# DESIGN AND MANUFACTURING PROBLEMS LEADING TO PREMATURE FAILURE IN RECENTLY MADE MOTOR AND GENERATOR WINDINGS


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***Abstract*** - The rotor and stator windings used in large motors and generators are generally reliable with a life of 20 years or more. However, in an effort to reduce cost to remain competitive, many machine manufacturers have had to develop novel winding designs and manufacturing methods. They have also had to reduce material usage. The result has been windings that operate at higher electrical, thermal and mechanical stresses. Unfortunately, in some cases the consequence of the new manufacturing methods and higher design stresses has been premature failure of the windings. This paper reviews several case studies of premature deterioration or failure of recently made machines. The case studies will include premature stator winding deterioration due to:

- Stress relief coating malfunction
- Insufficient spacing between high voltage components
- Poor installation within the stator slot
- Poor stator endwinding support

Ways to avoid these premature winding problems such as better specifications, increased vigilance during manufacture and on-line monitoring are briefly reviewed.

*Index Terms* — stator winding, motor, generator, premature failure, on-line monitoring

## I. INTRODUCTION

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 [1]. For example, Figure 1 shows the peak PD activity vs. winding manufacturing date for 9 of the world's largest manufacturers of air-cooled motors and generators. This figure shows that for on-line PD readings measured in recently, 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.

Maughan has recently published a catalog of premature winding problems he has seen [2]. This paper presents additional examples of advanced insulation ageing that this author has recently seen in air-cooled motor and generator stators. Many of these deterioration processes resulted in premature winding failure. This paper also postulates reasons why some recently made stator winding insulation systems have higher PD activity, and some steps the user may take to reduce the risk of premature stator winding failure.

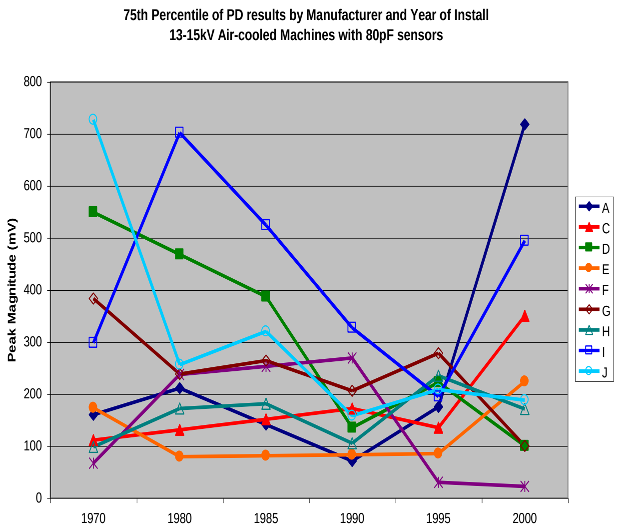


Figure 1: Peak PD data vs year of manufacture

## II. ELECTRIC STRESS CONTROL COATING PROBLEMS

In the past 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, bearing oil 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 higher temperature. Perhaps it is for this reason that there seems to be a recurrence of this problem in the past few years.

Figure 2 shows a generator stator where a very noticeable white band is visible at the junction of the semicon coating and the silicon carbide coating. Figure 3 shows a winding where the semicon has virtually disappeared in the slot due to poor application of the semicon coating. Figure 4 shows the PD resulting when a 6.6 kV motor stator was now equipped with PD suppression coatings.

Figure 2: Semicon and grading coating overlap deterioration (white powder) due to poorly applied or inadequate coatings

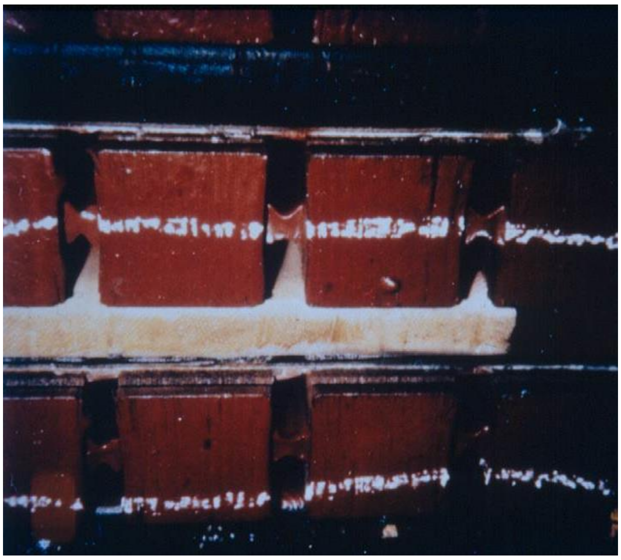

Figure 3: Destruction of the coil semicon coating in the stator slot due to PD and ozone. The wedges have been removed from the slots

