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VOLUME 3

IMPROVING MOTOR RELIABILITY IN NUCLEAR POWER PLANTS

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M. Subudhi and J.H. Taylor

M.W. Sheets
Nutech Engineers

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ENGINEERING TECHNOLOGY DIVISION
DEPARTMENT OF NUCLEAR ENERGY, BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973

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M. Subudhi and J.H. Taylor
Engineering Technology Division
Brookhaven National Laboratory
Upton, New York 11973
and
M.W. Sheets
Nutech Engineers
San Jose, California 95119

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ABSTRACT

Stator coils of a naturally failed 400 hp motor from the Brookhaven National Laboratory test reactor facility were tested for their dielectric integrities. The motor was used to drive the primary reactor coolant pump for the last 20 years. Maintenance activities on this motor during its entire service life were minimal, with the exception of meggering it periodically. The stator consisted of ninety individual coils which were separated for testing. Seven different dielectric tests were performed on the coils. Each set of data from the tested coils indicated a spectrum of variation depending on their aging conditions and characteristics. By comparing the test data to baseline data, the test methods were assessed for application to motor maintenance programs in nuclear power plants. Also included in this study are results of an investigation to determine the cause of this motor failure. Recommendations are provided on the aged condition of a second identical primary pump motor which is the same age and presently in operation. Recommendations are also presented relating to each of the dielectric test methods applicability to motor maintenance programs.

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SUMMARY

This report presents the findings of a study made on the windings of a 6 pole, 400 horsepower, 2400 volt, form wound motor. The motor was used to drive the recirculating cooling water pump for the Brookhaven National Laboratory (BNL) High Flux Beam Test Reactor. The stator winding of the motor failed after over 20 years of service requiring the motor to be replaced. The objectives of this study were (1) to identify the cause of the stator winding failure and (2) to assess the ability of various dielectric test methods to determine stator coil condition for application to nuclear power plant maintenance programs. The tests evaluated include dc resistance test, surge test, dc leakage test, ac dissipation factor test, ac capacitance test, ac leakage test, and AC hipot test.

The subjec. motor and the transformer which supplies it are part of an ungrounded system at the BNL test reactor facility. Ground faults were found in both the motor and in a cable from the transformer secondary side. The faulted transformer cable was saturated with oil.

Based on the failure analysis of this system which was performed as part of this study, it is unlikely that a failure surge from the motor caused the transformer secondary cable failure. It is also unlikely that simultaneous ground faults occurred in both the transformer cable and the motor stator windings. Hence, it is believed that the oil saturated transformer secondary cable grounded first producing an arcing ground which in turn failed the motor windings. As a result, there exists the possibility that the stator winding system on a second identical motor driven by this transformer was weakened by this event. It is therefore recommended that the second motor be replaced. In addition, it is recommended that the ungrounded system be grounded or have ground fault detectors installed to prevent the recurrence of a similar event.

With regard to the evaluation of various dielectric test methods for motor maintenance programs, the conclusions drawn from this study are based on the results of the diagnostic motor test discussed herein. Table S-1 summarizes the conclusions for each test method. It should be noted that not all tests must be performed on an insulating system to monitor its degradations due to aging since several of the tests provide redundant information. Currently dc insulation resistance and/or polarization index tests are the only dielectric tests generally performed on motors by the nuclear power plant industry. Additional tests for monitoring the average aging condition of insulating materials and/or local deteriorations such as hot spots, turn shorts, and corona discharges should be considered for inclusion in existing preventive maintenance programs. Tests can be selectd as required from those discussed herein to provide a balanced maintenance program.

Table S-1 Summary of Dielectric Test Results

Potential Test Method	Aging Effects Monitored (Dielectric Integrity)	Degradation Type[1]		Applications				Remarks
				Preventive Maintenance		Corrective Maintenance	Motor Size	
		Average	Local	Trending	Go/No Go			
Dc Insulation Resistance	Moisture control, environmental contaminations (dust, foreign particles)	X			X	X	All	Trending is questionable with the existing test equipment.
Surge [3]	Turn short, phase unbalance, connection problems		X		X	X	<600 volts	Digital storage of wave patterns would enhance the use of this test.
Dc Leakage Current (dc hipot) [3]	Moisture control, environmental contamination	X			X	X	All	An alternate to dc insulation resistance test.
Ac dissipation factor [4]	Cracks and voids	X		X		X	All [2]	For larger high voltage motors power factor test is preferred.
Ac capacitance [4]	Thinning or deterioration	X		X		X	All	Same as dissipation factor test.
Ac Leakage [4]	Cracks, voids, thinning	X			X	X		Test parameter values are too small to trend.
Ac hipot	Overall degradation to affect the breakdown voltage	X	X	Not Recommended		X	All	A potentially destructive test. Should be used with discretion.

Notes:

1 Average degradation is referred to an overall condition of the insulation. Local degradations include turn short, hot spot, corona discharges, etc.

2 Power factor test is an alternate to this dielectric test, and either test can be performed on all size motors.

3,4 Obtained by using the same test equipment

1. INTRODUCTION

Electric motors used in nuclear power stations are of various sizes ranging from fractional to several thousand horsepower. The operating experience [1] of these motors has revealed that the stator windings and the bearing assemblies contribute to a significant percentage of the experienced failures. Monitoring the condition of the bearing assemblies in the case of integral and larger horsepower motors is achieved by lubricant analysis, temperature measurement, and vibration monitoring. Small integral and fractional horsepower motors are often equipped with sealed or shielded pre-lubricated bearings with no re-greasing capabilities and do not require maintenance except for replacing the bearings at the end of their qualified life. However, monitoring the condition of the winding insulation systems still remains as an undeveloped area. Selecting the types of test methods that are practical and viable for accomplishing this task in a nuclear power plant environment was one of the initiatives for the testing described in this report.

A recent survey [2] of nuclear facilities indicated the only tests performed on most motors by plant maintenance personnel were dc insulation resistance and polarization index tests. Both of these tests measure the condition of insulation with respect to its moisture content, and the results are useful prior to performing an ac high voltage test and/or starting the motor after maintenance. The objective of the 10 hp motor plug reverse testing [3] performed by NUTECH for BNL was to determine which test methods can be used to assess insulation condition. This study on the 400 hp motor augments the small motor test findings.

1.1 Background

The following background data are based on the BNL Reactor Division, Unusual Occurrences Report [4].

The High Flux Beam Research Reactor (HFBR) test facility at BNL is a test reactor with two primary loops using heavy water as the reactor coolant and moderator. Each primary loop contains a 400 hp, 2,400 volt, 6 pole, form wound class B insulated motor to drive each primary pump inside the primary cell.

On March 9, 1986, with the reactor operating at 60 megawatts, one of the primary pumps (GA-101A) failed resulting in a low primary coolant flow rate. This resulted in a reactor scram[4].

On March 10, 1986, during preparations to test the insulation resistance of the GA-101A primary pump motor, phase 2 of the 2,400 volt number 1 13.8kV/2.4kV/440 volt incoming transformer was found to have a ground. This transformer is one of two that can supply all the HFBR electrical power. The number 2 transformer was shut down for repairs. Each phase of the 2,400 volt secondary side of the number 1 transformer has two 1,500 mcm cables in parallel. Only one of the two phase 2 cables was found to have a ground. The other phase 2 cable and the 4 other cables on phases 1 and 3 were found to have satisfactory insulation resistance.

Insulating oil from the transformer terminal box was found to have migrated along the failed phase 2 cable and into the number 1 transformer output breaker cubicle in the fan house (Bldg. 704). The transformer phase 2 ground was not present as of the end of February 1986. No oil migration existed in the remaining unfailed five cables. The terminal box insulating oil was successfully tested at 30 kV to prove its insulating ability. As an interim repair, the failed phase 2 cable was removed. The resulting lower current carrying capacity available with the remaining phase 2 cable was verified to be adequate to meet the ongoing HFBR operating electrical power requirements. The single cable was estimated to be able to carry approximately 845 amps, which was approximately 15-20% greater than the required current.

On March 10, 1986, the GA-101A primary pump motor winding insulation resistance was tested with a zero resistance to ground measured. The GA-101B primary pump motor was checked and found to have satisfactory insulation resistance. The decision was made to run the reactor at 40 megawatts, single loop with the "A" side isolated in order to meet the scheduled reactor startup which was March 19, 1986. At 1159 on March 19, the reactor was started to 40 megawatts for cycle number 225.

The failed motor was subsequently replaced by a spare motor. This made the failed motor available for testing to establish the cause of failure and also to determine and predict the potential limitations on the GA-101B motor, since both these motors were the same age.

Prior to performing this study, it was not clear whether the motor failed first due to a turn to ground short, creating a current surge which failed the transformer cable, or the transformer cable failed first, resulting in an overload on the two phases in the motor winding which subsequently failed, or both motor and transformer failed simultaneously. However, the motor had been in service at this facility for over 20 years with minimal maintenance activities and without any appreciable problems. Figure 1.1 shows the failed motor stator winding and the burned out area.

1.2 Objectives

The objectives of this study are as follows:

1. Identify the cause of stator winding failure for the primary coolant loop A pump motor (GA-101A) and predict the condition of the primary coolant loop B pump motor, (GA-101B).

2. Using certain dielectric test methods identified in this motor study and comparing the test data for all aged coils in the failed stator winding, determine the suitability of each test method for nuclear power plant motor maintenance programs in monitoring the age-related insulation degradations.

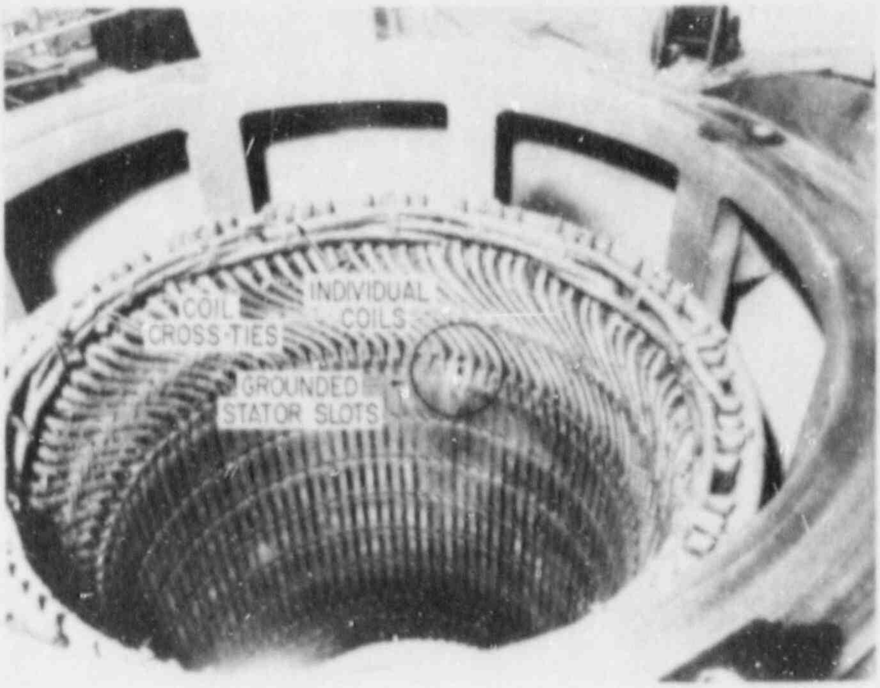


Figure 1.1 - Failed HFBR 400 hp motor stator.

