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Generator Rotor Thermal Sensitivity — Theory and Experience

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Introduction

Generator rotor thermal sensitivity is a phenomenon which may occur on the generator rotor causing the rotor vibration to change as the field current is increased. This has occurred on generator fields of all manufacturers at one time or another. The thermal sensitivity can be caused by an uneven temperature distribution circumferentially around the rotor, or by axial forces which are not distributed uniformly in the circumferential direction. The primary driver of this second cause is the large difference in coefficient of thermal expansion between the copper coils and the steel alloy rotor forging and components. If the rotor winding is not balanced both electrically and mechanically in the circumferential direction, the generator rotor will be unevenly loaded which can cause the rotor to bow and cause the vibration to change. In most cases, a thermally sensitive rotor will not prevent a generator from running, but may limit the operation at high field currents or VAR loads due to excessive rotor vibration.

This paper will discuss the types of thermal sensitivity, thermal sensitivity mechanisms and causes, and testing to diagnose for a thermally sensitive field. The paper will conclude with examples of thermally sensitive generator fields, corrective actions taken to eliminate the thermal sensitivity and recommendations for fields that are thermally sensitive. An appendix is included which answers commonly asked questions regarding thermally sensitive fields. (Note: the terms generator rotor and generator field are used interchangeably throughout this paper.)

General Generator Rotor Vibration

The vibration objective for a generator rotor is for the vibration to remain within acceptable limits and remain smooth at all operating speeds and under all operating conditions at rated speed within the capability curve. Inspection of the capability curve in *Figure 1* shows three distinct regions. Region A-B is limited by field heating, region B-C is limited by armature heating and region C-D is limited by armature core end heating. In general, a thermally sensitive field is not affected when operated in regions B-C or C-D since the field current is not high and, therefore, the rotor does not reach rated temperature.

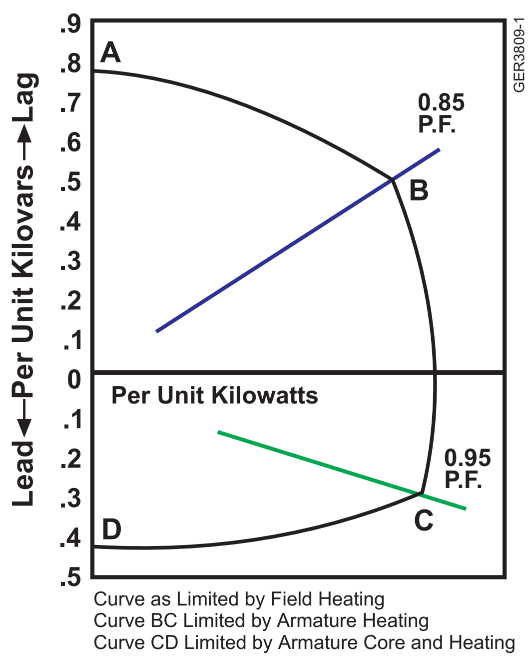


Figure 1. Typical reactive capability curve

However, as the field winding approaches the generator rating point at B, a thermally sensitive field will respond to the increase in field current by changing its vibration. This change might be in the form of a vibration increase or decrease, or a change in phase angle. All fields have some degree of thermal sensitivity; however, if the vibration levels remain within acceptable limits (2-3 mils Pk-Pk at the journals), thermal sensitivity is not normally an issue. It becomes an issue when the vibration exceeds acceptable levels during operation within the capability curve.

There are many causes of high vibration on a generator field. The most common are mechanical unbalance, thermal sensitivity, misalignment and bearing degradation. Other causes include rubbing, bent overhangs, rotor stiffness dissymmetry, out-of-round journals and other design deviations caused by abnormal in-service operation. Each of these causes has a predominate frequency and a characteristic response. The cause of the vibration can be diagnosed by a thorough analysis of the vibration data. For example, the most frequently observed cause of vibration is mechanical unbalance. This type of vibration is synchronous; that is, the vibration frequency equals the rotor rotational speed frequency. It does not respond to changes in operating conditions, such as generator load or field current. In most cases, unless the unbalance is excessive, mechanical vibration can be corrected by balancing. The remainder of this paper will only discuss generator field thermal sensitivity because it is generally the least understood and is relatively common.

Generator Rotor Thermal Sensitivity

A thermally sensitive rotor is characterized by a once-per-revolution frequency response signature due to a change in the rotor balance arising from the rotor bow. If the total vibration of the field stays within acceptable limits, the field is not considered "thermally sensitive." Vibration performance is frequently plotted on a polar chart, such as that shown on *Figure 2*, because vibration is characterized by amplitude and phase angle. If the vibration vector stays within the 2 or 3 mil circle, or whatever is chosen as an acceptable vibration level, the vibration is not considered to be a problem. This is true even if the phase angle changes and the vibration moves around the interior of this circle. The change in vibration and phase angle within the polar plot from the starting operating point to the end operating point is called the thermal vector.

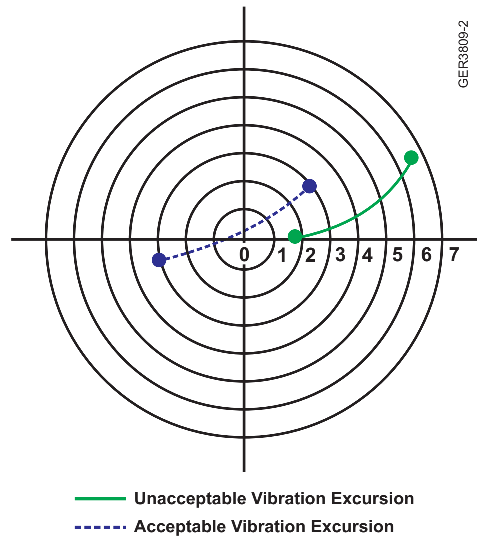


Figure 2. Typical polar plot showing a thermal vibration vector

There are two types of thermal sensitivity: repeatable (or reversible) and irreversible. Both types vary with field current; however, the reversible type follows the field current as it is increased and decreased. For example, if the vibration on a field increases from 1 mil to 3 mils as field current is increased and then decreases in the same manner as the field current decreases, then the thermal sensitivity is considered to be reversible. If this is the case, in many instances the field can be compromised balanced so that the thermal vector passes through zero and the maximum vibration remains within acceptable limits.

