# PREMATURE FAILURE OF MODERN GENERATORS

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**ABSTRACT:**

Making generators at lower cost has had a significant negative impact on the current fleet of newer generators, units less than about 30 years old. A number of factors have come into play, e.g., pressures to manufacture new machines more quickly and with less costly materials and processes, designs that push duties into higher and uncharted levels, "reinventing of old problems".

Couple these competitive market realities with reduction in number of engineers in OEM organizations and the loss of institutional knowledge as elders have retired, it is not surprising that some machines are failing much sooner than historically expected. This paper will present examples of some of the more critical missteps on various high-speed power generators and propose compensatory maintenance approaches for power plant engineers.

## POWER GENERATION INDUSTRY EVOLUTION

The power generation industry has undergone many fundamental changes in its 100+ year history, both in technologies and in government influences.

Relative to technologies, for example, evolution of cooling methods has included: 1) open-flow air cooling, 2) closed-flow with coolers, 3) hydrogen atmosphere cooling, 4) direct hydrogen and/or water cooling.

Relative to government influences, because power generation has been resource intensive and covered large geographic areas, government involvement was inevitable and necessary. During the high-growth period of the 1950s-1960s, an interesting situation existed in the USA, i.e., price fixing among the 3 manufactures of large turbine generators. The market was controlled by the original equipment manufacturers (OEMs) and prices were high! But with this high income, OEMs had the resources to evolve huge evolution in rating and design detail while still able to (generally) produce a good quality product. In addition, the OEMs had the resource to make available to the "western world" the high level of USA technologies that existed during this period, via licensee agreements.

Subsequent to the government ending of price fixing, the world-wide industry gradually entered into an increasingly intense competitive market. These associated cost pressures negatively impacted the industry in two predominant ways: 1) increasingly lower quality of the new generators, and 2) increasingly lower quality of technical support for addressing the inevitably high in-service problem rates.

The industry impact associated with these quality issues has been profound, and appears to be becoming increasingly so:

- The power generation companies are able to purchase generators at a lower price. But this initial investment saving can disappear in a few days of an outage involving $100,000 to $1,000,000 per day in lost-generation charges.
- The OEMs can become faced with complaint costs sufficiently large to reach magnitudes leading to the prospects of business failure.

In this situation, relationships between vendor and client inevitably suffer:

- OEMs may become reluctant to be candid in supplying urgently needed technical assistance to the individual owner of the failed generator. Or perhaps more important, reluctant to supply important information even to the industry in general.
- Owners may become sufficiently dissatisfied that they may go not to the OEM but to another manufacturer for replacement components, include the entire generator . . . and to another manufacturer for the next turbine-generator in a new power plant.

The situation addressed above appears at this time to be almost intractable. But the industry cannot afford to fail to address these issues.

Because these industry conditions are unlikely to be reversed in the near future, this paper will attempt to provide information which may assist owners in addressing the existing technical and business issues.

**<u>LOWER QUALITY OF NEW GENERATORS</u> –**
(PREMATURE FAILURES ON MODERN GENERATORS)

Historically utility-size generators were made with considerable margin in load capability. With the simultaneously advent of powerful computers and greatly increased competitive conditions between OEMs, this margin was largely removed. These new designs increased mechanical, electrical and thermal duties to a point where there is little margin left, and occasionally generators are produced with designs that exceed specification parameters.

The result is a fleet of generators that increasingly require major maintenance long before the historic target of 30 years for stators and 20 years for fields.

The following paragraphs will cite some examples.

**PROBLEMS ON MODERN GENERATOR STATORS**

**<u>Stator Endwinding Vibration</u>**

Endwinding vibration has been an ongoing problem on large generators. Problems have accelerated as engineers have designed for higher vibration driving forces and simplified support systems. Eliminating series blocking on an endwinding resulted in the broken bar shown in Photo 1.

