Thermal Shock Induced Failures of Cycloaliphatic Epoxy Apparatus Bushings

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Abstract

After a brief introduction to our company, this paper describes our experience with special 600-Amp and 1250-Amp cycloaliphatic epoxy bushings that cracked and failed while serving a cyclic load, how we determined the cause of the cracks, and what was done to correct the problem. This paper also describes the accelerated thermal shock test procedure used to test 200-Amp and 600-Amp bushings so we could be certain thermal fatigue would not be a problem in the future. Appended to the paper is a summary of the results of our tests.

Introduction

In 1970, Elliott Industries, Inc. began manufacturing Safefront pad-mounted distribution switchgear which connects to the utility system using separable insulated connectors (elbows). For several years bushings were purchased from other manufacturers. We soon learned that "air-terminated" bushings required special features and shielding not required with "oil-terminated" bushings. For ten years we worked closely with our bushing manufacturers to enhance the design of "air-terminated" bushings. Even so, our customers reported a small percentage of cracked bushings during this period. In 1980, Elliott Molding & Components Division was formed to produce high quality "air-terminated" bushings and other components. Existing bushing designs were improved and new bushing designs were developed. In addition to design tests, every bushing was production tested to guarantee that 100 percent of our bushings met or exceeded ANSI/IEEE Standard 386. 200-Amp bushing wells produced by Elliott Molding & Components Division have provided superior field service and, with over 10,000 in service, there have been no reported failures (except for two or three with studs twisted off at the time of installation). 600-Amp bushings produced by Elliott Molding & Components Division appeared to provide good field service, but a number of cracked bushings were reported. Investigation of each report led us to believe that the cracks were due to excessive cantilever loading, impact or improper removal from the mold during manufacture. Improved manufacturing control was implemented to eliminate any problem due to improper removal from the mold.

Discovery of a Thermal Problem

During the last quarter of 1983, we began molding special 600-Amp and 1250-Amp 35 kV bushings, which contained 1.25-inch diameter copper conductors in place of the usual 1.25-inch diameter aluminum conductors. After producing these parts for one and one-half years, a bushing failure due to a crack was reported by a customer. Investigation led us to believe that the crack was due to impact or excessive cantilever loading. After additional failures at the same location it was suggested that, because the equipment in that location served a highly cyclic load, thermal fatigue could be the cause of the crack.

This possibility was supported by a paper published in "IEEE Transactions" entitled "Thermal Fatigue Strength of Epoxy Supporting Insulators With Embedded Electrodes" written by Toshiharu Yamazaki and Nobumitsu Kobayashi. The authors point out that copper and aluminum cast in epoxy have an inherent mismatch of thermal expansion coefficients which induce thermal stress in the epoxy when the temperature fluctuates. Thermal fatigue, which results in unexpected mechanical failure, can occur due to long term repeated fluctuations of the temperature. They suggest reducing the temperature of an epoxy bushing to cryogenic temperatures as a possible proof test.

Flexcoat-I (the coating used on standard 600 Amp bushings that have aluminum conductors) was used to coat the copper conductors in the special bushings to compensate for the mismatch of thermal expansion coefficients. The mismatch of copper and epoxy is greater than the mismatch of aluminum and epoxy, so the special bushings with copper conductors were more likely to fail due to thermal fatigue. Reducing the temperature to a very low level would maximize stress and produce an accelerated failure if thermal fatigue was the cause of the field failures. Test bushings were placed in an insulated container filled with methanol. Dry ice was added to lower the temperature to minus 100 degrees F within 60 minutes. The test bushings cracked in the same manner as the field failures.

Flexcoat-II was developed and test bushings with Flexcoat-II coated conductors showed an improvement which was not consistent. Flexcoat-S was developed and test bushings with Flexcoat-S coated conductors consistently pass direct immersion in the minus 100 degree F methanol bath without cracking. A proof test which required seven bushings to cycle from plus 80 degrees F to minus 100 degrees F for two cycles without a single failure was performed. All seven bushings were cycled twice and electrical tests verified there was no electrical or mechanical damage. All the original special bushings with copper conductors were replaced by bushings with Flexcoat-S coated copper conductors and the failures were eliminated.

Continued Testing

We were no longer sure that our 600 Amp bushings with Flexcoat-I coated 1.25-inch diameter aluminum conductors were adequate to prevent premature thermal fatigue. We purchased a Blue M “Stabil-Therm” liquid nitrogen thermal shock chamber with a temperature range of plus 600 degrees F to minus 300 degrees F. This chamber would allow us to conduct accelerated thermal shock tests of our bushings in a gas, rather than a liquid. We decided to test all the bushings being produced (and older designs which had been discontinued) so we could be sure that the 600-Amp bushings would perform as well as the 200-Amp bushings, which had provided trouble-free field service.

