Experience With Stator Insulation Testing and Turn/Phase Insulation Failures in the Power Generation Industry

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***Abstract*—The reliability of medium voltage (MV) motors used for driving pumps, fans, and other loads in the power generation industry is critical for continued power production. Periodic testing of stator winding insulation, which is the most vulnerable component in MV motors, is an essential part of predictive maintenance for preventing unplanned reduction in the power generation capability. Korea Electric Power Corporation (KEPCO) Research Institute's 17+ years of experience on predictive maintenance of stator insulation for MV motors is presented in this paper. KEPCO's stator insulation test program and statistics of test records are summarized, and cases of recent turn and phase insulation failures that resulted in motor forced outages are investigated. Analysis of the turn or phase insulation failures and insulation test records performed on the failed motors show that it is difficult to predict turn or phase insulation failures with the insulation tests currently performed. Turn or phase insulation test methods are summarized and evaluated based on the findings of the investigation to help target future research efforts toward industrial needs.**

***Index Terms*—AC machines, phase insulation, predictive maintenance, stator insulation testing, turn insulation.**

I. Introduction

THIRTY to fifty medium-high voltage (MV-HV) motors are typically operated in each generating unit within power plants to drive the different types of fans, pumps, and other loads required for power generation. An unexpected failure of any of the motors can result in complete loss or reduction of the power production capability of the generating unit. Such failures can cause instabilities in the power system and result in significant economic loss for the power plant due to the repair and recovery time. According to a study on the reliability of 6312 motors operating in 65 power plants presented in [1], the stator winding groundwall (GW) insulation was the component that is most likely to fail (22% of failures). An example of GW insulation failure in a 6.6-kV, 550-kW circulating water pump motor is shown in Fig. 1, where the diameter of the hole in the GW insulation was approximately 8 mm. The survey also shows that many of the failures (34.1%) are caused by misapplication and misoperation of the motor by the end user. The reliability of the motor is not the sole responsibility of the motor manufacturer since not all failures are caused by design or workmanship issues. This implies that there is an opportunity to improve the reliability of the motor through improved operation and maintenance procedures.

Fig. 1. Ground wall insulation failure in 6.6-kV, 550-kW circulating water pump induction motor.

To improve the reliability of power generation by preventing motor failures, a predictive maintenance procedure for testing stator winding insulation was setup by the Korea Electric Power Corporation (KEPCO) Research Institute in 1999. A standard test procedure for stator insulation was established for efficient and consistent maintenance of all MV/HV motors operating in fossil fuel, combined cycle, nuclear, and pumped storage power plants in Korea. The reliability of power generation has significantly improved since periodic offline stator insulation

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testing has been performed. Refurbishment or rewind of stator insulation based on the insulation resistance (IR), polarization index (PI), dissipation factor ($\tan\delta$, ac leakage current (I_{leak}), and partial discharge (PD) tests has contributed significantly to reduce motor failures due to GW insulation breakdown [2]–[4]. This is expected considering that the stator insulation tests performed above are intended for testing the GW insulation.

Although motor reliability has improved, cases of insulation failures are still commonly observed in power plant motors, where most of the recent failures were caused by turn or phase insulation breakdown. The surge test can be used to screen out motors with weakened turn or phase insulation on the terminal end of the winding during an outage to prevent in-service failure [5]–[8]. However, it is a pass/fail test that is not capable of providing indications of insulation condition or remaining lifetime. It is not included in KEPCO's insulation predictive maintenance procedure since there are concerns that such an overvoltage test might lead to premature winding failure [9]–[10].

In this paper, KEPCO's experience with insulation testing on 4760 motors in 155 generating units in 37 power plants is summarized. The test records on the motors performed since 1999 are analyzed, and meaningful information regarding the test results and refurbishment or rewind recommendations are provided. The cases of recent motor failures due to turn and phase insulation breakdown in domestic power plants are also investigated. The pattern and consequences of failures, and the insulation test records for the failed motors are analyzed to provide insight into how turn or phase insulation failures can be prevented. Finally, test methods for existing turn and phase insulation condition assessment presented in the literature are summarized and evaluated.

II. Stator Insulation Testing

A. Test and Maintenance Procedure

Up to the 1990s, forced reduction in power generation or generator trips due to stator insulation failure in MV motors was common in domestic power plants. To prevent forced outages, periodic insulation tests were performed internally at some power plants. In 1999, KEPCO Research Institute has established a stator winding insulation test procedure and services to support domestic power plants perform insulation testing and maintenance in a consistent manner. The test procedure and warning/alarm thresholds were revised over the years based on the information on test data and motor failures accumulated in power plants to help reduce the risk of stator insulation failures. The recommended actions for the stator insulation maintenance are determined based on the measurements obtained from five different types of insulation tests (IR, PI, tanδ, I_{leak}, and PD). The testing and maintenance procedure is summarized as a flowchart in Fig. 2. All insulation tests are performed at the motor terminals. It is recommended that the motor be tested once every 5 years up to 10 years of service, and once every 3 years afterward. The testing period is decreased to once a year, if a warning is given from $\tan\delta$, I_{leak}, or PD tests.

The IR and PI tests are performed to screen out motors with contamination and moisture to check if ac tests can be

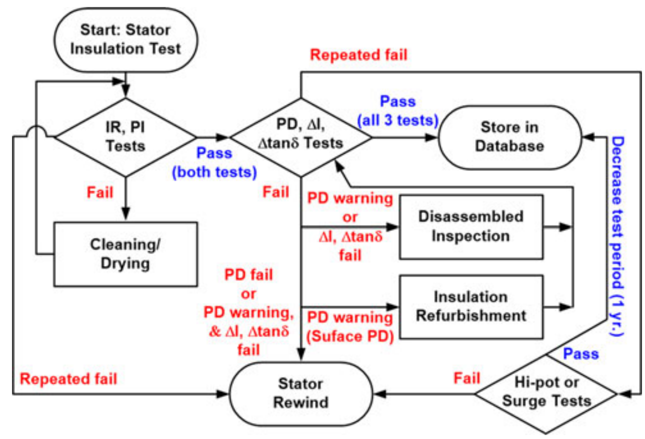

Fig. 2. Test and maintenance procedure applied to 6.6-kV motor stator insulation in domestic power plants.

