EXTENDING THE OPERATING LIFE OF CRITICAL HIGH VOLTAGE MOTORS

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Abstract – This paper presents an online partial discharge (PD) trending and data interpretation, related to several similar motors in critical non-spared services. Online partial discharge patterns and trending's were studied to demonstrate if aging conditions were relevant to the motor stator winding. Acquired Phase Resolved Partial Discharge (PRPD) plots were co-related with in-depth stator winding visual inspection which was a collaborative resolution between the Owner, the OEM, and Electrical Motor Services team. A detailed refurbishment and validation test plan was established to reduce surface electrical discharge activity and to extend the in-service life of the motor. A systematic approach with regards to field reconditioning solutions and the life cycle cost reduction was followed and will be explained.

Index Terms — Reliability, online monitoring, stator, insulation system, discharge, end-windings.

I. INTRODUCTION

Crude oil refining can require large rotating machinery to move products and utilities, during the distillation process. In the petroleum industry, utilization of steam as a source of horsepower for rotating equipment drivers has migrated to electric motors. Electric motors have proven to be more reliable and efficient to operate and have a lower life cycle cost. As many facilities have increased refining capacity, the utilization of large electric motors has increased in the installed fleet, with several applications up to 30,000 horsepower. The larger horsepower demand requires the use of high voltage motors and electrical distribution equipment to drive the loads. Applications can range from across the line starting, reactor assisted starting, Variable Frequency Drives, and Load Commutating Inverters.

The drivers are typically installed in a critical service with only one machinery train supporting the process due to the initial cost of the equipment. This design requires a high mechanical availability rate to sustain production as outages have a large impact on loss of production. In refining business, the machinery needs to stay in service until a scheduled outage is planned. In the 1980s and 1990s, run times were from 2-5 years, as we made improvements to our business, run times have increased to 5-10 years in some applications. These extended run times lead to an asset availability for maintenance once at the end of a 10 years run cycle. The maintenance opportunity windows are typically driven by fixed equipment critical path timelines and not the electrical motor maintenance. With opportunities stretched out, it is critical to have a well-defined maintenance scope and execution plan. Discovery work on the large motors can be devastating to the planned outage timeline and cost. Offline testing and evaluation of a high voltage motor winding and a visual inspection alone are conducive to discovery work after an extended in-service life. Removing the motor and reconditioning at each maintenance window is a strategy however, it is costly and may not be necessary. It also can lead to self-inflicted reliability issues with the complexity of removing the motor, transporting it to and from a repair facility and reinstallation.

Routine maintenance on-line monitoring programs are undoubtably a beneficial requirement for large electric motor reliability, especially for non-spared high voltage motors. Vibration analysis and lubricating oil analysis are key programs to have in place to ensure the equipment's rotating components are operating satisfactorily. What about the electrical components? High voltage motors that are in service for long operating intervals without maintenance opportunities, requires us to utilize online diagnostic tools to evaluate the insulation systems health. There are several tools available to analyze a motor circuit online, Current Signature Analysis and Partial Discharge are two widely utilized technologies. We have chosen to standardize on specific manufacturers to have consistent reliable data taken at routine intervals. This has proven to provide enough data points for trends to be valid. Analyzing the data can be confusing and complex, as it normally takes industry experts to assist in analyzing the data and comparing it to similar machinery to understand the health of the equipment. Making a reliability call on an electric motor for a 5-10 year run can be challenging to say the least, as failures are very costly to production and unscheduled maintenance cost. Another commonly asked question is that how many maintenance cycles before we must pull the motor for recondition or rewind? These are the scenario's we are faced with, along with managing life cycle cost of the motor.

In this paper, we will present 3 case scenarios of critical high voltage motors where the online PD assessments indicated a potential concern, how the test data was evaluated, and the development of the repair plans to increase the reliability of the stator windings.

II. PD MEASUREMENTS FOR INSULATION CONDITION ASSESSMENT

To measure online PD magnitudes using high frequency bandwidth, the instrument is used in conjunction with 80 pF couplers installed inside the motor main terminal box. The bandwidth of this arrangement for PD acquisition is 40 to 350 MHz. At motor rated operating conditions, Pulse Height Analysis (PHA) and Pulse Phase Analysis (PPA) plots are recorded. The PHA plot represents a relationship between the pulse magnitude and the pulse repetition rate for both negative and positive polarity PD counters. The horizontal axis is a linear representation of the magnitude of the pulses while the vertical axis is a logarithmic representation of the number of pulses per second. The PD results are presented in terms of NQN, which is total PD activity and Q_M numbers, which is the peak magnitude.