Test bushings were heated to plus 250 degrees F and stabilized for one hour. The temperature was lowered to a target temperature of minus 50 degrees F (on the first cycle) and stabilized for one hour, then reheated to plus 250 degrees F and stabilized for one hour. At this point each bushing was inspected for cracking and for material decomposition. If there were no cracks and no decomposition, the thermal cycle would be repeated, with the target temperature 50 degrees lower than the previous cycle (minus 100 degrees for cycle 2, minus 150 degrees for cycle 3, and so on), until failure of the bushing, or until the lower limit of the thermal shock chamber was reached (minus 300 degrees F).

Our tests show that 200-Amp bushings with adhesive coated 0.75-inch diameter copper conductors produced before 1980 would pass cycle 1 and cycle 2, then crack on cycle 3 at minus 150 degrees F. This explained the small number of cracked bushings reported for this design. The #1101-225A2 design produced after 1980 provided a greater epoxy cross section, relative to the conductor cross section. This 200-Amp design would consistently pass cycles to minus 200 degrees F. The #1101-225B design provided an even greater epoxy cross section and this 200-Amp design would consistently pass cycles to minus 250 degrees F. Since the #1101-225A2 and #1101-225B had provided trouble-free field service, we decided that all bushing designs must be able to consistently pass cycles to minus 200 degrees F.

Test results show that the 600-Amp interface dimensions of ANSI/IEEE Standard 386 would not provide enough epoxy cross section relative to the conductor cross section to withstand thermal fatigue unless a flexible coating is used to compensate for the difference in thermal expansion and contraction. 600-Amp bushings (a discontinued design) with Flexcoat-I coated conductors would not perform consistently. Although some passed cycles to minus 200 degrees F, others failed cycle 1 (minus 50 degrees F). Improved performance was found when the conductors were coated with Flexcoat-II. However, the improvement was not consistent. Some passed cycles to minus 300 degrees F, while others failed cycle 2 (minus 100 degrees F). Consistent improved performance was achieved when the conductors were coated with Flexcoat-S.

All Flexcoat-S bushings passed cycles to minus 250 degrees F and most passed cycles to minus 300 degrees F. Soon after we began these accelerated thermal shock tests, we realized that bushings with Flexcoat-S coated conductors were far superior. Starting October 17, 1985, all 600-Amp and 1250-Amp bushings have been produced with Flexcoat-S coated conductors. We are now sure that our 600-Amp and 1250-Amp bushings (with Flexcoat-S coated conductors) will provide the same trouble free service as our 200-Amp bushings.

Conclusion

Bushings with embedded conductors are subject to thermal fatigue in an unacceptably short time unless some method is provided to prevent thermal fatigue due to dissimilar expansion of the epoxy and the conductor. Our test results show Flexcoat-S eliminates the problem of premature thermal fatigue. Since 600-Amp bushings produced with Flexcoat-I and Flexcoat-II are subject to thermal fatigue in an unacceptably short service life, all of these 600-Amp bushings should be replaced with 600-Amp bushings produced with Flexcoat-S coated conductors.

