

RECENT PROBLEMS EXPERIENCED WITH MOTOR AND GENERATOR WINDINGS

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G.C. Stone
Fellow, IEEE
Iris Power LP
3110 American Drive
Mississauga, ON
L4V 1T2
Canada
gstone@irispower.com

M. Sasic
Senior Member, IEEE
Iris Power LP
3110 American Drive
Mississauga, ON
L4V 1T2
Canada
msasic@irispower.com

D. Dunn
Senior Member, IEEE
Aramco Services
9009 West Loop
Houston, Texas
77210
USA
Donald.Dunn@ieee.org

I. Culbert
Senior Member IEEE
Iris Power LP
3110 American Drive
Mississauga, ON
L4V 1T2
Canada
iculbert@irispower.com

Abstract - In many respects, large motors and generators in petrochemical plants have become a commodity product with intense competition amongst manufacturers from around the world to secure orders. This has resulted in pressure on machine designers to reduce manufacturing costs. Some of the methods employed to accomplish this include:

- Reducing the conductor cross section
- Reducing the insulation thickness
- Reducing the amount of steel core material
- Developing manufacturing methods that result in less time to manufacture.

Each of these methods tends to increase the operating temperature of the windings or put additional voltage stress on the electrical insulation. Many design and processing innovations have been successfully implemented. However, there are both anecdotal and statistical data that indicates that there are more problems with machines made in the past 10 years, as compared to machines made previously. Engineering firms and end-users perhaps need to provide comprehensive, yet reasonable, purchase specifications that allow all manufacturers to compete on a level playing field. This paper is mainly concerned with stator windings rated greater than 6 kV, and rotors of various sized machines.

Index Terms - Motor, Generator, Winding failure, rotor winding, stator winding, electrical insulation

I. INTRODUCTION

In the past decade or so, the motor and generator business has truly become global. Today, it is rare that a company will buy a machine from a local manufacturer, just because the machine is made nearby. Instead, many machine manufacturers from around the world are commonly put on a bidder's list. Since a significant portion of the cost of a new machine does involve labor costs, manufacturers based in high labor cost countries are most likely disadvantaged competing with low labor cost countries. There are three alternatives for the manufacturer:

- Establish a manufacturing operation in a low labor cost country

- Use advanced engineering insight to reduce the cost of the materials used in the machine
- Develop faster production methods that use less labor.

Sometimes all or combinations of these approaches may be utilized.

There tends to be some consequences in reducing the materials within the machine. Reducing the conductor cross section in a stator or rotor winding will normally increase the resistance of the winding, and hence increase the I^2R losses and thus increase the winding temperature. Similarly, reducing the amount of laminated steel in the stator or rotor cores for example by reducing the diameter will increase the core losses, again increasing operating temperature. Shortening of the endwinding in the stator windings will reduce the material usage and have the benefit of reducing the likelihood of endwinding vibration –but the electrical stress over the endwinding surface will be increased making the stator more prone to electrical tracking if contamination is present. Another popular measure to reduce cost is to reduce the groundwall insulation thickness of the stator winding [1]. The stator turn insulation can also be made from fewer layers or thinner tapes, which may increase the risk of failure due to voltage transients due to motor switch-on or inverters. Finally, the global vacuum pressure impregnation (GVPI) process (where the coils are all impregnated with epoxy at the same time in the stator) is being applied to ever-larger machines since this will beneficially reduce the amount of time and labor to make the stator compared to conventional machines (where the coils are first individually impregnated with epoxy and then inserted into the stator). However the GVPI process can make it more difficult to detect manufacturing problems since only the entire stator, and not individual coils, can be tested after impregnation.

As an example, in the last century, the desire to reduce material usage has resulted in a 14-fold increase in the electric motor watts per kilogram ratio. On average, in 1962, the ratio was 86 W/kg, and in 1995 it was 335 W/kg (Fig. 1).