However, if the vibration increases as the field current is increased but does not respond to a decrease in field current, then this type of thermal sensitivity is referred to as irreversible or slip-stick. If this situation occurs, the generator frequently must be taken off-line and brought down to turning gear speed to unlock the forces that induced the rotor bow. This type of thermal sensitivity is particularly troublesome and, in a few cases, there were no effective remedies to relieve this condition without disassembly of the winding. As a result, a field winding with this condition will limit load options for the owner since the generator will not be able to operate over its full electrical capability. *Figure 3* shows a plot of an irreversible field where the vibration increased with field current but locked in at the high vibration level when the field current was removed.

Testing for Thermal Sensitivity

If a rotor is suspected to be sensitive to field current, there are tests that can be performed to confirm this and to ensure that the condition is not due to megawatt loading of the turbine generator set. One of the tests that is important is a flux probe test. This will give a diagnosis of the condition of the field winding turn insulation and indicate which coils have shorts in the field winding. In most cases, the test will detect the number of shorts present in each coil and in which pole the shorts are located. (It should be noted that the presence of magnetic wedges may prevent accurate detection). This is an extremely useful diagnostic test since winding turn shorts are the most common cause of thermal sensitivity.

The other test that should be performed is one to isolate the effects of megawatt loading from VAR loading on the field. Vibration changing as a function of megawatt loading is not a thermal sensitivity mechanism. Megawatt loading may result in rotor vibration excursions as a result of bearing alignment shifts. The three-part thermal sensitivity diagnostic test is shown graphically in *Figure 4*.

The first part of the test is to apply constant field current to the field and then to vary the megawatt loading on the generator from 15–60%. Detailed vibration readings as well as other key generator parameters, such as generator voltage, currents and temperatures, should be monitored throughout all stages of the testing. Any significant changes in the generator vibration during any part of the testing should

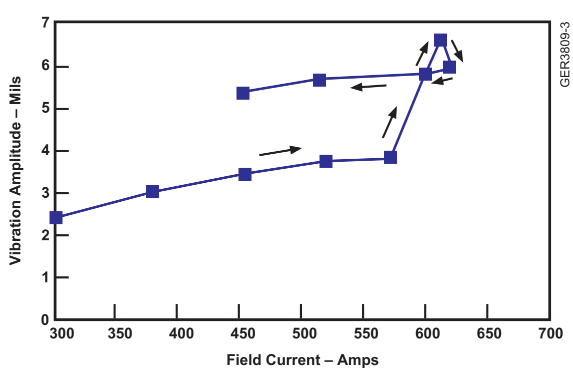


Figure 3. Vibration data showing irreversible thermal sensitivity

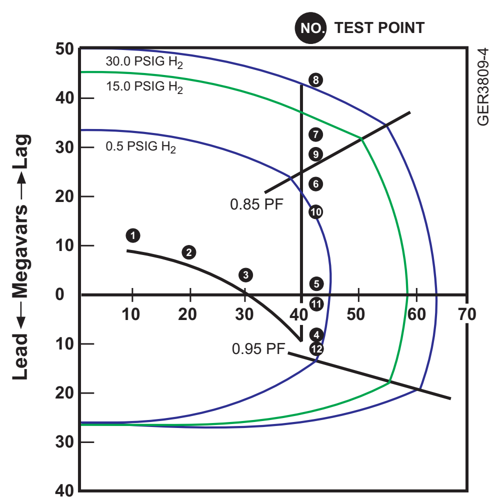


Figure 4. Testing procedure for thermally sensitive field

be noted. This first part of the testing would correspond to moving from point 1 to point 4 on *Figure 4*.

The second part of the test is to apply a constant megawatt load to the generator (approximately 60–80%) and then raise field current to maximum rated field current. Each test point should be held until steady state is reached. If the unit is unable to reach maximum field current attainable without a vibration excursion, the series should be repeated but be limited to the maximum field current attainable without exceeding acceptable vibration limits. Again, detailed test data should be taken. A significant change in vibration or phase angle with an increase in field current at constant megawatt load would indicate that the field is thermally sensitive.

This test should then be reversed; that is, decrease field current from its maximum value back down to the starting point. Again monitor all test data. If the vibration and phase angle return to their initial values, then the type of thermal sensitivity can be considered reversible and, in many cases, can be overcome with a compromised balance that moves the thermal vector through zero so that vibration limits are not violated. However, if the vibration levels do not return to the original values and remain high, then this field vibration is considered to be irreversible and corrective actions may involve modification to the field. The flux probe and thermal sensitivity tests are very important in monitoring and diagnosing a thermally sensitive field. GE offers specialized equipment and trained personnel to work with customers in performing this testing.