The Q_M is the magnitude of the pulses for one fundamental pulse category that has a repetition rate of 10 pulses per second and corresponds to the peak PD activity. The comparison of positive to negative PD indicates whether the PD is within the insulation, or near to the insulation surface. Similarly, NQN is an indicator of the average condition of the stator winding insulation, which is proportional to the total PD measured by the sensor. The negative NQN refers to the total activity from negative PD pulses, while positive NQN refers to the total PD activity from positive pulses [2]. The monitoring of trend in PD activity over time is the predominant indicator if insulation problems are occurring [3]. PD plots were carefully recorded and studied to determine the possible source of discharges which were later confirmed with extensive visual inspection.

III. CASE SCENARIOS

1. *Case Study A*

TABLE I
MACHINE NAME PLATE

Machine Type	Synchronous
Voltage Rating	13,200 V
Speed	4 pole, 1800 RPM
Enclosure	TEWAC
Horsepower	30,000
Application	Blower/centrifugal compressor

Twin 30,000 HP, 4 Pole, synchronous ,13.2 kV, motors (Blower and Gas Compressor applications) were manufactured for installation in 2004 at a Gulf Coast refinery. Table 1 depicts the motors name plate information. Operationally, these motors are started utilizing a singular Load Commutated Inverter (LCI) and subsequently transferred across the line for normal operation. The subject Blower Motor is then transferred back to the LCI for operational control.

In preparation for a maintenance outage in 2021, online partial discharge (PD) data was thoroughly analyzed. The collected PD on Phase-C was taken on an insensitive scale (200-3200mV). On that scale, a clear positive predominance, Qm+ of 369mV as shown in Fig. 1 was detected providing a good indication of surface PD. Comparing to the other phases, data collected on a 50-850 mV scale would be more precise as shown in Fig 2 and 3. The data collected is just at the edge of what is considered the “high” scale or an indication activity is higher than 90% of similar machines in the available data base. The data collected supported a detailed visual inspection as outlined in the company specifications.

