MONITORING OF GENERATOR CONDITION
– And Some Limitations Thereof

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Abstract: Historically turbine-generator condition was monitored by rather primitive instrumentation, e.g., ammeters, voltmeters, temperature sensors. More advanced instrumentation devices have been added in the last 25+ years, e.g., partial discharge, turn-short flux probe, core monitors.

But there still remains little or no detection capability for some of the major deterioration mechanisms, e.g., bar vibration without partial discharge, stator bar clip liquid leaks, series/phase joint copper cracking, developing field turn cracks, field insulation abrasion/cracks, retaining ring corrosion and cracks, field forging cracks.

This paper will discuss root causes and progression rates of some generator deterioration mechanisms. The resulting negative impact on generator reliability of extending the periods between outage inspections can be high. Advantages of remaining with the historic 5-year period between outages will be illustrated.

GENERATOR MONITORING CAPABILITY

Instrumentation

Generator stators and fields have historically been monitored by relatively unsophisticated instrumentation, reading various currents, voltages, temperatures, pressures, flows and vibration. In addition, instrumentation is included which will monitor the external systems; the latter will not be discussed in this paper.

The historic monitoring systems will commonly detect over-current, under-current, general over-temperature conditions, some local overheating conditions, abnormal vibration, incorrect pressures, field ground, phase current unbalance, stator single ground, stator line-to-line fault. But these standard devices do not detect many of the more common modes of failure. In order to increase the likelihood of detecting developing deterioration, more advanced instrumentation can be added: generator condition pyrolysis monitor, various partial discharge measurement systems, field turn short detectors, end winding and slot bar vibration monitoring devices, gas discharge rate monitors on liquid cooled stator windings. These non-standard or newer devices can be added to the generator without undue cost, particularly during a major outage.

With these advanced monitoring systems, additional protection may be gained against the presence of more subtle failure mechanisms. For example, slot discharge, some forms of stator bar vibration, field turn shorts, some additional forms of localized overheating, stator insulation delamination or cracks, stator over-flux, and some forms of series/phase joint deterioration.

Limitations

Even with the best of the monitoring systems, however, generators remain with little or no detection capability for some of the more common and serious deterioration and failure mechanisms:

- stator bar vibration without partial discharge or vibration sparking
- stator bar strand header water leaks
- developing cracks in stator bar connections
- field coil/turn distortion
- developing field turn cracks
- retaining ring corrosion and cracking
- forging cracks.

Unfortunately, equipment with the capability of detecting these problems does not appear to be forthcoming. Thus, the goal of performing maintenance on a predictive basis will continue to be uncertain at least into the immediate future. There will remain several failure mechanisms that can be found only by a careful and complete inspection and test program.

In the following section, comments will be offered on the properties and capabilities of some of the various generator monitoring equipments.

MONITORING EQUIPMENT

Mechanical

Field Vibration. In order to balance and properly monitor operation of a field, levels of vibration associated with field rotation must be accurately measured. Experience has shown that this is more effectively accomplished by measurement of vibration directly on the field journals with shaft-riding or proximity vibration detectors. These devices are highly valuable in assessing some types of field problems, e.g., vibration that is related to field temperature and/or current. If both magnitude and angle of vibration are measured, it is possible to easily assess the length and angle of a "thermal vector" and thus help determine optimum corrective actions.

Stator End Winding Vibration. A few larger generators, which are known to be subject to excessive stator end winding vibration, may have vibration detectors installed. These devices can be retrofit if necessary. This will allow observation of the growth in the levels of general end winding vibration, and thus help determine when an outage should be scheduled.

Thermal

Generator Condition Pyrolysis Monitor. This device monitors the generator for any source of excess heat, and with the addition of temperature sensitive paints, can give a general indication as to where the problem may be occurring. Early monitors were vulnerable to malfunction, particularly if not kept in good condition. The tendency to produce false alarms led to a tendency for operators to disregard the alarm. This proved to be a mistake in a few instances, since there were cases of generators failing in service shortly after occurrence of a disregarded monitor alarm.

Current models appear to have solved the reliability problems and can be a valuable generator monitoring device.

Stator Winding RTD's and TC's. There is a strong tendency for owners of generators to want to operate based on winding temperatures. But the information obtained from a resistance temperature detector (RTD) or thermocouple (TC) located in the slot is only peripherally related to actual winding copper temperature. Typically these devices are embedded in the slot where they read a temperature average of surrounding media: copper (through a thermal insulation blanket), tooth iron, and cooling gas. Thus, these devices tend to read 20 to 30C lower than actual winding copper temperature.

On gas cooled armature bars, some major manufacturers locate sensors to read the outlet gas temperature from a few armature bars, typically one device per half-phase, or a total of six. These TCs can immediately identify a failed bar connection in a typical two-parallel-circuit bar structure.