Causes of Thermal Sensitivity

It was mentioned previously that one of the prime reasons that generator fields are thermally sensitive is because of the large difference in coefficients of expansion between the copper conductors that make up the winding and the steel field forging. Whenever field current is applied, the copper tends to expand more than the steel forging. As field current is increased to large values that approach the rating of the unit, the difference in expansion between the copper and the steel can become significant and the forces generated large. If these forces are not distributed uniformly around the field circumferentially, they can cause the generator rotor to bow. This bowing is what causes the thermal sensitivity and it varies as field current is increased or decreased. This principle is simple, but because of the complex configuration of a generator field, there are many things that can influence and affect the susceptibility of a given field to thermal vibration. The following are some items which by themselves or in combination can cause a generator field to be thermally sensitive.

Shorted Turns

Shorted turns occur when there is a breakdown in the insulation between turns. They are the most common cause of thermal sensitivity. Depending on the distribution and number of shorted turns, there may or may not be an operating problem. Shorted turns in the coils adjacent to the poles are most significant. When there are shorted turns in a field, the pole of the field that has the higher number of shorted turns, there may or may not be an operating problem. Shorted turns in the coils adjacent to the poles are most significant. When there are shorted turns in a field, the pole of the field that has the higher number of shorts has a lower electrical resistance and, as a result, will be at a slightly lower temperature than the opposite pole. Therefore, the higher temperature pole will elongate in the axial direction more than the other pole and, as a result, the field will bow in that direction. (*See Figure 5.*) As field current is increased, the amount of bowing will increase and the field vibration and phase angle will be similarly affected. Shorted turns result in a reversible thermal sensitivity.

Blocked Ventilation or Unsymmetrical Cooling

Blocked ventilation, like shorted turns, can significantly affect the circumferential thermal balance of a generator field. This could occur if a foreign object were introduced into the field and disrupted the normal ventilation and cooling of the field. Direct-cooled windings are cooled by the cooling medium passing directly through holes that are designed and manufactured into the copper. A shifting of the insulation or plugging of these cooling passages could cause these fields to become thermally sensitive. The uneven temperature distribution would affect a field in the same manner as shorted turns. This type is reversible.

Insulation Variation

If a field is not wound uniformly from pole to pole in regards to insulation thickness and buildup, binding and uneven friction forces in the coil slots and under the retaining rings could result. Should this occur, the field coils might not be free to expand uniformly in the axial direction as field current is applied and, as a result, the field forging may be loaded unevenly and cause the field to bow. In this case, the coils with the highest friction or the ones that are binding will apply more load to the forging in the axial direction and cause the field to bow in that direction. Increasing the field current will cause the bow in the field to increase further. In some cases, the conductors in some slots may slip and cause a step change in the vibration. In other cases, the binding of the coils will persist and the rotor will remain bowed even after the field current has been removed. This condition has occurred on fields that have been in service for many years as the insulation has broken down or migrated and shifted in the slots. Care must be taken in the assembly of new fields and during field rewinds to ensure that the insulation is installed uniformly and according to proper design procedures and clearances. (*See Figure 6.*) In many cases, this type of thermal sensitivity is considered irreversible or slip-stick.

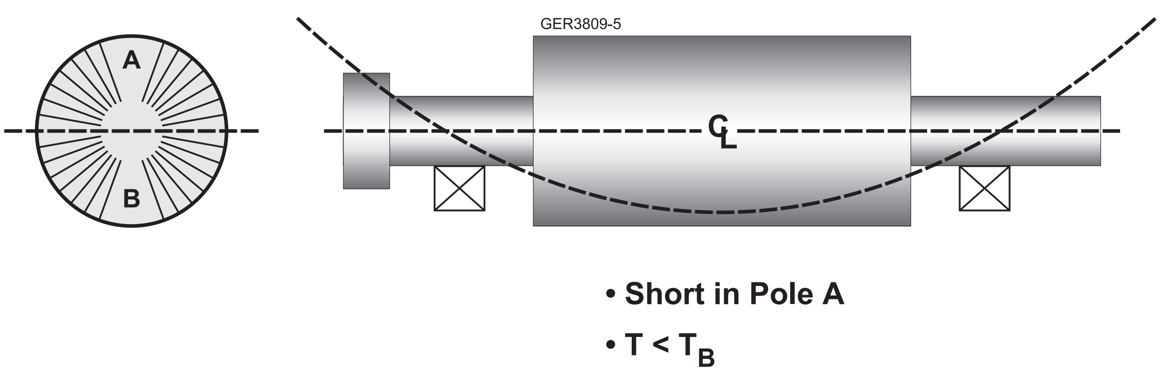


Figure 5. Temperature induced thermal sensitivity

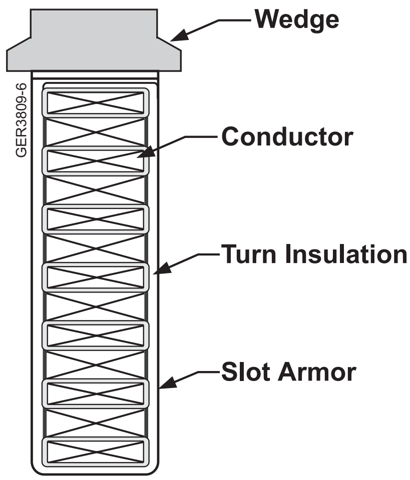


Figure 6. Typical slot configuration of a generator field

Wedge Fit

Generator rotors can become thermally sensitive if wedges are modified or replaced. This is especially true when only a portion of the wedges is replaced, such as a slot or two-in-one pole. If the tightness of the wedges does not remain uniform, then it can cause binding in the axial direction which could lead to bowing of the rotor. If wedges are replaced or modified, it is very important that this be performed carefully so that all wedges in the field have the same clearances and fit. (*See Figure 7.*) This condition usually produces irreversible thermal sensitivity.