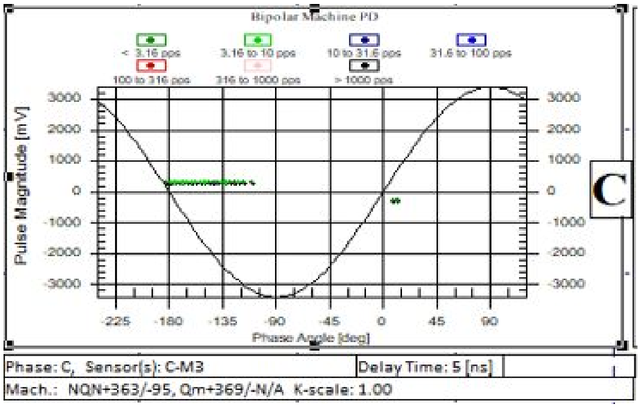


Fig. 1 Positive Predominance Qm+ 369mV

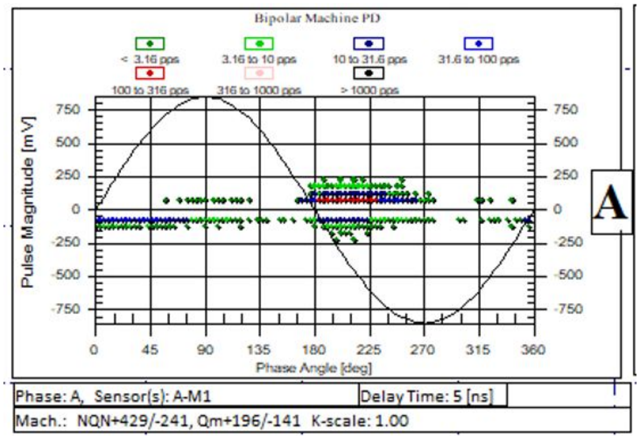


Fig. 2 Phase A PD Plot

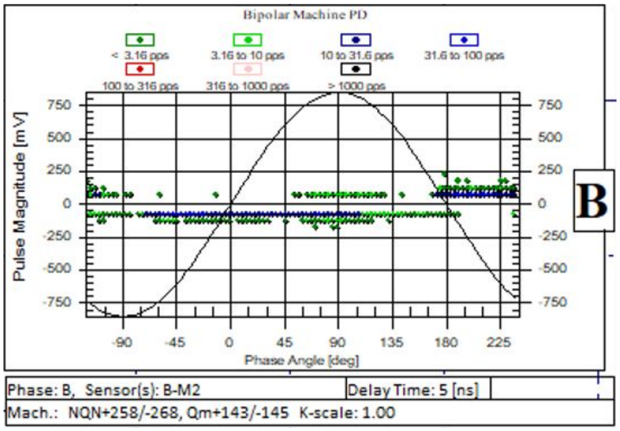


Fig. 3 Phase B PD Plot

During field inspection of the connection end of the winding (motor non-drive end), the rotor pole hardware and accessible V-blocks were all as expected with no indication of excessive heating and all devices were mechanically secure. There was no evidence of movement around coil blockings and all lashings and bracings were intact. A slight dusting was noted on the coils near the stator slots exits, which can contribute to surface discharge activity. Close inspection of the location where the coil exits the stator slot presented evidence of surface discharges as observed in Fig. 4. Signs of external discharges were found on all line lead coils and adjacent coils at the exit of the stator slot which confirmed the online PD analysis results.

Fig. 4 Surface Partial Discharge Activity

During field inspection of the opposite connection end of the winding (motor drive end), the rotor pole hardware caps and accessible V-blocks were all as expected with no indication of excessive heating and all blocking devices were secure. No evidence of movement around coil blocking was observed with all lashing and bracing intact. A Slight dusting was noted on the coils near the stator slots but was irrelevant. Close inspection of the location where the coil exits the stator slot presented evidence of surface discharge as shown in Fig. 5.

Fig. 5 Degradation to Conducting Armor at Slot Exit

Following discussions with the manufacturer, experienced motor service center, and internal electrical specialists, a decision was made to perform corrective actions in the field to extend the life of the winding and allow sufficient time and planning for future corrective action. To address the accessible areas of the stator winding coils that had been impacted by PD activity, a mitigation strategy and rehabilitation process was employed to restore the stress gradient and corona suppression system. The method of rehabilitation consisted of the following repair actions:

1. Protect the rotor using plastic sheet including the accessible shaft extension and secure in place with holding tape. This step protects from accidental dripping paint or resin from stator as shown in Fig. 6.

Fig. 6 Wrap Rotor for Protection

2. Using a flapper wheel or similar abrasive disk gently scuff the bore of the stator and obtain fresh iron on both ends 1” back at the stator core ends slot ends.
3. Fabricate a poke scrubber with ¼ scouring pad and top wedge to construct a coil cleaning bonnet as in Fig. 7.
4. Scrub between all coil extensions as they exit the stator core using alcohol if necessary.

Fig. 7 Tools Used for Cleaning Coils

5. Brush all debris out of the stator core and off coil extensions. Vacuum out remaining fibers and dust as illustrated in Fig. 8.
6. Using clean white rags and denatured alcohol spray bottle to clean coil extensions, circuit rings and lead/bus.
7. Clean stator leads, lead cleat and inside the Junction Box up to incoming service supply power leads.

Fig. 8 Removing Excess Debris

8. Using 4” painters tape - apply 2” back in the bore of the stator on both ends extending around the circumference 360 degrees.

9. Apply 1” painters tape extended 2” past - magnetic finger or finger plate around the circumference of the top and bottom coil extensions per Fig. 9.

Fig. 9 Painters Tape Applied

10. Mix Semi-Conductor (semi-con) paint (Black color paint) generously and apply around top and bottom coils extensions
11. Apply semi-con paint between painters tape in the bore of stator core and extending out on coil arm as shown in Fig. 10.
12. Allow Semi-Con paint to cure and remove painters tape on the coil extension and from the bore of the stator.

Fig. 10 Semi-con Paint Application

13. Using 1”painters tape apply around circumference of semi-con leaving 1 to 1-1/4” of exposed, semi-conductor paint.
14. Extend 6” out and apply second layer of 1” painters tape around the circumference of top and bottom coils as shown in Fig. 11.
15. Mix stress gradient paint (Gray color paint) generously and apply two layers between taped regions on the coil extension as illustrated in FIg 12.
16. Note: Apply first layer and allow it to dry before applying second layer.
17. Remove painters tape after gradient paint is cured.

Fig. 11 Painters Tape Applied for Gradient Paint

Fig. 12 Gradient Paint Layer Applied

18. Mix two-part epoxy and apply two layers using a compressed air syphon sprayer.
19. Apply first layer over coil extensions on both ends and circuit rings on the connection end of the stator core as shown in Fig. 13.
20. Apply second layer over coil extensions on both ends and circuit rings on the connection end of the stator core.
21. Allow two-part overcoat layers to cure as shown in Fig 14.