On water-cooled windings, TC's are typically located in the water discharge from each bar or pair of bars. In many designs, a common outlet is used for a top and bottom bar, thus if only one of the bars is starved, or if no flow exists, the device may not be at all sensitive to the condition. Furthermore, on some designs the connection rings are cooled in series with selected armature bars, and it is important to separate the TC's into the two comparable groups when evaluating TC readings. The net result of all this complexity on these instruments is that it is difficult to determine if malfunction of the generator is occurring, and predicting maintenance needs on the winding becomes a challenge.

Electrical

Shaft Voltage. Because shaft currents can be destructive, where problems or concerns arise with respect to shaft voltages, it may be desirable to add sensors to detect the presence of shaft currents. If a reliable insulation system has been applied to the proper bearings, and if good shaft grounding is maintained, the probability damage due to current flow should be small. But shaft current measurement may be useful on machines where a concern exists.

Field Ground. Because either single or double field ground conditions can be hazardous to equipment and personnel, industry standards recommend that the unit be brought off-line in the event of field ground alarm. The focus is on the hazard associated with a double ground in a field winding. But it must be kept in mind that single grounds frequently are resulting from a break in the copper winding. In all such cases, the ground is likely to be associated with arc burning of the field forgings. This damage can be rapid and severe. Since this constitutes the potential of serious hazard to equipment and personnel, immediate trip may be advisable on detection of a ground in the field winding.

The field ground device offers no information as to where the ground might be within the field, or external to the field.

Field Interturn Short Detection (Flux Probe). Field interturn short-circuit detection equipment has been available for many years, but only in recent years has this device come into extensive use. The field must be removed to install a permanent probe, and the field slot wedges under the probe region must be non-magnetic in order to obtain a reading on the slot. Ordinarily the latter is not a problem.

The flux probe has turned out to be a highly reliable device, with little exposure to error or ambiguous readings. The device will determine the precise slot in which the short exists, and can detect a single turn short in a 30-turn coil. However, it offers no information as to the axial position of a short.

Although isolated shorted field turns are undesirable, their existence is not necessarily a serious concern. If generator operation is satisfactory, i.e., vibration levels satisfactory and field current not excessive, an immediate outage to perform the complicated and costly repair may not be warranted. In this situation, it may be practical to plan for turn-short investigation and repair at the next scheduled outage.

Collector/Brushholder Rigging. Significant arcing of the brushes will cause erratic readings on the field temperature instrumentation. But there is no direct monitoring of the performance of the collector, other than cooling air in and out. Collector performance must be monitored uniquely by direct daily observation. Because ongoing maintenance is needed to keep collectors functioning properly, they are a major cause for generator forced outages. There are particular concerns on those many smaller machines that do not have insulated cartridge brushholders that allow safe and easy brush maintenance. Especially is there a concern with those designs without constant pressure springs, as frequent contact with exciter voltage is necessary to keep spring pressure within correct limits. There are now direct drop-in retrofit brushholders available that incorporate insulated handles as well as constant pressure springs.

Partial Discharge (PD)

General. With good sensors and monitoring instrumentation it is possible to obtain considerable data on the PD which is occurring in the generator. Interpretation of the significance of the data is the most difficult aspect of partial discharge testing. Absolute readings may not be as helpful as trend-line evaluation on a given machine, or comparison of results on similar units using the same test equipment.

Equipment. Sensors for the different test approaches vary in design, assembled location and signal output. The most common location is on the line leads or iso-phase connections near the high voltage terminals of the stator. Sensors may also be located permanently in the ends of selected stator slots. A third less frequently used sensor is a radio frequency current transformer located on the neutral grounding lead. Sensors are not standardized between testing companies, nor within a single testing company. The instrumentation which measures the sensor outputs is also quite different between companies. Thus it is not possible at this stage of development to make a definitive, concise statement relative to sensors and instrumentation.

Analysis of Data. Testing company approaches to analysis of data is also not standardized. One major PD vendor has relatively simple procedures and instrumentation, and a very large data bank. This allows generator owner engineering personnel with nominal available training to collect and analyze their own data. The owner can then make general comparisons of a specific generator with a significant population of similar generators. If the generator in question has PD values exceeding most other similar units in the data bank, the owner is cautioned to investigate the source of the high readings. Other testing vendors prefer to take all data with their own personnel and instrumentation, and then forward the results to a central engineering staff for analysis. Both approaches have given good results in monitoring generator performance.

In several cases units have been brought off-line for investigation of high readings, and significant problems have been found and corrected before major damage occurred. While some judgment of winding quality is made on absolute readings, all vendors rely heavily on trending of readings over time on a given generator. A winding that is trending rapidly upward is monitored closely and depending on readings, may be disassembled for inspection.