1.3 Scope

In order to achieve the aforementioned objectives, all available information related to the motor failure was collected and reviewed. This included an inspection of the installation site, as well as a detailed examination of the motor and transformer. In addition, operating and maintenance personnel at the facility were interviewed to provide insight on the events preceding the motor-transformer failures. Motor operating data obtained for this study included running current and temperature charts. Maintenance records for the motor and switchgear were also reviewed for possible causes of the motor failure.

The stator of the failed motor was thoroughly inspected for any visual indications of the motor failure. The stator was then opened, and the following tests were conducted on the coils:

1. Dc resistance tests,
2. Surge test,
3. Dc leakage test,
4. Ac Dissipation factor test,
5. Ac Capacitance test,
6. Ac leakage test, and
7. Ac high potential test.

These tests are described in detail in Volume 1 of this NUREG[2]. The first three tests are dc tests while the next four are ac tests. At the end of the first six tests, each coil was connected to an ac high potential unit to determine its breakdown voltage to ground. A partial discharge test was not performed on the coils because of leakage around the cut connections which would cloud the test results. This problem was noted during the AC High Potential Tests where coils failed instantly, presumably due to a ground path at the cut connections. To measure partial discharge (corona), a High Potential Tester must be used along with the partial discharge tester; the latter only shows the corona discharge from the ac high potential test.

Section 2 of this report discusses the motor preparation and test equipment used in this program. Section 3 is devoted to the probable causes of the failure, while Section 4 addresses the degradation of the motor insulation. The final section summarizes the test findings and provides recommendations with regard to how the test results from this motor can be used in the BNL study for condition monitoring to determine potential motor winding failures.

2. MOTOR PREPARATION AND TEST EQUIPMENT

This section describes the pretesting preparation of the motor windings and test equipment utilized in this test program.

2.1 Motor Winding Description and Preparation for Testing

At the time this study was started, the motor had been disassembled and the stator had been put aside inside the reactor facilities at BNL for testing. Figure 1.1 shows the failed stator with the damaged winding slots.

In preparation for testing, it was determined that the motor had a form wound winding with three terminal leads. On a form wound winding, all coils are wound and insulated separately, and are not in contact with adjacent coils. Therefore, the connection between the coils can be opened and all the coils can be tested individually. The ties holding the motor connection ring were cut so the connections could be separated and studied. At this point, it was determined that the motor had 18 groups of five coils and that the groups in each phase were connected in series, making a 6 pole Y-connected winding. Each group constitutes a pole, therefore, the motor was a 3 phase, 6 pole motor. It was also determined that the coil span was 1 to 13. That is, the top side of the coil was in slot 1 and the lower side of the coil was in slot 13. Figure 2.1 shows a sketch of the 3 phase, 6 pole, 18 group, Y-connected winding. The numberings on the sketch represent the stator winding coils (30 coils/phase). The grounded coil groups in each phase were determined from the insulation resistance test which was performed prior to separating each individual coil.

Before cutting the connections for individual and group testing of the coils, all connections and coils were identified by letters or numbers. Letters were used on inner group connections representing the cross ties of each phase coil connection and numbers were used on individual coils. The coil and connection identifications are shown on Figures 2.1 and 2.2. By connecting all the same letters in the winding arrangements in Figure 2.2 (also shown in Figure 2.1) one can develop the Y-connected stator windings. This figure illustrates the stator winding arrangement after it was spread out on a flat sheet. Figure 2.3 shows the pictorial view of the stator after all connections were cut, marked, and ready for other dielectric tests.

2.2 Test Equipment Description

The following paragraphs provide a brief description of the test equipment used to perform the insulation tests on the motor winding.

2.2.1 Biddle Dc Megger Tester (Catalog No.210400)

This tester is used to determine the dc resistance in megohms of the winding to ground insulation for complete windings and coils. The tester allows testing at 500, 2,500 and 5,000 volts dc. The test time can vary. Because of the high initial charging current inherent to megger testing, a one minute duration was chosen for the test. This insured that the charging current effects had dissipated and an accurate insulation resistance

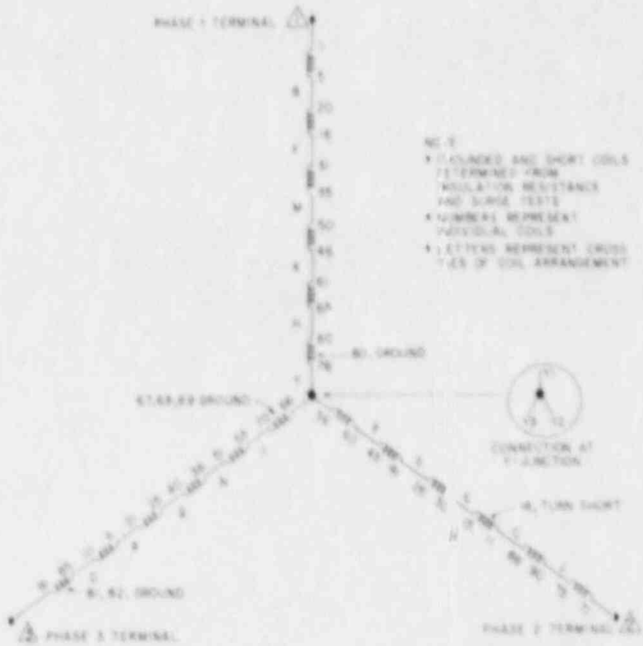


Figure 2.1 - Stator winding arrangement showing coil numbers.

measurement could be obtained. In the test program, each coil group was tested to ground at 2,500 volts dc. As determined by IEEE Standard 43-1974, a resistance value of 3.4 megohms or greater would indicate the insulation for this motor is in good condition. The high test values (100,000 megohms) obtained after one minute, indicating that a longer test time was not needed since resistance values would only increase further as any remaining charging current effects dissipated.

2.2.2 Baker Surge Tester (Model No.ST106)

This tester performs two separate functions; a surge tester and a dc high potential tester for measuring dc leakage current.

The surge tester was used to detect winding faults and defective turn insulation in the coils. Insulation is tested by impressing a series of brief high voltage pulses on the winding. If the insulation is sound at the voltage applied, the surge tester will show a single stable wave form. If the insulation breaks down, the pattern will be unstable.

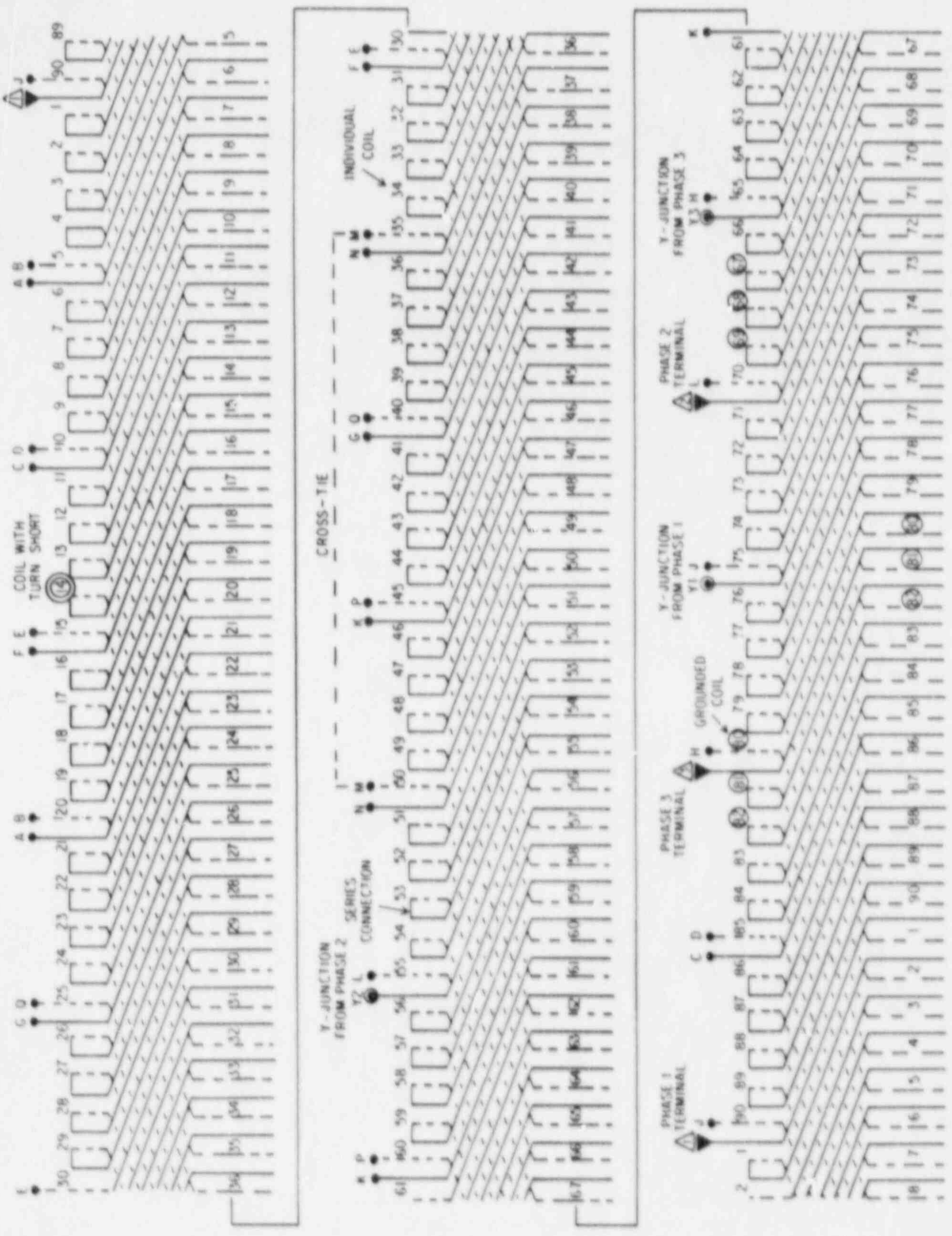


Figure 2.2 - Coil placement and failed coil locations.

