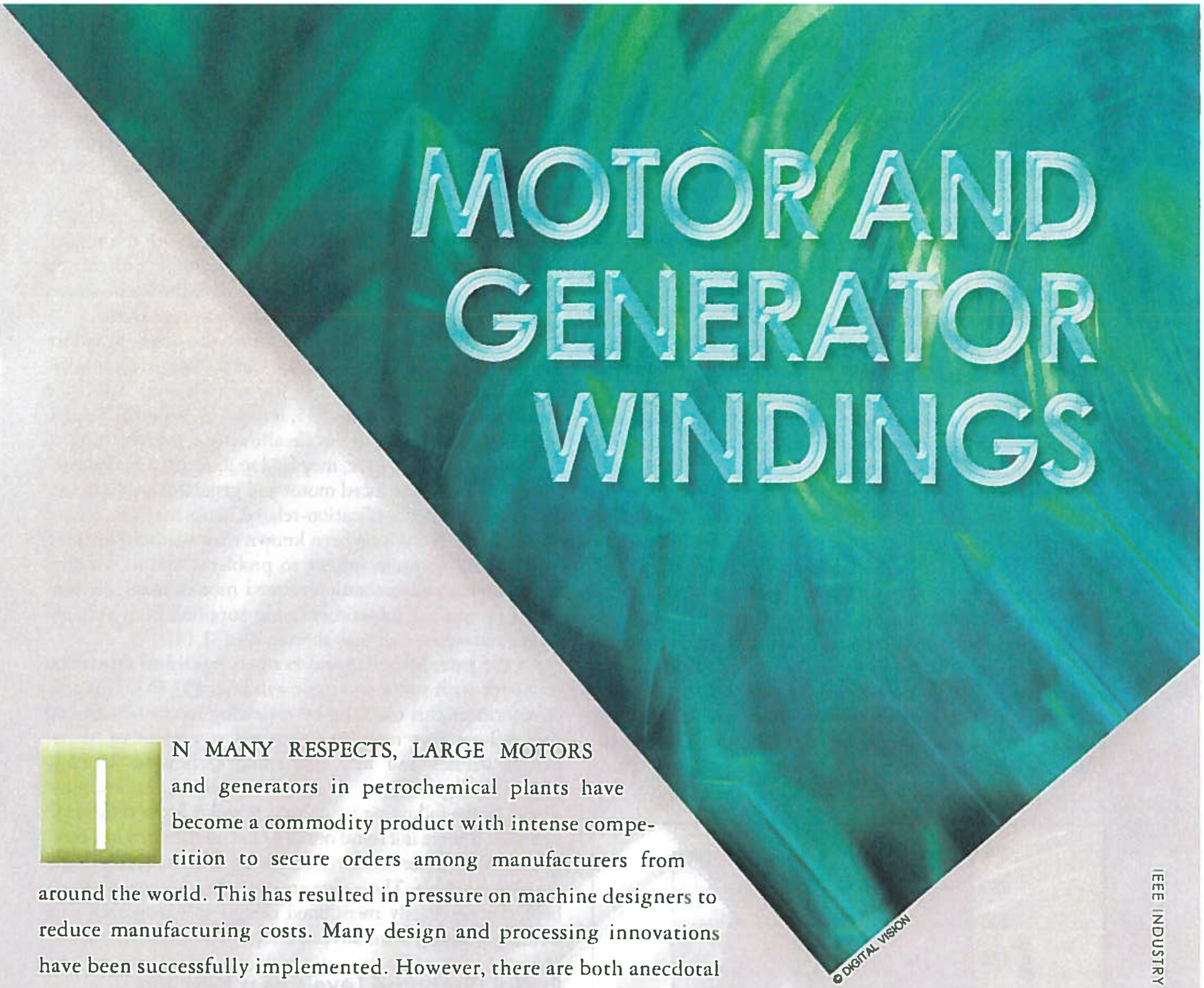
MOTOR AND GENERATOR WINDINGS



Recent problems experienced

BY G.C. STONE, M. SASIC, D. DUNN, & I. CULBERT

IN MANY RESPECTS, LARGE MOTORS and generators in petrochemical plants have become a commodity product with intense competition to secure orders among manufacturers from around the world. This has resulted in pressure on machine designers to reduce manufacturing costs. Many design and processing innovations have been successfully implemented. However, there are both anecdotal and statistical data that indicate that there are more problems with machines made in the past ten years when compared with machines made earlier. 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. Stator windings rated greater than 6 kV and rotors of various-sized machines are the main topics of discussion.