Distance Block Fitting

The distance blocks that provide the spacing in the generator field end windings must be spaced and fit properly. Uneven spacing and/or fitting can cause non-uniform forces to be transmitted into the field forging through the retaining rings or centering rings and, like all the other possible causes of thermal sensitivity, make the rotor bow and change dynamic characteristics. (*See Figure 8 and Figure 9.*) Uneven distance block fitting will cause reversible vibration.

Retaining Ring/Centering Ring Assembly Movement

Significant forces from the field coils are transmitted into the retaining ring and centering ring as field current is increased. If these rings are not installed properly, the field can be non-uniformly loaded and cause the rotor to bow. Also, if the shrink fit is insufficient, these rings can move on their shrink fits and cause a change in center of mass of the retaining rings. In this case, the field vibration signature will be

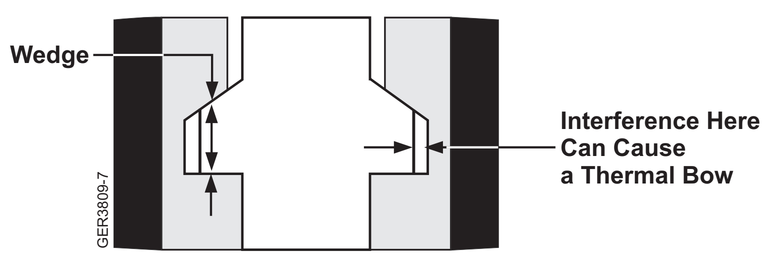


Figure 7. Coil wedge fitting

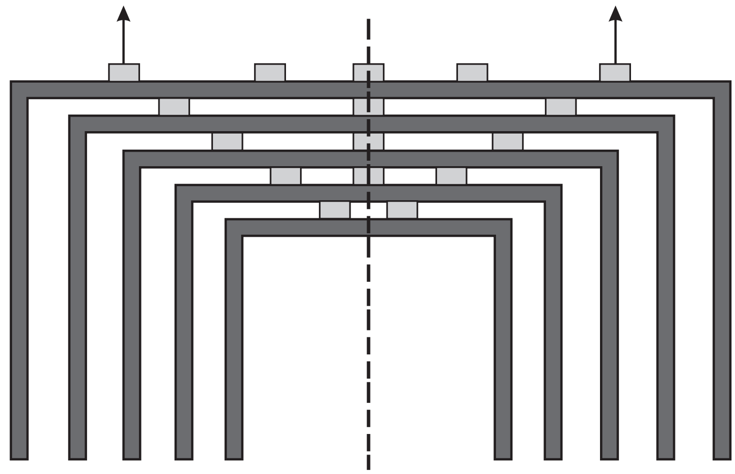


Figure 8. Generator end blocking design

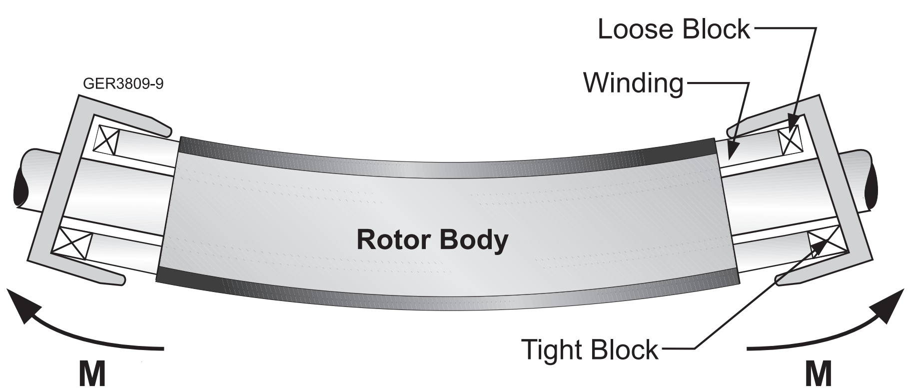


Figure 9. Bowing caused by uneven blocking

variable and the problem cannot be resolved until the light shrink is corrected.

It should be noted that rotors that have spindle-mounted retaining rings as compared to those that are body-mounted are much more susceptible to thermal sensitivity since the retaining rings are mounted on the more flexible spindle section of the shaft. Because of this, for the same amount of axial force, a spindle-mounted rotor will bow to a much larger extent. (*See Figure 10 and Figure 11.*) Movement of the retaining ring and/or centering ring can cause reversible and irreversible vibration.

Tight Slots

This rare condition will usually occur if, during a field rewind, the insulation system is changed and/or the copper is reused and is no longer flat due to distortion caused by handling and operation. It is important that the required design clearance is incorporated in a field