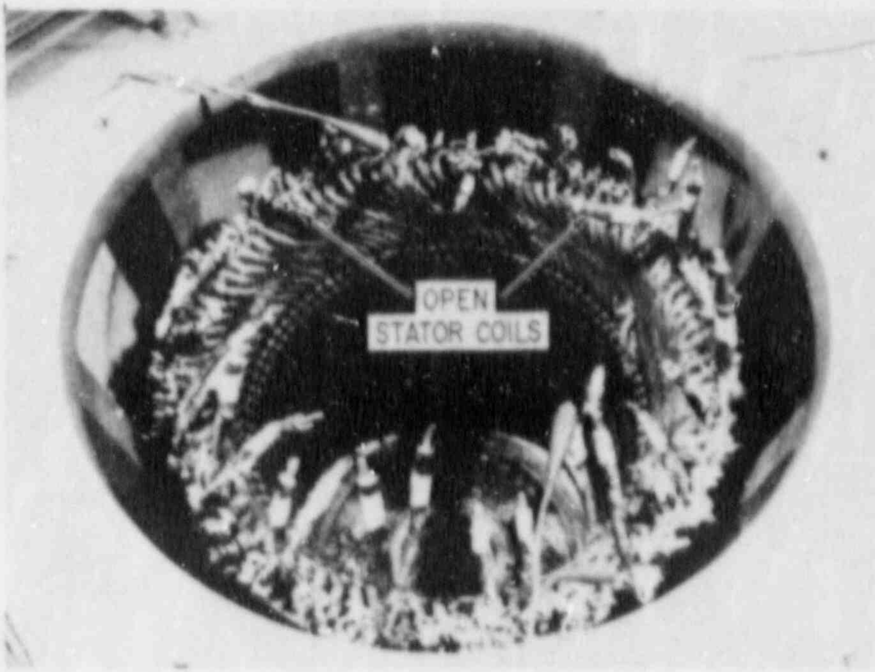


Figure 2.3 - Pictorial view of the stator coils with all coils separated and tagged.

Winding faults were detected by comparison of wave patterns between phases. Here coil testing was performed by comparing one coil to another coil at an impressed voltage of 2,500 volts. The coils each produced a specific wave pattern on the screen of the scope. Mismatches in the wave patterns indicated faults.

The second function of the Baker Surge Tester is a dc high potential tester. This tester was used to detect dc leakage current across the insulation to ground for individual coils or complete windings at 5,000 volts dc. In the test program, each coil was tested at 5,000 volts dc which is the maximum test voltage permissible with the tester used.

2.2.3 Biddle Ac Dissipation Factor/Capacitance Tester (Model No.670025)

This tester can be used to measure dissipation factor, capacitance and ac leakage current at different voltages. In the test program, dissipation factor, capacitance and current leakage were recorded for both 1,000 and 2,000 volts ac for a number of coils in the motor.

2.2.4 Ac High Potential Tester (Westinghouse, Style 1309928)

This tester can be used to test coils or windings at different ac voltages. This is a go or no-go test and is considered as a destructive test compared to the dc megger or dc current leakage tester. In the test program all coils were tested to failure.

3. FAILURE ANALYSIS

This section describes the possible cause of the motor failure and provides recommendations with reference to the second motor, GA-101B. The second motor operates on the same bus as the first motor, GA-101A, which failed.

3.1 Description of Failure

As indicated earlier, the GA-101A pump motor failed while the reactor was operating at 60 megawatts. Following the incident, an unsuccessful attempt was made to restart the pump. A later inspection revealed that the instantaneous trip tabs for phases 1 and 3 were tripped at the motor breaker. During the subsequent meggering procedure, a ground fault was found in one of the two phase 2 feeder cables between the transformer secondary (2,400 volt) side and the switchgear cubicle. Later inspection showed that the cable was saturated with transformer oil which had leaked from the transformer oil filled terminal box. Oil had run along the cable into the switchgear cubicle.

Interviews with plant maintenance and operating engineers, revealed no abnormal precursors which could indicate any incipient degradations in the motor windings. In addition, the previous maintenance records (megger data) indicated no sign of insulation deterioration. Running current, input voltage, and bearing oil temperature data monitored at the control room did not show any fluctuations or spikes before the motor failure.

3.2 Cause of Failure

The aforementioned findings were reviewed with experts in the field. Various possible causes of the motor failure were addressed, as discussed below.

Figure 3.1 shows a schematic of the circuit between he feeder transformer and the two recirculating pump motors. The 2,400 v .t side of the Δ/Δ transformer and the two Y connected motors are ungrounded. Each phase from the transformer secondary consists of two cables in parallel to provide the required current carrying capacity. In such an arrangement, each phase line current is shared by the two cables. As indicated earlier, one of the two cables from the phase 2 of the transformer was found to have an open circuit and probably grounded as indicated in Figure 3.1. The post-failure tests also found that the Y-connected stator windings of motor GA101A had grounded coils in phases 1 and 3.

Based on the above post-failure grounded conditions in the ungrounded transformer-motor system arrangement, as shown in Figure 3.1, it is evident that there exist three possible scenarios the system might have experienced prior to its failure. These are:

1. The motor failed first due to a turn to ground short creating a currrent surge which failed the transformer cable,

2. Two simultaneous failures occurred in the cable and motor windings, and

3. The transformer cable failed first resulting in an overload on the two phases in the motor winding which subsequently failed.

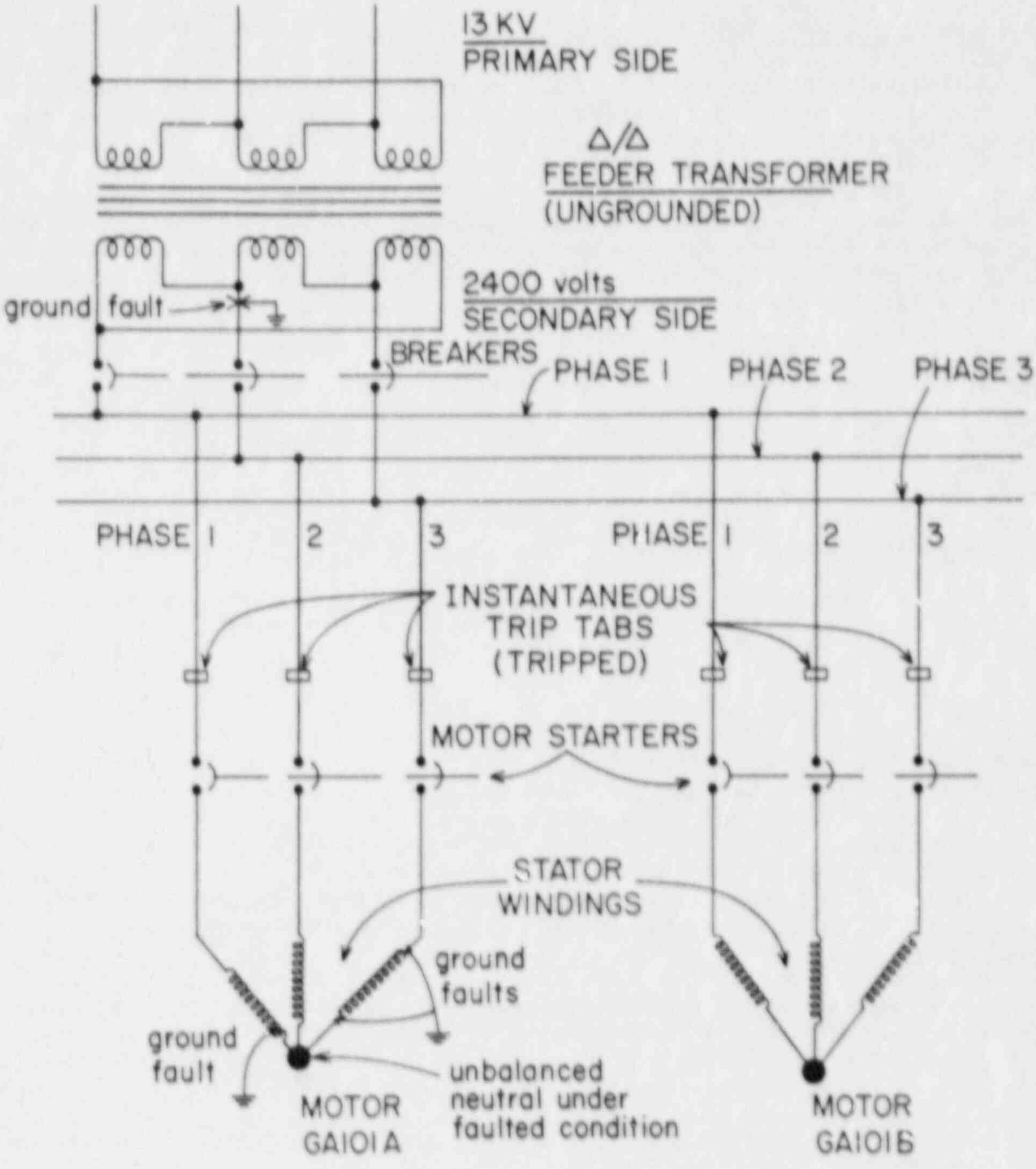


Figure 3.1 - Power supply to RCP motors from feeder transformer.

Before analyzing each of the above scenarios for the system modes of failure, one has to understand the behavior of an ungrounded system under single, double or multiple ground fault conditions.

The term ungrounded is used to identify a system in which there is no intentional connection between the system conductors and ground. However, in any system, there always exists a capacitive coupling between the system conductors and ground. Consequently, the so-called "ungrounded system" is in reality a "capacitively grounded" system by virtue of the distributed capacitance from the system conductors to ground [5].

Line-to-ground faults on ungrounded-neutral systems cause a ground-fault current to flow through the capacitance of cables, transformers, and other electrical equipment on the system. This current may have a magnitude from a few amperes to 25 amp or more on a large system. This is not, in general, enough to actuate protective devices, but it may do considerable damage if allowed to flow for a long period.

When the neutral of a system is not grounded, it is possible for destructive transient over-voltages, of several times the normal, to appear from line to ground during normal switching when a circuit has a line-to-ground fault. Tests have shown that over-voltages may be developed by repeated restriking of the arc during the interruption of a line-to-ground fault. Experience has proved that these over-voltages may cause failure of insulation at other locations on the system. Thus, a line-to-ground fault on one circuit may result in damage to equipment and interruption of service in other circuits.