Alternatives for the Manufacturer

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 list. Since a significant portion of the cost of a new machine involves labor costs, manufacturers in high labor-cost countries are most likely disadvantaged

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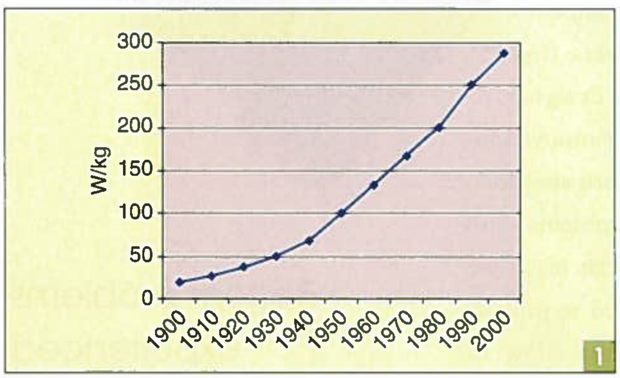
when competing with low labor-cost countries. There are three alternatives available for the manufacturer:

- 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.

Consequences

Sometimes all or combinations of these approaches can 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 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 and again the operating temperature. Shortening the end winding in the stator windings will reduce the material usage and has the benefit of reducing the likelihood of end-winding vibration. However, the electrical stress over the end-winding 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 ground wall 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 caused by switching



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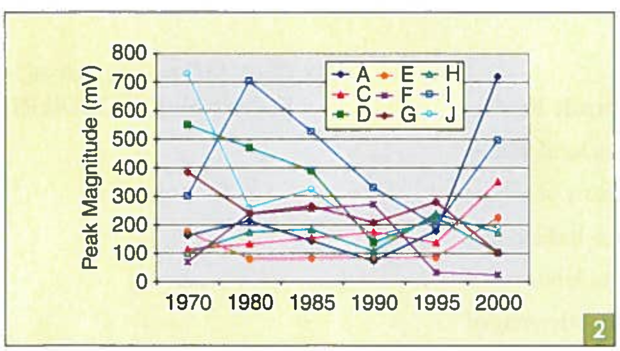
Motor output per unit mass as a function of production year [2].



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PD for nine manufacturers versus year of stator manufacture. Seventy-fifth percentile of PD results by manufacturer and year of install for 13–15 kV air-cooled machines with 80 pF PD sensors.

on motor 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 compared to conventional machines (where the coils are first individually impregnated with epoxy and then inserted into the stator). However, the GVPI process makes it more difficult to detect manufacturing problems since only the entire stator, 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 an average, in 1962, the ratio was 86 W/kg and in 1995, it was 335 W/kg (Figure 1).

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 published articles on problems with stator and rotor windings [5], [6]. This article 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 in large motors and generators. Although by nature the examples shown in the following are anecdotal and it is not possible to establish if there is a trend or not based on them, more objective data on stator winding condition of modern machines are now available. These data are presented to show that perhaps the previously mentioned design and manufacturing trends are having some adverse effect on machine reliability.

Partial Discharge Levels as a Function of Manufacturing Date

As part of the analysis of online 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 those made by the same manufacturer more than ten years ago [7]. Generally, the higher the PD activity, the closer a stator winding insulation is to failure. Figure 2 shows the peak PD activity versus winding manufacturing date for nine of the world's largest manufacturers of air-cooled motors and generators rated from 13 to 15 kV. This shows that for online 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.

Stator Winding Problems

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 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.

In the 1970s, there were a number of machines that exhibited very high PD and ozone concentrations from either or both coatings that were caused by manufacturing problems. The problems seemed to originate from coatings where graphite and/or silicon carbide was nonuniformly dispersed in the insulation matrix or 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 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 temperature. Perhaps, it is for this reason that there seems to be a recurrence of this problem in the past few years.

Figure 3 shows a turbine generator stator where a very noticeable white band is visible at the junction of the semicon and silicon carbide coatings. Figure 4 shows a winding where the semicon has virtually disappeared in the slot due to poor application of the semicon coating that then lead to PD and ozone, subsequently causing the original problem area to extend. This will normally only occur in air-cooled machines rated 11 kV or more. However, the introduction of voltage source converter drives has shown that these problems can occur on motors rated 3.3 kV or more [3], [4].