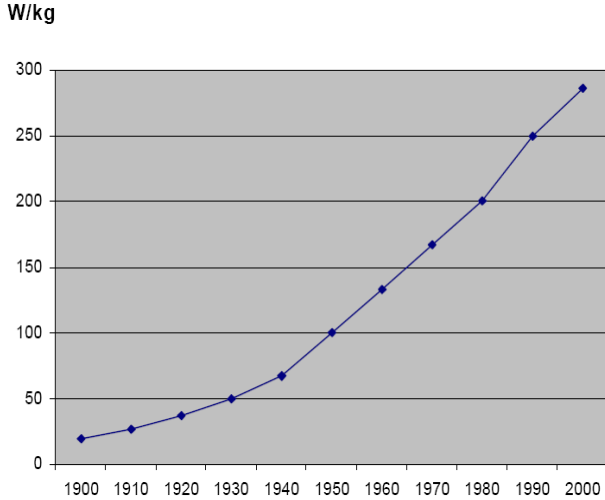


Fig. 1: Motor output per unit mass as a function of production year [2].

All of these measures, while allowing a manufacturer to be more cost competitive, may lead to some unintended consequences such as reduced motor and generator winding life. In addition, other application-related issues may also reduce winding life. It has long been known that weather protected motors may be more subject to problems due to winding contamination than totally enclosed motors. Also, conventional motors are sometimes being supplied from voltage-source converters that may shorten life [3,4].

In the past Maughan and Bonnett have published papers on problems with stator and rotor windings [5,6]. This paper continues this tradition by reviewing recent failures and “near” failures that may have occurred as a result of higher design stresses and new processing techniques. Although by nature, the examples shown below are anecdotal, and it is not possible to establish if there is a trend or not based on them, some more objective data on stator winding condition of modern machines is now available. This data is presented to show that perhaps the above design and manufacturing trends are having some effect on machine reliability.

II. PARTIAL DISCHARGE LEVELS AS A FUNCTION OF MANUFACTURING DATE

As part of the analysis of on-line partial discharge (PD) data performed on thousands of motors and generators, it has been noted that stators made by some manufacturers in the past decade have much higher PD than stators made by the same manufacturer more than 10 years ago [7]. For example, Fig. 2 shows the peak PD activity vs. winding manufacturing date for 9 of the world’s largest manufacturers of air-cooled motors and generators rated from 13-15 kV. This figure shows that for on-line PD readings measured in 2003, four manufacturers are exhibiting much higher PD on recently made stators, than they typically experienced on their machines made before 1995. Since high PD can be often associated with rapid aging of the stator winding insulation system, the high PD in recently-manufactured stators is of concern.

III. STATOR WINDING PROBLEMS

A. Electric Stress Control Coating Problems

Most stator windings rated greater than 6 kV employ a graphite-loaded paint or tape on the surface of the coils in the slot [8]. This ‘semicon’ coating prevents PD between the surface of the coil and the stator core in any small air gap that inevitably exists at this interface. In addition, most manufacturers use a silicon carbide-loaded paint or tape on the coil for 10 cm or so outside of the slot. This silicon carbide coating overlaps the semicon coating, and reduces the high electric field that would otherwise exist at the end of the semicon coatings.

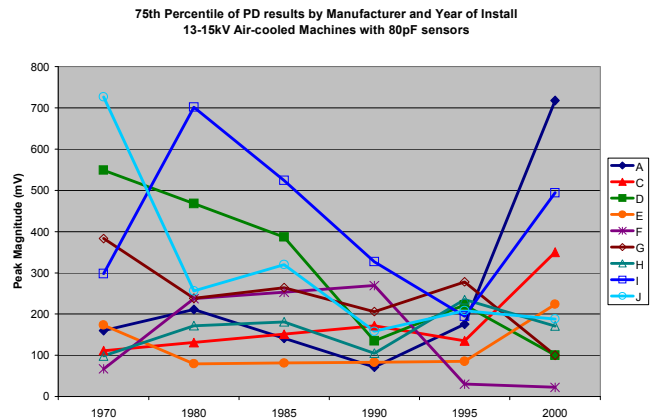


Fig. 2: PD for 9 manufacturers versus year of stator manufacture.