Partial Discharge Capability. While PD testing is relatively new, it is being found very useful in monitoring stator windings for some critical deterioration mechanisms. Analysis of the data banks from those PD testing companies with significant amounts of data has been performed. These data indicate that serious maintenance issues have been found by PD readings on about 6% of generators with installed PD equipment. Compared with other instrumentation, 6% represents a rather high value.

As with other monitoring devices, a significant signal may not be seen until substantial deterioration to the winding has occurred.

Development and evolution of PD testing continues to move upward at a high rate, and it can be expected that PD testing will become continually more valuable as the technology continues to evolve and personnel skill levels continue to increase. However, as with other monitoring devices, a valid stator rewind decision cannot be made exclusively on the basis of partial discharge readings alone.

LIMITATIONS OF MONITORING CAPABILITY

Some deterioration mechanisms that are not assessed by monitoring equipment are discussed below. Note that these are important and common deterioration and failure mechanisms.

Stator Bar Vibration. Historically, vibration has been a significant root-cause of service failure. Vibration tends to be a fast-acting form of deterioration, with failure occurring in many months or a few years. Unless the vibration is generating PD or sparking, there is no instrumentation that monitors bar vibration. The vibration will simply continue, and in most cases at an accelerated rate, until the insulation is worn thin and fails, or the vibration results in fractured and failed bar strand copper.

Stator Bar Strand Header Water Leaks. Leaks in the strand header connection braze are a slow failure mechanism, resulting in failure after a few years operation, up to perhaps 20 years of service. These leaks have resulted in many stator partial rewinds and full rewinds, and a few in-service failures. The leaks may be as small as a few ounces of water a week. There is no monitoring device that detects insulation becoming wet due to these tiny leaks. There is some indication that EMI test may find a wet bar, but not until the insulation is damaged beyond repair. The leak will continue until in-service failure, or found by hipot.

Stator Winding Connection Cracks. These cracks tend to develop over relatively short periods of time, perhaps only 2 or 3 years of operation. The root cause tends to be resonance vibration. Vibration may start immediately upon placing the winding in service if the winding has not been properly designed and tested. Or the resonant vibration may develop over a few months or years, as the component natural resonant frequency decreases into the driving frequency range due to operating temperature and winding wear. Unless vibration detectors are installed, and are installed in the correct locations, there is no instrumentation which will detect this usually severe deterioration mechanism.

Field Coil/Turn Distortion. Distortion tends to develop slowly – many months to several years. There is no monitoring of this condition as it is developing. Eventually the deterioration may be detected by developing turn shorts, large increase in required field current, vibration, and/or field ground.

Field Turn Cracks. Turn cracks tend to be a slow developing deterioration mechanism – a few to several years. There is no detection until fracture occurs. At this point, current will continue to flow (as in a welding arc). The arc will quickly burn through the insulation and give field ground indication. But since the industry standards focus on the hazard of a possible second ground, the generator is unlikely to be immediately tripped. In which case the arcing and burning of the winding and forgings will continue until vibrations levels trip the unit, or components start to fracture, or the unit is removed from service for investigation.

Retaining Ring Corrosion and Cracking. There is no monitoring of this extremely serious deterioration mechanism. Deterioration may occur rapidly. In one recent case, just 18 months after being removed for the full NDE series, an 18/5 retaining ring failed catastrophically. There was no warning of impending danger.

Forging Cracks. All of the rotating field forging components are subject to possible cracking. In particular, cracks are being found on the field forging under the retaining ring shrink fit and at the body axial centerline. These cracks seem to focus on specific designs of specific manufacturers. In general, there is no detection capability for such cracks until the crack becomes so large as to affect field operating vibration.

CONCLUSION

Accurately predicting the timing and scope of all needed maintenance on an operating generator is not possible with the present state of the art of generator monitoring, inspection and test. However, skillful use of all available knowledge on a specific generator can minimize the maintenance costs required to maintain a high level of reliability on the generator. To accomplish this goal, good operation and maintenance records are vital, as well as attention to all available monitoring information, performance of a high caliber inspection, and judicious use of a selected set of appropriate off-line tests.

But it is advisable to keep in mind that even with the best of the monitoring systems, generators remain with little or no detection capability for several of the more common and serious deterioration and failure mechanisms, some of which are discussed above.

Thus extension of periods between outages should reflect the known information on a specific generator: operating hours, importance of the unit to the system, and condition assessment using all of the above mentioned tools. The historic five years between inspections may not be appropriate. But on the other hand, an arbitrary and long period between generator inspections may result in neither reliable life nor low maintenance cost.