Semicon and grading coating overlap deterioration.

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

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 more than 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 ground wall 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 ground wall insulation. The mechanism is sometimes referred to as slot discharge because once the semicon coating is abraded, PDs occur between the coil surface and core, further increasing the rate of deterioration.

Figure 5 shows a coil in the process of being removed from a stator where the semicon and about 30% of the ground wall thickness have been abraded away. The manufacturer had not mechanically secured the coils in the slots by means such as side packing, ripple springs, two-part wedges, conformable restraint in the slots, and so on.

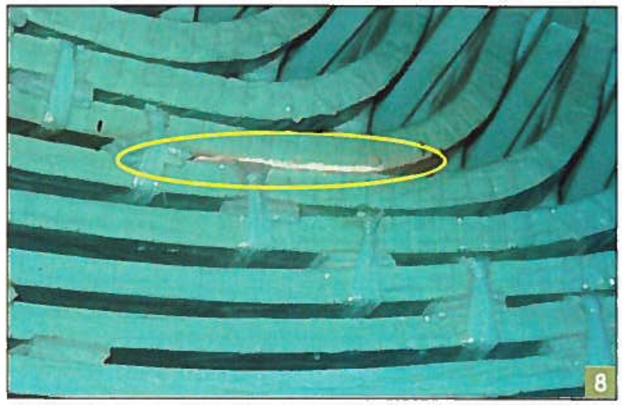
Normally, one would not expect loose coils to be a problem in a global VPI stator since the coils are effectively glued to the stator core. However, if the coils are made too small for the slot and subjected to frequent load cycling that creates shear stresses between the coils and stator core, then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

Vibration Sparking

A problem similar to loose coils in the slot is called vibration sparking (or sometimes spark erosion). For the occurrence of vibration sparking, the coil must be loose in the slot (and thus be conventional winding rather than 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 along the semicon on the coil surface, steel laminations, and key bars behind 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 damage the coil insulation. Vibration sparking, therefore, requires two design or manufacturing errors. Although Figure 7 shows a generator, in the 1970s it was noted on some motors in the United Kingdom [9].

Coil abrasion due to loose windings in the slot of a turbo generator. The coil is in the process of being removed from the core.

Damaged bar surface due to loose coils in the GVPI stator.



The PD occurring between high-voltage coils in two different phases.

This failure process can be very aggressive, resulting in failure in a short time of about five years. Although most manufacturers are careful about making the semicon have a minimum resistance, there is a set of turbine generators made in the past ten years where the material is too conductive and failures occur (Figure 7). Vibration sparking is driven by the magnetic flux, and thus damage can occur anywhere within the winding, unlike the surface PD and loose coil problems described previously, which can only occur near the phase terminals.

End-Winding PD

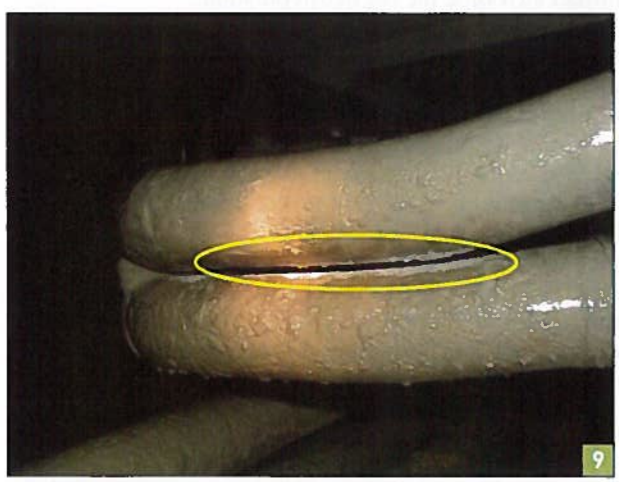
Coils operating at high voltage and placed adjacent to other high-voltage coils in another phase require a minimum separation to avoid PD in the air space between coils. This PD will gradually erode the ground wall insulation and may lead to phase-to-phase stator failure. The higher the voltage class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

Unfortunately, in many motors and generators rated 6 kV or more, we have noted inadequate spacing and, consequently, high PD and ozone. Figure 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. Figure 9 shows the same situation but between two circuit ring buses that are in different phases. Figure 10 shows the PD between the grounded pressure finger at the end of the core and side of a coil where the manufacturer did not extend the semicon stress-relief coating far enough into the end winding. 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 may take several years to result in failure 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.