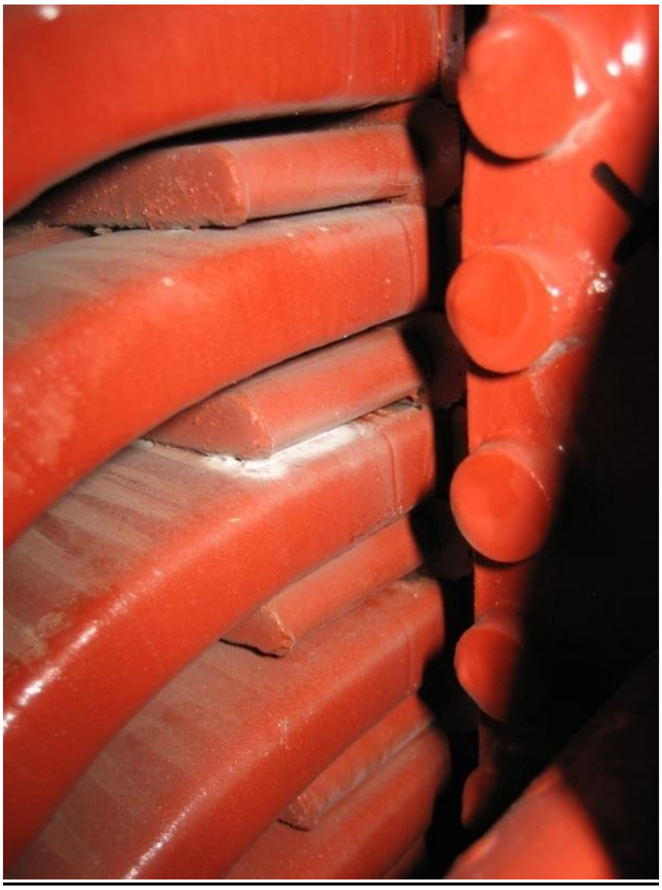

Figure 4: Motor stator where the stress relief coatings appear to be missing – resulting in PD (white powder) between the pressure finger and the surface of the coil

### III. 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. Otherwise PD will result. 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 [3].

Unfortunately, in many motors and generators we have noted inadequate spacing in machines rated 11 kV and above and consequently high PD (and ozone). Figure 5 shows the white residue caused by ozone resulting from PD between two coils in different phases that were installed too close to one-another.

### IV. LOOSE COILS IN THE SLOT

Coil vibration in the slot has long been a problem in all non-global VPI stators (usually generators) made with thermoset insulation systems such as epoxy mica. The first instances were reported over 60 years ago [3]. 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 semiconductive layer of the bar or coil is abraded away, and then the groundwall insulation (Figure 6). The mechanism is sometimes referred to as slot discharge, because once the semiconductive coating is abraded, partial discharges occur between the coil surface and the core, further increasing the rate of deterioration.

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.

Figure 5: PD occurring between high voltage coils in two different phases, where the spacing is insufficient to prevent the PD. Note that the spacing between adjacent coils is irregular, as a result of poor manufacturing processes.

Figure 6: Bar abrasion due to loose windings in the slot of a turbo generator that did not have sufficient sidepacking or a radial follow-up wedging system. The bar is in the process of being removed after failure.

## V. ENDWINDING VIBRATION

In the past several years many manufacturers of large 2 pole and 4 pole motors and generators have experienced problems with relative movement of stator bars and coils outside of the slot. As occurs within the slots, the current through the endwinding creates magnetic fields which interact with one another – resulting in large magnetic forces at twice the ac frequency (100 Hz in a 50 Hz machine). Normally the endwinding support structure is strong enough to resist the magnetic forces and prevent coil or bar movement. However, if the design or manufacture is flawed, the endwinding structure, or subcomponents such as the leads between the coils and the circuit ring bus may have a natural frequency near twice the line frequency. In this circumstance there will be a mechanical resonance that can lead to relative movement between the coils/bars and the support structure. This leads to insulation fretting (Figure 7). Eventually the insulation is abraded away – exposing the high voltage conductors and perhaps leading to a ground fault. In extreme cases copper fatigue cracking can occur- which can completely destroy the stator winding.

Figure 7: The white powder (fretting) on this motor stator endwinding is caused by relative movement between the coils and the endwinding support ring.

## VI. AVOIDING PREMATURE STATOR FAILURE

The premature failures described above were 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 winding design that cause the insulation system to operate above about 120C and/or with an average groundwall electric stress above 3 kV/mm.
- The endwinding PD is probably 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.

- Insufficient attention paid to the endwinding design so that there are natural vibration frequencies close to the 100/120 Hz magnetically-induced forces.

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 IEC 60034 are:

- For a 30-year life, require a Class F insulation system to be operated at a Class B temperature rise.
- Require that the groundwall insulation system to pass a voltage endurance type test similar to those specified in IEEE 1043 and IEEE 1553 (regrettably there is no IEC equivalent specification that is well defined with a pass-fail criteria). Requiring a voltage endurance test is probably better than specifying the maximum design electric stress, since this 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.
- Require a partial discharge test on the new winding, [4, 5].
- For multi-turn coils, require a voltage surge test both on coils (for non global VPI stators) and complete windings, according to IEEE 522 (IEC 60034 Part 15 is generally easier to pass).
- For non-global VPI stators, 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 and the core to be no more than 0.1 mm or so.
- To guard against surface PD, require a black-out or UV inspection test to be passed (IEEE 1799) [6]
- Perform a "bump "test on the endwinding to ensure there are no natural frequencies near twice the current frequency [7].
- Install on-line condition monitoring tools to measure PD or endwinding vibration during normal operation of the machine [3].
- Insist on the right to make unannounced factory inspections during manufacture of the stator.

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. It would be beneficial if manufacturers could educate users on the trade-offs of cost vs. life they make when designing a new winding.

## VII. CONCLUSIONS

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 over 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.

## VIII. REFERENCES


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## IX. VITA

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