In the 1970s, there were a number of machines that exhibited very high PD and high ozone concentrations from either or both coatings that were caused by manufacturing problems. The problems seemed to originate from coatings where the carbon and/or silicon carbide was non-uniformly dispersed in the insulation matrix or where the application method resulted in microvoids just under the coating. In both cases the result was PD. This high PD created ozone that chemically attacked the insulation (not to mention the heat exchanger metal and rubber components) and the properly made areas of the coatings, resulting in the spread of the problem. This problem seems to be worse if the winding insulation operates at higher electric stress and/or higher temperature. Perhaps it is for this reason that there seems to be a recurrence of this problem in the past few years.

Fig. 3 shows a turbine generator stator where a very noticeable white band is visible at the junction of the semicon coating and the silicon carbide coating. Fig. 4 shows a winding where the semicon has virtually disappeared in the slot due to poor application of the semicon coating. This will normally only occur in air-cooled machines rated 11 kV and above. However, the introduction of voltage source converter drives has shown that these problems can occur on motors 3.3 kV and above [3,4]

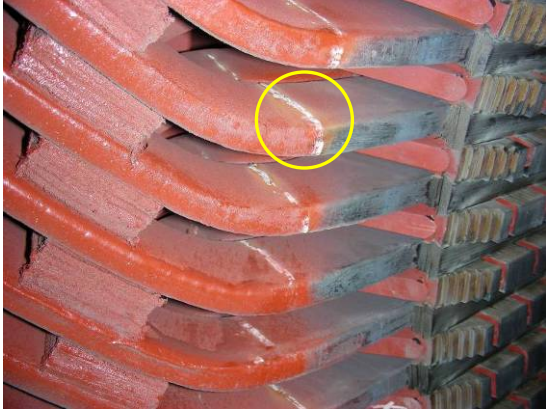


Fig. 3: Semicon and and grading coating overlap deterioration.



Fig. 5: Bar abrasion due to loose windings in the slot of a turbo generator.



Fig. 4: Destruction of the coil semicon coating in the stator slot due to PD and ozone.

B. Loose Coils in The Slot

Coil vibration in the slot has long been a problem in all non-global VPI stators made with thermoset insulation systems such as epoxy mica. The first instances were reported over 50 years ago [5,8]. The root cause of the problem is that at full load, the twice power frequency magnetic forces will vibrate the coils if the coils are not tightly held in the slot. Consequently, the groundwall insulation rubs against the laminated steel core – a very abrasive surface. First the semicon layer of the bar or coil is abraded away, and then the groundwall insulation. The mechanism is sometimes referred to as slot discharge, because once the semicon coating is abraded, partial discharges occur between the coil surface and the core, further increasing the rate of deterioration.

Fig. 5 shows a bar in the process of being removed from a stator where the semicon and about 30% of the groundwall thickness has been abraded away. The manufacturer had not mechanically secured the coils in the slots by means such as sidepacking, ripple springs, two part wedges, conformable restraint in the slots, etc.

Normally one would not expect loose coils to be a problem in a global VPI stator, since the coils are effectively glued to the stator core. However, if the coils are made too small for the slot, and are subjected to load cycling that creates shear stresses between the coils and the stator core, then loose coils and slot discharge may occur in some designs (Fig. 6).

C. Vibration Sparking

A problem similar to loose coils in the slot is called vibration sparking (or sometimes spark erosion). For vibration sparking to occur, the coil must be loose in the slot (and thus be conventional winding rather than being GVPI). However, a manufacturer must also make the semicon in the slot too-conductive [9]. Essentially, if the coil can vibrate in the slot, an area along the coil surface may become isolated from the core. A current loop can then be created between the semicon on the coil surface, the steel laminations and the key bars at the back of the core. If the semicon is conductive enough, current will flow through this loop due to the main magnetic field in the core. When the coil vibration causes the semicon to lose contact with the core, the current is interrupted and a spark is created that can be damaging to the coil insulation. Vibration sparking therefore requires two design or manufacturing errors. Although this problem is most likely on generators, in the 1970s it was noted on some motors in the UK [9].

