

“Generator Field Winding Shorted Turns: Observed Conditions and Causes”

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Generatortech, Inc.’s experience in the field of generator rotor shorted turn detection has helped in developing an understanding of the types and causes of shorted turns, the general frequency of occurrence and the eventual disposition of the problems.

In the past two decades, the use of on-line testing of generator rotor windings has surged. The benefit of on-line testing has been recognized throughout the power generation industry and the installation of air-gap flux probe monitoring equipment has become almost standard procedure for utilities and OEM’s. On-line testing for field winding shorted turns gives operators positive answers that can be used in trouble shooting generator operational problems and helps determine whether rotor rewinding is required. Because of the perceived value of on-line testing, most first time users soon embark on programs to retrofit their entire fleets with air-gap flux probes.

The Frequency of Generators Operating with Shorted Turns

During the past 13 years, Generatortech has acquired data from a large number of generators. Analysis of the data allows us to make some general observations about the prevalence of shorted windings in operating generators. Naturally, our data is skewed somewhat due to the fact that we are frequently called on to review data from machines with problems. However we analyze many non-problem generators as well.

It would appear that in excess of 50% of installed generators are operating with shorted turns. (Fig. 1)

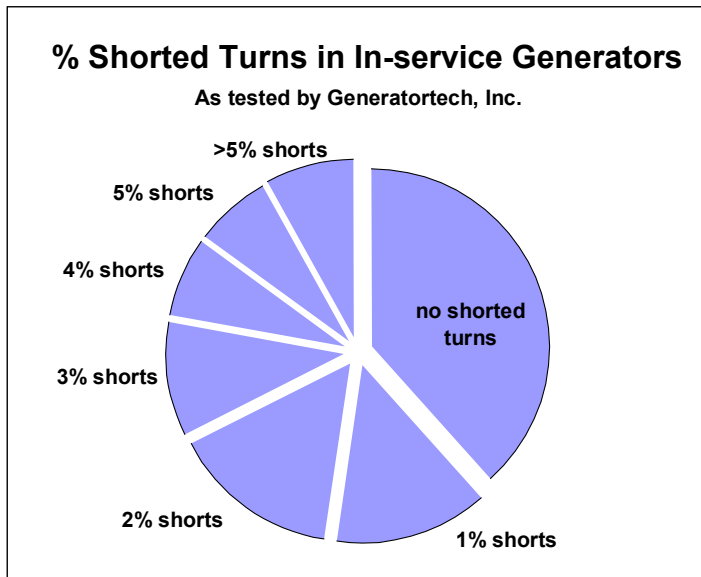


Figure 1

The majority of the generators operating with shorted field windings tend to have no operational problems related to the shorts. Operational problems normally begin to be experienced when the percentage of shorted turns exceeds 5% of the total number of turns. Eight percent of the cases reviewed by Generatortech over the last 13 years have greater than 5% shorted turns. The problems experienced by these machines range from *excessive vibration* to *reduced load capability* to *forced outage*.

The Nature of Operational Problems

Vibration

The most likely problem with operation in the presence of shorted field windings is excessive vibration. Vibration in *two pole* rotors occurs due to uneven heating of the rotor forging. When turn shorts cause an unequal distribution of active turns between poles, the amount of heat (I^2R losses) between poles is also unequal. This unequal heating will cause the rotor to bow and thereby introduce vibration. The coil location of turn shorts is the key to determining if the rotor will experience vibration problems. In general, unequal turn distribution in smaller coils (1,2, 3) will have a greater effect whereas unequal turn distribution in the larger coils will have a lesser effect. For instance, one could expect vibration problems with only 5% shorted turns in the # 1 coil of one pole of a seven coil rotor where no vibration problems would be expected if the same percentage of turn shorts were present in the # 6 or # 7 coils. Figure 2 depicts the rotor bow due to shorted turn conditions.