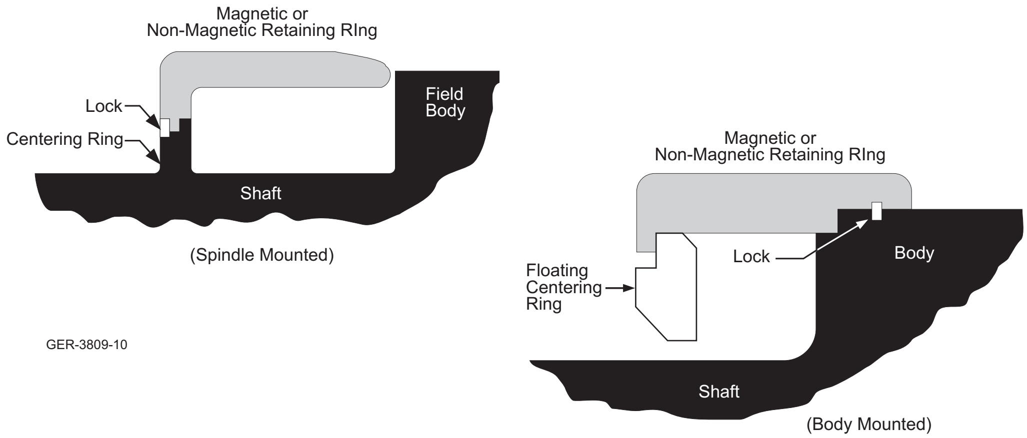


Figure 10. Typical retaining ring mounting configurations

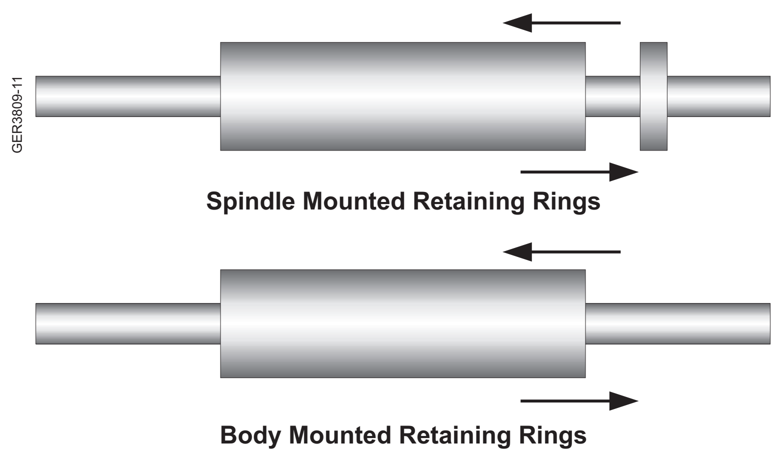


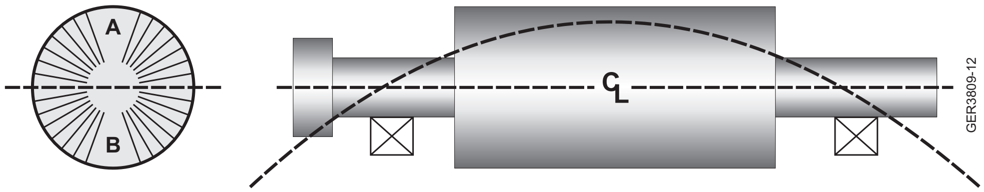
Figure 11. End winding blocking force transfer

rewind. Tight slots will cause the copper to move unevenly in the axial direction as field current is applied and result in rotor bowing. This condition typically causes the irreversible type of vibration. (*See Figure 12.*)

Heat Sensitive Rotor Forging

GE has no generator rotors that have exhibited heat sensitive rotor forgings. However, other manufacturers are reported to have experienced this phenomenon. This rare condition occurs due to non-uniform material characteristics throughout the generator rotor forging and has no relation to the configuration of the field or the copper. Because of the non-uniform properties, as field current is applied the rotor forging expands unevenly in the axial direction and causes the rotor to bow. This condition is caused by problems in the manufacture and heat treatment of the forging at the material vendor.

The preceding causes for generator rotor thermal sensitivity are those that are most common-



– Binding in Slot #1 in Pole A
– Copper is Restricted When Current Increased
– Pole B is Unrestricted

Figure 12. Mechanically induced thermal sensitivity

ly encountered, but are by no means a complete listing. Other things which can cause dissymmetry, such as misuse of adhesives, use of incorrect materials and some types of misoperation, can also cause fields to be thermally sensitive. Anything that creates non-uniform heating, expansion forces, friction, etc., as field current is changed can result in thermal sensitivity. In some cases, the problem is not due to just one of the above or other causes, but a combination of them. As mentioned previously, all rotors have some degree of thermal sensitivity. The key is to control the level of sensitivity through good design and manufacture.

GE Thermal Sensitivity Findings

In a fleet of more than 7,000 generators, less than 0.5% of all active generator fields have reported operational problems associated with thermal sensitivity. Of these, only one field was not able to operate as a result of the condition. The others could operate but were limited by high vibration which exceeded acceptable limits at high VAR loading conditions. In general, thermal sensitivity does not cause a forced outage but may limit operational flexibility of the generator.

GE has done a great deal of testing and research to better understand the phenomenon of generator field thermal sensitivity. This work has led to the changing of design parameters for new fields and field rewinds to minimize the risk and effects of thermal sensitivity.

GE has also done an extensive amount of work to define solutions for fields that have been found to be thermally sensitive. One of the initial areas of work was to determine which of the large number of types of generator fields in the GE fleet were most susceptible to thermal sensitivity. There are a large number of rotor configurations in the GE fleet that operate at a wide range of temperatures. A summary of the different configurations in the GE fleet is shown in *Figure 13*. These fields range from the small spindle-mounted retaining ring designs with conventional cooling to the large body-mounted retaining ring design with direct-conductor-cooling.

While all generator rotors are thermally sensitive to some degree, these studies have shown that rotors with spindle-mounted retaining rings and conventional cooling are more likely to experience high levels of vibration amplitudes, particularly at high reactive loads. If the rotor operates near unity power factor and does

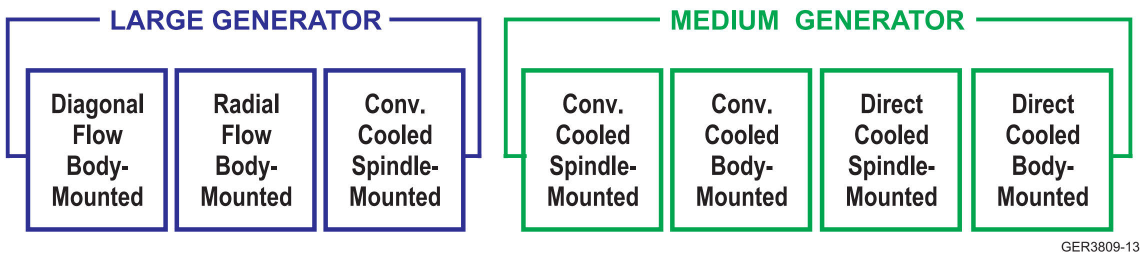


Figure 13. Typical GE generator rotor configurations

not push the field current limits, even rotors which are prone to thermal sensitivity are unlikely to experience vibration excursions. This is assuming that other factors are not involved, such as misassembly of the rotor or an operational incident.