This failure process can be very aggressive, resulting in failure in as short as about 5 years. Although most manufacturers are careful to make the semicon have a minimum resistance, there is a set of turbine generators made in the past 10 years where the material is too conductive, and failures are occurring (Fig. 7). Vibration sparking is driven by the magnetic flux, and thus damage can occur anywhere within the winding, unlike the slot discharge process described above which can only occur near the phase terminals.



Fig. 6: Damaged bar surface due to loose coils in GVPI stator.



Fig. 8 PD occurring between high voltage coils in two different phases.



Fig. 7: A neutral end stator bar damaged by vibration sparking.

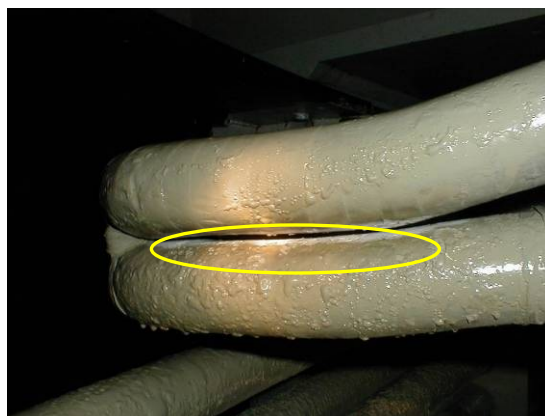


Fig. 9 PD between circuit ring busses that are too close together.

D. Endwinding PD

Coils operating at high voltage and placed adjacent to other high voltage coils in another phase require a minimum separation to avoid PD in the air space between coils. This PD will gradually erode the groundwall insulation and may lead to phase-to-phase stator failure. The higher the voltage class of the machine and the thinner the groundwall insulation, the greater must be the spacing [1,8].

Unfortunately, in many motors and generators rated 6 kV and above, we have noted inadequate spacing, and consequently high PD (and ozone). Fig. 8 shows the white residue caused by ozone resulting from PD between two coils in different phases that were installed too close to one-another. Fig. 9 shows the same issue, but between two circuit ring busses that are in different phases. Fig. 10 shows the PD between the grounded pressure finger at the end of the core and the side of a coil where the manufacturer did not extend the semicon stress relief coating far enough into the endwinding. This resulted in a high electric stress between a line end coil and the pressure finger, and hence PD and ozone. In all three cases of inadequate spacing, the failure process is purely by PD and ozone attack, which are slow processes if the insulation is composed of epoxy mica. However, if such PD occurred between phase leads in the motor terminal box, failure could occur much sooner since such leads often have only rubber insulation, which is much less resistant to PD attack.



Fig. 10: PD occurring between a core pressure finger and a high voltage coil.

E. Endwinding Vibration

A well known problem that seems to be happening more and more frequently during the past 10 years is caused by inadequate support of the coils in the endwinding area. The current flowing in the coils gives rise to a 120 Hz magnetically induced vibrational force, just as can occur in the slot, with the force being proportional to the current squared. During motor starting, there is a 36 times higher magnetic force between the coils in the endwinding. If the blocking and bracing in the endwinding has not been designed well enough to withstand the starting forces, the coils may become a little loose. Under normal operating conditions, these slightly loose coils will begin to move (also at 120 Hz). The relative movement between the coils and support rings and at the blocking between coils leads to fretting of the insulation and a characteristic white powder (Fig. 11). Note that this white powder is not the same as the one that occurs from PD (Fig. 8-10). Powder due to fretting can occur anywhere the coils are loose, including the neutral-end coils. Powder due to PD will only occur on coils at or near the phase terminals.

If the fretting problem is not corrected, then eventually the insulation will be abraded down to the copper, at which point there is a high risk of a ground fault.



Fig 11: White powder due to fretting at interfaces caused by endwinding vibration.

IV. STATOR CORE PROBLEMS

Stator cores are made of thin laminated sheets of magnetic steel, each insulated on its surface, to prevent circulation of eddy currents through the stator core. In the case of damage to this inter-laminar insulation, eddy currents will start to flow in the same direction as stator coils, leading to increased losses and heating of the stator core. Therefore, it is important that the inter-laminar insulation remains intact during manufacture, operation and refurbishment of the stators.