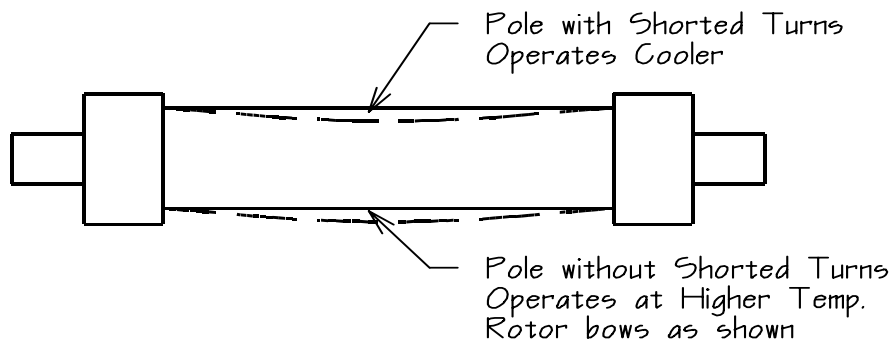


Figure 2 - Rotor Bow Due to Shorted Turns

One telltale sign of shorted turn induced vibration is the variation of vibration magnitude on increase in load. Increased field current increases differential heating on the rotor forging, increasing bowing and subsequent vibration. Some machines are observed to show the opposite effect. That is, the rotor vibration decreases with increase in load. When this is the case, it is clearly the effect of compensation balancing that has been done to offset shorted turn induced vibration levels at load. The balancing weights were placed to compensate for rotor bowing at full load, but actually throw the balance off at lower loads when rotor bowing is not as great.

Prior to the widespread use of on-line air-gap flux probe testing, balancing programs would be performed to compensate for shorted turn induced vibrations. If the results of the vibration testing indicated that static weights were required at the pole centerline, it could be suspected that shorted turns were the problem. As an example, one recently analyzed rotor was found to have shorts in the #1 coil of one pole and the #2 coil of the opposite pole. Upon removal, the rotor was found to have two sets of balance weights in place. One set on each pole had been placed to compensate for the shorted turn induced

vibration. The balance weights had been applied at different times to compensate for shorted turn conditions that had developed.

Vibration in *four pole* rotors is due to primarily to magnetic unbalance. As opposed to two-pole rotors, where all flux leaving and entering the forging remains symmetrical, four poles rotors will not maintain symmetry in the presence of shorted turns. Small percentages of unsymmetrical shorted turns will result in induced vibration.

Diminished Capacity

Excitation systems for generator fields have a certain amount of excess capacity. However, fields with numerous shorted turns can sometimes require reducing full load values of MW's and/or MVAR's. In the cases that we have observed that require load reduction, shorted turn indications are on the order of 5-10% or greater. Machines in this category are candidates for a rotor rewind at the earliest opportunity.

Increased Field Current

The output of a generator is a direct function of the amp-turns values of the rotating field. Any reduction in the number of active turns in a field will require a corresponding increase in the excitation current in order to maintain the amp-turn value. These increases in field current are a direct cost to the power producer. Likewise, increases in field current result in higher hot spot temperatures in the field winding. The increase in hot spot temperature accelerates the breakdown of insulation systems and increases the effect of temperature related deformation of the windings.

Both the increase in losses and temperature can be calculated to help determine when corrective action should be made.

Retaining Ring Damage

The most serious condition caused by shorted turns is arcing damage to the retaining ring. The cases we have observed are those where the top turn of one coil comes into contact with the top turn of an adjacent coil. The arcing from this contact will burn through the retaining ring insulation and cause a defect in the retaining ring itself. A structural defect in the retaining ring is a very serious condition requiring immediate shutdown due to the danger to plant personnel. This type of shorted turn condition will give either a momentary or sustained field ground indication. Once a ground indication is found, flux probe testing should be conducted to determine if shorted turns are present. Any flux probe test that shows that entire coils are out of the field circuit should lead to the suspicion that retaining ring damage may have occurred.

