ADVANCED WINDING MACHINE DEVELOPMENT AT SANDIA NATIONAL LABORATORIES*

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ABSTRACT

Sandia National Labs, New Mexico is designing and testing an improved version of its state-of-the-art capacitor winding machine. The new CL1610 winding machine is based on the mechanical design of three previous Sandia designed winding machines using a precision tool plate and guide roller design to provide very accurate material alignment and minimum roller drag. It features closed-loop tension control, precise material acceleration and velocity control, programmable logic controllers, and an improved and expanded operator interface.

The new machine will increase Sandia's capacitor fabrication capability by applying the tension control accuracy we now have for narrow width films and small diameter windings to films up to 0.2 m in width and windings up to 0.25 m in diameter. Tension control of ±0.05 N will be maintained on the new machine through a range of 0.25 to 4.90 N. The machine will implement variable tension control with the goal of optimizing the electrical performance of the wound capacitors. The tension variation will be based on a model developed at Sandia that calculates internal mechanical stresses and will serve to specify all mechanical stresses in a finished capacitor. The new machine will also have the capability to wind non-cylindrical capacitors while maintaining the tension control of ±0.05 N we currently have for cylindrical capacitors.

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*This work was performed at Sandia National Laboratories supported by the U.S. Department of Energy (DOE) under contract number DE-AC04-76DP00789.

The capability to wind two to sixteen ply extended and buried foil capacitor designs with the widths and diameters mentioned above will be available with the new machine. Take-up mandrel velocity and acceleration will be controlled using a stepper motor that can be programmed to operate between 0 and 60 RPM and 0 and 3000 rev/min/min. In addition, the number of active turns, the number of pre- and post-insulating wraps, and the number of turns to the foil termination can all be programmed.

Operator errors will be reduced by automation techniques and instruction sets built into the PC interface. The machine will be controlled with a Macintosh computer that communicates with both the stepper motor controller and the programmable logic controller (PLC). Using a Sandia designed software interface on the Macintosh, all of the process parameters are entered by the operator before winding begins. Variable tension will be controlled through the same interface. The operator will enter the material properties and geometric characteristics of the capacitor and the computer will generate the tension variations necessary to achieve the desired mechanical stresses. The PLC will control winding tension and spindle braking, while the stepper motor computer will control take up spindle velocity, acceleration, and material travel distance. All of the process parameters obtained from the fabrication of a capacitor are entered into the computer automatically, or by the operator, and can be stored for later analysis.

INTRODUCTION

Sandia National Laboratories, New Mexico (SNL/NM) has recognized the need for precision capacitor roll winding capability since the development of

Fig. 1 Three Generations of Sandia Winding Machines

perfluorocarbon capacitor technology in the early 1980's. Several winding parameters were found to be critical to the electrical performance of plastic film capacitors impregnated with perfluorocarbon liquids. Uniform, controlled looseness was found to dramatically improve capacitor performance because it created a uniform distribution of the impregnated liquid (1). It was later discovered that performance maximums exist with respect to the winding tension (2). Studies have also indicated that excessive wander of plies, wrinkles, take-up velocity control, drag, and human factors affect capacitor electrical performance and reliability (1,3).

Current, on-going research indicates that constant tension winding of cylindrical capacitors allows highly variable internal mechanical stresses to accumulate (4). The research also implies that capacitors that are wound cylindrically and then pressed flat have even more significant mechanical stresses introduced during the pressing process. While never studied statistically, most breakdown failures in flat capacitors are observed in the curved ends where stresses would be highest. Electrical performance degradation caused by these internal stresses has never been quantified because the capability to wind capacitors without the stresses did not exist.

The new CL1610 winding machine will provide SNL/NM with the capability to determine the effects of constant or variable winding tension stresses and flattened capacitor stresses on electrical performance. The machine's variable tension winding capability will allow the internal winding stresses to be controlled at any level. This capability will provide electrical performance comparisons between uniform high and low stress states and nonuniform stress states. The machine will also have a constant material velocity capability that will allow flat capacitors to be wound on a flat mandrel with uniform or variable tension control. Wound flat capacitors can then be compared to pressed flat capacitors and changes in electrical performance can be measured accurately.