Core problems can be created during the design or manufacturing of the core, as well as in operation and during the rewinding process. To weaken the bond of coils to the stator core in global VPI motors, stators are placed in ovens and heated. The coil pullout force required to remove an old stator winding decreases significantly with an increase in heating time and temperature. If a critical temperature is exceeded, weaknesses in inter-laminar insulation can be introduced and may result in

higher core losses, increased operating temperature and shorter remaining stator core life.

Generators used in industrial environments tend to be, due to their smaller size and fewer units installed within the plant, somewhat less protected compared to larger units within utilities. As a consequence, such machines might experience different operational events more frequently. One particularly dangerous event is over fluxing of the core. It can be defined as excessive excitation for the operational speed of the unit, which can take place with the unit synchronized or not. In a non-synchronized regime, two scenarios are most likely: tripping of generator from full load without timely tripping of excitation system and attempts to excite the machine with inaccurate voltage information coming from the potential transformer due to poor connections. A single over fluxing damage can be small, but cumulative effects of subsequent over fluxing events may result in an electrical core failure.

Fig. 12 indicates one such failure, on a 13.8 kV, 40 MW air cooled generator installed in an industrial power plant.

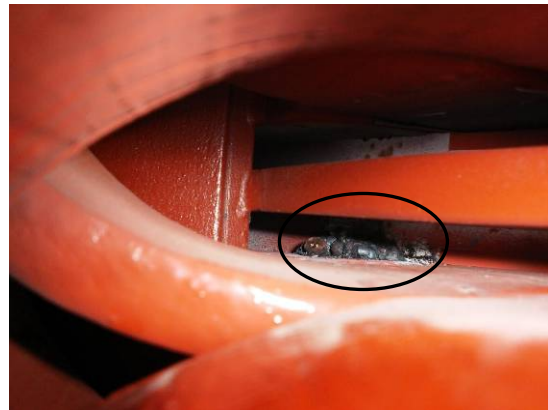


Fig. 12. Melted stator core as a result of over fluxing events.

In spite of the very high temperature that melted the core, the stator bar insulation did not fail, and there was no indication of this problem. The melted core was discovered during low-power (electromagnetic core imperfection detector -EICid) core test, conducted during regular maintenance.

V. ROTOR WINDING PROBLEMS

Rotor winding problems are often a function of the rotor design, poor manufacture, and/or misapplication. The most common rotor winding types are:

- Induction motor squirrel-cage rotor windings
- Synchronous motor and generator salient pole field windings
- Turbine generator round rotor field windings

A. Induction Motor Squirrel-Cage Rotor Windings

The major causes of rotor cage winding failures are breaks in the winding structure and these are mainly dependent on the type of cage winding construction used. In the larger induction motor rotors, the windings are fabricated copper, copper alloy or

aluminum. In smaller rotors, the windings are often cast aluminum.

In this type of winding the ends of the bars and shorting rings are outside the core and therefore subjected to increased stresses from both thermal and mechanical forces during every start if it is direct-on-line. These stresses are higher if the driven equipment has a high inertia since the thermal stresses are much greater due to the fact that the high starting current is present in the rotor winding for a much longer time. If these stresses are high enough, bar (Figure 13), shorting ring (Figure 14), brazed joint or welded joint breaks will result from frequent motor starting. Fabricated aluminum rotor windings are more susceptible to failure from this cause, especially for high inertia drive applications. This is because the mechanical properties of aluminum are poorer at higher temperatures, which can be a few hundred °C at the tops of the bars. In addition, aluminum has a lower thermal conductivity than copper which further contributes to higher endwinding temperatures during starting. However, fabricated copper/copper alloy windings can also fail from this phenomenon. Figure 15 shows the cross-section of the rotor slots in a cast aluminum rotor that clearly has voids due to poor casting. Such voids can produce the same effects as cracked or broken bars on motor performance [6].



Fig. 13: Damage to an induction motor rotor core due to loose bars in the slot.