performed. For 6.6 kV motors, which are most common in the domestic power industry, the IR value is measured with a dc voltage of 5 kV applied to the GW insulation for 1 min. A threshold level of 100 MΩ or higher (IR corrected to its 40 °C value) is used for determining if the GW insulation strength is sufficient for motor operation or ac testing [2]. The PI is obtained by taking the ratio between the 10 min and 1 min IR values measured at the same dc voltage level to observe the insulation's ability to polarize. GW insulation is considered to be in good condition if PI is higher than 2 [2]. IR and PI tests can provide the indications of moisture absorption, contamination, or severe damage in the GW insulation. If the motor fails the IR or PI test, the tests are repeated after cleaning and drying. The procedures for insulation cleaning and drying can be found in many resources [5]. If the winding fails the IR and PI tests again, a stator rewind is recommended (see Fig. 2).

The $\Delta\tan\delta$ and ΔI_{leak} values are obtained from the tanδ and I_{leak} measurements obtained with 25%, 50%, 75%, 100%, 125%, 144%, 157%, and 175% of rated line to neutral voltage applied to the GW insulation (0.95, 1.91, 2.76, 3.81, 4.76, 5.5, 6.0, and 6.6 kV for 6.6 kV motors). The ΔI_{leak} test is not a common insulation test used only in some Asian countries. The $\Delta\tan\delta$ and ΔI_{leak} values are the % difference in the values (or slopes) at 25% and 100% rated line to neutral voltage. High values of $\Delta\tan\delta$ [3] and ΔI_{leak} indicate PD problems in the insulation that result in increased losses at higher applied voltage such as thermal degradation. The threshold levels used for determining failure (alarm) of $\Delta\tan\delta$ and ΔI_{leak} tests for 6.6 kV motors are $>$8.5% and $>$10%, respectively. The change in $\tan\delta$ and I_{leak} values as a function of test voltage are observed to obtain more information on the cause of high $\Delta\tan\delta$ and ΔI_{leak}, if needed.

The offline PD test is also performed on MV-HV motors rated 4 kV and above, since it can provide an early indication of many insulation problems that lead to failure [4]. The maximum PD pulse magnitude at 100% and 125% rated line to neutral voltage ($Q_{m,100}$ and $Q_{m,125}$) are measured to obtain PD activity at the weakest part of the insulation. The PD inception voltage (PDIV) and PD pulse pattern (positive/negative pulses) are measured and recorded to obtain information on the cause and location of PD. An IEC 60270 compliant instrument (Haefely DDX 9101) with a frequency range of 30 to 400 kHz was used for the measurements. For 6.6 kV motors, a warning is given if $Q_{m,125}$ exceeds 10 000 pC. The winding is considered to have high risk of failure (alarm), if $Q_{m,125}$ exceeds 30 000 pC. If the PDIV is lower than 50% of the rated line-neutral voltage, the winding is considered to be in bad condition and likely to have slot surface GW discharge.

If the warning threshold is exceeded for any of $\Delta \tan \delta$, ΔI_{leak}, or PD tests, a retest after disassembled inspection and cleaning is recommended. If $Q_{m,125}$ is higher than its warning threshold of 10 000 pC and if the PD pattern indicates slot surface discharge (positive pulses at negative ac input voltage cycles), insulation refurbishment is recommended. The winding is cleaned after rotor removal, and global vacuum pressure impregnation is performed for refurbishment. If the winding fails any of the three tests after disassembled inspection or refurbishment, a stator rewind is recommended if it fails ac/dc hi-pot and/or surge tests, as summarized in Fig. 2. If the failure threshold for PD is exceeded or if the PD warning threshold is exceeded with $\Delta \tan \delta$ and ΔI_{leak} test failures, a stator rewind is recommended.

The warning or alarm levels for the tests are determined and updated based on experience. They are not strict thresholds as the values for new motors vary depending on the characteristics of the insulation material used. The $\Delta \tan \delta$, ΔI_{leak}, and Q_m measurements were noticeably higher for motors from some manufacturers, even for new units. For such motors, variation over time, comparison between identical motors from the same manufacturer, years of service, and additional test results such as change in $\Delta \tan \delta$ and ΔI_{leak} as function of voltage, PD pattern, PDIV were referred to when making the recommendations. The actual insulation testing cycle and maintenance action is determined based on many factors such as the availability of maintenance resources (budget, manpower, spare motors) and schedule for power production.

B. *Summary of Insulation Testing of Power Plant Motors*

The stator insulation test reports from February 1999 to April 2016 were analyzed to observe the statistics on motors identified with high risk of failure. The MV motors at 37 fossil fuel, combined cycle, pumped storage, and nuclear power plants were tested, and the results of the stator insulation tests and recommendations made were recorded for 17+ years. The stator testing team at KEPCO have performed a total of 11 854 sets of tests on 4760 MV–HV motors supporting 155 generating units in 37 domestic power plants. The number of power plants, generating units, MV/HV motors, and stator tests performed for each type of power plant are summarized in Table I Most of the motors operating at fossil fuel, combined cycle, and pumped storage plants are rated at 6.6 kV, and the motors in nuclear plants are rated at 4.16 or 13.8 kV.

The 11 854 IR, PI, $\Delta \tan \delta$, ΔI_{leak}, and PD tests performed on the 4760 motors were analyzed, and the number of tests where the warning and alarm level were exceeded were counted. The tests at nuclear power plants were excluded from the study since the tests were performed at the motor control center and not at the motor terminals due to the risk of exposure to radiation. The number of times the alarm levels were exceeded for each test are summarized in Table II for each type of power plant. The cases of low IR/PI measurements were mainly due to moisture absorption, contamination of winding, or insulation fitting in motors located close to the sea. The stator passed the IR/PI retests for most cases after cleaning and drying. The measurements of $\Delta \tan \delta$ and ΔI_{leak} tests had a similar trend in that they both have high values if one increases.