SNL/NM has continues to improve our research winding capability in order to provide capacitors with increased structural integrity, reliability, energy density, and electrical performance. The new winding machine, the CL1610, will be an improvement in the current state-of-the-art performance for tension and material velocity control and will maintain the state-of-the-art in acceleration control, guide-roller drag and wobble, material alignment, wrinkle prevention, and human factors. SNL/NM winding machines are designed for and built to operate in a research environment and provide automatic tracking of process parameters for more accurate quantification of winding parameter effects on capacitor electrical performance.

BACKGROUND

In the early development of perfluorocarbon filled capacitor technology, it was discovered that "traditional" winding equipment did not fabricate capacitors with adequate electrical performance. Traditional then referred to winding machines using friction, such as a Prony brake, to control film and foil tension. In general, these machines also employed low mechanical precision in the guide-rollers and supply spindles. Significant effort was put into the development of basic winding technology and equipment. This development led to the discovery of a relationship between uniform winding looseness and discharge life. Uniform looseness is created by very accurate tension control and implies that the perfluorocarbon liquid is distributed uniformally throughout the winding. The Weibull plot in Figure 2 shows the relationship between winding looseness and discharge life. The discovery of this relationship was firm evidence of the need for accurate tension control throughout the capacitor winding sequence including startup and termination. Material wander, wrinkling, machine alignment, guide-roller drag, and the tensioning mechanism were identified as the key machine processes and features required to optimize the winding process (1).