Fig. 13 Application of Two-part Epoxy

Note: Supplemental heat may be required.

Fig. 14 Drying of Two-part Epoxy

22. Apply clear RTV or silicon between top and bottom coil extensions filling the gap between them as visible in Fig. 15.
23. Fill with room temperature vulcanizing (RTV) or silicone the region extending from the point coil they exit the stator until they cross and extend out. Two applications may be required to completely fill the region depending on spacing between the coils.

Fig. 15 Application of Silicone

24. Due to the high PD activity in line lead coils and no evidence of surface discharge on neutral leads, it was strongly recommended to swap the neutral wye connections with the line leads in the junction box.
25. The existing bus work configuration may require modification to accommodate this swap in connections as illustrated in Fig. 16.

Upon return to service, online partial discharge testing was performed to validate successful completion of the field work. When compared to the database of similar windings, the updated statistical ranking became negligible and stable [1]. The results suggest success with the field recondition work and most importantly, the swap of neutral connections with line leads in the main terminal box should continue to provide reliable service until the next major outage planned in 5 to 7 years.

Fig. 16 Bus Work Redesign to Swap Connections

2. *Case Study B*

TABLE II
MACHINE NAME PLATE

Machine Type	Synchronous
Voltage Rating	13,200 V
Speed	4 pole, 1800 RPM
Enclosure	TEWAC
Horsepower	30,000
Application	Blower/centrifugal compressor

A 30,000 HP, 4-Pole, synchronous,13.2 kV, motor was installed in 2008 at a Gulf Coast refinery. Table II depicts the motor name plate information. The process condition during its service life was fluctuating which caused several operational cycling and extended acceleration times during certain starting conditions. In 2014, the motor was shut down for offline testing and inspection, with no notable findings. Planning for a 2017 outage, the motor's operational conditions were evaluated, and the motor had slightly elevated vibration trends and an increasing upward PD trend, but the amplitudes of PD were not high enough to flag a concern. A plan was created for the next maintenance window in 2017 to perform a visual inspection and perform offline electrical testing. During the visual inspection, excessive heating was discovered on the rotor poles, and some degradation of the insulation system at the slot exit areas were noticed. Motor winding conditions are reflected in Fig. 17.

At this time the stator insulation system degradation was not fully understood, and the areas of concern were top coated with an epoxy resin.

Fig. 17 Stator Winding at Slot Exit Locations (continued)

Fig. 17 Stator Winding at Slot Exit Locations

Over the next couple of years, the machine experienced several starts and stops, while monitoring the operational conditions of the motor through online mechanical analysis and PD testing During the analysis an increasing mechanical vibration was noted. The online PD levels magnitudes were closely evaluated and found to be low in magnitude with an increasing trend over time as shown in Fig. 18, PD trending and Fig 19 PDPR Plots for each phase. A plan was developed for the next maintenance opportunity to remove the motor from service and replace it with a spare motor due to the increased heating on the rotor and increasing vibration trends, the PD trend was not a concern at this time.

