Experience with Stator Insulation Testing & Turn/Phase Insulation Failures in the Power Generation Industry

May 7, 2018

Heedong Kim, Taesik Kong
Korea Electric Power Company Research Institute, Daejon, Korea

Sang Bin Lee
Korea University, Seoul, Korea

Objectives

- **Summary of KEPCO's 17+ yrs. experience on stator insulation testing for mains-fed, MV AC motors**
  - Predictive maintenance program & statistics on test records (99'~)
  - Analysis of 15 cases of turn/phase insulation failures (11'~)
- **Provide insight on turn/phase insulation failures**

Stator Insulation Failures

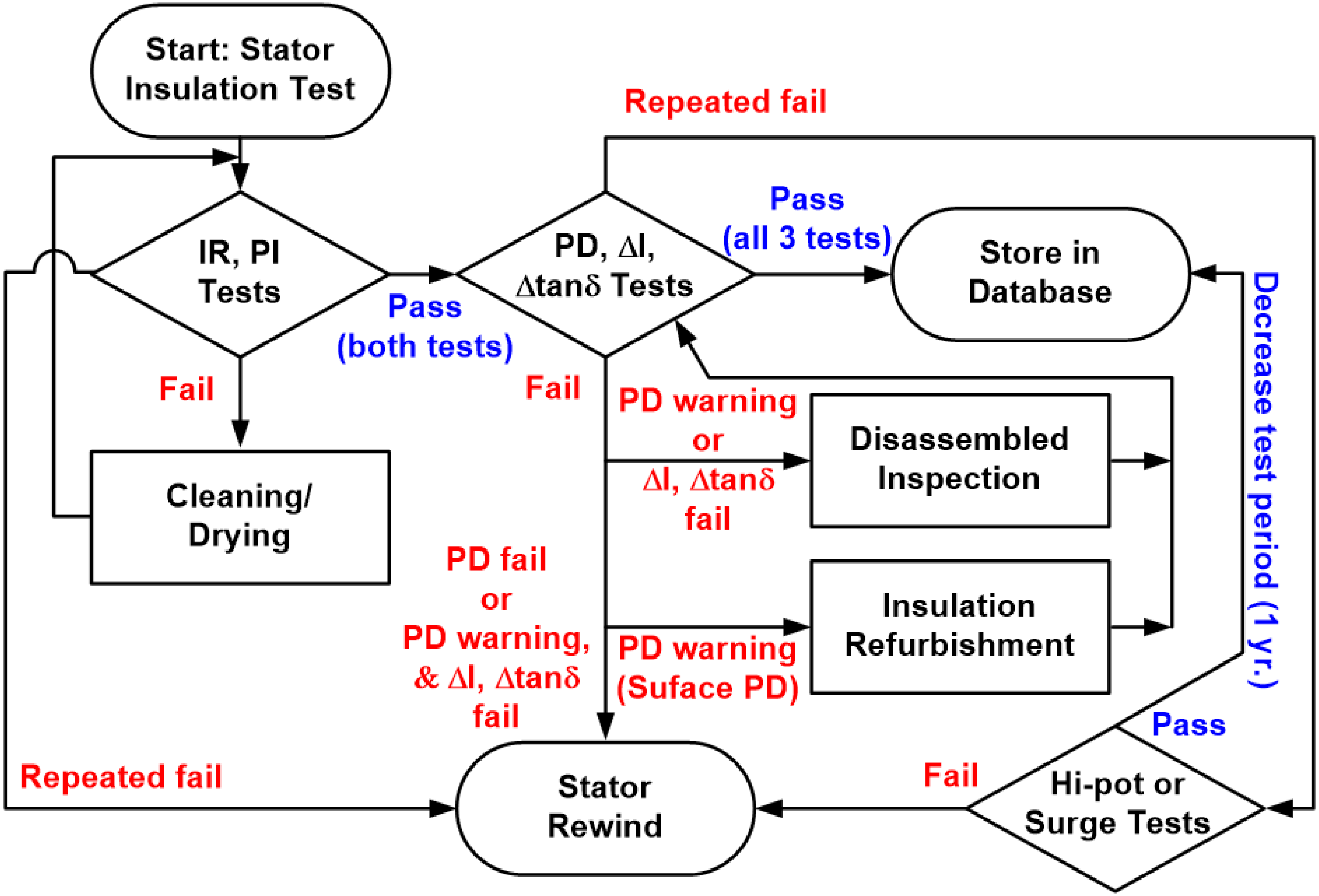
- **Leading cause of forced motor outages in power plants [1]**
  - Complete loss or reduction in power generation capability
  - 83.6% groundwall (GW) insulation, 16.4% turn insulation failure
  - Most commercial tests intended for GW insulation testing
- **Significant reduction in GW insulation failures w/ predictive maintenance (PM) program**