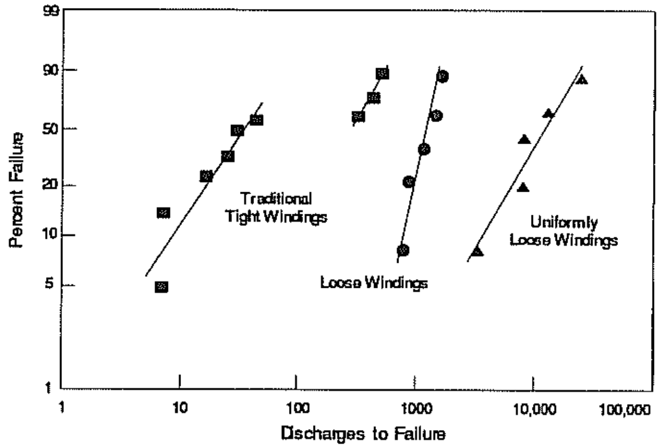

Fig. 2 Weibull Plot of Winding Looseness and Discharge Life

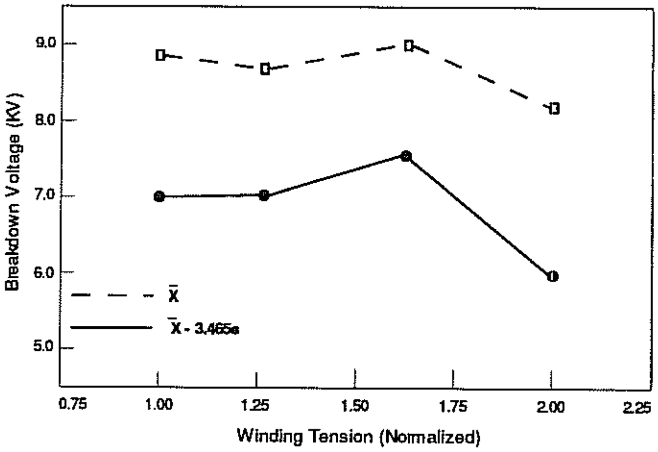

Fig. 3 Performance Optimums in Breakdown Voltage vs. Winding Tension

More recent work indicates that capacitor performance optimums can be found by investigating the effect of winding tension. A matrix of high energy perfluorocarbon liquid/plastic capacitors were fabricated using different tensions and then tested for DC life, operational performance life, and short term breakdown (STB). The experiments indicated that DC life performance increased as the winding tension was lowered and that the STB performance had optimums with respect to tension. Figure 3 shows that STB performance at optimum was 20% better than the performance at tensions 20% away from the optimum (2). These results added more evidence that winding tension control did have a strong influence on capacitor electrical performance. In the course of conducting the above experiments, it was found that slow and smooth takeup of the material is a fundamental parameter for controlling the material wander and wrinkling (3).

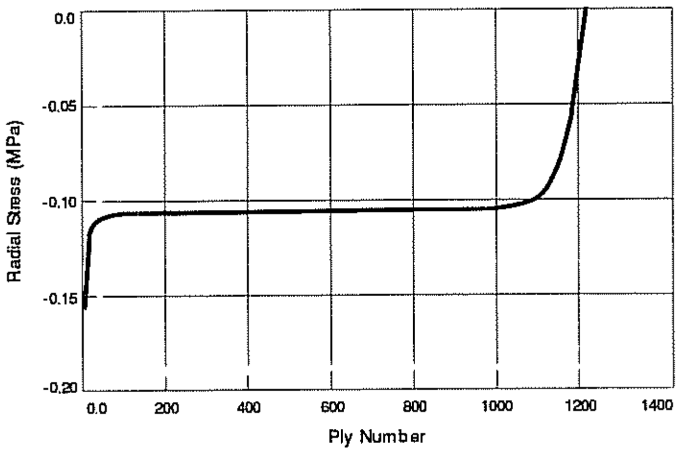

Fig. 4 Internal Capacitor Winding Radial Stress Predictions

An analytical model, developed at SNL/NM, of a capacitor-like winding, indicates that highly variable, complex stresses (Figure 4) can be obtained that may cause electrical performance degradation (4). Material plies can slip circumferentially during the winding process due to excessive air entrainment or large wound tension gradients causing misalignment of electrical leads or local ply wrinkling. Loss of initial winding tension in the plies occurs as winding progresses causing discrete ply wrinkling. Excessive radial pressures within the capacitor can cause significant ply thinning. All of these conditions may be further degraded during capacitor processing. Mechanical anomalies such as these may lead to inductance changes, design capacitance changes, and poor DC life and STB performance.

The mechanical design of the winding machine itself can contribute to capacitor electrical performance. A dynamic analysis of an SNL/NM designed winding machine indicates that for a stiff machine, material accelerations can be achieved that will cause inertial loads responsible for tension variations of the same magnitude as the nominal tension. The inertial loads are even more pronounced for winding non-cylindrical capacitors because of the accelerations present. Using a constant tension, which is the current method, for non-cylindrical windings causes cyclic changes in the velocity and acceleration of the ply materials and thus large tension variations. As demonstrated in (1), uniform tension is a significant contributor to capacitor performance. Human factors can also play an important roll in capacitor quality meaning that the machine must be designed with the operator as an important component for operation. Part handling techniques, such as the methods for attaching or terminating ply materials, can significantly affect capacitor repeatability.

The current SNL/NM winding machine design goals and philosophy are intended to overcome the problems listed above. The methods used include improved machine alignment, reduced guide-roller drag and wobble, tensioning mechanisms which reduce apparent machine stiffness, improved tension control including variable tension control, smooth material acceleration and velocity control, constant material velocity control, and a continually improved human interface.