In an ungrounded-neutral system with a fault in one phase, a second ground fault on another phase may occur before the first fault is removed. The second fault could be caused by an over-voltage condition induced by the first fault, as previously discussed. With only one ground fault, the load would still be supplied and the system would remain operational. However, with two or more ground faults in the system a short circuit flow path could be established through the ground which would bypass the load. Hence, multiple ground faults in an ungrounded system could cause the current to bypass (or drain as leakage to the ground) the load leading to the system failure. A single ground fault of relative unimportance may, therefore, eventually result in considerable damage due to relatively high line-to-line fault currents and the interruption of one or more circuits.

With this understanding of the system characteristics, the postulated failure modes can be examined. If the motor-transformer system failed according to mode 1 (motor failed first), the two motor faults would have occurred prior to the transformer cable fault. The resulting short circuit could then have caused a current surge which failed the transformer cable. This scenario would, however, imply that the motor winding insulation was severely degraded to the point where spontaneous failure was possible without any outside influence. This is not supported by the test findings discussed in Section 4 of this report. Although the possibility exists for this mode of failure to have occurred, its probability is considered to be small.

The second mode of failure (motor and transformer cable fail simultaneously) would have the same implications as mode 1 with regard to the condition of the motor insulation. The possibility of this mode occurring is further reduced since the motor and transformer cable would have to fail spontaneously at the same time. This mode of failure was, therefore, considered to be the least likely of the three for operation under normal conditions.

The above explanations lead to the conclusion that the oil saturated transformer cable grounded first and produced an arcing to ground which in turn failed the motor (mode 3). The following discussions justify this mode of system failure. Before the Phase 2 secondary transformer lead grounded, the voltage to ground on all phases was zero volts for the ungrounded system. Once one of the two cables from the Phase 2 transformer secondary grounded the voltage to ground on that phase remained at zero. This caused the corresponding phase terminal on the motor winding to be at zero potential to ground, whereas the voltage to ground at the motor terminals for phases 1 and 3 was raised to 2400 volts. The increase in potential resulted in overstressing the aged insulation in these two phases which caused them to fail. Usually the insulation between each line to ground is adequate to withstand full line-to-line voltage (i.e., 2,400 volts). However, if this voltage is applied to age-degraded insulation, it can result in failure. Insulation tests performed on the stator windings revealed weak and degraded conditions existed in a number of coils.

3.1 Recommendations

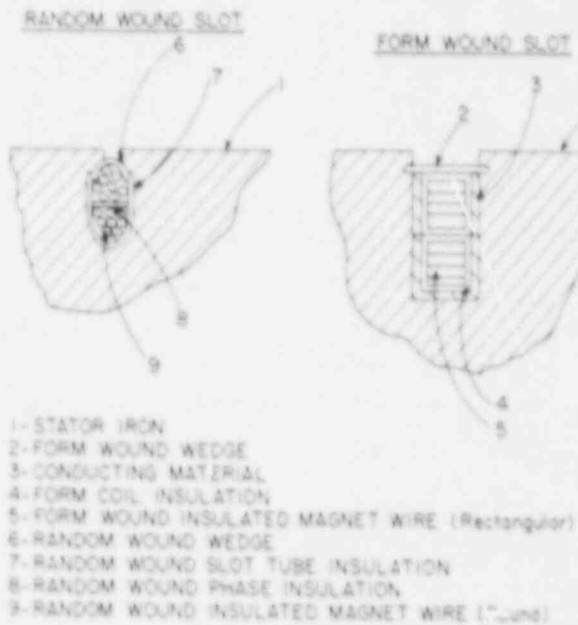
Based on the analysis presented, it is believed that the ground fault in the transformer cable was the initiating event leading to motor failure. The cable ground fault caused an over-voltage condition in the motor windings which resulted in failure of the age-degraded winding insulation. Since the same transformer supplies a second identical motor, it could also have experienced an over-voltage condition. The second motor is the same age as the failed motor and the high voltage could have further degraded the winding insulation. It is therefore recommended that replacement of the second motor (GA-101B) be considered in the near future.

To avoid future occurrences of this type of failure, it is additionally recommended that the motor-transformer system design be modified to include a ground. If a system ground cannot be provided, ground fault detectors should be installed.

4. FAILED MOTOR WINDING STUDY

This part of the study analyzes the test data to assess various test methods which could be used to detect deterioration of motor winding insulation.

The subject motor had form wound windings. In the manufacturing process, these coils are wound separately, insulated, placed in the stator core, and then treated. Figure 4.1 illustrates this insulating system in a stator slot and compares it with a random wound winding which is commonly used for small motors. Because of its design, the coils of a form wound winding can be separated and tested individually. This allowed each of the 90 coils of the subject motor to be studied thereby revealing the statistical nature or variation which would be expected in the results.



CAPACITANCE FORMULA

$C = \frac{\epsilon A}{4 \pi S}$

C = CAPACITANCE
ε = DIELECTRIC CONSTANT
A = CROSS SECTION AREA
S = THICKNESS

Figure 4.1 - Coil arrangements in random and form wound stators.

4.1 Test Results

All of the test results on coil groups and individual coils from the 400 horsepower motor are presented in Tables 4.1 and 4.2. Table 4.1 includes dc resistance (megger), surge, dc leakage, ac dissipation factor and ac capacitance test data. Table 4.2 presents ac leakage and AC hipot test results. The results of each test are discussed below.

Table 4.1 Failed Motor Test Results: Insulation Resistance, Surge, Dc Hipot, Dissipation Factor & Capacitance Tests

* Test per 5 coil group

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	* 2500 Vdc Megger Megohms x 10^3	2500V Surge Test	5000Vdc Leakage Current Test Milliamps	Ac Dissipation Factor Test				Ac Capacitance Test			
									Voltage	% D.F	Voltage	% D.F	Voltage	Capac pf	Voltage	Capac pf
10/21/86	1	1	1	13	Lead 1		OK	0	1001	4.4	2020	4.9	1001	570.0	2020	568.8
10/22/86	2	1	2	14												
10/22/86	3	1	3	15		100										
10/23/86	4	1	4	16												
10/23/86	5	1	5	17												
	6	3	6	18					1006	4.7	2010	4.7	1006	548.6	2010	560.4
	7	3	7	19												
	8	3	8	20		100										
	9	3	9	21												
	10	3	10	22												
	11	2	11	23					1000	4.8	2000	5.4	1000	549.6	2000	560.4
	12	2	12	24												
	13	2	13	25		100										
	14	2	14	26			Short		1001	4.3	2020	4.8	1001	550.0	2020	563.4
	15	2	15	27			OK									
	16	1	16	28					1005	4.5	2000	5.5	1005	550.0	2000	541.8
	17	1	17	29												
	18	1	19	30		100										
	19	1	19	31												
	20	1	20	32												
	21	3	21	33					1000	5.1	2010	5.5	1000	574.4	2010	579.2
	22	3	22	34												
	23	3	23	35		100										
	24	3	24	36												
	25	3	25	37												

Table 4.1 Failed Motor Test Results: Insulation Resistance, Surge, Dc hipot, Dissipation Factor & Capacitance Tests

* Test per 5 coil group

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	2500 Vdc Megger Megohms x 10^3	2500V Surge Test	5000Vdc Leakage Current Test Milliamps	Ac Dissipation Factor Test				Ac Capacitance Test			
									Voltage	% D.F	Voltage	% D.F	Voltage	Capac pf	Voltage	Capac pf
	26	2	26	38			OK	0	1006	5.1	2010	5.1	1006	560.0	2010	525.4
	27	2	27	39												
	28	2	28	40		100										
	29	2	29	41												
	30	2	30	42												
	31	1	31	43					1003	5.1	2040	5.5	1003	566.0	2040	576.4
	32	1	32	44												
	33	1	33	45		100										
	34	1	34	46												
	35	1	35	47												
	36	3	36	48					1003	4.1	2010	4.6	1003	560.8	2010	558.0
	37	3	37	49												
	38	3	38	50		100										
	39	3	39	51												
	40	3	40	52												
	41	2	41	53					1008	5.3	2020	5.9	1008	570.6	2020	583.8
	42	2	42	54												
	43	2	43	55		100										
	44	2	44	56												
	45	2	45	57							2000	4.9			2000	564.4
	46	1	46	58					1005	4.5	2000	4.7	1005	1033.4	2000	1040.
	47	1	47	59							2010	4.5			2010	1040.
	48	1	48	60		100					2010	5.5			2020	564.0
	49	1	49	61												
	50	1	50	62							2000	5.6			2000	564.0

Table 4.1 Failed Motor Test Results: Insulation Resistance, Surge, Dc hipot, Dissipation Factor & Capacitance Tests

* Test per 5 coil group

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	2500 Vdc Megger Megohms x 10^2	2500V Surge Test	5000Vdc Leakage Current Test Millamps	Ac Dissipation Factor Test Voltage	% D.F	Voltage	% D.F	Ac Capacitance Test Voltage	Capac pf	Voltage	Capac pf
	51	3	51	63					1009	4.5	2000	4.9	1009	552.4	2000	547.6
	52	3	52	64												
	53	3	53	65		100										
	54	3	54	66												
	55	3	55	67												
	56	2	56	68	Y				1009	4.7	2010	5.3	1009	540.4	2010	546.4
	57	2	57	69												
	58	2	58	70		100										
	59	2	59	71												
	60	2	60	72												
	61	1	61	73					1007	4.7	2010	5.1	1007	567.2	2010	566.6
	62	1	62	74												
	63	1	63	75		100										
	64	1	64	76												
	65	1	65	77												
	66	3	66	78	Y				1004	5.7	2020	6.3	1004	591.2	2020	605.2
	67	3	67	79			Short	Ground	Ground							
	68	3	68	80		Ground	Short	Ground	Ground							
	69	3	69	81			Short	Ground	Ground							
	70	3	70	82			OK	0			2010	8.4			2010	664.0
	71	2	71	83	Lead 2				1005	7.2	2030	8.1	1005	690.2	2030	687.8
	72	2	72	84							2010	8.1			2010	720.0
	73	2	73	85		100					2000	18.5			2000	74C.0
	74	2	74	86							2010	9.0			2010	682.0
	75	2	75	87							2010	8.6			2010	682.0

4. FAILED MOTOR WINDING STUDY

This part of the study analyzes the test data to assess various test methods which could be used to detect deterioration of motor winding insulation.

The subject motor had form wound windings. In the manufacturing process, these coils are wound separately, insulated, placed in the stator core, and then treated. Figure 4.1 illustrates this insulating system in a stator slot and compares it with a random wound winding which is commonly used for small motors. Because of its design, the coils of a form wound winding can be separated and tested individually. This allowed each of the 90 coils of the subject motor to be studied thereby revealing the statistical nature or variation which would be expected in the results.