Summary of Test Results

Bushing No.	Temperature	Notes
E200-25A 200 Amp 25 kV Bushing Well (Replaced by #1101-225A2)		
Structural Adhesive		
*TB-1	-150 degrees F	Cracked at 5th Valley
*TB-2	-150 degrees F	Cracked at 4th Valley
*TB-3	-150 degrees F	Cracked at 1st/4th Valley
*TB-4	-150 degrees F	Cracked at 4th Valley
*780-88	-150 degrees F	Cracked at 5th/6th Valley
* 1978 production by another manufacturer (removed from field)		
1101-225A2 200 Amp 25 kV Bushing Well		
Structural Adhesive		
TB-5	-250 degrees F	Cracked at Valley 10
TB-7	-250 degrees F	Cracked at Valley 9
TB-8	-250 degrees F	Cracked at Valley 10
TB-1X	-300 degrees F	Cracked Around Shank
TB-2X	-300 degrees F	Cracked Around Shank
TB-1	-300 degrees F	Longitudinal Crack Valley 4 to 11
TB-3	-300 degrees F	Longitudinal Crack Valley 4 to 11
TB-10	-300 degrees F	Spiral Crack Valley 3 thru 9
TB-6	-300 degrees F	Cracked at Interface Post
TB-2	-300 degrees F	No Failure
TB-4	-300 degrees F	No Failure
TB-9	-300 degrees F	No Failure
1101-225B 200 Amp 25 kV Bushing Well		
Structural Adhesive		
TB-1	-300 degrees F	Cracked Top Skirt
B8636-19	-300 degrees F	Cracked Valley 6 & 11
TB-2	-300 degrees F	No Failure
B8571-12	-300 degrees F	No Failure
B8571-30	-300 degrees F	No Failure
B8585-56	-300 degrees F	No Failure
B8586-49	-300 degrees F	No Failure
B8597-13	-300 degrees F	No Failure
B8633-20	-300 degrees F	No Failure
B8633-35	-300 degrees F	No Failure
B8634-25	-300 degrees F	No Failure
B8636-43	-300 degrees F	No Failure
1201-E600-25A 600 Amp 25 kV Bushing (Replaced by #1201-625A2)		
Flexcoat I		
TB-1	- 50 degrees F	Cracked at 1st Valley
TB-2	- 50 degrees F	Cracked at 1st Valley
TB-3	- 50 degrees F	Cracked at 1st Valley
*B8160-1	-150 degrees F	Cracked at Interface
*B8160-3	-200 degrees F	Cracked at Interface
*B81160-11	-250 degrees F	Cracked at Interface
* 1981 Elliott Production (removed from field)		
1201-625A2 & A2F 600 Amp 25 kV Bushing		
Flexcoat II		
B8538-33	-100 degrees F	Cracked Around Interface
B8538-12	-150 degrees F	Cracked at Interface
TB-2	-200 degrees F	Cracked Entire Length
B8538-39	-250 degrees F	Cracked at Shank
B8538-37	-250 degrees F	Cracked at Shank
B8538-18	-250 degrees F	Cracked at Shank
B8538-25	-250 degrees F	Cracked at Shank
TB-1	-300 degrees F	Cracked Entire Length

Flexcoat-S

TB-1	-300 degrees F	No Failure
TB-2	-300 degrees F	No Failure
TB-3	-300 degrees F	No Failure
TB-4	-300 degrees F	No Failure
TB-5	-300 degrees F	No Failure
TB-6	-300 degrees F	No Failure

1201-625B2 600 Amp 25 kV Bushing

Flexcoat I

TB-1	-100 degrees F	Cracked Around Interface
TB-2	-100 degrees F	Cracked Around Interface
TB-3	-150 degrees F	Cracked at Interface & Shank
TB-4	-150 degrees F	Cracked at Interface & Shank

Flexcoat II

B8582-44	-150 degrees F	Cracked at Interface
B8582-47	-150 degrees F	Cracked at Interface
B8582-26	-200 degrees F	Cracked at Interface
B8582-41	-250 degrees F	Cracked Entire Length
B8582-46	-250 degrees F	Cracked Entire Length
B8582-43	-300 degrees F	Cracked at Shank
B8582-40	-300 degrees F	Cracked at Shank
B8582-45	-300 degrees F	No Failure

Flexcoat-S

B8582-56	-300 degrees F	No Failure
B8582-55	-300 degrees F	No Failure
B8582-58	-300 degrees F	No Failure
B8582-01	-300 degrees F	No Failure
TB-5	-300 degrees F	No Failure

1202-635B2 600 Amp 35 kV Bushing

Flexcoat II

B8561-04	-250 degrees F	Cracked Entire Length
B8561-07	-250 degrees F	Cracked Entire Length

Flexcoat-S

B8561-49	-300 degrees F	No Failure
B8561-54	-300 degrees F	No Failure
TB-1	-300 degrees F	No Failure
TB-2	-300 degrees F	Small chip next to conductor, OK
TB-3	-300 degrees F	No Failure

1403-1235B/BL 1250 Amp 35 kV Bushing

Flexcoat I (1403-1235 B Black)

B8449-12	-100 degrees F	Cracked at Flange
B8449-07	-150 degrees F	Cracked Between Skirt 11-17
B8449-13	-150 degrees F	Cracked at Interface

Flexcoat-S

TB-1	-300 degrees F	Cracked Entire Length

1611-625L 600 Amp 25 kV Special 90 degree Bushing

Flexcoat II

B8529-50	-200 degrees F	Cracked Entire Length
B8529-55	-200 degrees F	Cracked Entire Length
B8529-54	-200 degrees F	Cracked Entire Length
B8529-51	-200 degrees F	Cracked at Interface

Flexcoat-S

TB-1	-250 degrees F	Cracked Overlay*
TB-2	-250 degrees F	Cracked Overlay*
TB-3	-300 degrees F	No Failure
TB-4	-300 degrees F	No Failure
TB-5	-300 degrees F	No Failure

*After -300 degrees F, main body showed no failure