GW insulation failure, 6.6 kV, 550 kW

Insulation PM Testing (KEPCO)

- **PM program setup in 1999**
- **Tests performed**
  - Insulation resistance (IR), polarization index (PI)
  - Delta leakage current (ΔI_{leak}), delta tanδ (Δtanδ)
  - Off-line partial discharge (PD)
- **Test period**
  - 5 years (< 10 yrs. of service); 3 years (> 10 yrs. of service)
  - 1 year (insulation in poor condition)
- **Recommendations**
  - 1) Cleaning/drying; 2) Refurbishment; 3) Stator rewind

Testing & Maintenance Procedure



Summary of KEPCO Insulation Testing

- # of test records for 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	3,119	8,152
Combined cycle	9	30	362	695
Pumped storage	5	12	48	69
Nuclear	4	15	1,231	2,938
Total	37	155	4,760	11,854

  - Stator tests at nuclear plants excluded (performed at MCC)

- # of alarms for each test for type of power plant

Type of power plant	# of tests performed	IR	PI	ΔI_{leak}	$\Delta\tan\delta$	PDIV	$Q_{m,100}$	$Q_{m,125}$
Thermal	8,152	61	565	1,063	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	8,916	63	713	1,087	830	255	135	227

Summary of KEPCO Insulation Testing

- # of motors with 1, 2, 3 failure alarms produced with each type of test & # of refurbishment & rewind recommendations

Type of power plant	# of tests performed	1 failed test	2 failed tests	3 failed tests	Insulation refurbishment	Stator rewind
Thermal	8,152	499	793	30	47	110
Combined cycle	695	31	19	2	4	13
Pumped storage	69	1	0	0	0	0
Total	8,916	531	812	32	51	123

  - Active repair recommendations made for 174 of 8,916 motors (1.95%) with high risk of GW insulation failure

→ Significant reduction in GW insulation failures since 1999

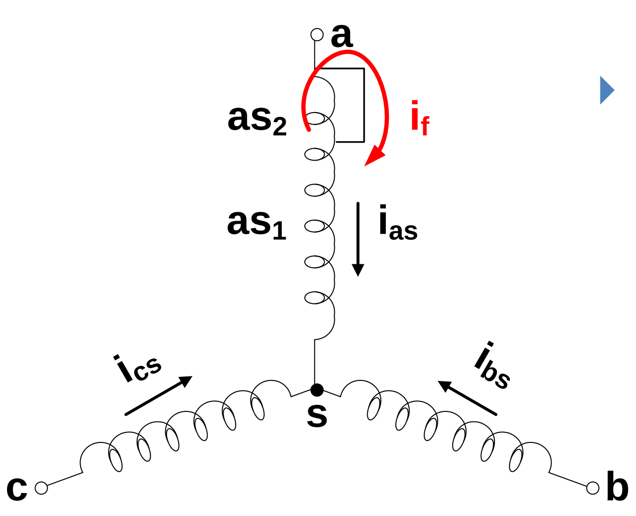
→ **Most recent insulation failures in turn or phase insulation**

→ GW failures still present when recommended testing cycle or repair actions are not followed (production or budget restraints)

Turn Insulation Failures

- **Root causes - combination of:**
  - Long term thermal & mechanical aging
  - Deficiency in turn insulation design or manufacturing
  - PD deterioration at turn-GW insulation interface (> 4 KV) [12]-[13]

  → Loss of elec./mech. strength: **Puncture due to short rise-time voltage surge or mechanical shock**



- **Typical fault location**
  - **Terminal end coil**: high electrical stress & turn voltage stress
  - **Endwinding (EW) slot exit**: bent portion w/ manufacturing & operating stresses