End-Winding Vibration

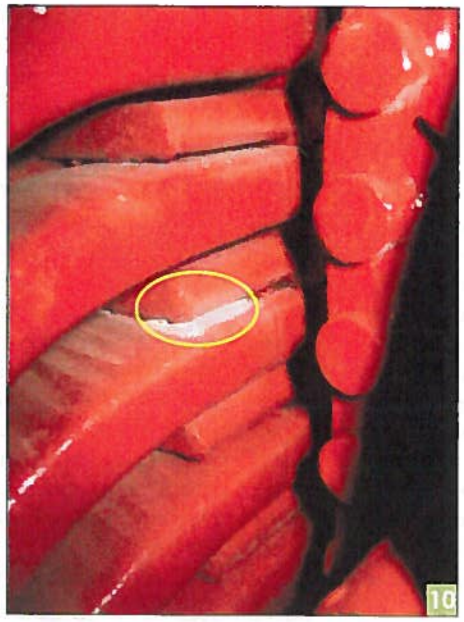
A well-known problem that seems to be happening more and more frequently during the past ten years is caused by inadequate support of the coils in the stator end-winding area. The current flowing in the coils gives rise to a 120-Hz magnetically induced vibrational force, just as can occur in the slot, with the force being proportional to the square of the current. While starting the motor, there is a 36 times higher magnetic force between the coils in the end winding. If blocking and bracing in the end winding have 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

A neutral-end stator bar damaged by vibration sparking. The bar is in the process of being removed from the slot.



The PD between circuit ring buses that are too close together.

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 (Figure 11). Note that this white powder is not the same as the one that occurred from PD (Figures 8–10). The powder due to fretting can occur wherever the coils are loose, including the neutral-end coils, whereas the 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 copper, where there is a high risk of a ground fault.



The PD occurring between a core pressure finger and a high-voltage coil.

Stator Core Problems

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

Core problems can be created during designing or manufacturing the core, as well as in operation and during the rewinding process. In a rewind, 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 interlaminar 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 with larger units within utilities. As a consequence, such machines might experience different operational events more frequently. Particularly, one dangerous event is overfluxing 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 nonsynchronized regime, two scenarios are common: tripping of generator from a full load without timely tripping of the excitation system and attempts to excite the machine with inaccurate voltage information coming from the potential transformer due to poor connections. The damage caused by a single overfluxing event can be small, but cumulative effects of subsequent overfluxing events may result in an electrical core failure.

Figure 12 indicates one such failure, on a 13.8 kV, 40 MW air-cooled generator installed in an industrial power plant. In spite of the very high temperature that melted the core, the stator coil insulation did not fail, and there was no indication of this problem. The melted core was discovered during a low-power core test conducted during regular maintenance using the electromagnetic core imperfection detector [8] test.

Rotor Winding Problems

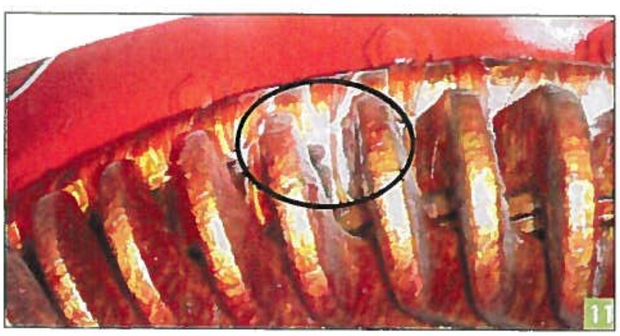
Premature rotor winding problems may result from rotor design, poor manufacture, and/or misapplication. The most common rotor winding types are as follows:

- induction motor squirrel-cage rotor windings
- synchronous motor and generator salient pole field windings
- turbine generator and motor round rotor field windings.

