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GE Power Systems

GE Generator Rotor Design, Operational Issues, and Refurbishment Options

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Overview

With the average age of the GE generator fleet rapidly approaching the limit of the original intended life, utilities and industrial users are seeking alternatives to replace this aging equipment with new generators. One component of the generator that is typically refurbished, upgraded or uprated is the generator rotor (field). Degradation of the generator field can be caused by a number of factors, including a breakdown in insulation due to time and temperature and mechanical wear. This degradation can lead to shorted turns, a field ground, or an in-service operational incident that can require premature maintenance work. The type of work needed to repair and upgrade depends upon the generator rotor design, length of time in service and the manner in which the rotor was operated.

This paper covers various types of generator fields, including both conventionally-cooled (indirect copper cooling) windings and direct-cooled copper windings as well as those with spindle and body mounted retaining rings. The options for rewinding, modifying, upgrading or uprating are provided for each field type. Also addressed in this text are the problems typically encountered when dealing with generator rotors, including:

- Shorted turns
- Field grounds
- Thermal sensitivity
- Negative sequence heating
- Contamination
- Misoperation
- Forging damage

The issue of balancing generator rotors after rework or modifications is also discussed. This paper concludes with a discussion on generator rotor reliability and its life expectancy—which varies considerably based on the type and configuration of the generator rotor and the manner in which it is operated.

Function of a Generator Rotor

This section covers the generator field's function in two main areas: a brief description of the mechanical configurations, and a brief description of the electrical theory.

The generator rotor represents an excellent combination of electrical, mechanical and manufacturing skills in which the field coils are well insulated, supported and ventilated in a compound structure rotating at very high speed (typically 1800 or 3600 rpm). Furthermore, though the rotor experiences great mechanical stress and high temperatures (in some cases up to 266˚F–311˚F/130˚C–155˚C) while subjected to electrical voltage and current, it is expected to function in this manner for years without failure. The three design constraints that limit the size and life of generator rotors are temperature, mechanical force and electrical insulation.

Figure 1 shows a basic mechanical outline for a typical generator field. Note the major components:

- Turbine coupling
- Main cooling fans
- Retaining rings
- Coil slot
- Balance plug
- Collector rings
- Collector fans

There are, of course, variations on this configuration. For example, while the illustrated design uses radial fans, other designs use axial fans.

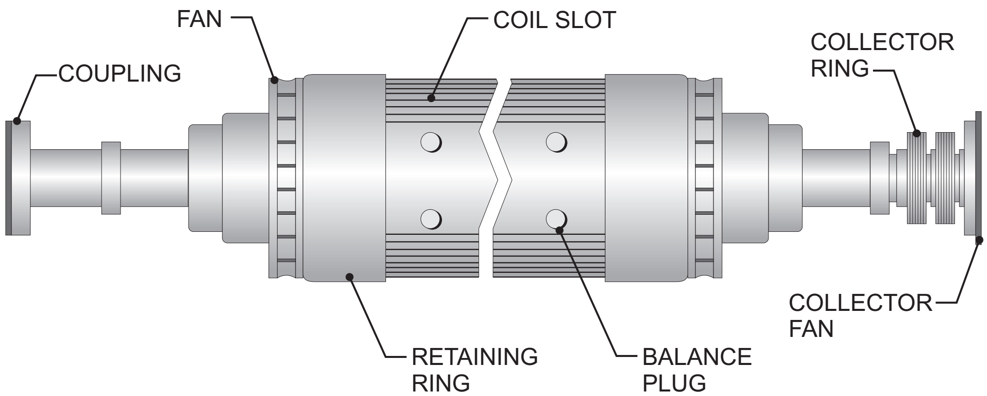


Figure 1. Generator field

A typical collecter end configuration is shown in *Figure 2*, which also shows a cutaway view of vital electrical components such as:

- Collectors
- Collector terminals
- Bore copper
- Main terminal
- Main lead
- Retaining ring
- Coil endwindings (shown from the side)
- Axial fan