Turn Insulation Failures

- **Consequences**
  - Induction of high amplitude circulating fault current in shorted loop
  - Localized heating: melted copper & damage over wide area
  - GW insulation failure (and/or stator core damage)

  → Tripping of motor: forced outage

Case Studies - Turn Insulation Failure

- **13 cases of turn insulation failure (2011-2016)**
  - Investigation based on direct observation (or dissection), reports, interviews from on-site maintenance team or repair shop
  - Variance in amount of information available for each case

	Application	V_{rated} (kV)	P_{rated} (kW)	Poles	Yrs. of service	Situation at failure		Failure location			Turn insulation material	Stator core lamination damage
						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
M2	Condensate pump	6.6	310	4	5	Startup	0	EW	Slot exit	-	Glass fiber	None
M3	Condensate pump	6.6	350	4	7	Operation	24 hr	Slot	Mid-slot	-	Glass fiber	None
M4	Condensate pump	6.6	350	4	8	Startup	0	EW	Slot exit	>3	Glass fiber	None
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
M8	Induced draft fan	6.6	4300	8	8	Operation	12 hr.	Slot	Mid-slot	1	Glass fiber	None
M9	Transport blower	6.6	205	4	7	Startup	0	EW	Slot exit	2	Glass fiber	None
M10	Circulating pump	6.6	350	4	16	Startup	0	Slot	Mid-slot	-	Enamel	None
M11	Pulverizer	6.6	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
M13	Primary air fan	6.6	1678	4	15	Operation	10 mo.	EW	Slot exit	3	Glass fiber	None

Turn Insulation Failure - Observations

- No noticeable trend in correlation between turn failure & application, rated power, number of poles, years of service
- 7 of 13 failures occurred at motor startup
  - 6 of 7 failures located at EW slot exit (M1, M2, M4, M5, M6, M9)
  - 2 of 3 failures in 1st or 2nd coil (M5, M9)
  - Typical failures: fast risetime voltage surge & mechanical forces
- 6 of 13 failures occurred during operation >12 hrs after startup

Endwinding Failures - Observations

- 9 of 13 failures in EW at or near slot exit – typical failures reported
  - Bending stresses present at manufacturing

	Application	V_{rated} (kV)	P_{rated} (kW)	Situation at failure		Failure location			Turn insulation material	Stator core lamination damage
				Failure at startup/ operation	Time to failure after last startup	EW/ slot	Location	Coil # from Terminal		
M1	Condensate pump	6.6	310	Startup	0	EW	Slot exit	-	Glass fiber	None
M2	Condensate pump	6.6	310	Startup	0	EW	Slot exit	-	Glass fiber	None
M3	Condensate pump	6.6	350	Operation	24 hr	Slot	Mid-slot	-	Glass fiber	None
M4	Condensate pump	6.6	350	Startup	0	EW	Slot exit	>3	Glass fiber	None
M5	Boiler feed pump	6.6	2250	Startup	0	EW	Slot exit	1	Glass fiber	None
M6	Boiler feed pump	6.6	2250	Startup	0	EW	Slot exit	-	Glass fiber	None
M7	Induced draft fan	6.6	4300	Operation	3 mo.	Slot	Mid-slot	1	Glass fiber	None
M8	Induced draft fan	6.6	4300	Operation	12 hr.	Slot	Mid-slot	1	Glass fiber	None
M9	Transport blower	6.6	205	Startup	0	EW	Slot exit	2	Glass fiber	None
M10	Circulating pump	6.6	350	Startup	0	Slot	Mid-slot	-	Enamel	None
M11	Pulverizer	6.6	450	Operation	6 mo.	EW	-	-	Glass fiber	None
M12	Primary air fan	4.0	485	Operation	1 wk.	EW	Bend	>3	Mica	None
M13	Primary air fan	6.6	1678	Operation	10 mo.	EW	Slot exit	3	Glass fiber	None