WINDING MACHINE DESIGN

Commercial winders prior to the early 1980's used the Prony brake system to control tension (Figure 5). Several problems existed with this system including the

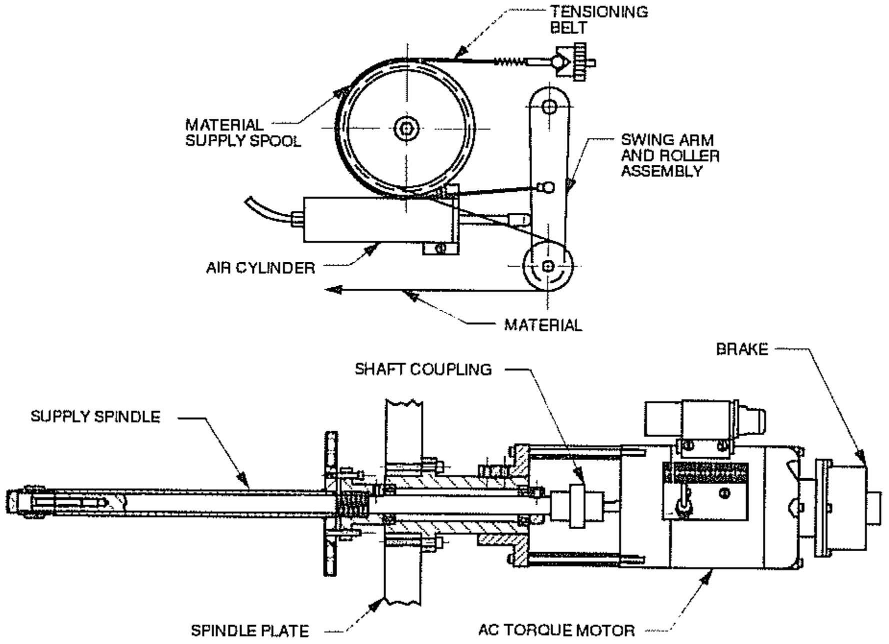

Fig. 5 Prony Brake System Compared to AC Torque Motor System

fluctuation of friction, and thus tension, with pulley speed, the loss of tension when the machine is stopped to insert flag leads or make adjustments, and the loss of tension control and repeatability in the low tension range where most perfluorocarbon capacitors are wound. The Prony brake was replaced by a spindle that was coupled to an AC torque motor (Figure 5). This new spindle rotated in precision instrument bearings with spring washers to preload the shaft and prevent end play. A brake mounted on the end of the motor allowed the spindles to be locked in position. The motor applied constant, dynamically controlled torque over a wide range of speeds including stall or near zero speed. The motor produced a torque proportional to the input voltage so tension was controlled by varying the supplied voltage. The material tension for each spindle was measured by a load cell mounted in contact with the swing arm and roller assembly. The operator had complete control of the tension on each spindle, could monitor the actual tension level on an indicator, and could adjust the tension during the operation as necessary, creating a slow closed-loop system (1).