Figure 3 shows a typical cross-section of a radial cooled slot section. Other configurations will be described later. Note the main components of the slot:

- Coil wedge
- Creepage block
- Slot armor
- Turn insulation (groundwall insulation)
- Copper turns
- Subslot cover

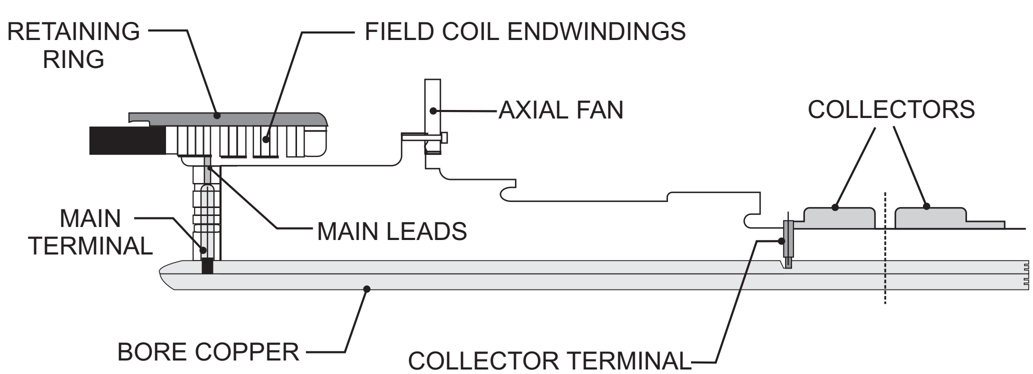


Figure 2. Collector end of generator field

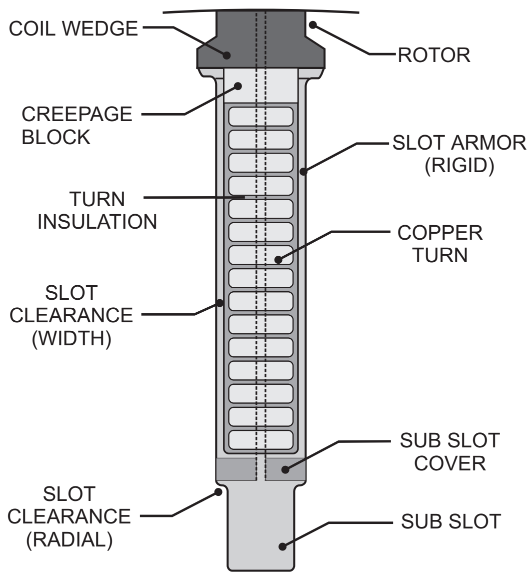


Figure 3. Radial cooled slot

To understand the intricacies of the field winding design, it must be remembered that the basic function of the rotor is to produce a magnetic field of the size and shape necessary to induce the desired output voltage in the stator. The rotor can be visualized as a large rotating electromagnet with north and south poles. As illustrated in *Figure 4*, the magnetic flux that radiates from the rotor follows the magnetic circuit across the air gap, through the stator core and then back across the air gap into the rotor to complete the loop.

Simply stated, the primary function of the field winding is to provide the path for the DC current needed to magnetize the field. However, reaching this goal is not so simple. It involves many tradeoffs in trying to satisfy all the mechanical, electrical, thermal, and manufacturing constraints. Consider just this basic list of requirements for the field winding and its components:

- The winding and associated components must withstand centrifugal loading at speed and possible overspeed.
- The winding and its insulation system must fit within the space available for the rotor slot. The amount of space available for the rotor slot is dependent on the stresses in the rotor teeth—the more area used for the slot, the higher the tooth stresses.
- The insulation system must be sufficient to protect the winding from ground faults and turn-to-turn shorts throughout the operating envelope.