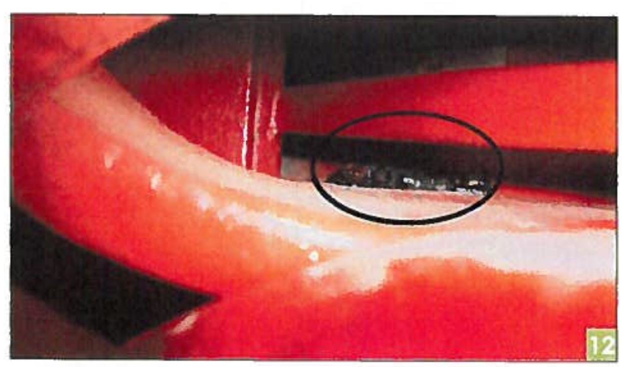
Induction Motor Squirrel-Cage Rotor Windings

The major causes of rotor cage winding failures are breaks in the winding structure that mainly depend on the type of cage winding construction used. In the larger induction motor rotors, the windings are fabricated from copper, copper alloy, or aluminum, whereas in smaller rotors, the windings are often cast aluminum.

In these types of windings, the ends of the bars and shorting rings are outside the core and therefore subjected to increased stresses from both thermal and mechanical



The white powder due to fretting at interfaces caused by stator end-winding vibration.



Melted stator core as a result of overfluxing events.

forces during every direct online start. 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. With frequent starting, if these stresses are high enough, breaks may occur in rotor bars or in the short-circuit ring (Figures 13 and 14). Breaks may also occur in brazed or welded joints. 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 degrees celsius at the tops of the bars due to the skin effect. In addition, aluminum has a lower thermal conductivity than copper that further contributes to higher end-winding temperatures during start. However, fabricated copper/copper alloy windings can also fail in this phenomenon.

Another common problem with fabricated squirrel-cage rotor windings results from loose rotor bars. During the motor start, when the rotor current can be five to six times the full-load running value, the loose bars vibrate under the influence of the resulting high electromagnetic forces. This causes arcing between the rotor bars and ridges at the tops of the rotor slots that retain the bars and resultant core burning (Figure 15).This arcing weakens the core slot bridges and can eventually lead to the bars coming out of the slots and striking the stator core or winding. Loose rotor bars can also result in migration of the complete cage winding in one direction if there are no mechanical stops between the ends of the rotor core assembly and cage winding short-circuit rings. Such cage movement can lead to rotor bar breaks in the sections between the core and short-circuit ring, at the end where they have become shorter, due to increased thermal stresses during starting the motor.

Figure 16 shows the cross section of the rotor slots in a cast aluminum rotor that has voids due to poor casting. Such voids can produce the same effects as cracked or broken bars on the motor performance [6].

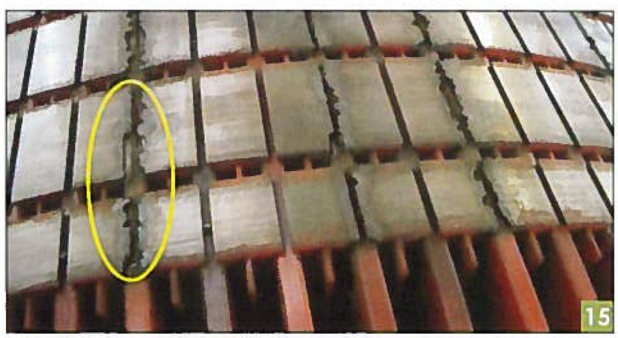
Synchronous Motor and Generator Salient Pole Field Windings

There are two types of windings used in salient pole rotors. These are the strip on edge and multilayer 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 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 and intercoil connections, and crack the coil insulation if the rotor winding is not adequately braced. Figure 17 gives an example of a top pole insulating washer that failed under such forces.

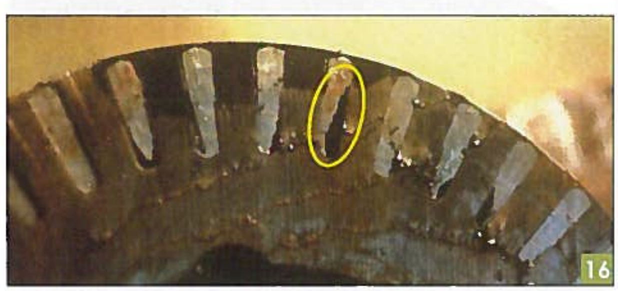
If the pole winding bracing is inadequate or becomes loose, the resulting coil vibration and movement of the coils on the poles will cause abrasion of the conductor and ground insulation. Inadequate interpole bracing in large, high-speed machines will lead to coil distortion, whereas erosion from loose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

Breaks in rotor bars and the short-circuit ring.