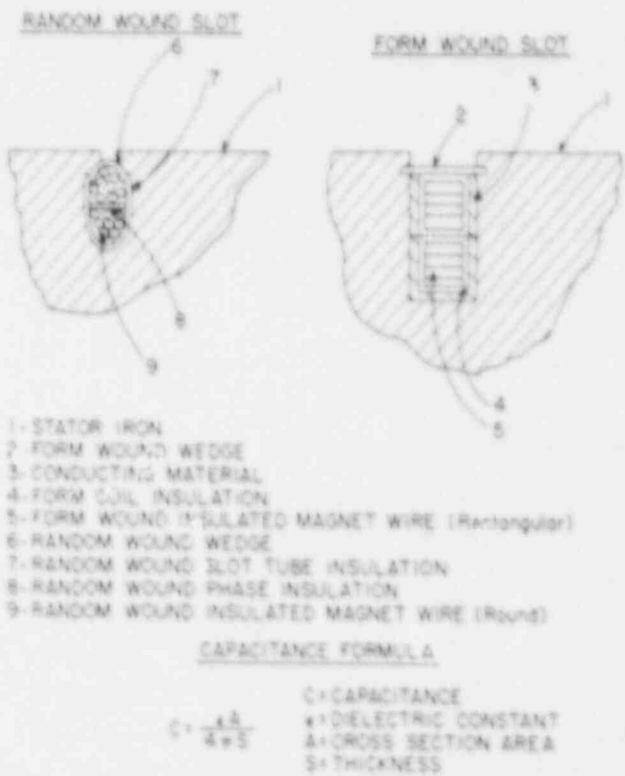


Figure 4.1 - Coil arrangements in random and form wound stators.

4.1 Test Results

All of the test results on coil groups and individual coils from the 400 horsepower motor are presented in Tables 4.1 and 4.2. Table 4.1 includes dc resistance (megger), surge, dc leakage, ac dissipation factor and ac capacitance test data. Table 4.2 presents ac leakage and AC hipot test results. The results of each test are discussed below.

Table 4.1 Failed Motor Test Results: Insulation Resistance, Surge, Dc Hipot, Dissipation Factor & Capacitance Tests

* Test per 5 coil group

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	* 2500 Vdc Megger Megohms x 10^3	2500V Surge Test	5000Vdc Leakage Current Test Milliamps	Ac Dissipation Factor Test Voltage	% D.F	Voltage	% D.F	Ac Capacitance Test Voltage	Capac pf	Voltage	Capac pf
10/21/86	1	1	1	13	Lead 1		OK	0	1001	4.4	2020	4.9	1001	570.0	2020	568.8
10/22/86	2	1	2	14												
10/22/86	3	1	3	15		100										
10/23/86	4	1	4	16												
10/23/86	5	1	5	17												
	6	3	6	18					1006	4.7	2010	4.7	1006	548.6	2010	560.4
	7	3	7	19												
	8	3	8	20		100										
	9	3	9	21												
	10	3	10	22												
	11	2	11	23					1000	4.8	2000	5.4	1000	549.6	2000	560.4
	12	2	12	24												
	13	2	13	25		100										
	14	2	14	26			Short		1001	4.3	2020	4.8	1001	550.0	2020	563.4
	15	2	15	27			OK									
	16	1	16	28					1005	4.5	2000	5.5	1005	550.0	2000	541.8
	17	1	17	29												
	18	1	19	30		100										
	19	1	19	31												
	20	1	20	32												
	21	3	21	33					1000	5.1	2010	5.5	1000	574.4	2010	579.2
	22	3	22	34												
	23	3	23	35		100										
	24	3	24	36												
	25	3	25	37												

Table 4.1 Failed Motor Test Results: Insulation Resistance, Surge, Dc hipot, Dissipation Factor & Capacitance Tests

* Test per 5 coil group

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	2500 Vdc Megger Megohms x 10^3	2500V Surge Test	5000Vdc Leakage Current Test Milliamps	Ac Dissipation Factor Test				Ac Capacitance Test			
									Voltage	% D.F	Voltage	% D.F	Voltage	Capac pf	Voltage	Capac pf
	26	2	26	38			OK	0	1006	5.1	2010	5.1	1006	560.0	2010	523.4
	27	2	27	39												
	28	2	28	40		100										
	29	2	29	41												
	30	2	30	42												
	31	1	31	43					1003	5.1	2040	5.5	1003	566.0	2040	576.4
	32	1	32	44												
	33	1	33	45		100										
	34	1	34	46												
	35	1	35	47												
	36	3	36	48					1003	4.1	2010	4.6	1003	560.8	2010	558.0
	37	3	37	49												
	38	3	38	50		100										
	39	3	39	51												
	40	3	40	52												
	41	2	41	53					1008	5.3	2020	5.9	1008	570.6	2020	583.8
	42	2	42	54												
	43	2	43	55		100										
	44	2	44	56												
	45	2	45	57							2000	4.9			2000	564.4
	46	1	46	58					1005	4.5	2000	4.7	1005	1033.4	2000	1040.
	47	1	47	59							2010	4.5			2010	1040.
	48	1	48	60		100					2010	5.5			2020	564.0
	49	1	49	61												
	50	1	50	62							2000	5.6			2000	564.0

Table 4.1 Failed Motor Test Results: Insulation Resistance, Surge, Dc hipot, Dissipation Factor & Capacitance Tests

* Test per 5 coil group

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	2500 Vdc Megger Megohms x 10^3	2500V Surge Test	5000Vdc Leakage Current Test Milliamps	Ac Dissipation Factor Test				Ac Capacitance Test			
									Voltage	% D.F	Voltage	% D.F	Voltage	Capac pf	Voltage	Capac pf
	51	3	51	63					1009	4.5	2000	4.9	1009	552.4	2000	547.6
	52	3	52	64												
	53	3	53	65		100										
	54	3	54	66												
	55	3	55	67												
	56	2	56	68	Y				1009	4.7	2010	5.3	1009	540.4	2010	546.4
	57	2	57	69												
	58	2	58	70		100										
	59	2	59	71												
	60	2	60	72												
	61	1	61	73					1007	4.7	2010	5.1	1007	567.2	2010	566.6
	62	1	62	74												
	63	1	63	75		100										
	64	1	64	76												
	65	1	65	77												
	66	3	66	78	Y				1004	5.7	2020	6.3	1004	591.2	2020	605.2
	67	3	67	79			Short	Ground	Ground							
	68	3	68	80		Ground	Short	Ground	Ground							
	69	3	69	81			Short	Ground	Ground							
	70	3	70	82			OK	0			2010	8.4			2010	664.0
	71	2	71	83	Lead 2				1005	7.2	2030	8.1	1005	690.2	2030	687.8
	72	2	72	84							2010	8.1			2010	720.0
	73	2	73	85		100					2000	18.5			2000	740.0
	74	2	74	86							2010	9.0			2010	682.0
	75	2	75	87							2010	8.6			2010	682.0

Table 4.1 Failed motor test results: Insulation Resistance, Surge, Dc Hipot, Dissipation Factor & Capacitance Tests

* Test per 5 coil group

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	2500 Vdc Megger Megohms x 10^3	2500V Surge Test	5000Vdc Leakage Current Test Milliamps	Ac Dissipation Factor Test				Ac Capacitance Test			
									Voltage	% D.F	Voltage	% D.F	Voltage	Capac pf	Voltage	Capac pf
	76	1	76	88	Y				1004	8.4	2010	9.2	1004	710.6	2010	712.6
	77	1	77	89							2000	10.4			2000	814.6
	78	1	78	90		Ground					2010	18.5			2010	862.6
	79	1	79	1							2010	7.9			2010	748.0
	80	1	80	2			Short	Ground	Ground							
	81	3	81	3	Lead 3		Short	Ground	Ground							
	82	3	82	4			Short	Ground	Ground							
	83	3	83	5		Ground	OK	0								
	84	3	84	6							2010	17.4			2010	688.2
	85	3	85	7							2020	6.3			2020	584.8
	86	2	86	8					1001	5.5	2000	6.3	1001	554.4	2000	568.4
	87	2	87	9							2020	15.8			2020	900.0
	88	2	88	10		100					2010	12.9			2010	1065.8
	89	2	89	11							2000	5.7			2000	1054.6
	90	2	90	12							2020	5.7			2020	555.2

Table 4.2 Failed Motor Test Results: Ac Leakage and Ac Hipot Tests

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	Ac Leakage Current Test				Ac High Potential Test		
						Voltage	Milliamps	Voltage	Millamps	Breakdown Voltage KV	Time to Failure	Coil Held 1 Minute at 5000 Volts
10/23/87	1	1	1	13	Lead 1	1001	.3	2020	.6	5	Inst.	
10/24/87	2	1	2	14						5	Inst.	
	3	1	3	15						5	Inst.	
	4	1	4	16						6		x
	5	1	5	17						7		x
	6	3	6	18		1006	.3	2010	.5	6		x
	7	3	7	19						5.5		x
	8	3	8	20						6.5		x
	9	3	9	21						4.5	Inst.	
	10	3	10	22						6.5		x
	11	2	11	23		1000	.3	2000	.5	6.5		x
	12	2	12	24						5.5		x
	13	2	13	25						6		x
	14	2	14	26		1001	.3	2020	.6	6		x
	15	2	15	27						6		x
	16	1	16	28		1005	.3	2000	.5	8		x
	17	1	17	29						7.5		x
	18	1	18	30						[illegible].5		x
	19	1	19	31						5	40 sec.	
	20	1	20	32						6.5		x
	21	3	21	33		1000	.3	2010	.6	6.5		x
	22	3	22	34						5	Inst.	
	23	3	23	35						7.5		x
	24	3	24	36						6.5		x
	25	3	25	37						5.5		x
	26	2	26	38		1006	.3	2010	.5	7		x
	27	2	27	39						7.2		x
	28	2	28	40						5	Inst.	
	29	2	29	41						5	35 sec.	
	30	2	30	42						5	Inst.	
	31	1	31	43		1003	.3	2040	.6	5.5		x
	32	1	32	44						5.8		x
	33	1	33	45						7		x
	34	1	34	46						1	Inst.	
	35	1	35	47						6		x