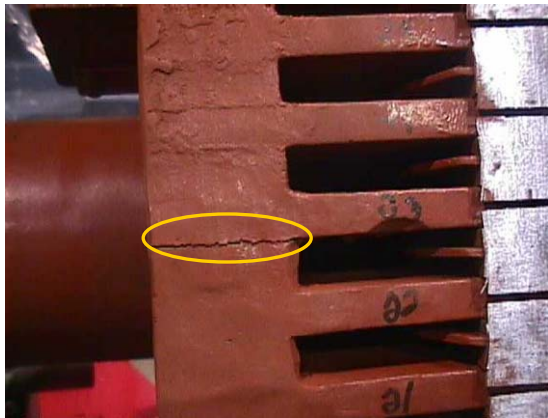


Fig. 14: Cracked short circuit ring.

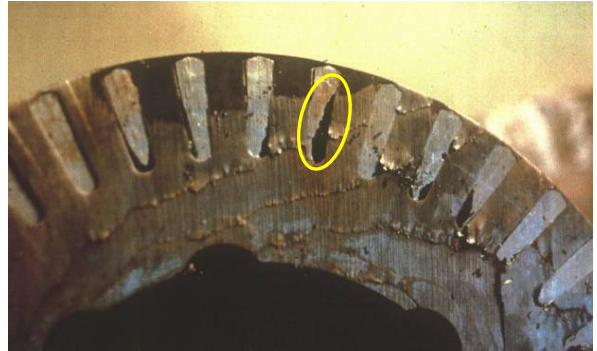


Fig. 15: Voids in a cast aluminum rotor bars in rotor slots due to poor manufacturing.

B. Synchronous Motor And Generator Salient Pole Windings

There are two types of windings used in salient pole rotors. These are the "strip-on-edge" and "multi-layer wire wound" types [8]. Like stator winding insulation, the insulation in salient pole windings can degrade due to thermal deterioration or thermal cycling. Among the most common causes of failure in salient pole rotor windings are the continuous centrifugal forces imposed on them by rotation and the cyclic centrifugal forces induced by starting and stopping. It is therefore important that all components of the insulation system have adequate mechanical properties to maintain their integrity under such forces.

The radial and tangential centrifugal forces imposed on rotor winding insulation system components tend to distort the coil conductors, inter-coil connections and crack the coil insulation if they are not adequately braced. Fig. 16 gives an example of a top pole washer that failed under such forces.

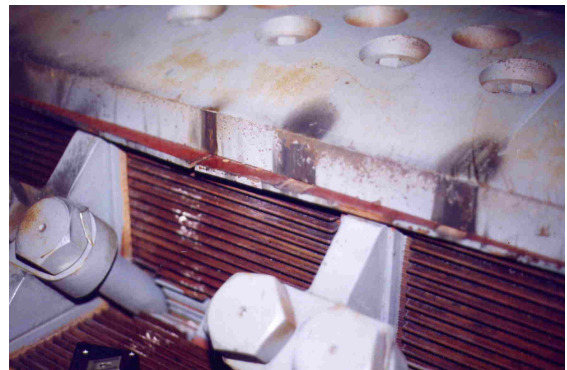


Fig. 16: Top pole washer failure from mechanical forces.

If the pole winding bracing is inadequate or becomes loose, the resulting coil vibration and movement of the coils on the poles will cause abrasion of the conductor and ground insulation. Inadequate inter-pole bracing in large, high-speed machines will lead to coil distortion, whereas erosion from loose windings will occur mainly during starts and stops. Winding looseness can also lead to pole washer and inter-coil connection cracking from fatigue.

C. Round Rotor Field Windings

This type of winding can mainly be found in turbine generators, but is also used in some high speed 2-pole compressor motors fed from variable voltage and frequency drives. Fig. 17 shows abrasion of slot cell (ground) insulation due to relative movement of components due to load cycling. This can be minimized by the use of materials that provide slip planes which allow relative motion between components.