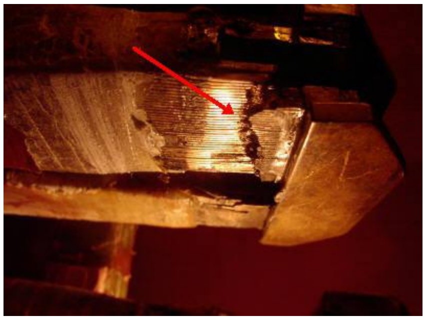

Photo 1. Broken series connection.

Local endwinding resonance resulted in the failure shown in Photo 2.

Photo 2. Several inches of copper burned away on a stator bar.

Protection against these type failures is probably best obtained by being sure that bump test is performed on new windings and reworked windings. Resonant values should be outside the 115-140 Hz range (for 60 Hz generators).

**<u>Stator Bar Slot Vibration</u>**

Large indirectly cooled generators tend to be made with many stator slots and tall, narrow bars. This design approach maximizes the area for transferring heat through the groundwall insulation. But it also allows the tall, narrow bar to vibrate sideways in the slot, probably driven by the core vibration. This vibration results in vibration sparking, a fast acting destructive phenomenon. Photos 3 & 4.

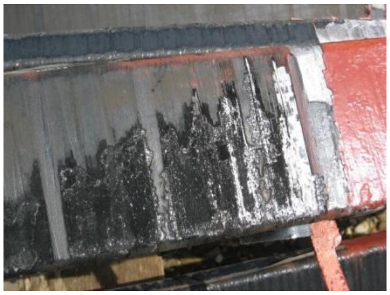

Photo 3. Side of a bar deeply damaged by vibration sparking.

Photo 4. Side packing almost completely eaten away by vibration sparking.

It has been supposed by designers that side filler would not allow side vibration, but since incremental thickness packing cannot fill the space fully, vibration can occur. Corrective action probably requires rewind to remove the fatally degraded bars and allow installation of side pressure springs.

## Dry Endwinding Support Ties

The integrity of endwinding support systems on some generator designs relies heavily on bonding of the ties to the support structure, connection rings and stator bars. Some OEMs have used a *wet* tie to make this bond as strong as possible. ("Wet" meaning that the glass for making the tie is drawn through a high bonding strength resin as the tie is being made.) For cost and simplification reasons, a changeover was made to *dry* ties. ("Dry" meaning that the glass is pre-impregnated with a resin that is dried, slightly cured, to allow for ease of application.)

These dry ties have not performed well and have led to numerous problems. Photos 5 & 6.

Photo 5. Dust generation from failed dry tie.

Photo 6. Bare copper exposed from wear of a dry tie.

A few years of operation may result in heavy wear at several locations, leaving significant exposure to phase-to-phase fault. The resulting arc will be massive and may severely damage the generator.

Scope of repair depends upon the amount of damage. If the integrity of the insulation is undamaged, simply replacing the dry ties with wet ties may be all that is required. But at the other extreme, corrective action has apparently required generator replacement.

## Bolted Joints

Bolted connections have been used in the electrical industry since its infancy. Safely carrying current through a bolted joint requires two primary conditions: clean non-oxidized surfaces and high local contact pressure. Meeting these two conditions for high current applications is something of an art, an art dependent upon passing known skills down from generation to generation of skilled personnel. If lost, the results can be joints that begin to destructively over heat. Photo 7.

Photo 7. Failing flexible lead, high voltage bushing to isophase bus.

A joint similar to Photo 8 was made up with stainless steel bolts. Stainless steel has a propensity to gall, and in this case the nut-to-bolt galling absorbed the torque of the wrench and left some bolts loose, but with apparent proper torque. The result was joint failure, massive arcing, thorough contamination – and a stator and field rewind, plus weeks of frame, cooler and core cleaning.