Table 4.2 Failed Motor Test Results: Ac Leakage and Ac Hipot Tests

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	Ac Leakage Current Test				Ac High Potential Test		
						Voltage	Milliamps	Voltage	Milliamps	Breakdown Voltage KV	Time to Failure	Coil Held 1 Minute at 5000 Volts
	36	3	36	48		1003	.3	2010	.6	7.5		x
	37	3	37	49						Ground	Inst.	
	38	3	38	50						4.5	Inst.	
	39	3	39	51						Ground	Inst.	
	40	3	40	52						4.5	Inst.	
	41	2	41	53		1008	.3	2020	.6	5	Inst.	
	42	2	42	54						3.5	Inst.	
	43	2	43	55						4.5	Inst.	
	44	2	44	56						5	Inst.	
	45	2	45	57				2000	.6	5	30 sec.	
	46	1	46	58		1005	.5	2000	.9	5	Inst.	
	47	1	47	59				2010	.9	Ground	Inst.	
	48	1	48	60				2020	.6	4.5	Inst.	
	49	1	49	61						1	Inst.	
	50	1	50	62				2000	.6	5	Inst.	
	51	3	51	63		1009	.3	2000	.5	5	5 sec.	
	52	3	52	64						2	Inst.	
	53	3	53	65						4.5	Inst.	
	54	3	54	66						4.5	Inst.	
	55	3	55	67						5	10 sec.	
	56	2	56	68	Y	1009	.3	2010	.5	5	Inst.	
	57	2	57	69						1	Inst.	
	58	2	58	70						1	Inst.	
	59	2	59	71						3	Inst.	
	60	2	60	72						6.5		x
	61	1	61	73		1007	.3	2010	.6	6.5		x
	62	1	62	74						Ground	Inst.	
	63	1	63	75						4.5	Inst.	
	64	1	64	76						1	Inst.	
	65	1	65	77						4.5	Inst.	
	66	3	66	78	Y	1004	.3	2020	.6	6		x
	67	3	67	79		Ground						
	68	3	68	80		Ground						
	69	3	69	81		Ground						

Table 4.2 Failed Motor Test Results: Ac Leakage and Ac Hipot Tests

Date	Coil No.	Phase	Slot Top	Slot Bottom	Lead or Y	Ac Leakage Current Test				Ac High Potential Test		
						Voltage	Milliamps	Voltage	Milliamps	Breakdown Voltage KV	Time to Failure	Coil Held 1 Minute at 5000 Volts
	70	3	70	82				2010	.7	4	Inst.	
	71	2	71	83	Lead 2	1005	.4	2030	.7	4.5	Inst.	
	72	2	72	84				2010	.7	.5	Inst.	
	73	2	73	85				2000	.8	Ground	Inst.	
	74	2	74	86				2010	.7	Ground	Inst.	
	75	2	75	87				2010	.7	5	Inst.	
	76	1	76	88	Y	1004	.4	2010	.7	6		x
	77	1	77	89				2000	.8	.5	Inst.	
	78	1	78	90				2010	.9	.5	Inst.	
	79	1	79	1				2010	.7	4	Inst.	
	80	1	80	2		Ground						
	81	3	81	3	Lead 3	Ground						
	82	3	82	4		Ground						
	83	3	83	5						3	Inst.	
	84	3	84	6				2020	.8	1	Inst.	
	85	3	85	7				2020	.6	6		x
	86	2	86	8		1001	.3	2000	.6	7		x
	87	2	87	9				2020	.6	3	Inst.	
	88	2	88	10				2010	.9	2.5	Inst.	
	89	2	89	11				2000	.9	6		x
	90	2	90	12				2020	.6	4.5	Inst.	

4.1.1 Dc Resistance (Megger) Test

This test was used to determine the dc resistance to ground for each of the coil groups. The purpose of the test was to identify the coil groups with failed and/or weak coils. The results are presented in Table 4.1.

The test was performed with a dc voltage of 2,500 volts impressed on each coil group. Table 4.1 shows that failed coils existed in the phase 1 coil group containing coils 76-80. The failed coil was determined to be coil 80 using the surge test and dc hipot test. In the phase 3 coil groups containing coils 66-70 and 81-85, the individual failed coils were 67, 68, 69, 81, and 82. Coils 81 and 82 were the lead coils of the Phase 3 terminal end, while coils 67, 68, and 69 were at the opposite end of the Phase 3 coil group (see Figure 2.1). Figure 2.2 shows that coils 68 and 80 were in the same slot, as were coils 69 and 81. Coils 67 and 82 were in different slots with other unfailed coils. All other coil groups meggered above 100,000 megohms.

In a planned maintenance program, the dc resistance (megger) test can be best used to determine the effects of the environment and other outside factors on the winding and coils. Because of the problems with charging current and other effects on the megger when reading values on the order of 100,000 megohms and above, existing testers make it difficult to determine insulation degradation during a planned maintenance program. Megger equipment which eliminates charging current effects and other interference might allow this test method to be more useful in determining the degree of insulation degradation.

To further explore the effects of dc testing on the individual coils at higher dc voltages, a dc leakage current test was performed with the Baker Surge Tester as discussed in the next section.

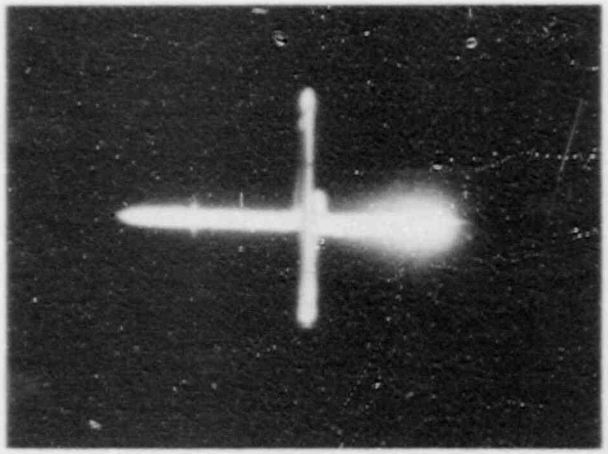
4.1.2 Surge Test and Dc Leakage Current Test

The testing performed with the Baker Surge Tester has two parts. These include the surge test for detecting turn shorts in the coils and the dc high potential leakage current test. Results from both tests are discussed in this section. Table 4.1 presents a summary of the results.

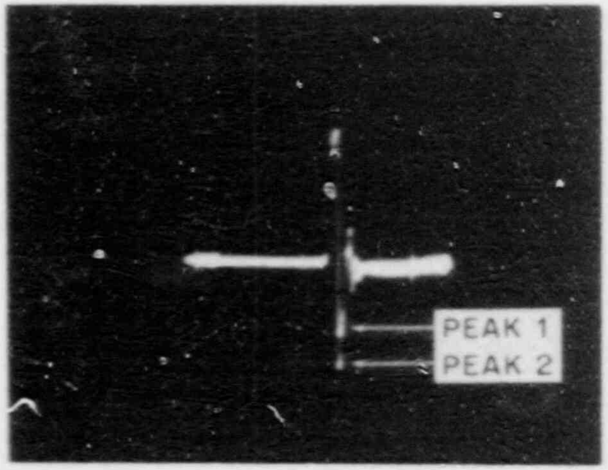
4.1.2.1 <u>Surge Test</u>

All coils in the motor were surge tested at 2,500 volts after the series connections were cut. This particular test indicated the obviously grounded coils and a turn short in coil 14.

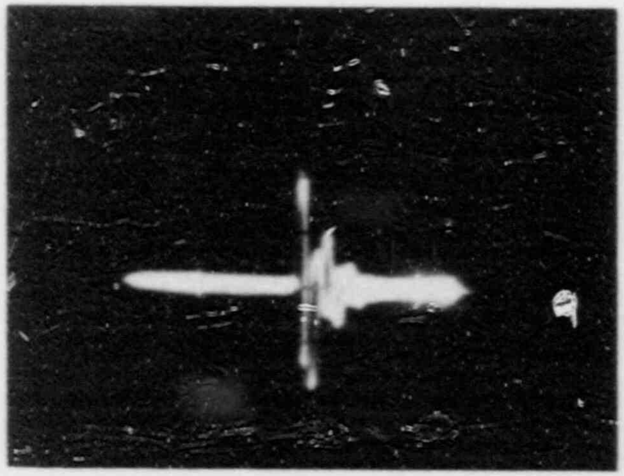
Figure 4.2 illustrates the superposition of standing voltage wave traces on the oscilloscope for four different coils tested. Coils 1 and 46 were first determined to be good coils. These coils were then used as a baseline to compare against other coils for evaluating their condition. Figure 4.2(a) indicates a perfect match between coils 1 and 46. A perfect match indicates that both coils are good since it is extremely unlikely that two coils would degrade to exactly the same degree, which is what would be required to produce the same wave pattern. Therefore, it is concluded that the insulation on



(a) COILS 1 & 46: PERFECT MATCH



(b) COILS 14 & 1 : SIGNAL MISMATCH (SHORT)



(c) COILS 1 & 67: SIGNAL MISMATCH (GROUND)

Figure 4.2 - Surge test results: standing voltage wave patterns on the oscilloscope.

coils 1 and 46 has not degraded enough to show any abnormal wave pattern and the coils are good. Coil 14, on the other hand, was determined to show a shorted coil pattern as indicated by the mismatch with coil 1 in the Figure 4.2(b). This test determined that coil 14 has a turn short somewhere in the coil. Figure 4.2(c) is a typical mismatch pattern between coils 1 and 67 indicating the latter coil has grounded. Similar traces were observed for other grounded coils (68, 69, 80, 81, and 82).

The magnitude of the voltage pulses used for surge testing is limited by the breakdown voltage of the insulation to ground. In very large high voltage motors, which usually include considerable amounts of copper, the voltage pulses will dissipate very rapidly. The maximum voltage available for testing may not be sufficient to produce pulses which can travel through the motor and still have a large enough magnitude to be reliably measured. Surge testing would, therefore, provide little information for detecting failures in very large motors. The surge test can be best used on random wound motors which are rated for a lower voltage and have less copper. In addition to detecting ground faults and turn shorts, the test will detect connection problems and unbalance between phases.

4.1.2.2 Dc Leakage Current Test

The second part of the testing done with the Baker Surge tester is the dc high potential leakage current test. In the test program, it was used as a means of high potential testing all the coils in the motor. This is essentially a repetition of the insulation resistance test but at a higher voltage and it was performed on all coils. This test was conducted at 5,000 volts dc. With this tester, the leakage current is measured rather than the resistance to ground. As indicated in Table 4.1, no leakage current was detected by the meter except for the grounded coils identified above. The test did not identify the turn short in coil 14.

This test provided little information for determining the condition of the unfailed coils. Therefore, this test is most useful only as an alternate to meggers in determining the effects of the environment and other outside agents on windings and coils prior to motor startup. It would not be useful for monitoring insulation condition to detect degradation due to aging.

4.1.3 Ac Dissipation/Capacitance/Leakage Current Tests

The ac tests were performed using the Biddle Dissipation Factor/Capacitance Tester. A number of coils were tested for their dissipation factor, capacitance and ac leakage current to determine the insulation condition by comparison with baseline coil data. The results of the tests, which were performed on 36 selected coils, are discussed in this section. Table 4.1 presents the results of the dissipation factor test and the capacitance test, while Table 4.2 includes the leakage current test. Comparing the data for all tested coils (i.e., 36 coils total), it was established that a certain number of coils were in good condition, while others indicated abnormal (i.e., higher) parameter values. It should be noted that the baseline parameter values indicating a "good" coil for this study correspond to a coil insulating system exposed to 20 years of service life and are different from those of a new or refurbished stator winding. Table 4.3 presents the baseline data used for the three test parameters considered here.