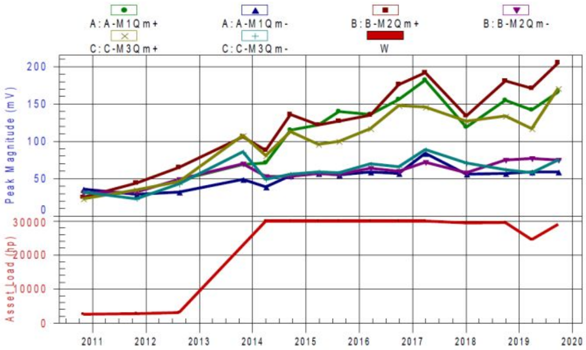


Fig. 18 Online PD Trending

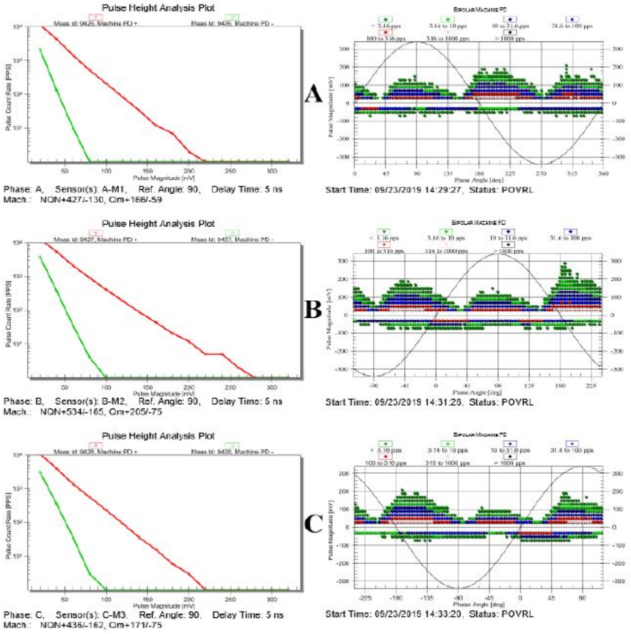


Fig. 19 Individual Phases PRPD Plots

In 2020, the motor was removed from service during a maintenance window and sent to a repair facility with the major scope of work being focused on the rotor rebuild and a stator recondition. The motor stator passed all initial incoming electrical test and was disassembled, and the rotor removed. The stator was cleaned and successfully passed all electrical diagnostic test. A detailed visual inspection was performed and showed major concerns with multiple areas of insulation degradation at the slot exit and the stress gradient to suppression tape joint, Fig. 20 Stator Slot Exit. The locations of the damaged areas were on the connection end of the coils for the first couple of turns.

Fig. 20 (continued)

Fig. 20 Loss of Conducting Armor at Slot Exit Locations

A diagnostic test plan was developed from our motor repair procedures and the OEM, based on IEEE guidelines to fully test the stators insulation system. The test plan included:

- Visual Inspection
- Stator test per IEEE 43
    - Insulation resistance test, 5000 Vdc, 1minute
    - Polarization Index "PI" test, 5000 Vdc, 10 minute/1 minute
    - Phase resistance check
- Phase inductance
- Capacitive and Dissipation Factor test per IEEE 286
- Offline PD per IEEE 1434 and IEC 60034-27-1
- Corona Probe test of slot area per IEEE 1434
- Corona Camera test per IEEE 1799
- Surge Test per IEEE 522
- AC high Pot per IEEE Std 4
    - Test at 60% 0f 2E+1 (17.2 kV)
    - Test at 65% of 2E+1 (18.6 kV)
- Corona inspection was performed during test and was visual on several coils and increased with voltage steps
- Insulation Resistance per IEEE 43
- Polarization Index at 5000 vdc
- AC High pot at 75% of 2E+1 (21.5 kV)
- DC High pot per at 30 kV IEEE 95
- Insulation Resistance per IEEE 43
- Polarization Index

The diagnostic test results and visual inspection report was reviewed to make decision on the repair scope. The windings successfully passed the electrical testing; however, the offline PD test confirmed surface activity, Fig. 21. And in Fig. 22. The degradation of the insulation system was discussed thoroughly with the OEM for the best viable technical solution.