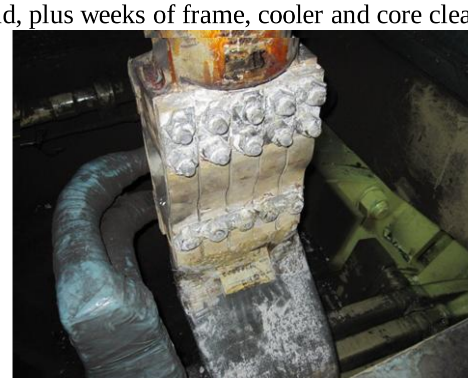

Photo 8. Bolted high current connection.

Prevention of bolted joint problems involves being certain that: 1) connecting surfaces are properly plated, 2) the surfaces are clean, 3) the selected torque values are correct, and 4) the nut/bolt torque is not resulting from galling or other friction conditions.

## Core/Frame Structure

On 2-pole generators, the core must be isolated from the frame by a flexible attachment. Otherwise the inevitable "vibration" of the core outside diameter, typically about 2 mils, will transmit intolerable vibration and noise to the frame. (The term "vibration" is commonly used, but the condition is actually deformation of the core due to magnetic pull of the field flux on the core.) Photo 9 is the core-to-frame support structure for the generator shown in Photo 10. In Photo 9, the core (yellow arrow) is attached directly to the keybar/bore ring fabricated structure (blue arrows), which is directly connected to the frame outer wrapper (white arrow).

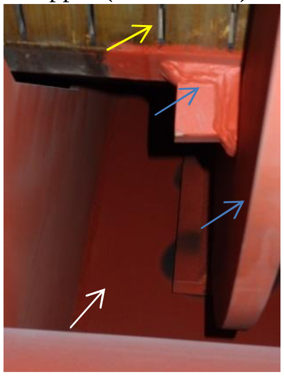

Photo 9. Core-to-frame attachment arrangement.

Photo 10. Outer frame.

This configuration eliminates the cost of the isolation components, but leaves the generator vulnerable to noise levels approaching 116 dB, and the prospects of frame and foundation cracking.

Operation may be acceptable if the noise levels can be tolerated and frame and/or foundation cracking is not occurring. Otherwise, this condition may not be correctable without stator (or generator) replacement.

**Series and Phase Connection Insulation**

These connections are difficult to insulate with mica tapes. Thus for many years, there has been widespread use of a much faster and lower cost insulating method, i.e., the use of insulation consisting of non-conducting box filled with non-mica potting compound. This is perfectly adequate at the low voltage difference of the series connections. But if air gap clearances are less than about 3/8" at phase-to-phase locations, partial discharge can occur. Photos 11 & 12 are at one such line-to-line phase break.

Photo 11. Failed phase connection.

Photo 12. Phase-to-phase copper burning due to non-mica connection insulation failure.

Designers now typically use potting compound on the series connections, but tape the phase connections with mica tapes. Or alternatively, assure adequate physical spacing.

On direct-gas-cooled stator windings it is impossible to fully insulate the connections – access for gas flow must be permitted. Numerous massive winding ring-of-fire failures have resulted on machines where the insulating surfaces and air gaps have become heavily contaminated, for example due to an arc resulting from a broken bar or connection. Photo 13.

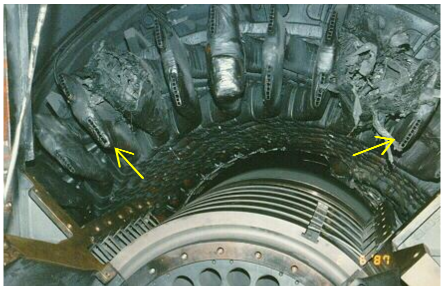

Photo 13. Ring-of-fire failure of a stator endwinding. Arrows identify typical exposed bare conductor locations.

On stators manufactured with bared conductor, there does not appear to be mitigating capabilities other than attempting to assure that no gross contamination occurs.

**Global Vacuum Pressure Impregnation**

Vacuum pressure impregnation (VPI) of *individual* stator bars with asphalt began 100 years ago. Stator bar VPI with thermoset resins began about 1949 and has been successfully used to make high quality stator windings since that date.