Table 4.3: Baseline data for dissipation factor, capacitance and ac leakage current tests.

(For 20 year old naturally aged stator coils)

Test Parameter	Baseline Data for a Normal Coil
Dissipation Factor	4.5 - 5.0 (%)
Capacitance	540-600 (pf)
Ac Leakage Current	~ 0.3 mA @ ~ 1000V ~ 0.6 mA @ ~ 2000V

4.1.3.1 Dissipation Factor Test

Dissipation factor has direct correlation with the power factor of any insulating system. For power factor values lower than 10%, the dissipation factor and power factor yield approximately the same values. Higher coil dissipation factors indicate that the resistive component of the current is higher than that in a perfect or good coil. This is believed to be caused by the presence of cracks and voids in the coil insulating material due to embrittlement and abnormal environmental and mechanical conditions.

The dissipation factor test was performed at a voltage of approximately 2000 volts for all 36 coils. In addition, 18 of the coils were tested at approximately 1000 volts to determine if there was any functional relationship between dissipation factor and applied voltage. As shown in Table 4.1, the results indicate that dissipation factor has very little dependence on applied voltage. With a 100% increase in voltage, the majority of the coils showed an increase in dissipation factor of approximately 10%. This suggests that dissipation factor can be measured at lower voltages to avoid unnecessarily stressing the insulation.

Figure 4.3 shows the distribution of the 36 coils tested at 2000 volts. Eight (8) coils were found to be good coils with dissipation factors less than 5%. Another fifteen (15) coils were found to have a dissipation factor of less than 7% and were considered to be in acceptable condition. The remaining thirteen (13) coils exhibited aging in their insulating materials. These coils (70-79, 84, 87, and 88) are presumed to have developed cracks and voids in their insulation resulting in the higher dissipation factors.

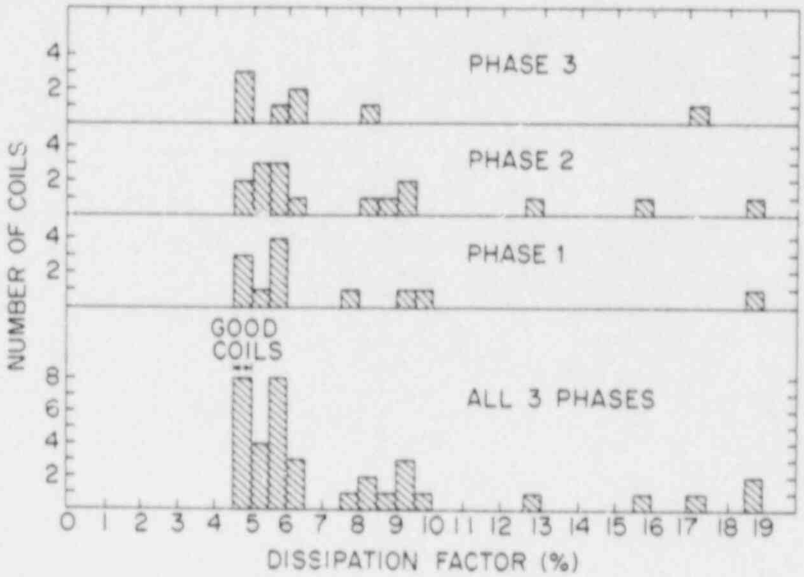


Figure 4.3 - Dissipation factor at 2000 volts.

4.1.3.2 Capacitance Test

Figure 4.1 presents the formula for capacitance[6] showing its relationship with reduced wall thickness. From the formula it is apparent that where the thickness of the insulation is reduced, the capacitance is increased. An increase in capacitance value could, therefore, be an indication of a reduction in insulation thickness in the slots. This could be due to insulation deterioration accompanied by deposition of additional conducting material which is a typical problem when a coil is over heated and carbon from the burning process replaces the insulation.

The ac capacitance test was performed on 36 coils at approximately 2000 volts.In addition, a number of coils were tested at approximately 1000 volts to determine the effects of varying voltage on the measured capacitance. As with dissipation factor, the capacitance values showed little change with voltage. For a 100% increase in voltage, capacitance changed an average of less than 2%. Test results are shown in Table 4.1.

The distribution of capacitance values among the 36 tested coils is shown in Figure 4.4. As shown, twenty (20) of the coils indicated normal values while the remaining sixteen (16) coils exhibited higher capacitance in their insulating materials. From the above discussion, it can be concluded that

these 16 coils have probably experienced thinning in their insulation materials due to their age and environmental conditions. Of the 16 coils with high capacitance, coils 46, 47, 70-79, 84, 87, 88, and 89 are definitely showing signs of insulation thinning.

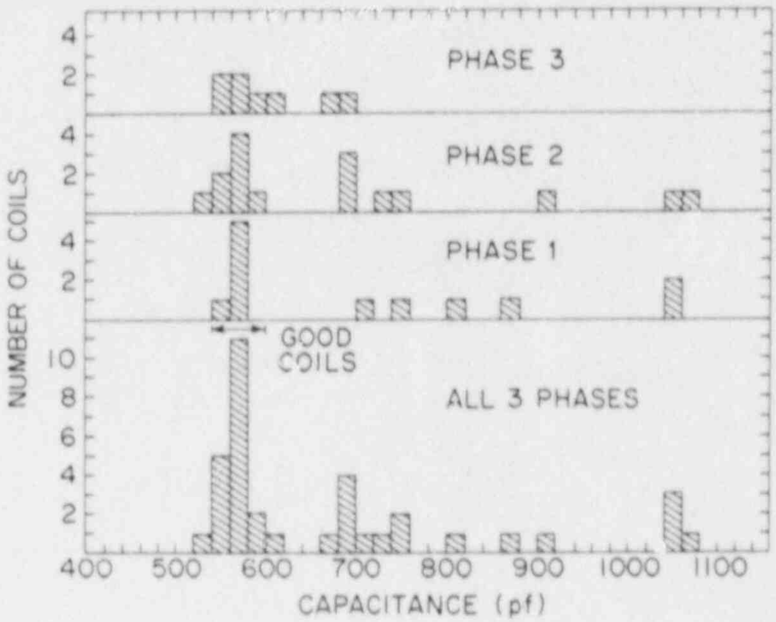


Figure 4.4 - Capacitance at 2000 volts.

4.1.3.3 Ac Leakage Current Test

The third test parameter, ac leakage current, is a direct measure of leakage current from the conducting coil through the insulating material. If any of the above mentioned conditions (i.e., cracks, voids and/or thinning) exist in the insulating material, the leakage current will increase indicating insulation deterioration.

Each of the 36 coils were tested for leakage current using a voltage of approximately 2000 volts. A number of coils were also tested at approximately 1000 volts to demonstrate the effects of varying voltage. As expected, the leakage current varied in direct proportion to the change in applied voltage.

Figure 4.5 shows the distribution of leakage current for the 36 coils tested. As shown, fifteen (15) of the coils indicated a higher leakage current at an impressed voltage of 2,000 volts than the baseline data presented in Table 4.3 (0.6 mA @ 2000 v). Comparing the data from Table 4.1 with Table 4.2, it is seen that all of these coils have also indicated higher dissipation factors and/or capacitance values. This is consistent with expected results since increased dissipation factor or capacitance would indicate the insulation is in a degraded condition. The degraded insulation should show an increased leakage current. The ac leakage current test, therefore, verified the findings of the dissipation factor and capacitance tests.

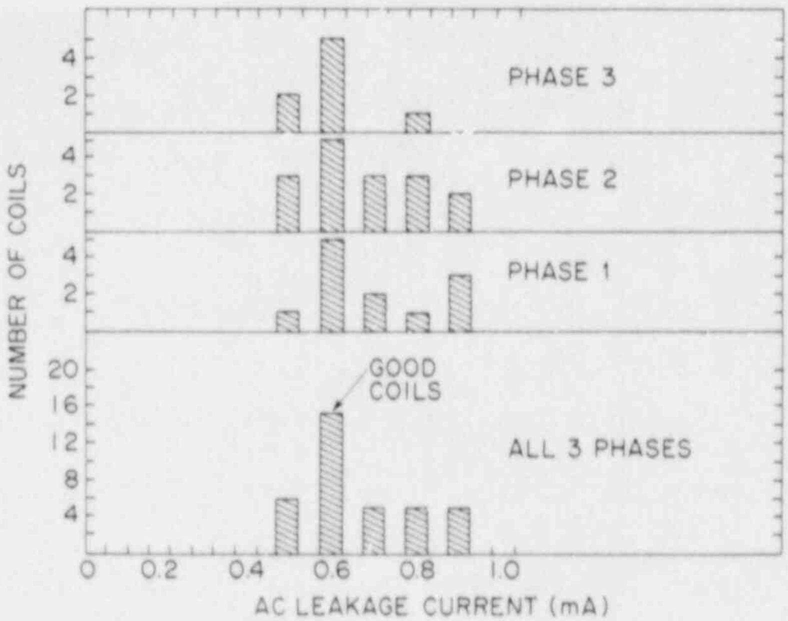


Figure 4.5 - Ac leakage current at 2000 volts.

4.1.3.4 <u>Discussions</u>

Based on the results of the three tests performed, several observations can be made as discussed below. The test data presented in Tables 4.1 and 4.2 are summarized in Table 4.4. As shown, sixteen (16) coils indicted age related deterioration.

It is observed that when there is a high capacitance value for a coil, high leakage current exists, as shown for coils 46, 47, and 89. All these coils had capacitance in the range of 1,000pf as compared to 570pf for 33% of the total number of coils. They also had a leakage current of .9 milliamps as compared to .6 milliamps for 45% of the coils. This indicates a possible thinning of the insulation for these coils. Therefore, the above 3 coils could be classified as having a high probability of failure if they were returned to service.

Coils 70 and 84 showed higher dissipation factors but almost normal capacitance values. This indicates that these two coils have developed more crack voids rather than thinning of the insulation. Nevertheless, these two coils indicate higher ac leakage currents and would also have a high probability of failure.