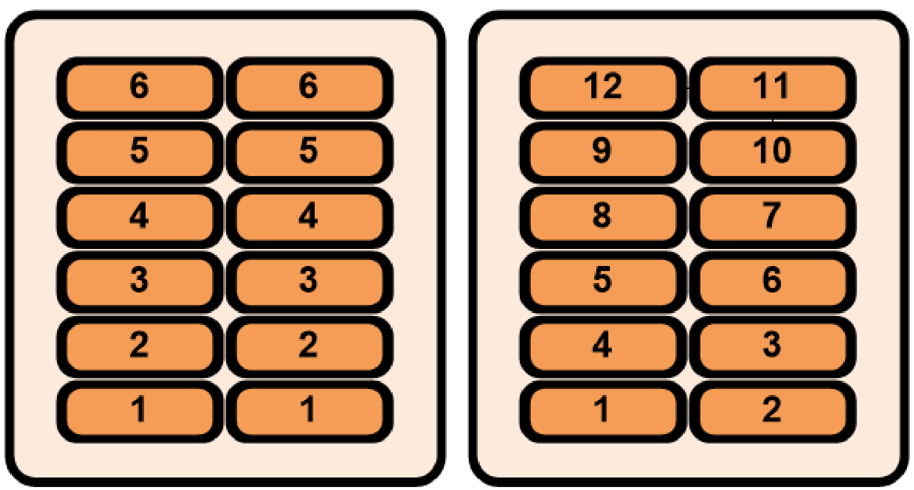
Turn Insulation Failure - Observations

Endwinding Failures - Observations

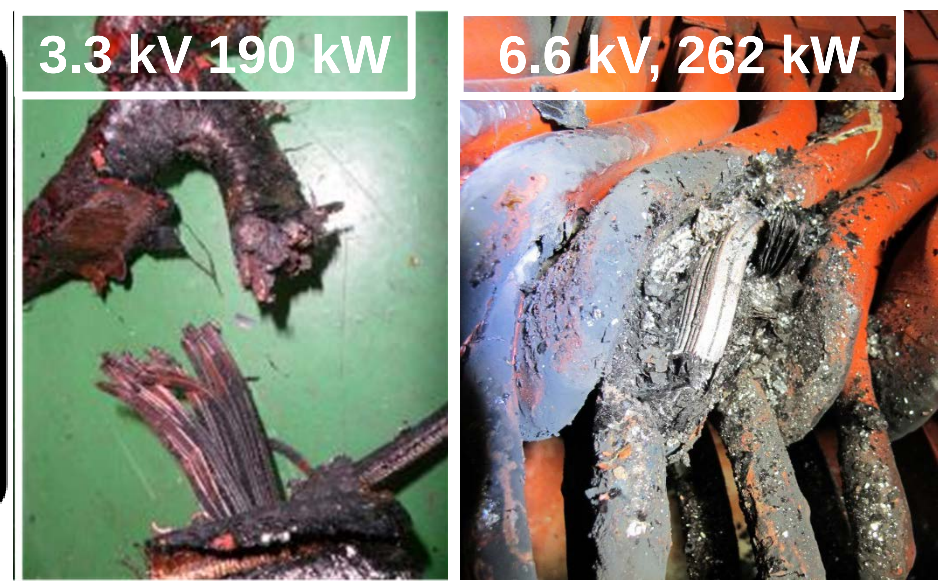
- Melted copper & burning over wide area observed for ALL cases
- Turn failure does not necessarily cause GW insulation failure
  - Turn fault can cause tripping of open phase, imbalance, phase current relays before GW failure
  - M12: no visual signs of GW current path + high IR value
  - Turn failures in the tip of EW common w/ crossover coil designs

Endwinding Failures - Observations

- “Crossover” coils common in MV motors w/ low power ratings
- Multiple & neighboring turns placed in slot width in same layer [15]
- Bending of coils required in EW (near tip)
- Higher electrical & manufacturing (bending) stresses in turn insulation near EW tip (terminal end coil)