Figures 3, 4 and 5 relate to our observations of cases of coil-to-coil shorts. Figure 3 shows the locations that coil-to-coil shorts have been observed. Figure 4 is a sample of flux probe test data showing a coil-to-coil short. Figure 5 is a photo of a short between coils 6 and 7 of a seven-coil field.

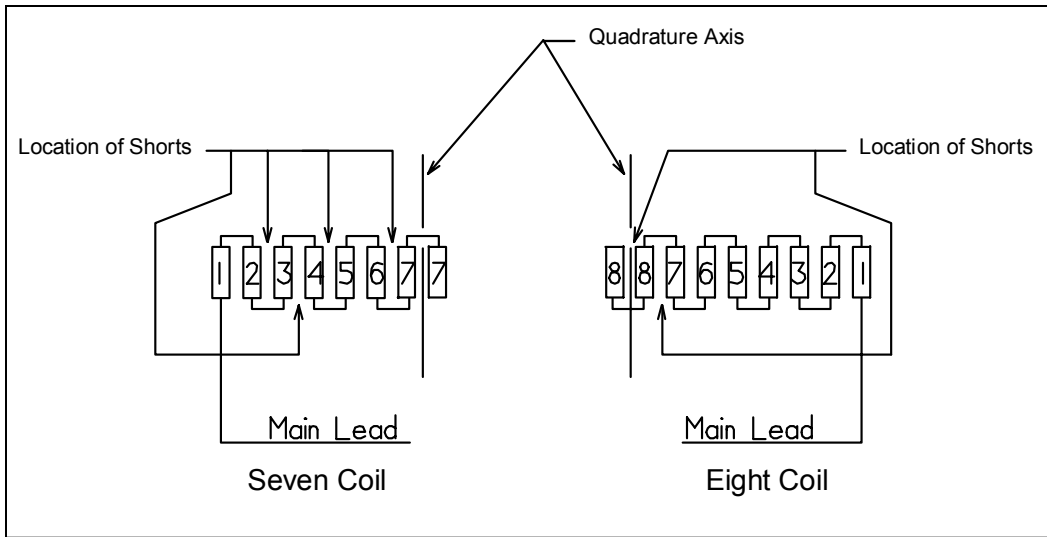


Figure 3

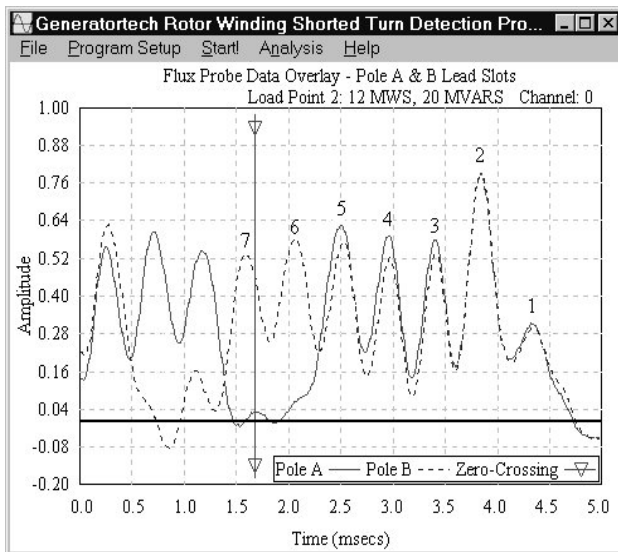


Figure 4 – Coil 6 and 7, Pole A shorted

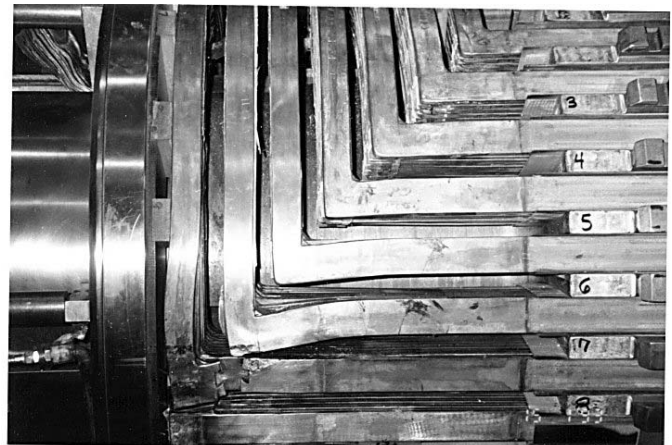


Figure 5-Elongated Coil 6 contacts Coil 7

The Causes of Shorted Turns

End Strap Elongation

End strap elongation is the result of frictional forces between the top turn end straps and the retaining ring insulation. If the coefficient of friction between the retaining ring insulation and top turns is too great, the expansion of the retaining ring due to centrifugal force will stretch the top turns beyond their yield point. At the start of the next Start/Stop cycle, the end strap(s) are slightly longer than they were at the start of the previous cycle. After a number of cycles, the end straps have expanded to a point where they come into contact with turns of an adjacent coil. Higher rotor vibration will normally occur and a jump in field current will be experienced. On a seven-coil field, for example, two coils shorted out will require a 14% increase in field current. End strap elongation problems can be mitigated by careful selection of insulating materials and/or the application of intermediate layers of material that decrease the coefficient of friction.

Body Copper Foreshortening/Soft Copper

Body copper foreshortening is a result of the body copper being unable to expand freely along the length of the rotor. In general, the copper conductors will expand faster and further than the rotor body. Blocking arrangements and friction due to centrifugal forces tend to act against the free expansion of the body copper. When the copper cannot fully expand, it tends to compress within the slot in the rotor body. When these compression forces exceed the allowable material stress, the material deforms within the slot. The end result is a shorter length of copper at the end of the Start/Stop cycle. After a number of cycles, the deformed copper can cause cracking in the turn insulation within the body or cause serious misalignment of the end turns. If end turn misalignment is severe enough, the stacked turns of the affected coil cannot support its own weight under centrifugal force. Most copper foreshortening problems are the result of using materials with insufficient yield strengths.

Blocking Problems

Although not as prevalent as other turn short causes, end-winding blocking problems have been the cause of a number of shorted rotor winding conditions that we have observed over the years. The purpose of end-winding blocking is to maintain the alignment of the end-windings during operation. The cases observed by Generatortech are either missing blocks or blocks that have moved out of position as shown in Fig. 6. Most blocking arrangements have been developed and/or refined by manufacturers through experience with past problems. Service organizations should pay close attention to the manufacturers recommendations for blocking installation during rewinding.