Damage to an induction motor rotor core due to loose bars in the slot. (Photo courtesy of EASA.)

Cracked short-circuit ring. (Photo courtesy of EASA.)



Voids in cast aluminum rotor bars in rotor slots due to poor manufacturing. (Photo courtesy of EASA.)

Turbine Generator and Motor Round Rotor Field Windings

This type of winding can mainly be found in turbine generators but is also used in some high-speed two-pole compressor motors fed from variable voltage and frequency drives. Figure 18 shows abrasion of slot cell (ground) insulation due to relative movement of components caused by load cycling. This can be minimized by the use of materials that provide slip planes, which allow relative motion between components.

Avoiding Premature Stator Failure

The premature failures described previously were mainly a consequence of the design and/or manufacture of the stator. Specifically [12], they are caused by the following reasons:

- 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 at greater than about 120°C and/or with an average ground wall electric stress more than 3 kV/mm.
- The end-winding PD is usually caused by 1) poor dimensional control of the coil and/or inconsistent alignment of adjacent coils in the slots, 2) too short an end winding that does not allow enough circumference at the coil ends for sufficient air spacing between the connections, and/or 3) 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.

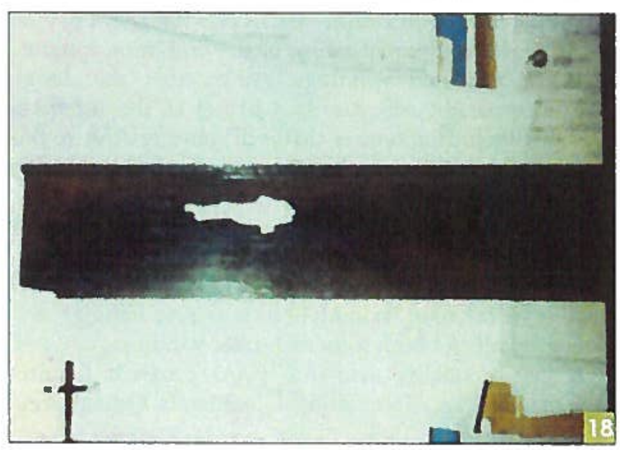
Probably the best way to avoid premature stator winding insulation problems is to have an adequate technical purchase specification. Some suggestions for terms to include in such a purchase specification, in addition to the relevant parts of National Electrical Manufacturers Association Specification for Motors and Generators 1 (NEMA MG1) and International Electrotechnical Commission (IEC) 60034, are as follows:

1) A 30-year life requires 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 be only a few years.
2) The ground wall insulation system is required to pass a voltage endurance-type test similar to those specified in IEEE 1043 and IEEE 1553. The requirement of passing 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. Further assurance requires spare coils from the production batch for a stator to be subjected to a voltage endurance test.
3) Stators rated greater than 6 kV require a PD 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) [8]. These tests will ensure that the coils are properly impregnated and clearances in the end winding and motor terminal boxes are sufficient [10], [11].

Top pole washer failure from mechanical forces.

4) Multiturn coils require a voltage surge test on all coils (for nonglobal VPI stators) and 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 that the turn insulation will withstand voltage surges from the circuit breaker operation.
5) Nonglobal VPI stators, where coils are not glued into the stator, require the use of a wedging or side-packing 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 core to be not more than 0.1 mm.
6) Insist on the right to make factory inspections during manufacture of the stator to ensure that key tests are being done and process controls are in conformance [8].

Some of these suggestions are included in API 541 and 546. Note that most of the aforementioned 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 has a responsibility to operate the machine within specification, keep the windings clean and tight, and preferably visually inspect the



Slot cell electrical failure to ground.

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 versus lower life cycle cost, it would enable users to make more informed purchasing decisions.

Avoiding Premature 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 nonmetallic 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 was not advised that the 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:

- 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 cetrifugal 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 quality assurance (QA) program requirements, e.g., International Standards Organization (ISO) 9001–2008
- 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 expected number of starts.

Conclusions

The following two conclusions can be made:

1) Problems such as coil abrasion in the slot, electric stress relief coating deterioration, and PDs in the end winding have led to failures in as short as five years. This anecdotal information is supported by the fact that PD for some manufacturers is higher for recently made machines than for similar machines made more than ten years ago.
2) To avoid premature failures, users of modern air-cooled machines should ensure that they have a good purchase specification and the manufacturer has an appropriate QA program in place.

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