For each set of tests, the number of tests where the failure alarm level was exceeded are summarized in Table III in which the number of insulation refurbishment/rewind recommendations are made. Recommendations for disassembled inspection, cleaning, and drying followed by a global VPI was made for 51 motors (refurbishment), and a full stator rewind was recommended for 123 motors. Active repair/rewind was recommended for 174 motors (out of 8916 cases) with stator insulation suspected with high risk of failure (1.95% of all motors tested). Therefore, it is not surprising that the occurrence of generator trips or reduction in power output due to motor stator

TABLE I
NUMBER OF POWER PLANTS, GENERATING UNITS, TESTED MV MOTORS, AND STATOR TESTS PERFORMED FOR EACH TYPE OF POWER PLANT (1999–2016)

Type of power plant	# of power plants	# of generating units	# of MV motors tested	# of tests performed
Thermal	19	98	3119	8152
Combined cycle	9	30	362	695
Pumped storage	5	12	48	69
Nuclear	4	15	1231	2938
Total	37	155	4760	11 854

TABLE II
NUMBER OF MOTORS WITH FAILURE ALARM PRODUCED FOR EACH TYPE OF INSULATION TEST

Type of power plant	# of tests performed	IR	PI	ΔI_{leak}	$\Delta\tan\delta$	PDIV	$Q_{\text{m},100}$	$Q_{\text{m},125}$
Thermal	8152	61	565	1063	828	245	127	207
Combined cycle	695	2	43	24	22	10	8	19
Pumped storage	69	0	5	0	0	0	0	1
Total	8916	63	713	1087	830	255	135	227

TABLE III
NUMBER OF MOTORS WITH 1, 2, AND 3 FAILURE ALARMS PRODUCED WITH IR, PI, $\Delta \tan \delta$, ΔI_{LEAK}, AND PD ($Q_{m,125}$) TESTS; NUMBER OF MOTORS WITH INSULATION REFURBISHMENT AND STATOR REWIND RECOMMENDATIONS

Type of power plant	# of tests performed	1 failed test	2 failed tests	3 failed tests	Insulation refurbishment	Stator rewind
Thermal	8152	499	793	30	47	110
Combined cycle	695	31	19	2	4	13
Pumped storage	69	1	0	0	0	0
Total	8916	531	812	32	51	123

insulation failure has decreased significantly since initiating the test procedure described in Section II-A.

Although there was a noticeable decrease in failures when compared to before predictive maintenance was performed, they have not been eliminated. GW insulation failures are still present, and they mainly occur because the recommended testing cycle or repair actions have not been followed due to production or budget restraints. Motor failures that occur due to insulation breakdown have been closely monitored since 2011, and most of the recent insulation failures were in the turn or phase insulation. This is expected since all insulation tests are performed with the voltage applied to the GW insulation only (see Section V), and because turn insulation failures are not uncommon. According to the study performed in [1], 16.4% of stator insulation failures were caused by turn insulation failures, and the rest were GW insulation failures. A summary of the investigation on turn insulation failures that occurred in domestic power plants since 2011 and phase insulation failures since 2015 is given in Sections III and IV.

III. Turn Insulation Failures

Most turn insulation failures have been observed to occur in the terminal end of the stator in the endwinding (EW) near the slot exit [5], [11]–[13]. The high-voltage stress in the terminal end turns due to fast rise-time surges, and high-GW voltage resulting in PD degradation at the turn-GW insulation interface, have been identified as causes of terminal end EW turn failures [12]–[13]. Air pockets are formed in the EW when it is bent during manufacturing, or due to EW vibration or differential thermal expansion between copper and insulation, making the EW turn insulation vulnerable to electrical stress. In addition to electrical aging, thermal and mechanical aging due to starting or operating stresses gradually weaken turn insulation over time. Other contributors to turn insulation aging and failure that cannot be ruled out are deficient design and defects introduced during manufacturing. Weakened turn insulation can break down when exposed to electrical or mechanical stresses that exceed the withstand capability of the turn insulation. With turn insulation breakdown, a high-amplitude circulating current is induced in the short-circuited loop [14]. The heat produced by the current causes melting of the copper conductor and damage over a wide area, as shown in Figs. 3–8, and leads to tripping of the motor [5], [12]–[16].

Thirteen cases of forced motor outages in domestic power plants due to turn insulation failures from 2011 to 2016 are investigated and reported in this section. There are many more cases of turn insulation failures that have not been identified, reported, and/or documented by the power plants that could not be included. The motor application, ratings, information on the failure, and test records for the turn insulation failures are summarized in Table IV, where the motors have been numbered from M1 to M13. All motors are rated at 6.6 kV except for the M12 (4 kV). The information on the location of the failure and test records are missing for some cases as the information was not recorded or permission was not granted to publish the data. Although the number of failed motor samples is not large, there

Fig. 3. Turn insulation failure in EW slot exit of 6.6-kV, 205-kW transport blower motor (M9).

Fig. 4. Turn insulation failure in EW slot exit of 6.6-kV, 310-kW condensate extraction pump motor (M1).

Fig. 5. Turn insulation failure in EW slot exit of 6.6-kV, 1678-kW primary air fan motor (M13) with zoomed in view of melted copper.

was no observable correlation between the likelihood of failure and motor application, output power, number of poles, or years of service before failure. The distribution in the ratings of the failed motors was representative of the overall motor population operating in power plants.

The motors failed at startup for 7 of 13 cases, and all startup failures (M1, M2, M4, M5, M6, M9) except 1 case (M10) were

Fig. 6. Turn insulation failure in EW bend of 4-kV, 485-kW primary air fan motor (M12).

Fig. 7. Turn insulation failure in slot portion of 6.6 kV, 350-kW condensate pump motor (M3).