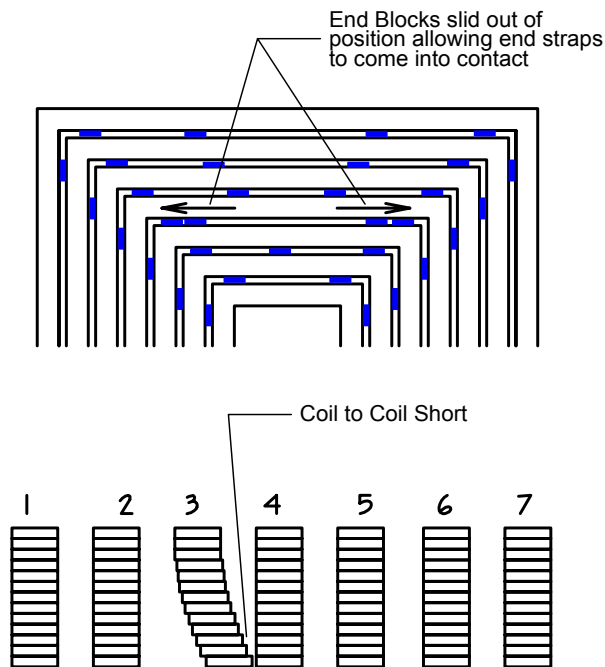


Figure 6 –Coil Short due to migrating end blocks

Foreign Material Contamination/Moisture

Manufacturers have by and large addressed the root causes of the failure mechanisms discussed above over the years. Harder or stronger coppers for windings, new insulation materials, improved blocking patterns, and interface materials with lower coefficients of friction have all been introduced to address the problems. One type of shorted turn development mechanism has not been adequately addressed to date. These are the shorted turns due to foreign material/moisture. Machines with this type of shorted turn condition commonly have increasing numbers of shorted turns over time. A typical example of a field winding with progressive shorted turns is shown in Table 1. As can be seen, this machine progressed to an unusable condition in a short period of time.

Coils with Shorts	Year 1	Year 2	Year 3	Year 4
Pole B				
Coil 2			1-2	2-3
Coil 5			1-2	1-2
Coil 7		1-2	2-3	3-4
Pole A				
Coil 5				1-2
Coil 6				1-2
Coil 7	2-3	2-3	3-4	4-5
Total Percent Shorts	1.7 – 2.2%	2.2 – 3.7%	5.0 – 8.1%	8.1 – 13.2%

Table 1 – Progression of Shorted Turns on Sample Machine

Shorted turns due to foreign material contamination, including moisture are probably the most prevalent of cases found in the field today. Although the failure mechanisms are not yet fully understood, certain indicators are becoming increasingly common. The main substances believed to play a significant role in the development of shorted turns are moisture, lead carbonate and hydrocarbons from gas turbine exhaust. Lead carbonate is derived from lead based solder used by some manufacturers to assembly coolers. The lead, combined with carbon dioxide from purging and moisture contributes to the formation of lead carbonate. Gas turbine exhaust products are obviously derived from the combustion of gas that drives the turbine and are only of concern in air-cooled generators.

These contaminants, which are dust particles, are moved throughout the generator with the cooling gas. The contaminants are then deposited in most locations around the inside of the generator. Because of the physical arrangement of the components, the area under the retaining ring becomes a collection area of high concentration. In the presence of moisture, this now represents a problem. Although non-conductive in their dry state, the contaminants will absorb moisture and create a low resistance creepage path.

One area where this contamination based creepage path has created a problem is at the inner surface of the retaining ring insulation. Figure 7 shows the ventilation circuit in one generator design configuration. The gas from the axial fan flows directly under the retaining ring to the end winding copper.