It was recognized in the 1960s that Global Vacuum Pressure Impregnation (GVPI) would be a fast and inexpensive method of making a stator. (With GVPI the *entire* stator wound with "dry" coil insulation is placed in a very large VPI tank. The entire stator winding is impregnating in a single operation.) Because of the obvious cost benefits, GVPI has long been used on motors and smaller generators. Beginning about 1975, GVPI became popular with some OEMs for making large generators, up to the range above 400 MVA. These windings have been subject to some early maintenance issues, including:

- Slot partial discharge and possibly vibration sparking, which seem to be related to a slip plane between bars and core.
- Difficulties in performing a rewind, which result from the VPI process bonding the stator bars into the slots. It is difficult-to-impossible to remove the winding to allow rewind. Where rewind is performed, the process is slow and the core is vulnerable to damage. On a GVPI generator, for quality and outage time considerations, stator replacement may be preferable to attempting rewind.

Notwithstanding these limitations, because of the major advantages to GVPI, this process will continue to be popular for large generators.

**Step-down at End of Core**

High design uprate of generators requires that the core have a much greater step-down of the iron at the ends of the core. Because the top of the top bar now is above the core iron, there is high air-gap flux cutting the copper at the top of the top bar and there will be a significant electromagnetic side-force driving side vibration on the top bar. This seems to be resulting in vibration sparking and other concerns on the winding. Photo 14.

Photo 14. Dust generation probably resulting from vibration due to side forces on top bar.

This is a relatively new phenomenon, and assistance of the OEM should be obtained for assessing the possible scope of concern and possible corrective options.

**Tape Migration on Stator Bars**

This was a highly destructive deterioration mechanism on asphalt windings on large (>40 MW) pre-1960 generators. Photo 15.

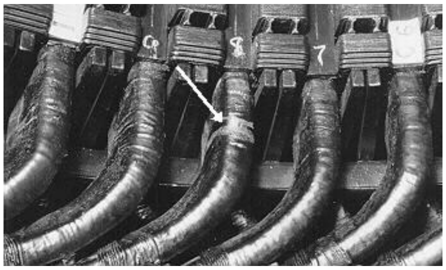

Photo 15. Typical tape separation ("girth crack") on a pre-1960 stator bar.

This migration was eliminated by use of thermoset windings. But the problem has recurred on post-1970 small (<20 MW) coil-wound generators that were made with an inappropriate asphalt material. Photo 16.

Photo 16. Remaining groundwall measured 20% of original thickness.

The unit shown in Photo 16 had been in service about 20 years. The winding failed at line-to-neutral voltage.

Correction in general will require stator rewind.

**High Electrical Stress on Stator Windings**

Historically the electrical stress across the stator bar groundwall has increased very slowly over time. This is because electrical duty increases at about a $9^{th}$ power of stress – volts/mil (vpm). On the asphalt/mica windings, stress was about 45 vpm. With the introduction of polyester/mica systems in the 1950s, stress was increased to around 54 vpm. With the introduction of epoxy/mica systems in the 1960s, stress initially went into the 60-65 vpm range. Designs up into the 90 vpm range are now being produced. Consider that a 20% increase in vpm increases duty by$1.2^9$, or about 500%.

While to date, generators have rarely failed due to purely electrical duties, it can be expected that as stress levels increase, pure electrical failures will begin to be seen.

**PROBLEMS ON MODERN GENERATOR ROTORS**

Design margins in fields have not been impacted as greatly as those on stators, largely because there never has been a great amount of design margin on fields. But also, since copper mechanical properties are so marginal, there has not been much opportunity for cost reduction and increase in duties on fields.

Design temperature on fields has been fortunately slow to evolve upward. High temperature insulation materials are available. But designers recognize that copper has inherently low mechanical properties even at room temperature. These already poor mechanical properties begin to fall off rapidly as the temperature of the copper increases above about 130C.

Direct cooling has been the greatest uprate tool on fields – because this has allowed not only reducing average copper temperature, but more particularly hot-spot temperature. Direct cooling does bring problems, primarily due to cleanliness issues in contaminated atmospheres.