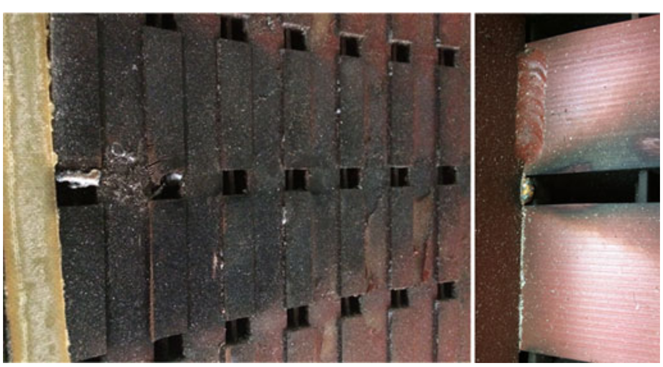

Fig. 8. Turn insulation failure in slot portion of 6.6-kV, 4300-kW induced draft fan motor (M7).

located in the EW slot exit. Records on the location of the turn failure from the terminal is available for three cases, and the fault can be observed in the first or second coil for two cases (M5, M9), which is consistent with what has been observed in [11]–[13]. It is likely that they are related to the stress on the turn insulation due to the fast rise-time voltage during motor startup puncturing weakened turn insulation. Six out of thirteen turn failures occurred during motor operation, and they occurred at least 12 h after startup, as shown in Table IV.

Nine out of thirteen turn failures were located in the EW at or near the slot exit, as shown in Figs. 3–5 (M9, M1, M13), except for 1 case where the fault was located at the bent portion of the EW, as shown in Fig. 6 (M12). Melted copper that erupted from the EW copper conductor through the insulation was observed near the slot exit along with burning of insulation in Figs. 3–6. For the M12 and M13 failures, small particles of melted copper splattered over the EW could be observed (Figs. 5 and 6). An IR value of 0 MΩ was measured and possible paths from failure location to the core were observed for M1, M9, and M13. However, a nonzero IR was measured for M12 and a GW path was not visually observable, as can be seen in Fig. 6. Although it is stated in many resources that a turn fault eventually causes a GW failure and is mistaken as a GW insulation failure [12]–[16], an exception was observed. Turn failures in the knuckle (tip) of the EW described separately in Section V is also common in stators with crossover coil design [17]. The two cases show that it is not necessarily a direct GW path that causes motor trip for these failures, since winding asymmetry or open phase due to a turn fault can also trip the relays.

There were four cases of turn insulation failures in the slot portion of the winding (M3, M7, M8, M10), where the failures were not located close to the slot exit. For all four cases, burning of the insulation and core surface, and melted copper were observed, as shown in Figs. 7 and 8 for M3 and M7, respectively. The turn insulation failed in the first coil from the terminal end during operation for two of the four known cases, which implies that electrical stress on the turn insulation is the likely cause of aging and failure of the turn insulation. Although surge arrestors and capacitors are installed in the motor control center for all MV motors in power plants for limiting the risetime and amplitude of the voltage, the turn failure for 4 of 7 cases occurred in the first or second coils from the terminal end.

Failure in the interlaminar insulation was not observed in any of the 13 cases during visual inspection or core loop tests performed during the rewind. All the MV motors are solidly grounded to the ground network of the plant, and therefore, the ground current is expected to be high. Absence of interlaminar insulation failure under turn faults imply that the relays acts fast enough to prevent core lamination damage due to ground current. There are also cases where there is no ground current through the laminations if trip is caused by winding asymmetry or open circuits, and ground current flow is through the stator core end plate in EW slot exit failures.

The motors M7, M8, M12, and M13 are drive fans that provide cooling for the generator. Their failure resulted in a 50% reduction of the generator output capability. The rewind-cost for M7, M8 (4300 kW) was US $130 000. The cost of rewind increases with motor size—it was US $26 000 for M1, M2 (310 kW). The loss of profit for the power plant due to lost power generation can be between US $25 000 and US $100 000 per hour for a 500-MW generating unit (according to the 2011–2016 domestic per day minimum and maximum cost per kWh [System Marginal Price]). Considering that installation of a spare motor takes approximately 12 h, the loss of 50% generation capability will result in a loss of US $150 000 to US $600 000. This changes with the cost of electricity, which fluctuates with cost of fossil fuel and “supply and demand” that has daily and seasonal variations.

TABLE IV
CASES OF MV MOTOR FORCED OUTAGES DUE TO STATOR WINDING TURN INSULATION FAILURES IN DOMESTIC POWER PLANTS (2011–2016)

	Application	V_{rated} (kV)	P_{rated} (kW)	Poles	Yrs. of service	Situation at failure		Failure location			Turn Insulation material	Stator core lamination damage	Insulation tests (mo. before failure)
						Failure at startup/operation	Time to failure after last startup	EW/slot	Location	Coil # from Terminal			
M1	Condensate pump	6.6	310	4	3	Startup	0	EW	Slot exit	–	Glass fiber	None	1
M2	Condensate pump	6.6	310	4	5	Startup	0	EW	Slot exit	–	Glass fiber	None	28
M3	Condensate pump	6.6	350	4	7	Operation	24 h	Slot	Mid-slot	–	Glass fiber	None	0.5
M4	Condensate pump	6.6	350	4	8	Startup	0	EW	Slot exit	>3	Glass fiber	None	0.25
M5	Boiler feed pump	6.6	2250	2	3	Startup	0	EW	Slot exit	1	Glass fiber	None	–
M6	Boiler feed pump	6.6	2250	2	4	Startup	0	EW	Slot exit	–	Glass fiber	None	–
M7	Induced draft fan	6.6	4300	8	5	Operation	3 mo.	Slot	Mid-slot	1	Glass fiber	None	28, 46
M8	Induced draft fan	6.6	4300	8	8	Operation	12 hr.	Slot	Mid-slot	1	Glass fiber	None	0.5, 57
M9	Transport blower	6.6	205	4	7	Startup	0	EW	Slot exit	2	Glass fiber	None	23
M10	Circulating pump	6.6	350	4	16	Startup	0	Slot	Mid-slot	–	Enamel	None	–
M11	Pulverizer	66	450	8	5	Operation	6 mo.	EW	–	–	Glass fiber	None	–
M12	Primary air fan	4.0	485	6	9	Operation	1 wk.	EW	Bend	>3	Mica	None	0.5, 31, 68
M13	Primary air fan	6.6	1678	4	15	Operation	10 mo.	EW	Slot exit	3	Glass fiber	None	