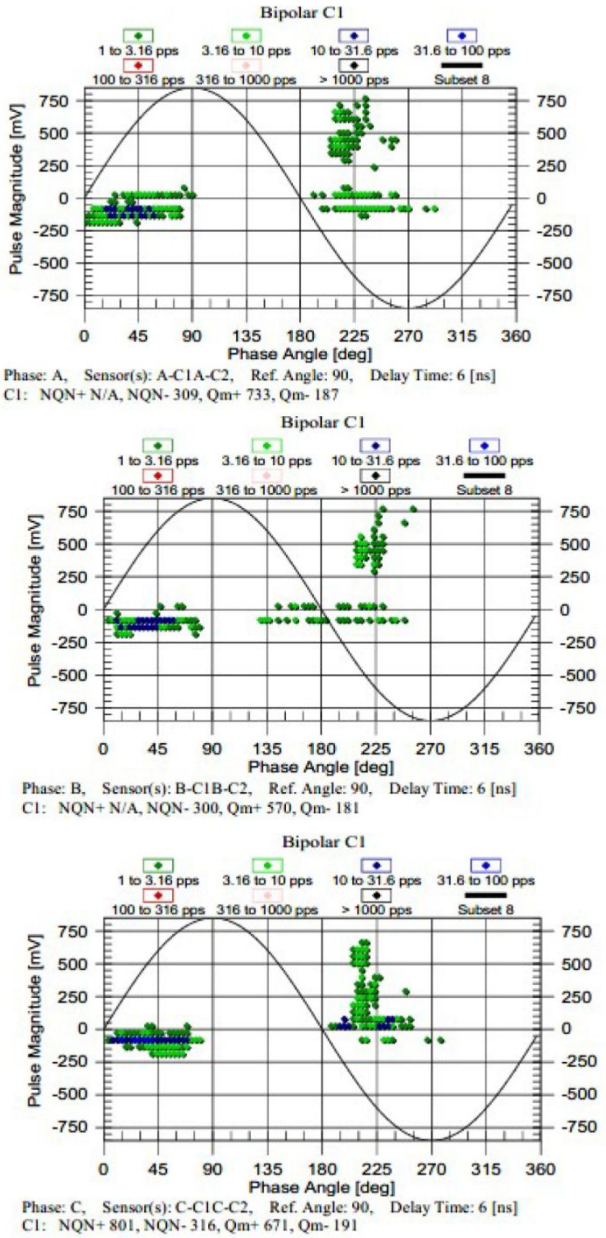


Fig. 21 Offline Partial Discharge Test at 9.6 kV

Fig. 22 Observation of Visual Corona

As mentioned previously, the machine has seen excessive starts and stops with an increasing mechanical vibration while in-service. The combination of mechanical and thermal stresses and the thermal growth of the stator coils in the axial direction could have resulted in cracks to both end windings and in the corona suppression system especially, at the stator slot exit locations. Presence of micro-cracks in the line lead coils and a slow degradation of conducting armor while the machine is in-service can be expected due to presence of higher electrical stress. With the online PD trends and the visual confirmation of armor deterioration at the slot exits an upward trend would be expected over the next 10-20 years of service.

The decision was made to perform a complete rewind of the stator based on the criticality of the services, the condition of the insulation system and the rotating element was being rebuilt. Since the decision was made to rewind the stator, we used this opportunity to perform additional testing to better understand the insulation systems condition by allowing us to test to failure. Working with the OEM we developed a comprehensive destructive test plan. The test plan included elevated AC high pot voltages per IEEE Std 4. If during the test a flashover would occur or the test set would trip, the stator would be discharged, and a visual inspection performed to investigate a damaged area. If the test was successful, the next voltage level test would be performed. The test plan was as follows:

- AC Hipot per IEEE Std 4 2E+1 28.6 kV for 1 minute per phase with the other phases grounded

Passed with no flash over

- Insulation Resistance at 5000 Vdc
- AC Hipot at 30 kV for 1 minute per IEEE std 4

Passed with no flash over

- AC Hipot 35 kV for 1 minute

Passed with no flash over

- AC Hipot at 37.5 kV - Passed with no flashover

The stator ground wall insulation was found to be acceptable and in very good condition during AC hipot test with no failure up to 37.5 kVrms, which is almost 31% above the 2E+1 (28.6 kVrms) AC hipot level. However, upon completion of the test, it was concluded that the insulation system was not degraded or destroyed but high levels of PD was noted on the surface of the windings. No further tests were performed. This testing helped us understand that while the insulation system was experiencing surface PD activity, the winding insulation system demonstrated high dielectric strength capabilities.

3. *Case Study C*

TABLE III
MACHINE NAME PLATE

Machine Type	Synchronous
Voltage Rating	13,200 V
Speed	4 pole, 1800 RPM
Enclosure	TEWAC
Horsepower	30,000
Application	Blower/centrifugal compressor

A 30,000 hp, 4 pole, synchronous,13.2 kV, motor was installed in 2004 at one of our refineries. Table III depicts the motor nameplate information. Its service was an un-spared blower application which was in service continuously for 10 years. In 2014, during a unit outage the motor was inspected and electrically tested. The winding passed the offline testing and inspection with no noteworthy findings. The equipment was placed back in service with the expectation of an additional 10 years of service. During its operation routine monitoring of the machine vibration and on-line partial discharge was performed. While planning for an outage in 2021, the operational parameters were reviewed closely, and a plan was developed to perform offline electrical testing and a visual inspection. The online PD data had been trending upward, reference Figs. 23 & 24. A plan was developed to perform a detailed inspection of the windings, paying close attention to the slot exit and corona suppression to stress gradient joint.