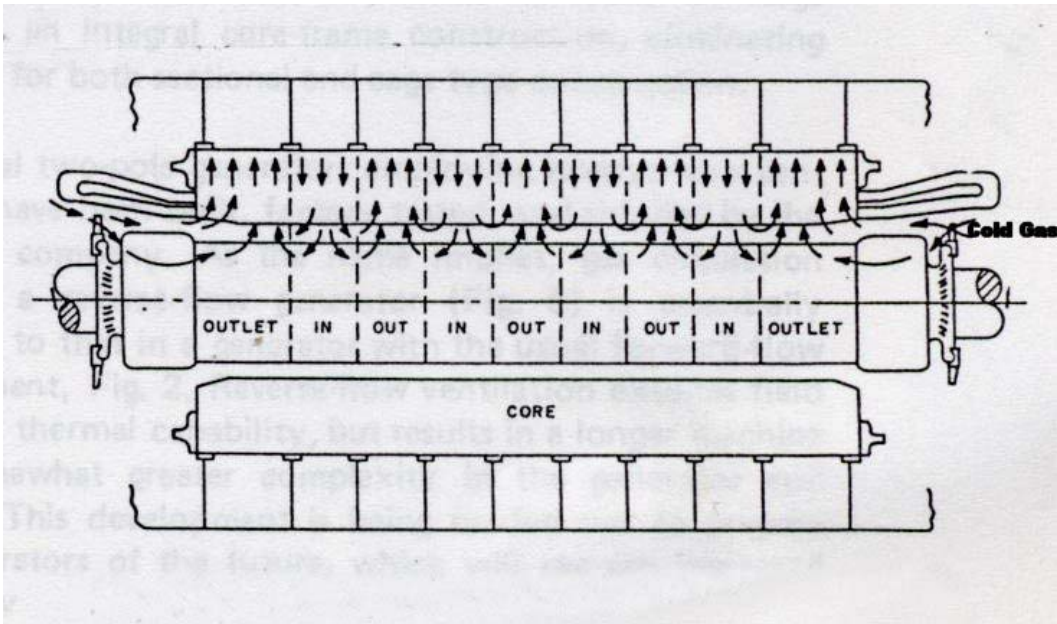


Figure 7 - Ventilation Circuit

Contaminants are impinged on the inner retaining ring insulation surface due to centrifugal forces. Moisture, introduced to the cooling gas, by any number of ways, will be absorbed by the contaminants creating a conductive bridge between coils. Creepage paths in this location have caused coil-to-coil failures. (Fig. 8 and 9) On air-cooled generators, hand wrapping of the top one or two turns may aid in precluding this type of failure.

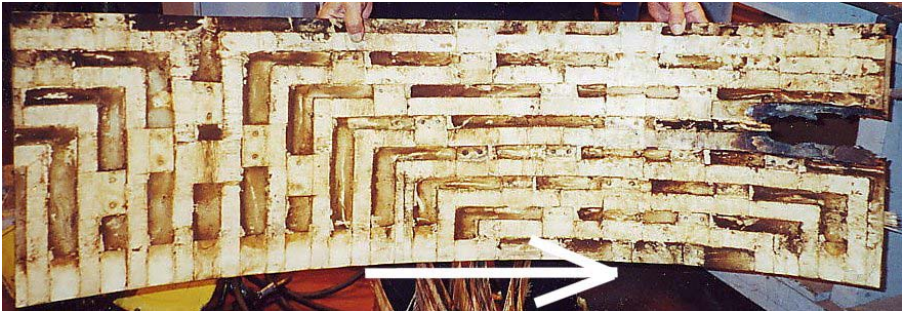


Fig. 8 – Burned R.R. Insulation Contaminant Induced Coil-to-Coil Short



Fig. 9 – Blocking from Fig. 7 failure

Figures 8 and 9 show the after effects of a Coil 4 to Coil 5 short to the retaining ring. Both coils were shorted out. Figure 8 is the inner layer of the ring insulation from an air-cooled generator. Similar conditions have been observed in hydrogen cooled generators. The light colored areas are the outlines of the end windings and blocks. The dark areas are contaminants deposited by centrifuge action on the retaining ring insulation surface. Note the rotational direction arrow and note that the heaviest buildup of

contamination is at the leading edge of the blocking. It has been our experience that coil-to-coil shorts due to contamination normally occur at the leading edges of the blocks.

The contamination/moisture problem also occurs between individual turns in the end-winding region. Although the mechanism that deposits the contamination is not fully understood, it is likely that a combination of a number of physical effects is at play. The physical evidence of contamination between turns, however, is clear. The most likely scenario to fit the observations we have made is that condensed moisture is drawn into the space between turns during cool down by capillary action. This capillary action also draws contaminants into the space. Moisture condenses on critical areas during cool down when the dew point of the cooling gas is higher than the surface temperature copper windings. (Figure 10)