Straight-up coil   Crossover coil



Slot Winding Failures - Observations

- 4 of 13 failures near center of slot

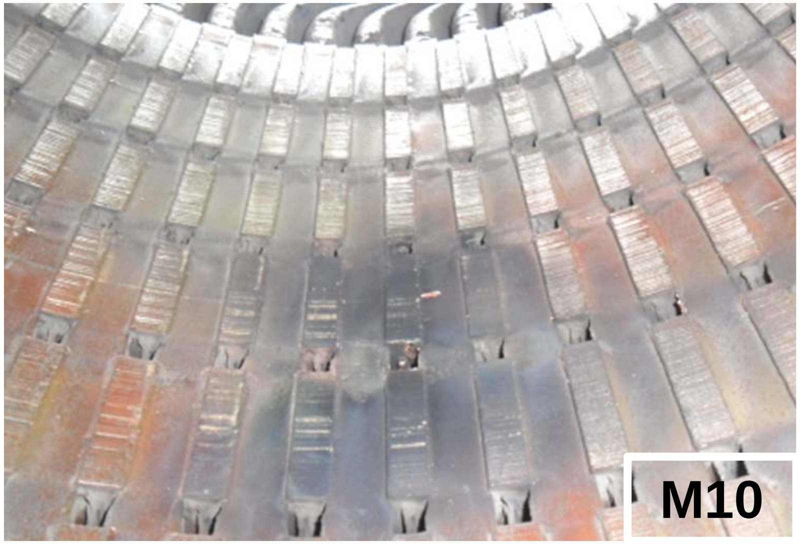
	Application	V_{rated} (kV)	P_{rated} (kW)	Situation at failure		Failure location			Turn insulation material	Stator core lamination damage
				Failure at startup/ operation	Time to failure after last startup	EW/ slot	Location	Coil # from Terminal		
M1	Condensate pump	6.6	310	Startup	0	EW	Slot exit	-	Glass fiber	None
M2	Condensate pump	6.6	310	Startup	0	EW	Slot exit	-	Glass fiber	None
M3	Condensate pump	6.6	350	Operation	24 hr	Slot	Mid-slot	-	Glass fiber	None
M4	Condensate pump	6.6	350	Startup	0	EW	Slot exit	>3	Glass fiber	None
M5	Boiler feed pump	6.6	2250	Startup	0	EW	Slot exit	1	Glass fiber	None
M6	Boiler feed pump	6.6	2250	Startup	0	EW	Slot exit	-	Glass fiber	None
M7	Induced draft fan	6.6	4300	Operation	3 mo.	Slot	Mid-slot	1	Glass fiber	None
M8	Induced draft fan	6.6	4300	Operation	12 hr.	Slot	Mid-slot	1	Glass fiber	None
M9	Transport blower	6.6	205	Startup	0	EW	Slot exit	2	Glass fiber	None
M10	Circulating pump	6.6	350	Startup	0	Slot	Mid-slot	-	Enamel	None
M11	Pulverizer	6.6	450	Operation	6 mo.	EW	-	-	Glass fiber	None
M12	Primary air fan	4.0	485	Operation	1 wk.	EW	Bend	>3	Mica	None
M13	Primary air fan	6.6	1678	Operation	10 mo.	EW	Slot exit	3	Glass fiber	None

Slot Winding Failures - Observations

- 4 of 13 failures near center of slot
  - Clear signs of melted copper and ground current path

Slot Winding Failures - Observations

- Clear signs of melted copper and ground current path



Slot Winding Failures - Observations

- Core inter-laminar insulation failure not observed for any of the 13 cases
  - Visual inspection, core loop test performed during rewind
  - Relays act fast enough to prevent core damage even with large ground current with solid grounding in domestic power plants
  - Not all faults result in ground current through stator core
    - EW failure not close to core (M13, crossover coils)
    - Trip caused by asymmetry or open circuits
    - Ground current flow through core end plate

Case Studies - Turn Insulation Material

- Strong correlation between failures & turn insulation material
  - Glass fiber: 11 cases; enamel: 1 case; mica-based: 1 case
  - % of glass fiber turn insulation **very high** considering that 50% of MV motors glass-fiber based & 50% mica-based in Korea