Problems on field windings have tended to remain relatively constant (and relatively high) over the years, e.g., grounds, turn shorts, coil shorts, coil migration, distortion of turns and coils, broken turns, broken pole-to-pole and coil-to-coil connections, broken collector connection, slot and turn insulation migration.

Historically, failure of field forgings has caused a few catastrophic failures. Fortunately, it was possible to increase the quality of forging materials to a point where failure is now very rare. The primary remaining quality/cost issue on forgings would be those many 18/5 (18% manganese-5% Chrome) retaining rings still in service. On those generators operating with 18/5 rings it is vital that the rings not be exposed to water accumulation, in particularly the ring inside diameters.

**LOWER AVAILABILITY OF TECHNICAL SUPPORT – (PERSONNEL ISSUES RELATING TO PREMATURE GENERATOR FAILURES)**

**Inherent Personnel Limitations**

Undoubtedly cost pressure is the primary cause of increased failure rates of modern generators, and particularly on stators. Not only have these pressures resulted in less design margin in the generator, but have also seriously reduced the strength of the OEM generator design, manufacturing and service organizations.

A further negative factor relates to the inability to pass on to the younger generations the knowledge of the previous generations of design and service engineers. Because much of the knowledge of how to build a generator is in a real sense an *art*, this has repeatedly led to "reinventing old problems". Cases in point mentioned above: application of dry stator winding ties leading to numerous winding problems, and failure to correctly make up a bolted electrical joint leading to massive stator winding failure.

Under existing industry conditions, it has simply not been possible to maintain the quantity and skill levels of technical talent to adequately perform the required design, manufacturing and maintenance tasks.

There are secondary contributors to the degradation of inherent talent. Three come to mind: 1) power generation is no longer a "glamor" business for attracting the needed top talent demanded for production of the complex and not well understood generator, 2) the present generation of design engineers is spread so thin it is difficult for an individual engineer to become highly skilled in any one discipline, and 3) the advent of computer-aided design had reduced the "feel" for the design that came from designing with a hand calculator and a 10" log-log, deci-trig *slide rule*.

Two incidents may illustrate the fundamental weakness of OEM organizations:

- A field had been forced out of service by a "thermal vector" of unbalance resulting from axial migration of coils in the slots of the field body. The key OEM field design engineer is at the white-board giving the owner his explanation to why this coil migration was occurring, i.e., the axial blocks under the retaining ring prevent this migration. Of course, it is the peripheral blocking that prevents migration, and this engineer could not be made to understand this obvious design principle.

- End-of-slot stator bar vibration occurs on some generators. This vibration results from incorrectly setting the endwinding support system such that the bars are held off the bottom of the slot at the ends of the core. The high electromagnetic downward force on the bars results in the bars destructively vibrating at the ends of the slots. The key OEM engineer was absolutely unable to visualize this condition and continued to believe that the problem resulted from oil contamination of the winding.

Another fundamental personnel problem results from the OEM, and independent, generator specialists being unwilling to say: "I don't know". These generator specialists (from OEMs or independent service providers) are trained to perform inspections, tests and maintenance on generators. Few have the technical and experience basis on which to perform the extremely challenging failure root cause analysis. Unfortunately, few specialists seem willing to say, "I don't know", and all recognize that it normally will be very difficult to obtain assistance of a qualified, capable engineer from the OEM engineer organization.

The result is often incorrect diagnosis of major failures on large power producers and this can be exceptionally costly to the owner. For example . . .

**Secondary Impact of Personnel Limitations – Inadequate Failure Root Cause Diagnosis**

Historically diagnosis of new and complex generator failures was done by OEM factory engineers. This was the case because accurate diagnosis can be significantly assisted by a technical education background and by generator engineering design experience. But with the contractions in number of OEM expert engineers, there are now available few OEM engineers with good diagnostics capability. Because personnel of this caliber are vital to other OEM efforts, obtaining their services at a power plant may be a challenge. Thus it has become increasingly difficult to obtain personnel that are capable of performing diagnostics.