There was a strong correlation between the failures and turn insulation material used. The turn insulation material in 11 of 13 motors was glass fiber, and the other 2 motors had mica and enamel material. Enamel insulation is rare as it is not recommended for motors rated above 3.3 kV due to reliability issues. Glass fiber itself has high resistance to PD and electrical breakdown strength, but the organic polymers that surrounds the round glass fiber are known to have weak electrical properties subject to failure [5]. The number of MV motors in domestic power plants with glass fiber and mica turn insulation is about the same. Therefore, it can be concluded that motors with glass fiber turn insulation are more prone to insulation failure. Among the motors with failed turn insulation were four distinct sets. Each of these sets consists of two motors (M1-M2, . . .). The motors of each set from the same manufacturer have the same insulation design, and use the same insulation materials. Based on this observation, it was recommended to rewind all motors of the same set as soon as one of them fails due to a shorted turn. It was also recommended that mica turn insulation material should be used when the motor is rewound, and that newly purchased motors rated 6 kV and above should have mica turn insulation.

The observations made above show that turn insulation failure is related to design, material, and/or manufacturing defects since identical motors from the same manufacturer fail. There is evidence from the failure location and startup failures that they are also related to electrical, mechanical, and thermal aging. It can be concluded that the failures observed in the power plants were caused by a combination of electrical, thermal, and mechanical aging stresses and insulation design and manufacturing.

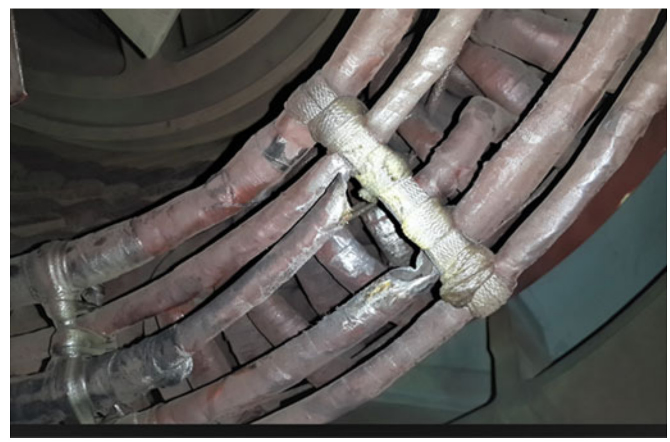

Fig. 9. Phase insulation failure in lead cable of 6.6-kV, 3800-kW boiler feed pump motor (M14).

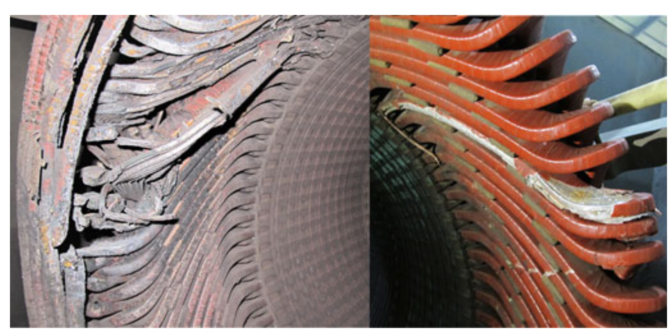

Fig. 10. Phase insulation failure between lead cable and EW of 6.6-kV, 4500-kW boiler feed pump motor (M15).

IV. PHASE INSULATION FAILURES

Failures in the phase insulation are not as common as GW or turn insulation failures, but can occur in the lead cables or EW close to the terminal end with high electrical stress. Phase insulation failure is unlikely to occur in the slot with stress-relief coatings and/or thick insulation that includes the GW insulation of the coils and the midstick coil separator. The EW is fixed with support rings, EW block material, and lashes to prevent insulation wear due to vibration. The insulating blocks and lashes are also used for separating coils or lead cables of different phases in the EW, as shown in Figs. 9 and 10. The spacing between different phases of the EW or lead cables can be insufficient due to deficiencies introduced in the design or

TABLE V
CASES OF MV MOTOR FORCED OUTAGES DUE TO STATOR WINDING PHASE INSULATION FAILURES IN DOMESTIC POWER PLANTS (2015–2016)

	Application	V_{rated} (kV)	P_{rated} (kW)	P	Yrs. of service	Status at failure	Failure location	Stator core lamination damage	Test records (mo. before failure)
M14	Boiler feed pump	6.6	3800	2	9	Operation	Lead cable	None	19 53
M15	Boiler feed pump	6.6	4500	4	12	Operation	Lead cable-EW	None	56 116

manufacturing, or movement/vibration during operation. There can also be contamination in the EW or lead cables with foreign material, oil, or moisture. Surface leakage current, PD, and/or short rise-time impulses can gradually degrade the insulation with insufficient spacing and/or contamination.

Phase insulation failure leads to very high current flow causing significant damage to the stator winding. Two cases of motor outages due to phase insulation failure have occurred since 2015 at domestic power plants. The application, motor ratings, and information on the phase insulation failures and test records are summarized in Table V. An open-phase failure during operation of a 6.6-kV, 3800-kW motor that resulted from a phase insulation failure between lead cables is shown in Fig. 9. In Fig. 10, a case of failure between the lead cable and EW insulation of different phases is shown for a 6.6-kV, 4500-kW motor. It can be seen in Fig. 10 that the high-phase current caused significant damage in the stator winding. The high mechanical vibration that is proportional to the square of the current caused cracking of the insulation on the other axial end of the same coil. Surface leakage current and arcing due to a combination of insufficient EW spacing and contamination due to coal dust is suspected as the cause of the failures. Both failures occurred in the lead cables at the terminal end of the winding where the phase voltage is the highest.