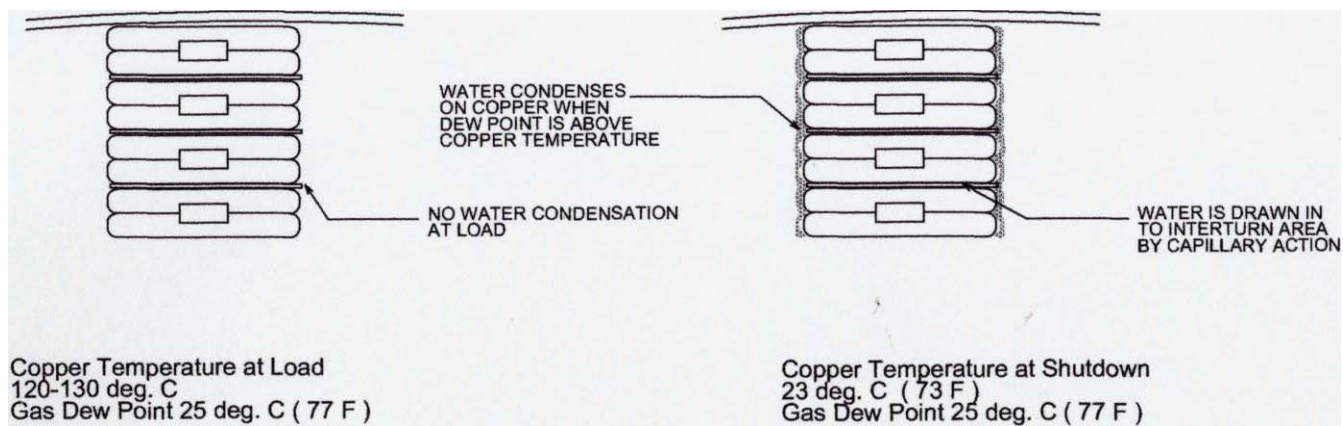


Figure 10 – Condensation of Water on End Windings due to High Dew Point of Cooling Gas

Once the contaminants are in place between the turns and the generator is put back in service, very high stresses in the interturn insulation, at the contaminant location, are developed. The presence of moisture further degrades the fiberglass interturn insulation. The combination of degraded insulation, high stress and a conductive path of moist contamination provides a very short turn-to-turn creepage path. (Approx. 0.015”) which will result in a spot weld between turns. The heat generated during the “welding” burns the interturn insulation. Figure 11 depicts 4 different sections of interturn insulation from shorted turn locations.

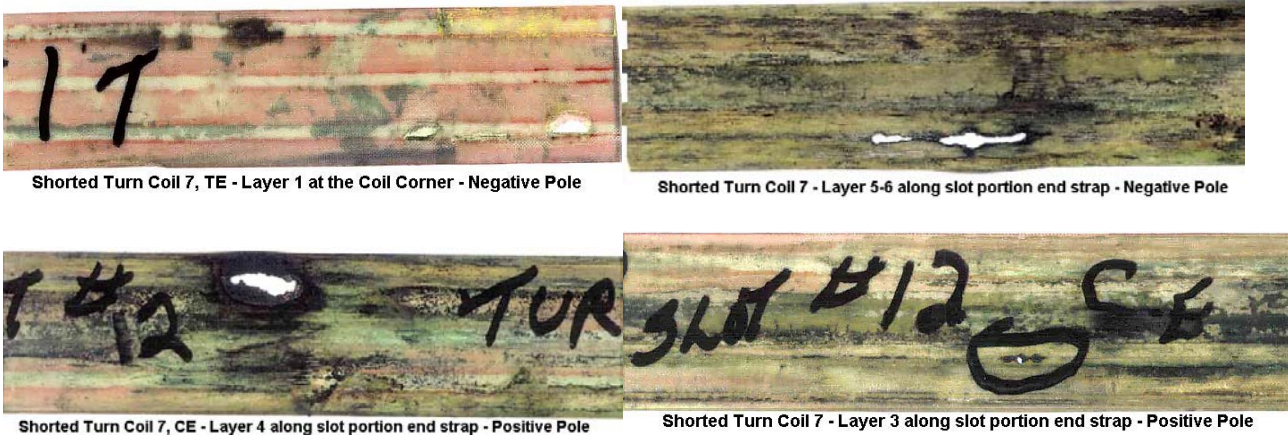


Figure 11 – Samples of Interturn Insulation with Shorted Turn Evidence

Once the small initial spot weld is formed, it is frequently broken due to relative turn-to-turn movement during start/stop cycles. Because of an oxide coat that forms on the surfaces of the broken initial weld, a subsequent spot weld will occur adjacent to the original location. This process can continue causing larger and larger holes in the interturn insulation.