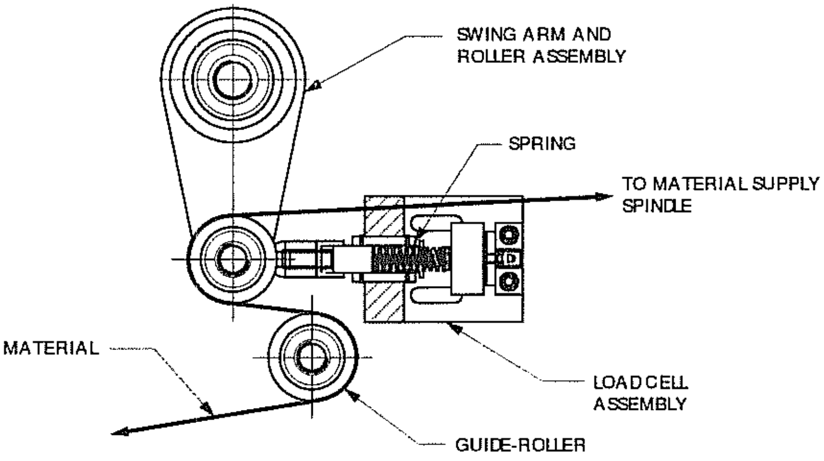

Fig. 6 Swing Arm and Guide-Roller Assembly

Improvements to the swing arm and roller assembly and the guide rollers were also made at this time. Precision instrument bearings replaced the high-load capacity, low precision ball bearings previously used by commercial vendors. The packing grease used in the high-load bearings became gummy after continuous use at low loads and low speeds and increased the rolling friction considerably. All of the new rollers were designed to allow easy replacement if the surface became damaged. Two guide-rollers were added at each guide position on the machine to obtain an S-shaped wraparound that provided greater engagement. Film or foil slippage due to inadequate contact caused by a shallow angle of engagement on the guide-rollers caused excessive material wander and wrinkling (1).

The spindle assembly was later redesigned to incorporate automatic closed-loop tension control. The tensioning mechanism no longer used an AC torque motor to control the tension but incorporated a combination clutch and motor system. The hysteresis clutch used in the system provides a torque output nearly directly proportional to the supplied current and independent of the differential speed between the input and output shafts. The motor drives the clutch input shaft in the opposite direction that the output shaft is driven with the unloading material. The clutch provides a constant torque output in this condition of continuous slip. The load cell assembly was also redesigned to reduce the apparent stiffness of the winding machine and provide better tension control during dynamic conditions. The force transducer was spring loaded to help filter any oscillations introduced to the swing arm dynamically (Figure 6). The swing arm and load cell system has an experimentally determined repeatability of 1.0% full scale load (3).

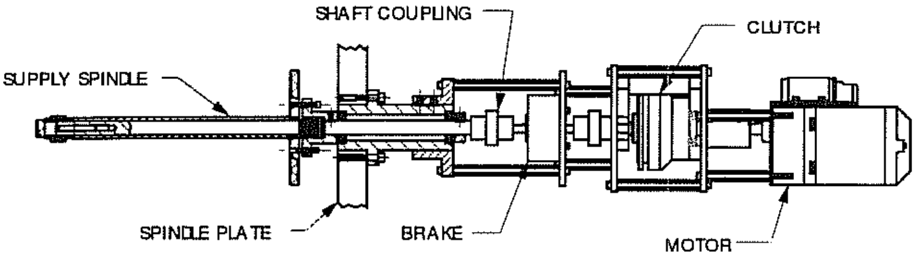

Fig. 7 CL1610 Supply Spindle Assembly

The clutch and motor system concept was maintained for the new machine because it is a system that creates torque directly and because it is independent of the rigidity of the web path (Figure 7). This system is also easily controlled with a simple voltage to current converter that uses the corrected output voltage values from the PLC to change the supplied current to the clutch. The reduced stiffness load cell assembly was also used on the new machine because of the huge improvements in tension control it provided over the previously very stiff assembly. All components were scaled upward on the CL1610 machine in order to accommodate a much higher tension range and larger diameter windings than the CL805 machine discussed in (3).

Mechanical design features have also been added to the CL1610 to improve the human interface with the machine. The guide-roller surfaces are anodized to prevent surface wear and color coded to help the operator thread the material through the machine properly. The supply material mounting system was simplified and expanded with a color coded spacer size system. The tension indicators were put into a rolling rack cart so they are accessible to the operator during calibration of all the spindles and the mounting system for the capacitor mandrels was converted from a manual system to an automatic, hydraulic system.

WINDING MACHINE CONTROL

The CL1610 winding machine will apply the tension control accuracy we now have for narrow width films and small diameter windings to films up to 0.2 m in width and windings up to 0.25 m in diameter. Tension control of ±0.05 N will be maintained on the new machine through a range of 0.25 to 4.9 N. The machine will implement variable tension control through the same range as constant tension control. The machine will also have the capability to wind non-cylindrical capacitors while maintaining a tension control of ±0.05 N through the range of 0.25 to 4.9 N that we currently have for cylindrical capacitors by maintaining a constant surface speed of the film. The capability to wind two to sixteen layer extended and buried foil capacitor designs with the widths and diameters mentioned above will be available with the new machine. Take-up mandrel velocity and acceleration will be controlled