V. TURN INSULATION FAILURES IN CROSSOVER COILS

There were also cases of turn insulation failures that occurred in the knuckle (or tip) of the EW near the terminal end in MV motors. This failure is described in a separate section since a well-documented case was not available, although several cases were observed according to the maintenance engineers. An example of a turn insulation failure near the knuckle of the EW in the coil close to the terminal end that occurred at a chemical plant is shown in Fig. 11. The motor failed during motor operation after 25 years of service. This 3.3-kV, 190-kW motor has "crossover" coil design [18], which is typical in MV/HV motors with relatively low power ratings. For such motors, strands are not required since the current rating is low, and multiple turns are placed in a single layer within the slot width to produce the required magneto-motive force. The turns are placed side by side, which is different from the "straight up" coil design with one turn in one layer within the slot width. In straight up coils, the voltage between adjacent turns is equal to the line-neutral voltage divided by the number of series turns. However, with multiple turns placed side-by-side in a layer in crossover coils, the voltage between neighboring turns between top and bottom layers exceeds the voltage per adjacent turn of straight up coils [18]. This increases the interturn voltage stress in form wound machines. In addition, since the neighboring turns must be placed in a different horizontal location within the slot, the shape of the individual turns are different. Therefore, it is necessary to bend the individual turns in the EW, typically near the knuckle of the EW, to insert all the turns in place. An example of a crossover coil is shown in the coil of a 6.6-kV 75-kW motor in Fig. 12. The abrupt bending mechanically stresses the insulation, and may lead to voids which make the insulation vulnerable to failure. Although one case of crossover coil failure

Fig. 11. Turn insulation failure near knuckle of EW of 3.3-kV, 190-kW motor.

Fig. 12. Example of crossover coil design for 6.6-kV, 75-kW 8 pole motor.

TABLE VI
TEST RECORDS OF INSULATION TESTS FOR MOTORS THAT FAILED TURN OR PHASE INSULATION

	Months before failure	IR (MΩ)	PI	PDIV (kV)	$Q_{m,100}$ (PC)	$Q_{m,125}$ (PC)	ΔI <%)	Δtan δ (%)	PD pattern
M1	1	59 300	3.54	2.3	28 000	32 000	3.01	1.85	Internal
M2	28	67 200	4.02	4.0	6200	8700	3.17	1.91	–
M2’	–	55 900	3.45	2.3	7300	12100	3.46	2.08	Internal
M3	0.5	59 600	5.81	2.8	3200	4900	2.29	1.55	–
M3’	–	29 700	5.02	2.8	9100	17 000	0.64	1.1	Internal
M4	0.25	24 800	4.01	2.5	6000	8200	2.52	1.88	–
M4’	–	28 200	5.33	2.6	3700	5800	2.51	1.92	–
M7	46	4800	2.33	2.6	8600	12 700	4.19	2.55	Slot
M7	28	6240	4.91	2.2	7700	16 000	4.23	2.52	Slot
M7’		1510	4.37	2.4	6000	11 000	5.75	3.17	Slot
M8	57	1390	2.89	3.5	1400	2400	7.6	4.2	–
M8	0.5	6090	3.58	1.9	19 000	24 000	6.92	3.89	Internal
M8’	–	2640	3.06	1.8	13 000	20 300	6.3	3.5	Internal
M9	23	37 800	2.51	2.1	7000	8000	8.02	2.03	–
M9’	–	38 000	2.13	2.0	7000	7500	5.01	2.22	–
M9”	–	41 500	2.20	1.9	7000	8500	5.42	2.54	–
M12	68	52 200	6.23	2.2	1900	2300	0.62	0.05	–
M12	31	35 200	2.81	2.9	1700	2600	0.09	0.12	–
M12	0.5	40 100	6.43	2.8	1800	2900	0.19	0.13	–
M12’	–	17 300	5.54	–	730	9300	0.02	0.1	–
M14	53	2350	9.62	3.4	3000	6500	0.66	0.5	–
M14	19	21 400	4.12	2.9	6600	25 000	0.72	0.69	Internal
M15	116	9520	8.48	3.4	1100	2200	1.96	148	–
M15	56	11 900	5.55	2.5	5500	11 500	1.91	1.3	Internal
M15’	–	1440	4.54	1.7	50 000	52 000	2.14	1.2	Internal

that occurred in the petrochemical industry is reported in this paper, many turn insulation failures similar to that of Fig. 11 have been observed at power plants. They were similar in that the failed motors were MV motors with relatively low power rating that have crossover coil design, and that the location of the failures was near the knuckle of the coil EW.

The increased likelihood of turn insulation failures in crossover coils is well known by motor manufacturers, and modified winding design and/or manufacturing procedures are employed in some cases. Introducing the coil bend at different winding locations for the different turns, or using sectionalized coils, where sections of the coils are insulated and connected in series, are options for improving the reliability. However, the increased cost due to additional or nonuniform manufacturing steps limits the application of the alternative designs.

VI. Test Records of Failed Motors

The stator design of most MV motors used in the power generation industry are Y-connected, since 6.6 kV motors at the given output ratings have low current ratings. Another important reason Y-connection is used over Δ-connection is because it has lower turn-to-turn voltage stress for the same number of turns for a given voltage of 6.6 kV. For most of the 6.6 kV motors in domestic power plants, the neutral point is not accessible from the terminal since the Y-connection is made internally. The three phases cannot be separated for testing for this reason. Therefore, when performing the IR, PI, Δtanδ, ΔI_{leak}, and offline PD maintenance tests from the motor terminal box, the turn and phase insulation are not “directly” stressed with dc or 60-Hz ac voltage applied between the three-phase conductors and frame. If the weakened turn or phase insulation is located at the turn-GW or phase-GW insulation interface, some of the GW insulation tests such as PD is expected to provide an indirect indication of weak insulation [12]–[13]. However, it is difficult to guarantee that degradation in the turn or phase insulation can be detected and prevented with the 5-GW insulation tests with the test voltage not directly applied to the turn or phase insulation. This could be confirmed from the fact that a significant percentage of recent insulation failures in domestic power plants were caused by failure in the turn or phase insulation and not GW insulation.