GE has incorporated the findings of these studies in both its new rotor designs and rewinds of fields in its existing fleet. There are a number of actions that have been taken by GE to minimize the susceptibility of its new and existing fields to thermal sensitivity. All configurations of rotors were monitored to assess their susceptibility to thermal sensitivity. This data was summarized and rotors were categorized regarding their susceptibility to thermal sensitivity. All field rewinds were reviewed and the most appropriate features used to minimize the risk of the field being thermally sensitive. The fields have been categorized by design so that for new fields and rewinds, the optimum field winding, blocking and insulation system is used. These changes have been permanently made in the GE generator design procedure so that they are used in all future generator development design and rebuild work. As a result of this extensive work, the number of thermally sensitive fields in the GE fleet has decreased significantly. The fleet will continue to be monitored to assure that thermal sensitivity is not a major issue regarding the reliability and availability of the GE generator fleet.

Examples of Thermally Sensitive Fields

There have been a number of items used to improve or eliminate the effects of thermal sensitivity on a generator field. For rewinds, this includes new insulation systems, modifications to the field forging and wedges, or converting from conventional to conductor cooling. Most new fields have been designed to incorporate body-mounted retaining rings and conductor cooling which have virtually eliminated thermal sensitivity on these fields.

GE has taken action to determine the root cause(s) of problem sensitivity and to devise means to correct it. Some of the more interesting cases which GE has analyzed (and continues to monitor) in its work are discussed next, and most have been improved to where rotor vibration is no longer an operational issue.

Case A: Hydrogen-Cooled Generator — Shorted Turns

A large steam turbine generator had been in operation for many years. With time, this field developed a vibration pattern directly related to field current. This vibration problem gradually increased with time. A flux probe test showed a large number of shorted turns in the field winding. The distribution of the shorted turns was such that one pole had a significantly larger number than the other. The behavior of this vibration was reversible in nature.

The field was disassembled and evidence of deterioration of turn insulation and shorted turns was present. The field was reassembled with a new insulation system and returned to service. The vibration levels of the rotor were within normal values and there was no evidence of any significant thermal sensitivity.

Case B: Air-Cooled Generator Insulation Degradation

An air-cooled gas turbine-generator was brought down for routine maintenance. During the outage, the generator's spindle-mounted retaining rings were inspected for moisture damage. The process involved removal of the rotor from the stator, removal and inspection of the retaining rings and slot wedges for pitting and rust damage, some minor machining of the retaining rings to remove surface indications, reassembly of the components and restoring the unit to service. Upon startup, the rotor demonstrated a significant increase in field current sensitive vibration — a condition that had not been present before the inspection. A compromise balance provided marginal relief, and a flux probe test failed to show sufficient shorts to account for the problem. Six months later, a sister unit at the site exhibited an almost identical problem. This vibration was irreversible in nature.

Attempts to resolve the problem by rechecking turbine-generator alignment, tightening generator end shield bolts and repairing turbine exhaust leaks into the coupling compartment proved unsuccessful. Further investigation found that there was a degradation in the insulation at the top of the slots and in the end-winding blocking. A plan was then developed to repair the rotors using hard copper in the top turns, new coil insulation caps, extra Teflon™ at the top coil turns, modified and repositioned blocking, and modified wedges. Subsequent implementation of these modifications proved successful in restoring normal rotor vibration levels to the generator. Similar procedures developed by GE have proven very effective in reducing thermal sensitivities on other high power-density generators with spindle-mounted rotor retaining rings, and ultimately resolved this situation when implemented.

Case C: Hydrogen-Cooled Generator — Variable Friction Influence

GE's analysis of rotor vibration changes on a hydrogen-cooled generator with conventionally-cooled coil windings and spindle-mounted retaining rings revealed both gradual and slip-stick types of thermal sensitivity – depending on the severity of field current changes. Calculations and testing by GE indicated the sensitivity was driven by forces developed from the axial expansion of the coils and asymmetrically transmitted to the rotor, causing it to bow. A "pre-warming" test demonstrated that the force dissymmetry was principally due to significant variations in the binding friction along the coil/insulation interface. By pre-warming the rotor coils at low rotor speeds (approximately 300 rpm) prior to synchronizing the generator, the coils were allowed to expand without binding from the centrifugal load, resulting in a significant lower vibration. This helped pinpoint the cause of the problem as non-uniform axial forces and friction. The rotor was later rewound with an enhanced treatment of the retaining ring insulation and coil cover insulation to minimize frictional restraint of the coils, as well as an improved copper ventilation scheme to reduce both the coil expansion and its frictional path to the rotor. The thermal sensitivity was eliminated and the unit is operating at acceptable vibration levels over the full generator rating. This case exhibited both reversible and irreversible vibration which was directly related to the amount of field current applied.

Proven Solutions

GE has addressed and studied the thermal sensitivity issue for many years and has developed several solutions to this problem. Some of the different ways GE has found to eliminate a thermally-sensitive field are:

GE Patented "Slip-Plane". One of the common causes of thermal sensitivity is non-uniform mechanical forces in the field winding. This can be due to uneven friction or binding in the slots. GE has developed a "slip-plane" which makes the axial winding forces that are transmitted to the field forging very uniform so that little if any field bowing occurs as field current is applied. The "slip-plane" equalizes the friction and forces at the top of the coil stack, thus eliminating the non-uniform forces that cause rotor bowing. This fix can be applied to a complete rewind as well as integrated into an existing winding. This solution would be particularly effective for indirectly cooled fields that operate at high field currents and field temperatures. It would also be appropriate for a field that demonstrates an irreversible lock-in type of vibration.