Figure 17: Slot Cell Electrical Failure to Ground

VI. AVOIDING PREMATURE STATOR FAILURE

The premature failures described above were mainly a consequence of the design and/or manufacture of the stator. Specifically:

- The electric stress control problems may be caused by poorly applied coatings. The deterioration process is accelerated in a winding design that causes the insulation system to operate above about 120C and/or with an average groundwall electric stress above 3 kV/mm.
- The endwinding PD is usually caused either by: (a) poor dimensional control of the coil and/or inconsistent alignment of adjacent coils in the slots; (b) too short an endwinding which does not allow enough circumference at the coil ends for sufficient air spacing between the connections; and/or (c) inattention to the air space and creepage distances needed when blocking and bracing are installed.
- The loose coil in the slot problems may be due to a slot content design that does not take into account the gradual shrinkage of insulating and wedging materials, or where the need for tight coils has been sacrificed to make the coils easy to install in the slot.

Probably the best way to avoid premature stator winding insulation problems is to have an adequate purchase technical specification. Some suggestions for terms to include in such a purchase specification, in addition to the relevant parts of NEMA MG1 and IEC 60034, are:

1. For a 30-year life, require a Class F insulation system to be operated at a Class B temperature rise. If the

winding operates close to its rated Class, the life may only be a few years.

2. Require that the groundwall insulation system to pass a voltage endurance type test similar to those specified in IEEE 1043 and IEEE 1553. Requiring a voltage endurance test is better than specifying the maximum design electric stress, since the latter may retard the introduction of new materials and processes. For further assurance, require spare coils from the production batch for a stator to be subjected to a voltage endurance test.
3. For stators rated greater than 6 kV, require a partial discharge test on the new winding, together with a 'black-out' test (which measures if there is visible surface PD when the lights are out and a voltage is applied to the winding). These tests will ensure the coils are properly impregnated, and clearances in the endwinding and motor terminal boxes are sufficient [10,11].
4. For multi-turn coils, require a voltage surge test on all coils (for non global VPI stators) and on spare coils processed with the stator for GVPI stators, according to IEEE 522 (IEC 60034 Part 15 is generally easier to pass). This will ensure the turn insulation will withstand voltage surges from circuit breaker operation.
5. For non-global VPI stators where coils are not glued into the stator, require the use of a wedging or sidepacking system that contains a follow-up restraint that ensures tightness as the slot contents shrink. This could include the use of two or three part wedges, ripple springs and/or conformable materials such as silicon rubber. Alternatively consider requiring a clearance between the side of the coil surface and the core to be no more than 0.1 mm.
6. Insist on the right to make factory inspections during manufacture of the stator to ensure key tests are being done and process controls are in conformance [8].

Some of these suggestions are included in API 541 and API 546. Note that most of the above terms may increase the cost of the stator winding, but will probably result in a longer winding life and less maintenance over the lifetime. The machine owner also has a responsibility to operate the machine within specification, keep the windings clean and tight, and preferably visually inspect the winding before the end of the warranty period. If manufacturers could provide details on the trade-offs involved in designing a new winding for lower initial cost vs. lower life cycle cost it would enable users to make more informed purchasing decisions,

VII. AVOIDING ROTOR WINDING FAILURES

The causes of premature rotor winding insulation failure resulting from design and manufacturing deficiencies, or mode of operation, can be summarized as follows:

- Operation of winding at a temperature close to its insulation system thermal rating
- Frequent load cycling
- Use of non-metallic materials with inadequate dielectric and/or mechanical strengths

- Lack of slip planes between rotor winding components that may move relative to one another as a result of mechanical forces and/or differential thermal expansion.
- Poor quality control during component manufacturing and rotor assembly
- Poorly defined application information, e.g., the motor manufacturer not advised that driven equipment has a very high inertia
- Inadequate creepage distances between strip-on-edge turns and ground in salient pole rotors or between turns and ground in round rotors

The best way to avoid the above problems is for the user to have a comprehensive technical specification that covers the important aspects of the rotor winding design. It is not sufficient to rely on standard specification such as API 546 since this does not contain all the necessary details for a reliable salient pole rotor winding design. Such specifications should be supplemented with additional details based on operating experience.

It is also important to ensure that the manufacturer has an adequate quality assurance program that covers design verification, component manufacture, rotor winding assembly and final testing of the assembled rotor. In addition the manufacturer must be given details of the mode of operation for the motor or generator to ensure that the effects of this are factored into the rotor winding design.