	Application	V_{rated} (kV)	P_{rated} (kW)	*Poles*	Yrs. of service	Situation at failure		Failure location			Turn insulation material
						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
M2	Condensate pump	6.6	310	4	5	Startup	0	EW	Slot exit	-	Glass fiber
M3	Condensate pump	6.6	350	4	7	Operation	24 hr	Slot	Mid-slot	-	Glass fiber
M4	Condensate pump	6.6	350	4	8	Startup	0	EW	Slot exit	>3	Glass fiber
M5	Boiler feed pump	6.6	2250	2	3	Startup	0	EW	Slot exit	1	Glass fiber
M6	Boiler feed pump	6.6	2250	2	4	Startup	0	EW	Slot exit	-	Glass fiber
M7	Induced draft fan	6.6	4300	8	5	Operation	3 mo.	Slot	Mid-slot	1	Glass fiber
M8	Induced draft fan	6.6	4300	8	8	Operation	12 hr.	Slot	Mid-slot	1	Glass fiber
M9	Transport blower	6.6	205	4	7	Startup	0	EW	Slot exit	2	Glass fiber
M10	Circulating pump	6.6	350	4	16	Startup	0	Slot	Mid-slot	-	Enamel
M11	Pulverizer	6.6	450	8	5	Operation	6 mo.	EW	-	-	Glass fiber
M12	Primary air fan	4.0	485	6	9	Operation	1 wk.	EW	Bend	>3	Mica
M13	Primary air fan	6.6	1678	4	15	Operation	10 mo.	EW	Slot exit	3	Glass fiber

Case Studies – Turn Insulation Material

- Mica paper: most common above 6.6 kV
  - Resistant to PD
  - Superior thermal properties
- Enamel turn insulation not common above 3.3 kV
  - Organic & non-PD-resistant
- Glass fiber
  - High breakdown strength, resistant to PD & tracking
  - Organic polymers around round glass vulnerable to failure

→ Motors with glass-fiber turn insulation have higher probability of failure

→ Rewind w/ mica-paper recommended for failed motors

Case Studies - Phase Insulation Failure

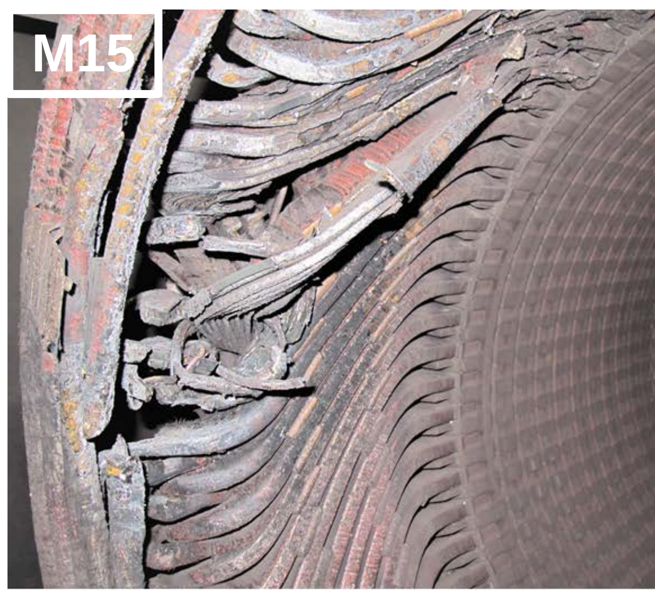
- **2 cases of phase insulation failures (2015-2016)**

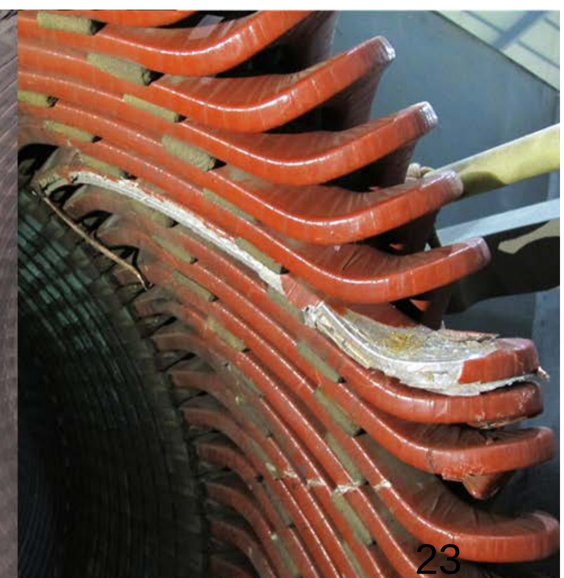
	Application	V_{rated} (kV)	P_{rated} (kW)	P	Yrs. of service	Status at failure	Failure location	Stator core lamination damage	Test records (mo. before failure)
M14	Boiler feed pump	6.6	3800	2	9	Operation	Lead cable	None	19, 53
M15	Boiler feed pump	6.6	4500	4	12	Operation	Lead cable-EW	None	56, 116

