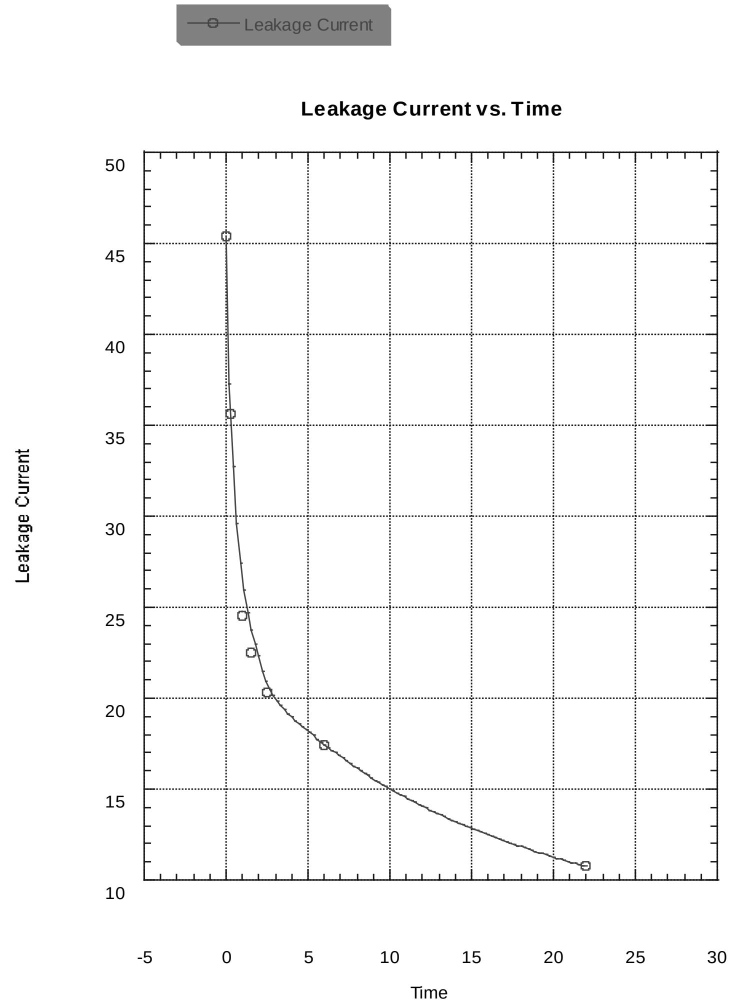

Figure 1. Leakage current versus time

slope, which was inter-preted as the viscosity of the resin decreasing as the resin began heating up to oven temperature. At the peak, the temperature of the resin in the coils is approximately 100 °C, so it appears that the resin begins to drain out of the coils, because less resin mass should reduce the leakage current. As the temperature of the resin continues to increase, the resin gels and the resin cures.

It may also be possible to compare processes and observe differences in efficiencies between the processes.