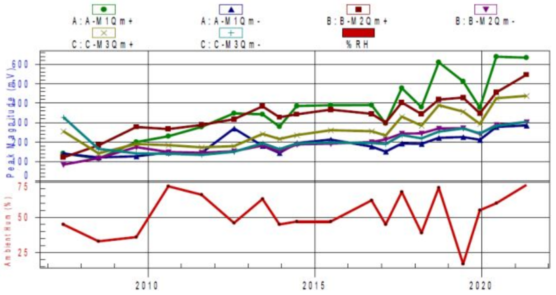
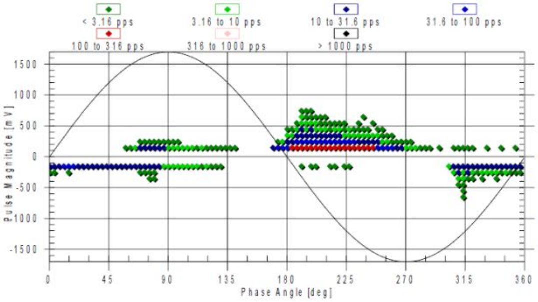
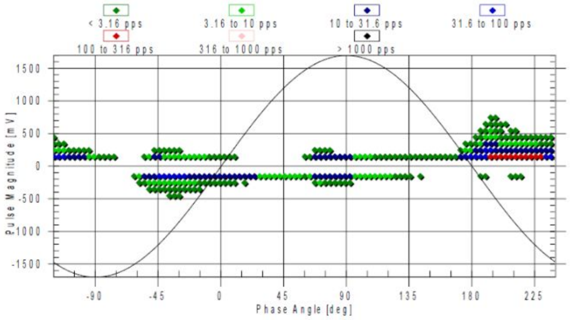


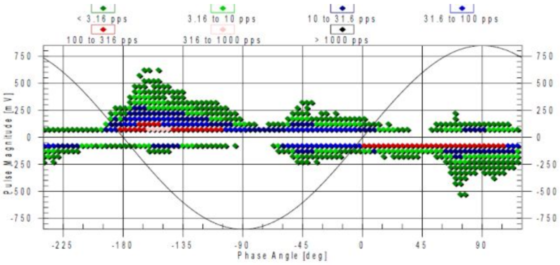
Fig. 23 Online PD Trends



Phase: A, Sensor(s): A-M1, Delay 5ns, Status OK
Machine: NQN+: 1427, NQN-: 517, Qm+: 635, Qm-: 286



Phase: B, Sensor(s): B-M2, Delay 5ns, Status OK
Machine: NQN+: 1189, NQN-: 629, Qm+: 547, Qm-: 303



Phase: C, Sensor(s): C-M3, Delay 5ns, Status OK
Machine: NQN+: 1072, NQN-: 705, Qm+: 438, Qm-: 304

Fig. 24 Online PD Plots

There were three areas of concerns found during the visual inspection (see Fig. 25 example), all of which were on line lead coils in the connection end of the stator winding. The areas were cleaned, and field repairs performed as shown in Fig. 26.

Fig. 25 Line-end Coil Showing Loss of Conducting Armor

Fig. 26 Restoration of Corona Suppression System

The winding Line and Neutral connections were switched to reduce the voltage stress on the coils, allowing T4, T5, and T6 to become the line leads and T1, T2, and T3 to be terminated at the neutral bus (see Fig. 27). Follow up online PD testing will be performed to evaluate the effectiveness of the repairs.

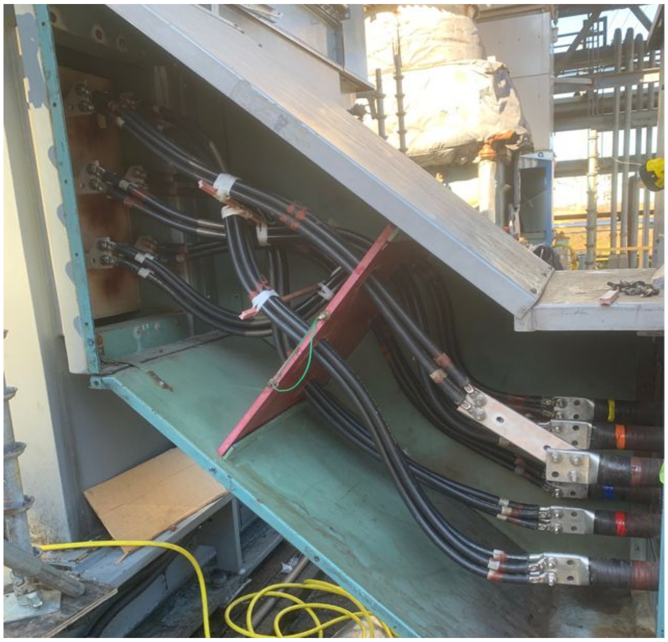


Fig. 27 Switching of Line and Neutral Ends

IV. CONCLUSION

To ensure a long reliable life for a critical high voltage motor, online testing of mechanical and electrical components, offline electrical testing, and detailed visual inspections are crucial. These inspections and testing results aid in the development of an applicable repair plan to leverage extended life strategies when maintenance opportunities are available. Understanding the test results and reviewing your assets condition reports when developing maintenance work scope for planned outages is vital to ensure an applicable rehabilitation scope is identified and funding for the repair budget is allocated. Discovery work scope identified during an inspection can be very costly and impact the outage budgets and timelines. Repairs in the field can successfully minimize insulation system deterioration due to surface partial discharge activity.