  - Typically occur in lead cables or EW close to terminal end
  - Typical root causes
    - Insufficient spacing conductors b/w different phases
    - Surface contamination
  - Results in very high current flow and significant damage

Phase Insulation Failure - Observations

- M14
  - Open phase failure due to phase insulation failure b/w lead cables
- M15
  - Significant damage due to insulation failure b/w lead cable & terminal end EW
- Cause of failure: surface leakage current & arcing due to insufficient spacing & coal dust contamination





Impact of Insulation Failure

- **Cost of rewind**
  - M1-M2, 310 kW condensate pump: 26,000 USD
  - M7-M8, 4,300 kW induced draft fan: 130,000 USD
- **Forced outage of induced draft fan (M7-M8), primary air fan (M12-M13)**
  - 50% reduction in generator power output
  - Loss of profit for power plant with 50% reduction
    - 50% reduction in power generation (12 hrs.) for 500 MW generating unit
    - 150,000 USD ~ 600,000 USD (based on 2011-2016 system marginal price in Korea)

Test Records of Failed Motors

- Voltage cannot be applied directly to turn/phase insulation with the 5 GW insulation tests for Y-connected MV motors w/ no access to neutral
- Insulation test records analyzed for motors that failed turn/phase insulation (identical motors also analyzed)

	Months before failure	IR (MΩ)	PI	PDIV (kV)	$Q_{m,100}$ (pC)	$Q_{m,125}$ (pC)	ΔI (%)	$\Delta \tan\delta$ (%)	PD pattern
M1	1	59300	3.54	2.3	**28000**	**32000**	3.01	1.85	Internal
M2	28	67200	4.02	4.0	6200	8700	3.17	1.91	-
M2′	-	55900	3.45	2.3	7300	**12100**	3.46	2.08	Internal
M3	0.5	59600	5.81	2.8	3200	4900	2.29	1.55	-
M3′	-	29700	5.02	2.8	9100	17000	0.64	1.1	Internal
M4	0.25	24800	4.01	2.5	6000	8200	2.52	1.88	-
M4′	-	28200	5.33	2.6	3700	5800	2.51	1.92	-
M7	46	4800	2.33	2.6	8600	**12700**	4.19	2.55	Slot
M7	28	6240	4.91	2.2	7700	**16000**	4.23	2.52	Slot
M7′	-	1510	4.37	2.4	6000	**11000**	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**	**19000**	**24000**	6.92	3.89	Internal
M8′	-	2640	3.06	**1.8**	**13000**	**20300**	6.3	3.5	Internal
M9	23	37800	2.51	2.1	7000	8000	8.02	2.03	-
M9′	-	38000	2.13	2.0	7000	7500	5.01	2.22	-
M9″	-	41500	2.20	1.9	7000	8500	5.42	2.54	-
M12	68	52200	6.23	2.2	1900	2300	0.62	0.05	-
M12	31	35200	2.81	2.9	1700	2600	0.09	0.12	-
M12	0.5	40100	6.43	2.8	1800	2900	0.19	0.13	-
M12′	-	17300	5.54	-	730	9300	0.02	0.1	-
M14	53	2350	9.62	3.4	3000	6500	0.66	0.5	-
M14	19	21400	4.12	2.9	6600	**25000**	0.72	0.69	Internal
M15	116	9520	8.48	3.4	1100	2200	1.96	1.48	-
M15	56	11900	5.55	2.5	5500	**11500**	1.91	1.3	Internal
M15′	-	1440	4.54	**1.7**	**50000**	**52000**	2.14	1.2	Internal

Test Records of Failed Motors - Observations

- IR/PI tests are screening tests & do not indicate insulation degradation
- Increasing trend or relatively higher value of $\Delta\tan\delta$ or ΔI_{leak} cannot be observed for failed motors
- High level or increasing trend in PD activity could be observed for some motors prior to turn or phase insulation failure (M1, M7, M8, M14, M15)
- PD activity for failed motors were much lower than that of motors with refurbishment / rewind recommendations (and even some identical motors that did not fail)

→ **5 GW stator tests cannot be relied on for advanced warning of turn or phase insulation failures**