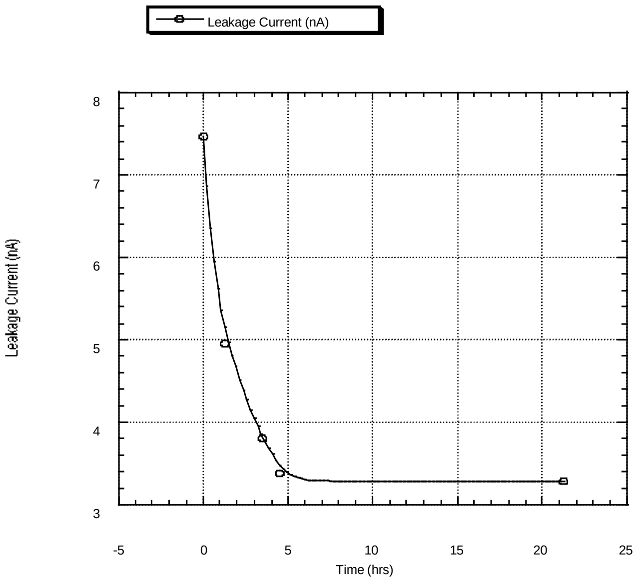

Figure **2.**

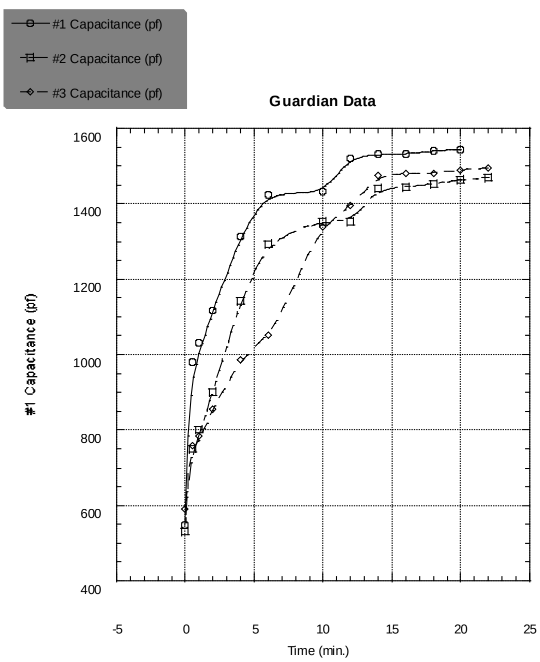

Figure 3.

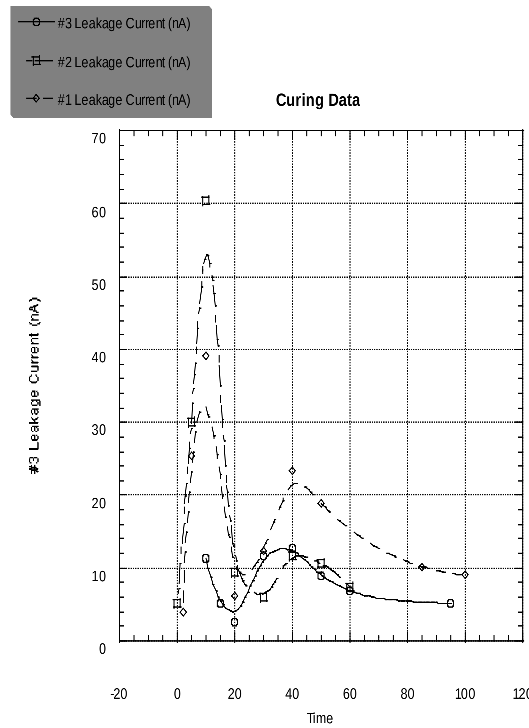

Figure 4

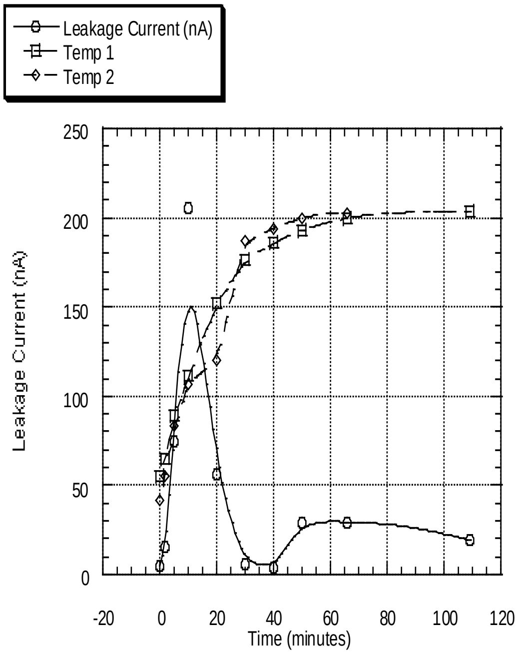

Figure 5. Leakage current vs time/Temperature

A third case was a large stator dipped in a polyester resin. Here a similar rise in leakage current as the stator approaches 150°C is seen; the resin drains some then gels and cures. Like the epoxy, the viscosity of the polyester reduces and becomes more conductive then drains out but not to the same extent as the epoxy. The gelation of the polyester happens faster than the epoxy because of its reactivity and enhanced cure rate.