Generator Field Redesign. For indirectly-cooled fields that operate at high field current and VAR levels, an option would be to modify the field to direct-cooled. Many times, these types of fields only have a thermal sensitivity problem at high VAR loads which results from the high differential temperatures between the copper windings and the field forging. Modifying the field to direct cooling will significantly lower this differential temperature and, in some cases, even allow the generator to be uprated. In cases where the field cannot be modified or outage time is critical, a new direct-cooled winding can be manufactured to accomplish the same results. Both new and modified direct-cooled fields have been installed in GE generators that have been thermally sensitive, and all sensitivity has been eliminated after the modification. This is appropriate for fields with both reversible and irreversible thermal sensitivity.

Generator Field Thermal Sensitivity Modifications. Since most of the differential motion between the copper winding and the field forging and retaining ring is at the top of the coil stack, the insulation, blocking and top turns of copper are subject to wear and distortion at this location. This is particularly true for fields that see many start-stops or operate at high field current with frequent load changes. A set of modifications has been developed to apply to these types of fields which modifies such components as insulation, creepage blocks, distance blocks and wedges. This can be done at a complete field rewind or by only modifying required components on an existing winding. These modifications, designed to renew the winding/insulation contact surfaces at the top of the slot, have been performed on many in-service generator fields as well as new field rewinds and, in all cases, have resulted in a significant decrease in thermal sensitivity. These modifications are appropriate for both reversible and irreversible thermal sensitivity.

Hydrogen Pressure Increase. For those generators that are hydrogen-cooled, increasing the hydrogen pressure will result in a reduced differential in temperature between the copper and the forging. If the thermal sensitivity is only seen at high field currents and VAR levels, the increase in pressure could be very useful in eliminating this restriction. The increased hydrogen pressure allows more heat to be removed from the copper winding. Increased hydrogen pressures have been used for many years on new generator designs to provide higher ratings.

Conclusion

GE has applied significant effort towards achieving improved understanding of thermal sensitivity and incorporating design techniques to minimize the effects of this phenomenon in the future. Whether it is a new field or a rewind of an existing field, the following items as a minimum need to be addressed during design and assembly to avoid thermal sensitivity problems:

- Retaining ring assembly
- End winding blocking
- Clearances in coil slots
- Improper application of adhesives
- Condition of copper
- Contamination in the field
- Wedge assembly
- Type of insulation
- Field rewind procedure

If careful attention is paid to these items, the risk of having a thermally sensitive field will be greatly minimized. GE recognizes that achieving good thermal sensitivity performance involves close attention to design details and manufacturing process quality. The following actions are being taken to gain improved understanding of the mechanisms involved and to improve performance.

- All thermally sensitive fields will be monitored and their operation and vibration characteristics will be followed closely.
- Features are incorporated into the design of new generator fields to minimize the effects of thermal sensitivity.
- All existing generator fields are reviewed prior to rewind to determine which insulation, blocking and cooling system to use to minimize the potential for thermal sensitivity. The options would include one of the following:
  - — Rewind the field in kind
  - — Modify the existing field to include new insulation and blocking systems
  - — Rewind with conductor cooling and a new insulation system, including modified blocking
  - — Replace the existing field with a new conductor-cooled field with body-mounted retaining rings

Appendix

Commonly Asked Questions Regarding Generator Rotor Thermal Sensitivity

1. **Question:** What is thermal sensitivity of a generator field?

   Answer: Because of the difference in coefficients of thermal expansion between copper and the field forging, the copper will expand axially much more than the steel alloy forging as field current is increased. If friction and mechanical forces are equal in the circumferential direction, no bending forces are induced which cause the rotor to bow and cause the vibration to change. This change in vibration magnitude and phase angle is termed the thermal vector. If this vibration change exceeds acceptable limits, the field is said to be thermally sensitive.

2. **Question:** What causes thermal sensitivity?

   Answer: There are a number of causes for thermal sensitivity of a generator field and, in some cases, the condition results from a combination of the causes. The most commonly thought cause is shorted turns which develop as the field insulation system deteriorates with age. However, there are many other things that can cause thermal sensitivity, including blocked ventilation or unsymmetrical cooling, insulation variation, wedge fit, distance block fitting, retaining ring/centering ring assembly movement, tight slots and heat sensitive forgings.

3. **Question:** What generator fields are affected?

   Answer: All generator fields have some degree of thermal sensitivity; however, it is not considered a problem unless the vibration levels exceed acceptable limits under normal operation. The most vulnerable fields are those that are indirectly-cooled and operate at high field currents. Typically, direct-cooled fields are much less susceptible to thermal sensitivity unless they develop blocked ventilation or a large number of shorted turns.

4. **Question:** How can it be determined if a field is thermally sensitive?

   Answer: Normally, a field is suspected to be thermally sensitive if the vibration magnitude and phase angle changes as the load on the generator is changed. However, it is not always clear if it is the megawatt or VAR load change that is causing the vibration change. To determine the mechanism that is causing the vibration change, a controlled thermal sensitivity test as described earlier in this paper should be performed.

5. **Question:** A field operated for 20 years without any significant thermal sensitivity. After a recent rewind of the field, the field is thermally sensitive. Why?