Switching the electrical stresses on the coil windings by swapping the line and neutral connections is a key task. The highest phase voltage stress occurs on the line lead coils and steps down to neutral potential equivalently based on the number of coils per group. By connecting the original line coils to the neutral star point of the winding reduces their operating voltage stress to the neutral potential. Swapping the neutral coils with the line leads effectively reverses the voltage stress approaching the original dielectric integrity of the winding. The opportunity to perform diagnostic testing on an insulation system that had known PD concerns, provided evidence that the insulation system's dielectric integrity was still intact which increased our confidence of the field repairs. Predictive maintenance programs, detailed inspections and testing plans, and a strategy to make field repairs based on predictive data, aid in extending the life of critical high voltage motors. It is necessary to understand that life extension may not be possible on every critical machine depending on the observed level of insulation system degradation. Therefore, combination of several offline and online diagnostic tests, detailed visual inspections, and a careful review by an expert and or the OEM to validate the suitability of machine for continuous reliable operation should be considered.

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VI. VITAE

Terry Perilloux has hours of education towards an Associate Degree in Electronic Engineering Technology with a certificate of completion in EET. Terry has numerous hours of accredited training in the electrical field. He has worked in the electrical field since 1985 where he began his electrical career in power generation, which he spent 4 years operating and maintaining electrical generators. In 1989, Terry was employed by Marathon Petroleum Company as an industrial maintenance electrician. In 2001 he transitioned into electrical supervision for the site, where he served in several technical and supervisory positions. In 2018 he was assigned a Corporate Electrical Specialist role for mid-stream assets, then in 2020 he transferred back to refining serving as a Corporate Electrical Equipment Specialist. Terry participates on the IEEE ESW committee as the co-chair of tutorials and is currently NFPA Certified Electrical Safety Compliance Professional “CESCP”. He has co-authored one technical paper previously.

Keith Lyles, CMRP received his B.Sc. degree in Accounting from Auburn University in 1992. Following graduation, he served as a Nuclear Machinist Mate in the US Navy. Keith is an Electrical Advisor for Marathon Petroleum’s Galveston Bay Refinery. He has been fortunate during his career to hold progressive, electrical reliability positions within Reliance Electric-Baldor-Integrated Power Services, BP, Praxair-Linde, and Marathon Petroleum. Keith actively participates as a member of the API 541, 546, 547 committees and is currently Chair of the IEEE PCIC Chemical Technical Subcommittee. He became a Certified Maintenance and Reliability Professional (CMRP) in 2008 and is a member of IEEE. He has co-authored multiple PCIC technical papers.

Saeed Ul Haq (M’00) received his B.Sc. degree in Electrical Engineering from UET, Peshawar, Pakistan, in 1991, M.A.Sc. degree from the University of Windsor, Windsor, ON, Canada, in 2001, and his Ph.D. degree from the University of Waterloo, Waterloo, ON, in 2007. During his Ph.D. program, his main research interest was to study the insulation problems in drive-fed medium-voltage motors. Dr. Haq is a registered Professional Engineer in the Province of Ontario, Canada. In the past, he was involved in extensive volunteer work for the IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP) and International Symposium on Electrical Insulation. In 2007, he joined the GE Large Motors & Generators Technology team at Peterborough, Ontario, Canada, as an Insulation Engineer. His area of interest is in the development of insulation systems for large rotating electric machines. Dr. Haq has authored or coauthored 100+ technical papers.

Tom Reid received his B.Sc. degree in Electrical Engineering from Mississippi State University in 1985. During his career with Reliance Electric, he was responsible for the design, development and testing of next generation small and medium AC motors. He also completed significant work with insulation systems earning five patents and six meritorious disclosures. During his career with Integrated Power Services, he has continued his research to develop insulation system technologies. He has extensive experience performing failure analysis for motors and generators. He has published numerous papers for the Electric Power Research Institute and Large Electric Motors Users Group. He has specific subject matter expertise with identification and mitigation strategies for partial discharge in high voltage motors and generators.