The polyester resin is more reactive than any epoxy because of the differences in chemistry. An epoxy resin must open up the rings of the epoxy molecule and the anhydride (hardener) ring structure must open before this chemical reaction can take place. A polyester resin reacts by breaking its double bond and the double bonds of the thermoplastic monomer (vinyl toluene, styrene, or DAP), and once the first double bond breaks a chain reaction propagates until the resin is fully cured. This kind of chemical reaction can be slowed down but not stopped. An epoxy resin's chemical reaction can be stopped to finish the reaction at a later time.

The last case is comparing a resin on a stator and determining the cure time at 2 different temperatures. Figure 6 shows 2 plots of a resin curing, one at 135°C and the other at 163°C.

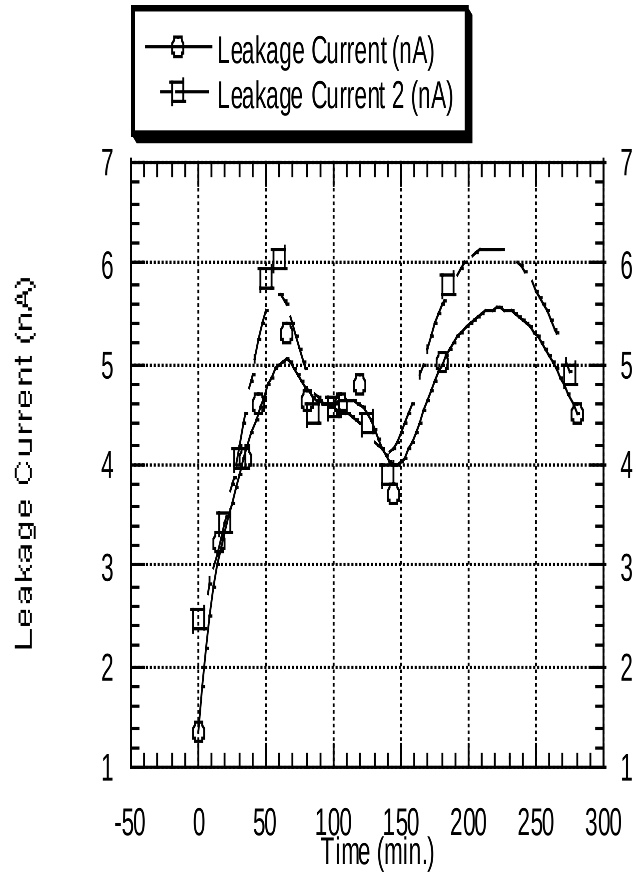

Figure 6. Leakage current vs time/temperature

The 135 °C curing plot shows a low amplitude broad curve, while the 163 °C curing plot exhibits a sharp and narrow peak. This allows a manufacturer to set a cure time that fits into a schedule for their plant. This method could be used to monitor cure so that the cure temperature does not effect the overall properties of the insulation system. If a resin is heated, too high in temperature, the chemical reaction is too fast and causes the reaction to terminate the polymer's growth. This allows for 2 or 3 molecules of lower molecular weight instead of 1 molecule that was planned. The interface between these molecules is an electrical stress point where the insulation system can prematurely fail.

Another possible problem would be a high temperature that could decompose part of the polymer, leaving a weakened insulation system that would fail prematurely.