Some of the important aspects of a technical specification and machine application that should ensure adequate rotor winding life are as follows:

- As for stator windings, specify a maximum winding operating temperature that is one temperature class below the thermal rating of the insulation system.
- For insulated windings ensure that the design incorporates adequate slip planes at the interfaces between components that will move relative to one another under mechanical and thermal expansion and contraction
- For motors that are frequently started and/or drive high inertia equipment such as centrifugal fans, consider using a "soft start" device or adjustable speed drive to reduce rotor winding heating during starting

More generally for both rotor and stator windings:

- Specify QA Program requirements, e.g., ISO 9001-2000.
- Ensure that there is adequate surveillance by the end-user, including hold points at critical stages, during manufacture of winding components, assembly and final testing
- Specify the expected life of the windings, for example 20 or 30 years, and the expected number of starts.

VIII. CONCLUSIONS

The following two conclusions can be made:

1. Problems such as coil abrasion in the slot, electric stress relief coating deterioration and partial discharges in the endwinding have led to failures in as short as 5 years of operation. This anecdotal information is supported by the fact that PD for some manufacturers is

higher for recently made machines than for similar machines made in excess of 10 years ago.

2. To avoid premature failures, users of modern air-cooled machines should ensure they have a good purchase specification and ensure the manufacturer has an appropriate QA program in place.

IX. ACKNOWLEDGEMENT

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XI. VITAE

Greg Stone is a Dielectrics Engineer with a PhD in Electrical Engineering from the University of Waterloo, Canada. For 17 years he was a rotating machine test engineer with Ontario Hydro. Since 1990, he has been with Iris Power, a manufacturer of diagnostic test equipment. He is a Past President of the IEEE Dielectrics and Electrical Insulation Society and Fellow of the IEEE and the Engineering Institute of Canada.

Mladen Sasic is Rotating Machines Specialist with IRIS Power, Canada. Prior to joining IRIS, Mladen was with ADWEL International LTD., where he was involved in design and application of test equipment for on-line and off-line testing of rotating machines. Mladen Sasic received a B.S. degree in Electrical Engineering from Sarajevo University, Yugoslavia in 1987. He is a senior member of the IEEE and is a registered professional engineer in Ontario, Canada.

Donald G. Dunn (S'87-M'91-SM'99) received a BSEE, in 1991 from Prairie View A&M University and in 1993 attended West Texas A&M University pursuing an MBA. He was employed by Diamond Shamrock from 1992 to 1998 as an Instrument, Electrical & Control System Engineer and worked on many diverse capital projects. From 1998 to 2006 he was employed by Lyondell Chemicals as a Principal IEA & Controls Engineer at the Channelview Complex. Since 2006, he has been employed by Aramco Services Company in a Consulting Engineering group in the Technical Services Department supporting Saudi Aramco and its subsidiaries. He is currently a senior member of the IEEE and the ISA. He has been a member of the IEEE for over 20 years. He has authored or co-authored in excess of twenty technical papers of which eight were for the IEEE Petroleum and Chemical Industry Conference (PCIC). In addition, Mr. Dunn has been an invited author and presenter at over thirty various IEEE and ISA International, National and Regional conferences. He has held numerous leadership positions within the IEEE and the ISA since 1996. He is a member of the IEEE Standards Association, IEEE 1242 Working Group and ISA Standards Committees SP5.6, & SP60. In addition, He is the chairman of ISA Standards Committee SP18 and IEEE P1714 and the Vice President Elect for the ISA Standards and Practices Board.

I Culbert graduated from a 4 year course in Electrical Engineering at Dundee Technical College, Dundee, Scotland in 1965. He then spent 10 years with Parsons Peebles (UK) and Reliance Electric (Canada) as an induction motor designer. He then joined Ontario Hydro (now Ontario Power Generation) as a motor and small generator specialist and was with them until April 2002. He is presently a rotating machines engineer with IRIS Power LP and has co-authored a number of papers. Ian is a registered professional engineer in the province of Ontario and a Senior Member of IEEE.