Our experience to date shows that the presence of moisture in the cooling gas is a significant problem when faced with the presence of contaminants. In hydrogen-cooled generators, close attention to the operating dew point should be made. The dew point should be controlled to be below 7.5⁰ C (45.5⁰ F) at the operating hydrogen pressure. Consideration should also be given to utilizing hydrogen dryer system if necessary.

A recent case presents a dramatic relationship between moisture and the development of a very high level of shorted turns. The generator in question was producing about a gallon of water per day from the H₂ detrainning trap. Flux probe tests showed that the generator was suffering from a large number of shorted turns that were distributed among many of the coils in the rotor. The rotor was recently disassembled during an outage to rewind the rotor and over 100 turn shorts were in evidence. Most of these turn shorts were located in the rotor body (Figure 12), which is in contrast to the other generator that suffered severe turn shorts related to moisture contamination.



Figure 12 – Samples of Interturn Insulation with Shorted Turn Evidence

Recommendations

Air-Gap Flux Probes

Our first and foremost recommendation in dealing with problems related to shorted turns in generator field windings is to make sure that you have the capability to perform on-line testing. The best method to do this is by installing an Air-Gap flux probe. Air-gap flux probe testing offers the distinct advantage of being able to detect shorted turns at operating speed and temperature. Installation of a probe must be done during an outage with the rotor removed. Once the probe is installed, data collection equipment and analysis software is available that allows you to evaluate your field and determine the number of turn shorts and the coil location.

Many times at Generatortech, we receive inquiries from generator operators who have experienced step changes in vibration or a field ground alarm and would like to know if they can test for shorted turns, but their machines are not outfitted with probes. They are obviously disappointed when they are informed that the definitive method to test for and quantify shorted turns is not available to them. Seldom do these operators pass up the next opportunity to install an air-gap flux probe.

Maintain Moisture Control in the Cooling Gas

Our investigations of turn insulation failures have clearly shown that moisture in the cooling gas is a significant problem. Moisture combined with contamination can create creepage paths leading to either turn-to-turn shorts or more significant coil-to-coil shorts. Generatortech considers that it is prudent to be aware of your operating dew point in hydrogen gas and maintain it at or below 7.5°C (45.5°F). This will assure that water will not condense on critical components when the generator is being shut down.

Investigate Failures and Causes

Once shorted turns have been identified and a decision to rewind has been made, a concentrated effort to determine the cause of the shorts should be made. The operator should specify to the service contractor performing the rewind that adequate care be taken in the disassembly to assure that the shorts are found. Disassembly work should be well documented with photographs. Retaining samples of turn insulation can also be useful in investigating the cause of failure.

Once the shorted turns have been found and characterized as to their cause, decisions can be made to determine if corrective action, either in the rewind procedure or operations, is required.

Periodic Inspection Under the Retaining Ring

Generatortech considers it good practice to perform boroscopic investigation under the retaining ring at every opportunity. Utilizing a boroscope to check the condition of the end-windings is a quick and easy way to identify pending problems. Significant distortion found under the ring is a cause for concern and may require remedial action prior to the rotor being put back into service.

Conclusion

Shorted rotor windings are a frequent occurrence in the power generation industry. In most cases, the shorted turn conditions do not present operational difficulties. However, in a significant number of cases, shorts in the field winding cause problems that require remedial action including reduced generator loading, forced outages or accelerating planned outage schedules.

Operators of generators should have the ability to perform on-line testing for field winding shorted turns and perform the testing periodically to develop trending information.

Operators and service companies should also attempt to uncover the causes of shorted turns that have been found in order to prevent reoccurrences.