   Answer: The steps that went into the field rewind should be reviewed and any changes from the original field should be investigated. Typically, anything that was done to the field to make it non-uniform in the circumferential direction can cause thermal sensitivity. This can be from mechanical and/or thermally induced force. Examples of things that can cause the problem are tight slots, non-uniform insulation thickness and size, distorted copper causing binding, uneven use of glues or resins in the rewind, non-uniform wedge fit, poor distance block fitting or positioning, and blocked ventilation.

6. **Question:** What restrictions should be placed on a field that is thermally sensitive?

   Answer: Unless acceptable vibration limits are exceeded, there should be no restrictions placed on the generator field as long as the generator is operated within its capability curve. For those cases where the vibration magnitude exceeds limits, it is sometimes possible to perform a compromise balance on the field such that the thermal vector passes through zero and, as a result, does not exceed vibration limits throughout its entire operating range.

7. **Question:** Why does some thermal sensitivity follow field current and is repeatable, while other types lock in and do not follow field current?

   Answer: Typically, thermal sensitivity that is caused by shorted turns, blocked ventilation or mechanical variations not related to non-uniform friction or binding are repeatable. If certain coils in a winding tend to stick or slip as field current is applied, and move nonlinearly in steps, vibration changes can be locked in and move very rapidly. These problems usually occur when the friction at the top of the coil slots is non-uniform or if there is binding in one or more slots which causes uneven bending forces in the field forging. This problem sometimes occurs as the field insulation deteriorates with age at the top of the coil and non-uniform friction and mechanical forces develop.

8. **Question:** What would cause a field that has not been thermally sensitive to develop thermal sensitivity while in operation.

   Answer: As a field ages, both thermal and mechanical loading on the insulation and blocking can cause changes in friction and distribution of mechanical forces. This can cause a change in the bending moment that is transmitted into the forging. Also, an in-service incident, such as negative sequence operation or motoring, operating out of the capability curve or overspeed, can cause changes which could induce thermal sensitivity into a field that was previously immune.

9. **Question:** What can be done to a generator field design to minimize/eliminate thermal sensitivity?

   Answer: Most new GE generator fields are designed to be direct-conductor-cooled with body-mounted retainer rings. These designs have been virtually free of thermal sensitivity due to the maximized cooling scheme and provisions made at the top of the coil to provide for uniform friction and mechanical forces at the copper-to-insulation interface. For existing field rewinds, many modifications have been made to individual generator field components and procedures to assure uniform loading on the copper and field forging. One of the potential design changes that can be incorporated is the GE patented "Slip-Plane" modification that will minimize the possibility of non-uniform loading developing at the top of the coil slots.

10. **Question:** A field has run many years as a base load unit at high megawatt loading and near unity power factor. It was recently changed to a peaking unit with operation near rated VAR loading. The field now has a significant thermal vector. Why?

    Answer: Operating near unity power factor does not challenge the capability of the field in terms of temperature and heating. However, as field current is increased and the field is operated near its VAR rating, the field will experience much higher temperatures and the differential copper-field forging axial expansion will increase. If the field winding has shorted turns or other winding problems which can induce non-uniform forces into the forging, these effects will be magnified as the field current is pushed to its limit.

11. **Question:** What advances in technology have been developed to eliminate thermal sensitivity?

    Answer: GE recently developed and patented a "Slip-Plane" system to be incorporated at the top of the coil stack to provide uniform friction between the top copper turn and the adjacent insulation. This results in uniform forces being transmitted into the field forging and little, if any, field bowing as field current is applied. New fields that are direct-cooled with body-mounted retaining rings tend to be very tolerant to thermal sensitivity. Modifications have been incorporated into the design of rewinds for existing fields to minimize the effect of thermal sensitivity.

12. **Question:** If a field has a minimal amount of thermal sensitivity, what can be done to

minimize its effect on the overall operation of the generator?

Answer: If the change in vibration does not result in vibration levels that exceed acceptable limits, nothing needs to be done to the field. However, if limits are exceeded very frequently, a compromise balance shot, which will move the "no-load" starting vibration point, can be tried such that the vibration will never exceed limits throughout the entire operating range.

13. **Question:** For a new field or one that has been rebuilt, how can the risk of the field being thermally sensitive while in operation be minimized?

    Answer: A high speed balance which includes an overspeed run, a thermal sensitivity test and a flux probe test will provide the most confidence that the field will not be thermally sensitive when returned to service. The flux probe test checks for shorted turns while the thermal sensitivity test is an attempt to apply field current to the winding which will model actual operation conditions. Experience has shown that if a field passes the thermal sensitivity test criteria in the high speed balance facility, the probability of having any significant thermal sensitivity during operation is very remote.

14. **Question:** Two identical generators are operated by two different users. One user has a field that is thermally sensitive and, as a result, limits operation. Why?

    Answer: When this occurs it is usually found that the units are operated very differently. If one user operated at base loads with minimal field current, normally, thermal sensitivity would never be an issue. However, if a unit is run with many start-stops and high field current, thermal sensitivity would be more likely — especially as the unit ages and the insulation deteriorates due to higher temperatures and mechanical wear due to differential motion between the copper and the insulation.

15. **Question:** What factors can affect a generator field when it is being rewound (both material and assembly methods)?

    Answer: It is of utmost importance that the correct insulation, blocking, resins, glues and other materials are used to maintain the insulating, mechanical and thermal characteristics of the field. Incidents have occurred where non-compatible materials have been used which resulted in higher temperatures, slot binding and insulation failure; all have led to thermal sensitivity. The same can be said about assembly methods. Thermal sensitivity can and has occurred if faulty assembly techniques, such as uneven use of glue, poor blocking fit and mixed insulation systems, are used. This would result in non-uniform circumferential loading, leading to thermal sensitivity.

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