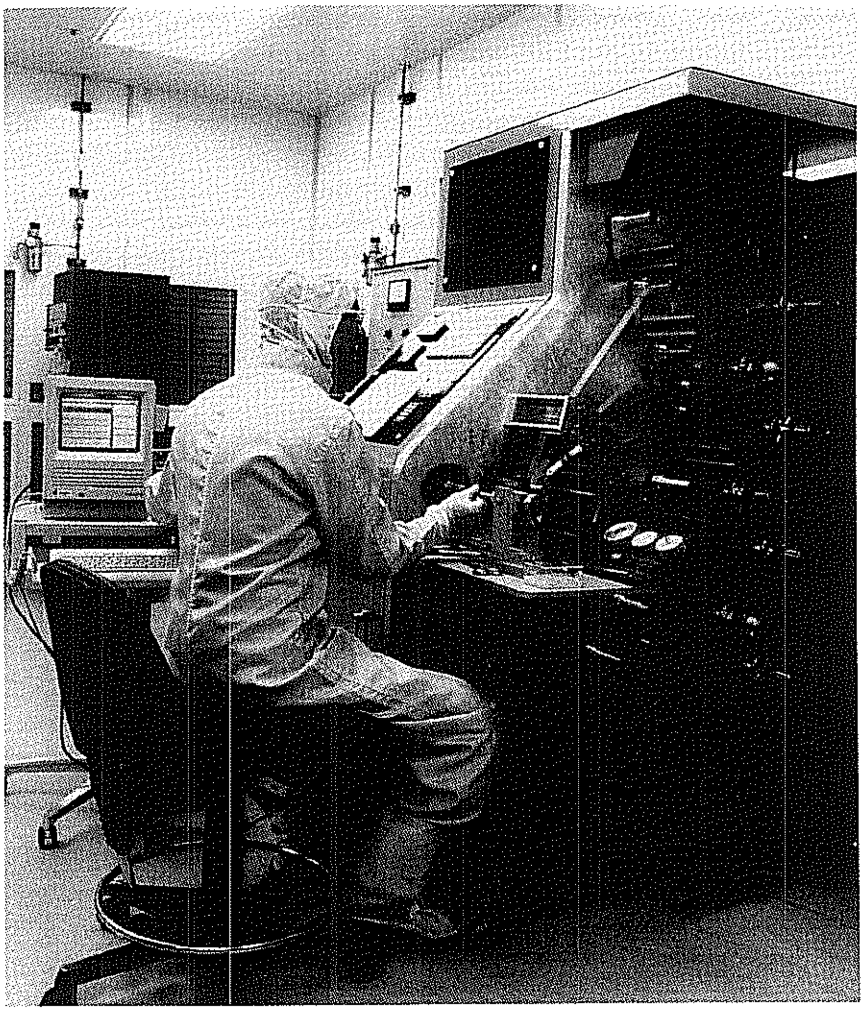

Fig. 8 Fabricating a Capacitor on the CL805 Winding Machine

using a stepper motor and can be programmed to operate between 0 and 60 RPM and 0 and 3000 rev/min/min in 0.02% of full scale increments. In addition, the number of active turns, the number of pre- and post-insulating wraps, and the number of turns to the foil termination are also programmed and controlled through the stepper motor.