The insulation test records for the motors that failed turn or phase insulation were analyzed to investigate if indications of weak turn or phase insulation could be found from the 5-GW insulation tests for preventing failure. All test records of IR, PI, $\Delta \tan \delta$, ΔI_{leak}, and offline PD tests performed before failure for the failed motors and identical motors operating in parallel are summarized in Table VI. The most likely location of PD (internal or slot/conductor surface) is given based on the amplitude and number of positive/negative PD pulses with respect to the voltage polarity for cases where $Q_{m,125}$ exceeded 10 000 pC. The test results for the failed motors are highlighted, and the results from some unfailed motors with identical design as the failed motors denoted with a prime (’) are also shown for comparison.

The test records of Table VI show that the IR and PI test results are well above the threshold levels for all tests performed. These tests are mainly used as screening tests before performing ac tests, and not for trending insulation condition. If a motor fails the IR or PI test, the motor windings are cleaned and dried and the tests are repeated. The ac tests are performed only when the PI and IR tests are passed. The range of absolute values of $\Delta\tan\delta$ and ΔI_{leak} depend on the insulation material used by the motor manufacturer. The values were relatively high for M1, M2, M3, M4, M7, M8, M9, and low for M12, M14, M15, where each group of motors were from two different manufacturers. In general, an increasing trend or relatively higher values of $\Delta\tan\delta$ and/or ΔI_{leak} could not be observed for the failed motors. They were not particularly higher when compared to identical or similar motors from the same manufacturer that did not fail.

High level or increasing trend in PD activity above the warning/alarm levels of 10 000/30 000 pC could be observed in some of the motors (M1, M7, M8, M14, M15) prior to turn or phase insulation failure. Since $Q_{m,125}$ exceeded the warning threshold, disassembled inspection was recommended for these motors according to Fig. 2. For M1, an annual inspection was recommended although Q_m exceeded 30 000 pC, since the PDIV, $\Delta\tan\delta$, and ΔI_{leak} measurements were within the threshold, and the motors from the M1 manufacturer had relatively higher Q_m values. The high PD activity for these motors could have been an indication of overall insulation aging, or an indirect indication of turn insulation degradation. M1 failed during the test runs at its fifth startup due to turn insulation breakdown 1 month after the inspection, however, the insulation repair was not considered to be urgent from the test results when compared to motors from the same manufacturer with high $\Delta\tan\delta$, ΔI_{leak}, and Q_m values that have been operating for many years. They were much lower than that of the motors for which stator refurbishment or rewind were recommended. For M2, M3, M4, M9, M12, M15, the PD measurements were below the warning level and/or lower than that of identical motors that did not fail. Tests performed less than 1 month before turn failure for M3, M4, and M12 did not show any signs of insulation degradation. The observations on the test records of Table VI show that the five stator tests currently being performed cannot be relied on to provide an advanced warning for turn or phase insulation failures.

VII. Evaluation of Existing Methods for Turn or Phase Insulation Condition Assessment

Most of the research efforts on insulation testing were focused on GW insulation condition assessment since it is where stator insulation is most likely to fail. The observations made in the preceding sections show that a test method for turn or phase insulation assessment is highly desirable for improving the reliability of stator insulation systems further. A literature survey and evaluation of existing turn or phase insulation test methods is given in this section to provide researchers with an overview of methods available and to help target future research efforts toward industrial needs.

The surge test applies high voltage, fast rise-time impulses to the winding and stresses the turn, phase, and GW insulation of the terminal end coil. It is currently the only commercially available test for offline maintenance testing of turn or phase insulation [5]–[10]. It is a pass/fail test that provides fault indication only if an arc is instigated between turns or between phases with weak insulation. Therefore, it cannot provide a quantitative assessment of turn or phase insulation condition. In addition, there are concerns on insulation damage since a high-voltage level representative of the worst in-service conditions must be applied for reliable testing. Although the surge test can potentially prevent costly in-service insulation failures due to fast rise-time surges, the main concern is the risk of failing insulation that could have operated without failure. For this reason, the MV motors in domestic power plants are surge tested only if requested. It cannot be concluded whether surge testing would have prevented the turn or phase insulation failures reported in Sections III and IV. However, it is possible that some of the in-service failures could have been prevented if testing was performed at a time close to failure for faults that occurred close to the terminal end insulation where the impulse voltage stress is high.

Majority of academic research activity on turn insulation testing over the last 20+ years was on developing on-line turn fault detection algorithms, usually for low-voltage random-wound stators. Turn faults were detected by monitoring the electrical asymmetry caused by the large circulating interturn fault current after the turns short. Turn fault detection is useful for relaying after the fault occurs and does not provide diagnostics information regarding the condition of turn insulation. It is claimed in [14]–[16] that the motivation for detecting turn faults at an early stage is to prevent further damage to the machine. The premise is that tripping of the relay after the turn fault inflicts significant damage to the stator core interlaminar insulation due to the ground current. It is claimed that implementing an online turn fault detector allows the motor user to get away with a stator rewind instead of a full or partial core restack/repair and rewind. However, it was observed in this study that undetected turn faults do not necessary cause damage to the stator core insulation. Stator core interlaminar insulation damage due to melted copper or ground current that requires a restack/repair was not observed in any of the 15 cases of turn and phase insulation failures in power plants with solid grounding where the ground current is not limited. The value of online turn fault detection seems to be limited in that it allows earlier detection and can possibly reduce the extent of the burning of laminations or melting of conductors; however, it is unlikely that it can prevent a core interlaminar insulation damage. The reason online turn fault detection has not been accepted by industry despite the research activity over the last 20+ years is because of its apparently limited value.

In [19]–[22], variation in the turn-to-turn capacitance (or impedance) with aging in random wound stators is proposed as an indicator of turn insulation condition. It is shown through accelerated aging of a twisted pair and motorette, or under-emulated motor insulation aging that the variation in the turn capacitance is large enough to change the frequency response in the hundreds of kilohertz to megahertz range. It has not been discussed if this method could be applied to form-wound stators. Monitoring of the change in the radial leakage flux [19], zero sequence current [20], or impedance spectra [21] under offline or online (superimposed on the voltage input) injection of a low-voltage signal are proposed for turn insulation condition assessment. However, it is yet to be verified on actual motors in the field under realistic aging, and there are many practical issues to be resolved for implementation in the field.