Conclusions

- GW insulation failures have been significantly reduced since stator insulation PM program has been initiated – 1.95% of stators refurbished or rewound with high risk of GW failure
- Motors w/ glass-fiber turn insulation had higher risk of failure - 84.6% of failures (rewound with mica-based insulation)
- Insulation system design & manufacturing important factor – 4 pairs of motors with identical design have failed (8 of 13)
- Phase insulation failures due to insufficient spacing & contamination caused significant damage
- It is difficult to predict turn or phase insulation failures with IR, PI, $\Delta\tan\delta$, ΔI_{leak}, & PD tests

Conclusions

- Turn or phase insulation failures do not necessarily cause GW insulation failure or GW current
- Core inter-laminar insulation failure was not observed in any of the 15 turn or phase insulation failures
- On-line PD monitoring may find phase insulation failure in advance, but not turn insulation failures
- Investigation of new concepts for turn or phase insulation condition assessment are in progress

Acknowledgment

- **Motor repair shops**
  - Chaewoong Lim, *SN Heavy Industry Co.*
  - Shinyoung Park, *Hansung Heavy Industrial Co.*
- **Motor testing services**
  - Daesung Yoon, *Korea Electrical Safety Services*
- **Power generation plants**
  - Jaehyun Park, *Korea Midland Power Co.*
  - Youngha Hwang, *Korea Western Power Co.*
  - Byunggu Park, *Korea Southeast Power Co.*
  - Youngman Kang, *Korea Southern Power Co.*
  - Chan Namkoong, *Korea East-West Power Co.*

References

1. P.F. Albrecht, J.C. Appiarius, R.M. McCoy, E.L. Owen, and D.K. Sharma, "Assessment of the reliability of motors in utility applications - updated," *IEEE Trans. Energy Convers.*, vol. EC-1, no. 1, pp. 39-46, Mar. 1986.
2. IEEE Std. 43-2013, IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery.
3. IEEE Std. 286-2000, IEEE Recommended Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation.
4. IEEE Std. 1434-2014, IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery.
5. G.C. Stone, I. Culbert, E.A. Boulter, and H. Dhirani, *Electrical insulation for rotating machines – design, evaluation, aging, testing, and repair*, IEEE Press Series on Power Engineering, John Wiley and Sons, 2014.
6. IEEE Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines, IEEE STD 522, 2004.
7. D.E. Schump, "Testing to assure reliable operation of electric motors," *Proc. of IEEE IAS Annual Meeting*, vol. 2, pp. 1478-1483, Oct. 1990.
8. J. Wilson, "Current state of surge testing induction machines", *Proc. of Iris Rotating Machine Conference*, 2003.
9. E. Wiedenbrug, G. Frey, and J. Wilson, "Early intervention", *IEEE Ind. Appl. Mag.*, vol. 10, no. 5, pp. 34-40, 2004.
10. J.H. Dymond, M.K.W. Stranges, and N. Stranges, "The effect of surge testing on the voltage endurance life of stator coils," *IEEE Trans. Ind. Appl.*, vol. 41, no. 1, pp. 120-126, Jan./Feb. 2005.
11. O.M. Nassar, "The use of partial discharge and impulse voltage testing in the evaluation of interturn insulation failure of large motors," *IEEE Trans. Energy Convers.*, vol. EC-2, no. 4, pp. 615-621, Dec. 1987.
12. N.K. Ghai, "Design and application considerations for motors in steep-fronted surge environments," *IEEE Trans. Ind. Appl.*, vol. 33, no. 1, pp. 177-186, Jan./Feb. 1997.
13. G.C. Stone, B.K. Gupta, M. Kurtz, and D.K. Sharma, "Investigation of turn insulation failure mechanisms in large AC motors," *IEEE Trans. Power App. and Syst.*, vol. PAS-103, no. 9, pp. 2588-2593, Sept. 1984.
14. H. Kim, T. Kong, S.B. Lee, T.-J. Kang, N. Oh, Y. Kim, S. Park, G.C. Stone, "Experience with Stator Insulation Testing and Turn/Phase Insulation Failures in the Power Generation Industry," *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, May/June 2018.
15. Michael Liwschitz-Garik, Winding alternating-current machines: a book for winders, repairmen, and designers of electric machines, Van Nostrand Technology & Engineering, 1950.