Table 4.4 - Tested Coils Showing Age-Related Deteriorations

Coil No.	Dissipation Factor (%) @ 2000V	Capacitance (pf) @ 2000V	Ac Leakage Current (mA) @ 2000V	Probable Aging Mechanism For Insulation	Ac Hipot Test Results Failure Mode and Breakdown Voltage
46	4.7	1040	0.9	Thinning	Instant @ 5kV
47	4.5	1040	0.9	Thinning	Instant @ 0kV
70	8.4	664	0.7	Cracks & Voids	Instant @ 4kV
71-79	7.9-18.5	682-862.6	0.7-0.9	Thnning, Cracks & Voids	Instant @ 0kV (coil 76 failed @6kV)
84	17.4	688.2	0.8	Cracks & Voids	Instant @ 1kV
87	15.8	900	0.8	Thinning, Cracks & Voids	Instant @ 3kV
88	12.9	1065.8	0.9	Thinning, Cracks & Voids	Instant @ 2.5 kV
89	5.7	1054.6	0.9	Thinning	Failed @ 6kV

The remaining coils (71-79, 87-88) in Table 4.4 showed a significant increase above baseline for all three test parameters. This indicates coils have experienced degradation by thinning as well as by an increase in cracks and voids.

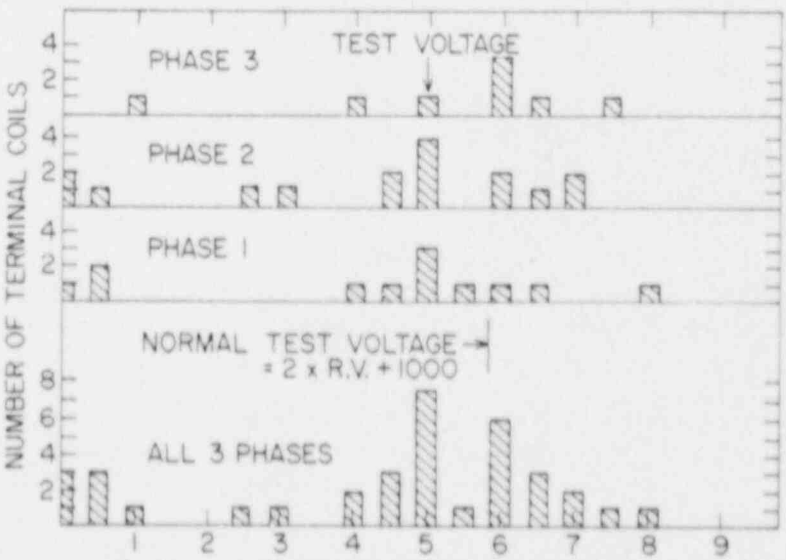


Figure 4.6 - Ac high potential test.

From the above results it is concluded that both the ac dissipation factor and capacitance tests are useful to determine and trend insulation degradation. It is recommended that one of these tests be considered for inclusion in a maintenance program. The ac leakage current test is also useful in determining insulation integrity, although it does not provide information as to the mechanism for degradation. It should be noted that coils with increased leakage current will develop larger I^2R heating effects which could accelerate the aging process and contribute to early failure. Leakage current could, therefore, be an important parameter to monitor.

A partial discharge test was not performed as part of this study. If the test were performed, however, it should have shown a low corona starting voltage for the coils with high dissipation factors, capacitance and/or ac leakage current. This is due to the thinning as well as the voids and cracks in the coil insulation.

4.1.4 Ac High Potential Test

The ac high potential test was the last test performed on the coils. The objective of the test was to determine the breakdown voltage for each coil. This is a destructive test and is not recommended for a preventive maintenance program. It was performed on all coils to study the ac dielectric breakdown distribution of the coils to support the tests from other tests.

The test was performed by gradually raising the impressed voltage from 0 to 5000 volt. If the insulation of a coil withstood this voltage level, the 5000 volts was held for one minute to examine the endurance limit of the insulation. If it withstood this endurance test, the voltage level was further increased until the insulating system grounded (i.e., breakdown voltage). The 5000 volt level was chosen for the endurance test instead of 5800 volts (2 x rated voltage plus 1000 volts) as recommended in the industry standards. This was because the motor was 20 years old and the insulation dielectric strength was reduced due to age-related degradation.

Figure 4.6 shows the distribution of ac breakdown voltage test results for coils considered in the other dielectric tests. The coils with high capacitance, dissipation factor or leakage current had different breakdown voltages ranging from instant ground to 6000 volts. Many of them failed prior to reaching the 5000 volt level. Some coils indicated instant ground. This may be due to damage done to coils resulting from difficulties in separating the cut series connection leads.

Lower breakdown voltage was indicative of weak insulation for the coil. Since this test consistently yielded lower breakdown voltages for those coils diagnosed weak by the other test methods, the nondestructive dielectric test methods were considered to be sufficient for maintenance programs. However, this ac high potential testing did validate the results from the other insulation test methods.

5. RECOMMENDATIONS AND CONCLUSIONS

5.1 Failure Analysis

As indicated in Section 3, it is believed that the motor failure was caused by the single ground on the ungrounded system at the supply transformer secondary cable which overstressed the insulation and caused the second ground in the motor. Because the motor had grounds in 2 phases, different from the phase containing the cable failure, it is believed that this failure mode is the most probable. The failures which occurred are consistent with those expected on ungrounded systems where arcing grounds, capacitance leakage current and full line-to-line voltage can overstress insulation in other parts of the system.

As a result of this analysis, it is recommended that the ungrounded system be grounded through a resistance or reactance. If this is not possible, ground fault detection should be installed to indicate when a ground exists on the system. It is also recommended that the second motor, which is installed on the same ungrounded system be replaced since it could have been damaged from the ground fault on the transformer cable. As shown in Section 4 of this study, megger testing does not have sufficient discrimination to detect degraded or damaged insulation. The second motor, therefore, could have damaged coils even though it has been meggered and no damage was indicated. This determination would be compounded by the fact that the tests on the failed motor showed that some coils were weaker than others due to aging.

5.2 Motor Winding Tests

The dielectric tests performed on the motor coils showed the insulation degradation of individual coils and gave the distribution of results for the 90 coils studied. The identification of weak coils by comparison to baseline data for good coils showed that the Dissipation Factor/Capacitance/Ac Leakage Current Tests were effective in determining coil degradation. The Surge Test identified a turn-to-turn short in one coil which was not detected by the other tests. All tests performed for this study detected the already grounded coils. It is concluded that with the exception of the ac hipot test, the other tests including the dc resistance test, surge test, and dissipation factor/capacitance (or ac leakage) test can be considered for a plant condition monitoring program although some limitations exist. In addition, the distribution of test results for the dissipation factor/capacitance test suggests that these test parameters can be trended for monitoring insulation conditions.

Based on the data analysis presented in this report, the following conclusions are obtained on each test parameter considered in this test program.

1. Dc Resistance Test - This test is recommended for plant motor maintenance programs and is suitable for all motor sizes. This test provides the insulation resistance value which, with guidelines presented in IEEE-Std-43, could determine the effects of the environment on the insulation system. These include insulation wetness and contamination due to dust and other foreign particles. While this test identified the grounded coils,

it failed to determine the degradation differences among other ungrounded coils. This test should be used for determining the insulation condition (go/no-go type) prior to any high potential test or starting the motor from a long shutdown condition after an extended shutdown or exposrue to a harsh environment.

Improvement in test equipment (megger units) is necessary to eliminate charging current problems during an application and interference caused from other sources to make this test more useful in determining the degree of insulation degradation. Compensation due to temperature of the motor should be considered in evaluating the test results.

2. Surge Test - The Surge Tester is a good tool for use in a maintenance program for detecting aged insulation. The test provides the capability to detect shorts between two phases of a three phase system as well as ground faults. The test will also detect connection problems and unbalance between phases.

   The surge tests can be best used on random wound motors which are rated for a lower voltage (less than 600 volts) and have less copper to dissipate the imposed voltage pulses. Surge testing is limited by the breakdown voltage of the insulation. Therefore, this test may not detect failures in very large motors which rapidly dissipate the voltage pulses. Because of this voltage limitation, the presently available surge testers can only be used in relatively small, low voltage machines. Although the benefits of this test are limited to small motor applications, the surge test can be used in rewound/repair shops for all sizes and types of motors as well as for individual coils.

   The development of digital equipment for storing wave forms will enhance the use of the surge tester in maintenance programs.

3. Dc Leakage Current Test - This is also known as a dc hipot test and is an alternate to the dc insulation resistance test. Hence, all conditions and limitations discussed in connection with the dc resistance test above (item 1) are applicable.

4. Ac Dissipation Factor Test - The dissipation factor (or power factor) test is a good test for maintenance programs to determine insulation degradation due to deterioration from cracks or voids in the insulation. The effectiveness of the dissipation factor test may be limited by the size of the motor being tested. For smaller motors this test is recommended. However, for larger machines the results may be clouded because of the higher test voltages required for the large number of coils. The dissipation factor test is always a good test for a repair shop for both random and form wound coils.

   The partial discharge test was not used in this program because of potential leakage around the cut connections between coils which could cloud the test results. The test may, however, be used for larger motors. Since the noise level is high at lower voltages, this test is limited by the background noise and sensitivity of the equipment. To use this testing on small low voltage motors, more sensitive equipment is needed which

includes better means of detecting corona inception voltages. The plotter approach used in the 10 horsepower motor study[3] appears to be one way to perform this test. If a partial discharge test were performed for this study, it would show low corona starting voltage for coils with high dissipation factors, capacitance and/or ac leakage currents because of insulation thinning, voids and/or cracks in the insulation.

5. Ac Capacitance Test - The capacitance test utilizes the same test equipment as the ac dissipation factor test and has similar limitations. These are discussed in the previous section (item 4). However, higher than normal values of the test parameter (capacitance) indicate thinning of the insulation due to heat or degradation. This test is recommended for a plant maintenance program.

6. Ac Leakage Test - The ac leakage current in the insulating system is directly related to the condition of the insulation as determined from the previous two test parameters. Hence, the discussion on this test parameter is the same as for the other two tests (i.e., ac dissipation factor and capacitance tests). This test is useful in determining the condition of the insulation.

7. Ac Hipot Test - This test is a destructive test and is not recommended for plant maintenance activities. However, this test can be used in rewound/repair shops or at the manufacturer to establish the insulation endurance at the breakdown voltage.

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Stator coils of a naturally failed 400 hp motor from the Brookhaven National Laboratory test reactor facility were tested for their dielectric integrities. The motor was used to drive the primary reactor coolant pump for the last 20 years. Maintenance activities on this motor during its entire service life were minimal, with the exception of meggering it periodically. The stator consisted of ninety individual coils which were separated for testing. Seven different dielectric tests were performed on the coils indicated a spectrum of variation depending on their aging conditions and characteristics. By comparing the test data to baseline data, the test methods were assessed for application to motor maintenance programs in nuclear power plants. Also included in this study are results of an investigation to determine the cause of this motor failure. Recommendations are provided on the aged condition of a second identical primary pump motor which is the same age and presently in operation. Recommendations are also presented relating to each of the dielectric test methods applicable to motor maintenance programs.

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