The machine will be controlled with three computers. A PLC controls the material tension, braking of the spindles, and other basic machine functions. The stepper motor controller controls the speed and acceleration of the material and the number of turns for the capacitor. A supervisory computer communicates with both the stepper motor controller and the PLC to store, track, and load the process parameters. All of the process parameters are entered by the operator before winding begins using a Sandia designed interface on the Macintosh supervisory computer. The interface uses a high performance graphical instruction system that is easily customized for any special requirements or for any special operator preferences. The operator is given instructions on the screen for any manual functions he must perform, and then told which of the simulated buttons to activate to proceed. The operator may then use the mouse to activate a button, or simply say the instruction printed on the button into a microphone, which initiates the machine. Variable tension will be controlled through the same interface. The operator will enter the material properties and geometric characteristics of the capacitor and the specified level of stress desired and the computer will generate the tension variations necessary to operate the machine. All of the process parameters obtained from the fabrication of a capacitor are entered into the computer automatically, or by the operator, and can be stored for later analysis. The processing information tracked by the interface software is easily copied to other computers for analysis by a variety of software tools.

The constant surface speed control system will utilize a servomotor controller with feedback from an encoder located at one of the guide-rollers located just in front of the capacitor. These two guide, or smoothing, rollers each have half of the plies moving over them at any given time so a single encoder should be able to feedback a close approximation of the surface speed for all the plies. The constant surface speed option will also utilize the same interface, with the required surface speed being the only unique process parameter requested.

The PLC utilizes a unique state language for programming. Each spindle on the machine is programmed as an individual state in a sixteen state process state monitor sequence. Each spindle has an on-off, non-linear control algorithm with a 0.5% to 2% of full scale dead zone, a 1 to 5 Hertz sampling rate and a 0.1 to 0.5 Newton/second response speed. Any high frequency tension variations are filtered by the sampling and response rates. The control algorithm is always under the control of the supervisory computer and can be halted at any point in the process. In this way, the machine can be manually suspended for material loading, calibration, material threading, and any required special processes.

CONCLUSIONS

High mechanical precision and accurate tension control winding machines built by Sandia National Laboratories, New Mexico, have been shown to increase the performance of perfluorocarbon liquid/plastic film capacitors compared to similar capacitors wound on less advanced machines. The accurate material velocity and acceleration control, tension control, and the improved human interface supplied on SNL/NM winding machines have improved capacitor reliability and repeatability. Further advances in variable tension control and constant surface speed control will allow us to continue to examine the effects of winding process parameters on perfluorocarbon liquid and dry capacitor performance.

The CL1610 winding machine represents a new state-of-the-art in tension and surface speed control for winding discrete film/foil capacitors. With the CL1610, SNL/NM will be able to quantify the effects of variable winding tension and constant surface speed winding on electrical performance of cylindrical and flat capacitors.

ACKNOWLEDGEMENTS

I wish to acknowledge the fabrication efforts and design input from A. A. Jojola, D. L. Greene, and Team 2484-1, and the support and design guidance from J. O. Harris and J. D. McBrayer.

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QUESTIONS AND ANSWERS

Q. What are the thicknesses and widths of the supply material you wind on this machine?

A. The mylar thickness varies from about 22 gage, which is 2/10 of a mil, up to 75 gage, which is 7.5/10 of a mil. The widths range from one inch to six inches, so they're small.

Q. How is the material routed through your machine?

A. After the material leaves the supply roll, it will make an S loop around the swing arm and idler roller. The material then enters the material separator and makes another S loop around the smaller rollers located there. It then goes over the smoothing rollers where one half of the material goes over the top roller and the other half goes over the bottom roller. These very accurate, very round, smooth rollers help to remove any wrinkles that may have developed. The material then goes through the web grip, which holds the material in place after it is cut, and is attached to the mandrel.

Q. How do you mount and position the material on the machine?

A. We mount the supply rolls onto flanges which are then mounted onto cylindrical spacers that slide over the spindle on the machine. The flanges and spacers are radially adjustable using set screws which allows us to accurately position poorly made supply rolls. Additional spacers are used to position the supply rolls on the spindles. This is necessary because the film and foil in capacitors are offset to provide the electrical arc-over margin. At the end of each spindle is a screw that provides the precise alignment of the materials by actually moving the spindle in and out of the machine in small increments.