During normal motor operation or with 50/60-Hz offline tests, a few tens of volts is applied between the turns, which is not enough electric stress to create PD. Therefore, offline PD testing at power frequency voltage cannot detect turn insulation deterioration. However, if short rise-time voltage surges or high-frequency ac is applied to the stator winding, the higher interturn voltage is likely to produce PD between turns if voids are present. This has been discussed in many papers for motors fed by voltage source PWM inverters [23]–[27]. In [28], the PDIV is monitored under 200 ns rise-time surge excitation under accelerated thermal aging (180 °C) of a random wound motor sample. The potential of using surge PDIV as an indicator of turn insulation condition is shown since PDIV decreases with aging of the insulation, whereas GW insulation indicators do not change. In [22], it is shown that PDIV decreases under 10 kHz excitation with change in turn capacitance of a twisted pair under accelerated thermal aging at 260–280 °C, which is similar in concept to [28]. PD measurement during short rise-time voltage surges is more challenging than 50 or 60 Hz, since the surge has frequency content similar to that of PD pulses; thus, special PD detectors are needed [23], [26]–[27]. These methods have also been applied for online PD testing of low-voltage and medium-voltage motors supplied from voltage-source PWM inverters [26]–[27].

A new concept is presented for performing the surge test intermittently when the motor is in-service in [29]–[30]. A circuit for applying the surge during motor operation and a series *RC* circuit for directing the surge to the motor instead of the supply are required for each phase. It is shown that the pulse to pulse error area ratio [8]–[9] under varying voltage levels can be monitored for detecting weakened turn insulation. The value of having an online surge test is that an advanced warning can be given for motors with weak turn insulation to prevent a forced outage, if the turn insulation does not break down as a result of surge test failure. However, it could be considered intrusive since inductors, capacitors, and IGBTs rated at test voltage levels are required, and motor operation is momentarily interrupted. Solutions to some implementation issues are presented in [30] to compensate for the influence of slotting or eccentricity.

Recently, insulation monitoring based on observing the current response to a voltage pulse [31]–[32], or high frequency (>100 kHz) switching [33] applied with the inverter was proposed for inverter-fed motors. With short rise-time or high frequency pulses produced with the inverter, voltage stress can be applied online or offline to the turn, phase, and GW insulation at the terminal end, where failure is most likely to occur. It is claimed in the paper that aging of the insulation causes change in the capacitance, leading to observable changes in current response to high frequency excitation. Testing on 5.5 kW and 1.4 MW motors under emulated insulation deterioration show that noninvasive monitoring of terminal end insulation condition can be provided without additional HW. This paper is currently in progress where the authors are working toward improving the sensitivity, simplifying the implementation requirements, and verifying the method under realistic insulation aging.

Although most offline electrical tests described above cannot detect insulation problems between phases in the EW, considerable experience indicates that online PD can reliably detect PD due to insufficient spacing and contamination. In an online PD test, there can be as much as full rated ac voltage between coils in different phases in the EW. Phase-to-phase PD can be distinguished from GW PD by displaying the PD from all three phases in special phase-shifted plots. Phase-to-phase PD occurs at the same instant of time on two phases with equal magnitude and opposite polarity. They are shifted by $+30^{o}$ and -30^{o} in each phase with respect to GW PD [34]–[35].

VIII. Conclusion

In this paper, a summary of KEPCO's experience accumulated from 17+ years of offline testing MV motors in 37 power generation plants in Korea have been provided. The recent cases of turn and phase insulation failures in power plants that resulted in forced outage of the motor and/or power generation capability have been analyzed along with the test records of the failed motors. Finally, concepts for turn or phase insulation testing have been reviewed and evaluated based on the findings. The conclusions drawn from this investigation can be summarized as follows.

1) GW insulation failures have been significantly reduced since the stator insulation testing and maintenance program has been initiated. Forced outage of motors due to GW insulation problems has been reduced with proactive refurbishments or rewinds to 1.95% of the motors identified with weak GW insulation.
2) 84.6% of the 13 MV motors with turn insulation failures had glass fiber turn insulation material. Considering that approximately half of motors use glass fiber turn insulation and the other half use mica-based turn insulation in domestic power plants, the probability of turn insulation failure can be reduced by using mica-based turn insulation, for motors 6 kV and above.
3) Insulation system design and manufacturing is an important factor in addition to electrical, mechanical, and thermal aging for turn insulation reliability considering that turn failures occurred on four pairs of motors with identical insulation system design.
4) Phase insulation failures that resulted in significant motor damage due to contamination and/or insufficient EW spacing were observed in the terminal end leads or EW.
5) Turn insulation failures near the knuckle of the EW are caused by deterioration in the turn insulation due to the stresses of abrupt bending, and increased interturn voltage in crossover coil designs. This type of turn insulation failure is common for MV motors with low-output power rating that have crossover coils designs. Design improvements for turn insulation and coil design can help prevent turn insulation failures.
6) Analysis of the insulation test records for motors with turn or phase insulation failures show that it is difficult to predict turn/phase insulation failures with the IR, PI, $\Delta \tan \delta$, ΔI_{leak}, and offline PD insulation testing.
7) Turn or phase insulation failures do not necessarily cause ground fault current leading to core insulation failure.

Stator core interlaminar insulation failure was not observed with visual inspection or core loop testing performed for all 15 motors with turn or phase insulation failures.

8) Conventional surge testing could potentially prevent turn or phase insulation failures in the terminal end of the winding, if testing can be performed frequently. Note that there is a risk that the surge test may fail the turn insulation in motors years before they would fail if no surge testing is done.
9) Conventional online PD detection may find phase-to-phase insulation problems in the terminal end of the winding, but not turn insulation problems.
10) Investigation of new concepts for turn or phase insulation condition assessment is in-progress for mains- and inverter-fed machines. Further research on verification and implementation of the methods and development of new test concepts are needed.

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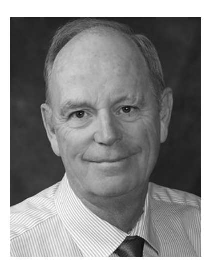

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