But root-cause diagnosis of generator failures is a particularly challenging task. Specifically:

a) Generators are complicated mechanically, and more particularly, the theory of the function of a generator is complex. While design and operation of most mechanical components of a power plant are somewhat "intuitively obvious" to a knowledgeable, intelligent person, there is little about a generator that is obvious to even the best of intuition.
b) Generators can fail in many failure modes. Plant personnel will have heard an OEM engineer say: "We haven't had this kind of failure before". This may be rightfully greeted with some skepticism. But in fact because there are so many ways a generator can fail, this comment may be quite true and accurate.
d) Typically no one in the power plant knows much about the function of the generator. In a power plant there will be several operating and maintenance personnel that quite clearly understand the turbine. These personnel often can greatly assist in determining why a component has failed. This is unlikely to be true of plant personnel with respect to the generator.
e) Often generator failure will involve major destruction to the failure location due to burning and arcing damage. Thus the actual root cause of failure will have been destroyed and assessment must be made primarily by implication.
f) Finally, even with the best generator monitoring instrumentation, often the plant records will shed little light on the failure root cause.

Mis-diagnosis of the root cause of generator failures can be exceptionally costly in that resulting corrective actions may not address the actual cause, thus leaving the generator vulnerable to repeat of the failure. The direct repair cost of such a failure can range from a few hundred-thousand dollars to many tens of millions of dollars. In addition, loss-of-generation costs can exceed $200 million on a major failure of a large generator.

Five real-life examples –

1. Ring-of-fire stator winding failure on a 900 MW water-cooled winding was incorrectly charged to the internal piping arrangement. Had the correct design error not been identified by further consultation, repeat of the massive stator winding failure would have been inevitable. Photo 13.
2. Stator winding failure on a 200 MW stator incorrectly charged to "lightning". Corrective action taken was based on this mis-diagnostics. The unit failed again several months later at the same location for the same cause – partial discharge. Photos 11 & 12.
3. On a 250 MW generator, contamination of a core end-package was judged to be from minor stator bar vibration and no corrective action was taken. The root problem was actually local core looseness Photo 17. The winding failed to ground a few weeks after return to service.


Photo 17. Knife check of locally loose core.

4. Core discoloration at the location of stator winding failure judged to be insignificant after inspection and deficient ElCid test. This 80 MW stator was then rewound without correcting the core-iron condition. The new replacement winding failed in service shortly after return to service. Photos 18 & 19.

Photo 18. Minor iron discoloration judged to be insignificant.

Photo 19. Same core location after a few hours of excitation.

5. Asphalt stator winding incorrectly diagnosed as having destructive migration of the groundwall. Photo 15. An inexperienced OEM engineer, and an inexperienced independent consultant, each recommended immediate stator rewind to avoid "catastrophic service failure". Their recommendations were vacated by a more experienced engineer, and this stator winding continues to operate safely many years afterward.

**CONCLUDING OBSERVATIONS**

There are no easy answers to the dilemma of marginal equipment and inexperienced service personnel. Generally a deficient design does not leave margin for modification to a lower duty design, and there seems no ready solution to the problems relating to technical personnel limitations. Unfortunately, the difficulties and challenges will remain until such time as the industry reduces the focus on first cost and addresses the long-term costs of power generation equipment.

Until that utopian condition arrives, from a power producer perspective, addressing these challenges can perhaps be summarized as follows:

1. Monitor the generator with state-of-the-art equipment.
2. Keep the monitoring equipment in good operating condition.
3. Be certain to record and retain all monitoring equipment information.
4. When failure occurs, assure that the failure investigation is thorough, and that the diagnostics information being provided from OEM and/or independent consultant personnel is plausible and reasonable.
5. If it is not, obtain additional technical support, and do this early, before critical information and valuable time are lost.

It seems clear that the problems facing the power generation industry will not be cleared up in the near future. The challenges will continue, and it is hoped that the above information will be of some assistance in handling these challenges.