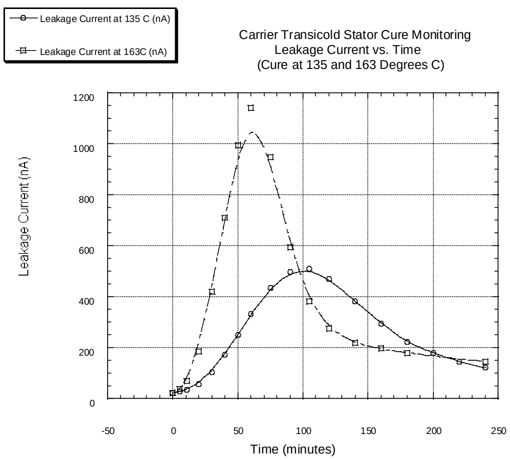

Figure 7. Leakage Current vs time [two temperatures]

This technique may help determine cure times that would allow a manufacturer to control the flow of stators or transformers so they get to their point of manufacture into product just in time. This allows for smooth flow of product out to customers. Inventory lying around costs money to a manufacturing company. Making decisions on what new processes a manufacturer can use to build new products is easier when there is a method that allows one to characterize or better understand the processes under consideration. Can a manufacturer save energy costs if it can efficiently process product components faster?

IV. ENERGY CONSIDERATIONS

The Energy Policy Act of 1992 requires the Department of Energy (DOE) to determine the feasibility of energy conservation[5] standards on electric motors, transformers, and other electrical devices where energy can be lost. The criteria for DOE is:

Would there be a potential for significant energy savings?
Is it economically justified?
Will it put anyone out of business?
Clearly it would be unreasonable to force companies to perform impossible tasks on technologies that do not exist. The interest is in using energy more efficiently. The same activities are being performed on electric motors and other products that use some form of energy.

A report[6] written by P. R. Barnes et. al. for DOE details a study on energy conservation standards for distribution transformers per the Energy Policy and Conservation Act (EPact). This report discusses how the electrical distribution system works and how more efficient distribution transformers will save energy. This translates into lower costs.

The President's Committee of Advisories on Science and Technology (PCAST)[7]PCAST has made recommendations on what new energy sources that money should be spent on to reduce our dependence on foreign oil and increased the source of energy for a growing world population. The highest energy consuming industries have been targeted for process improvements and emission reductions. Energy must be used more efficiently so that a growing population and future generations have the resources for better living conditions, continued and expanding employment.

The industries that are working with DOE[7] to improve processing are:
Forest products
Steel
Aluminum
Metal-casting
Chemicals
Petroleum refining
Glass

Other industries, such as ours are in the process of examining alternative methods to process motor and transformer assemblies. Increasing demands on capital resources and environmental awareness is driving this need for increased system efficiency.

Motor Stators and Transformer Coils are manufactured for the most part using enamel coated conductors – either copper or aluminum. The completed stator or coil assembly is then processed in a varnish . This process utilizes a resin base either in solution with a carrier such as water or an organic solvent or neat resin, alone. The varnished composite must be then cured to preclude chafing of the magnet wire enamel insulation and provide environmental protection and in many cases to reduce audible noise.

V. CONCLUSIONS

When a manufacturer understands the time and temperature requirements of a given resin or varnish in conjunction with curing equipment on hand and in use, the decision as to how long to bake and at what temperature is simplified. Energy use is refined and a better end product is the result.

The research undertaken in this work was motivated by a desire to establish a quantifiable to evaluate new versus old technology in any given production process leading to a measurable bottom line environmental impact through material selection and process design.

One can use a sensitive Megohmmeter to monitor the cure of a stator or transformer on-line or in the Laboratory. This test method can determine cure time of a product component in a production oven and:

1. Can characterize one process for comparison to another process to determine if a process may have an advantage over another.
2. Compare one resin versus another resin with different chemistries.
3. Provide significant energy savings.

We have just begun using this test method to streamline processing and are just beginning to understand its benefits. There may be other products or components where this method may be used to determine cure times or other benefits of resins or processes. Other possible products would include coils, capacitors, or other power electronic components where a resin is used to insulate and a megohmmeter can be electrically connected across. Significant savings cost both in processing and energy have been achieved.

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