Q. What is the purpose of the "dead band" around the tension set point in your control program?

A. The tension provided by the clutch will constantly fluctuate around the set point because of the slight fluctuation in the current being provided and because of inaccuracies in the clutch. The dead band allows these "natural" fluctuations to occur without affecting the current that we provide to the clutch. The five gram tolerance that the machine provides is approximately 2.5 times the dead band so adjustments are made well before the tolerance is exceeded. Our experience with the clutches indicates that our fluctuations will be larger if we constantly change the current being delivered to the system by providing a continuous feedback.

Q. I'd like a further explanation of the effect of the dead band you use in your control program and how that changes the tension control on each spindle. Also, doesn't the braking effect used to control tension lead to some of the fluctuations the dead band hides?

A. Tension is supplied to the winding machine by the take up motor, which turns the mandrel on which the capacitor is wound, and by each of the individual supply spindles which are fighting the rotation of the take up motor. The dead band simply eliminates the "noise" of the system. Each clutch is supplied with a current that is proportional to the torque it will deliver. The torque delivered by the clutches is continuous and the clutch is in a constant state of slip. Increasing or decreasing the current to the clutch simply increases or decreases the torque supplied, or the slip, without a braking action. The tension created with this torque is measured as a 0-5 volt output from a digital indicator and has natural fluctuations which are filtered out with the dead band.

Q. What are the speeds you use to wind the capacitors?

A. In general, we wind at 30 rpm, which is quite slow. A commercial capacitor vendor will wind considerably faster. Our reliability requirements and size limitations don't currently allow us to wind faster because we would lose too much control over the capacitor margins, the space factor, which determines how well the fluid will impregnate, and wrinkles.

Q. Are you ever pushed to try and wind capacitors faster?

A. No, primarily because of the small numbers of capacitors we fabricate. We have tried to wind faster and can control tension accurately, but not within the five gram tolerance we now use. The problem that arises is that at the low tensions we use, rapid accelerations will cause the inertial effects of the supply rolls to cause tension fluctuations. We can avoid that problem at low speeds and accelerations. If we increased our tension sampling rate and had clutches with a faster response, we should be able to compensate for the inertial effects and wind faster.

Q. I'd like to know something about the thickness of the aluminum foil that you're winding. Since it's considerably stiffer than the mylar, what is the effect of the variable tension since you're winding the aluminum roll with a higher stress level to begin with?

A. The aluminum foil is usually 22 gage or 20 gage, which is approximately 2/10 of a mil and very fragile. If you could look at the individual plies of material in the stress curve that Reuter developed, you would see that the aluminum foil is driven much further into compression than the mylar because of its stiffness. The variable tension control will be on individual spindles so the tension of the aluminum foil will be controlled independently of the mylar and can be much higher if necessary. A concern that we have is that, depending on the size of the finished capacitor, the tension may have to go very high and we may not be able to reach the peak without pulling the foil apart.

Q. Would the tension control be considered digital control, only on or off, and why do you call the system nonlinear?

A. In a sense, the tension control is on/off because of the dead band through which we effectively provide no error feedback. However, the amount of current delivered to the clutch is controlled continuously without necessarily changing it. The system reads the tension on the material and delivers to the PLC a 0-5 volt output which describes the full range of tension, whatever it may be. If the difference between this voltage and the setpoint voltage falls outside of the dead band, the PLC will increase or decrease its voltage output by the predetermined increment. The voltage to current converter then takes the output voltage of the PLC and delivers a proportional current to the clutch. The nonlinear description of the system indicates that the current output is not necessarily proportional to the tension reading output of 0-5 volts. It may take a higher current on any given clutch to produce the same tension at a lower current on another clutch. The system will put out whatever current is necessary to provide the set point tension.

Q. Wouldn't the stress level you see in the capacitor winding be decreased if the stiffness of the mandrel was reduced?

A. Yes, the results shown were compiled using only solid lexan mandrels. We are also looking at using hollow phenolic mandrels which have been instrumented with strain gages. We are expecting the stresses to decrease considerably in those experiments.