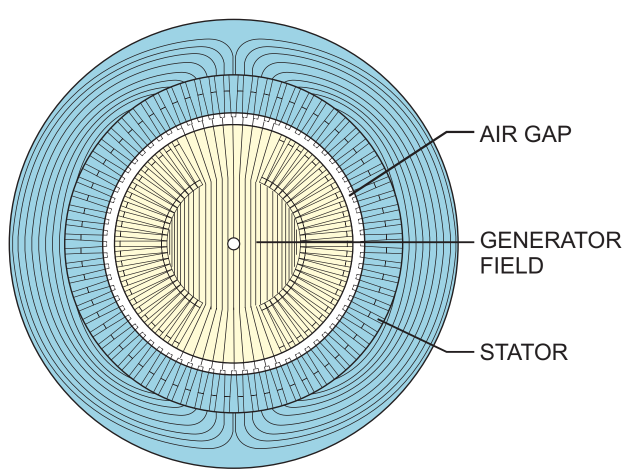


Figure 4. Rotor magnetic flux linking rotor and stator

- The insulation system must be strong enough to withstand the physical wear and tear of assembly and winding, and during operation (particularly when in the turning gear mode).
- The ventilation scheme must be sufficient to keep the temperature rises of the winding within the acceptable range. In the case of ventilated end windings the vent paths must be optimized to provide sufficient cooling while not exceeding the stress limits of the copper.
- The field MMF (magnetomotive force) must be sinusoidal in shape and of the desired magnitude.
- The winding must be symmetrical and balanced to prevent unacceptable vibrations.

The winding and components should be designed to require little maintenance during the 30 or more years of expected operation, which is the typical life for a base loaded control power station. Rewinds may be more frequent under extreme conditions such as an open ventilated gas turbine generator in a dirty environment, or frequent start/stops or load cycling.

Types of Generator Rotors

There are two basic types of generator rotors: conventional windings (indirect-cooled) and direct windings (conductor-cooled). Both types and their variations are discussed.

Conventional Windings

Smaller generators, which are not provided with conductor cooling, have ventilating ducts through which the cooling air passes. (*See Figure 5.*) With this arrangement, the heat generated in the coil is conducted through the slot insulation to the field forging, then to the cooling gas in the ventilating duct. The dielectric barrier forming the slot insulation is also the primary thermal barrier in the circuit; as current levels increase, additional rotor heat dissipation is required. The solution is to use a conductor-cooling arrangement, in which cooling gas flows directly through the conductors. This eliminates the thermal barrier of the slot insulation, allowing a continued increase in the current-carrying capability of a given size rotor.

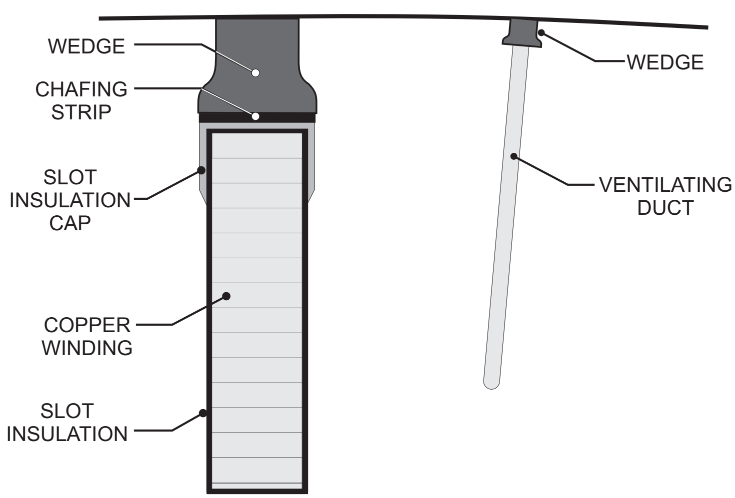


Figure 5. Indirect cooled coil slot

Generator Rotors with Aluminum Alloy Windings

As conventionally cooled generators were increased to larger sizes, the generator rotor stresses increased to unacceptable levels in the rotor and retaining rings. Aluminum alloy (condal) windings were incorporated on some generator rotors, enabling the rotor size and ratings to increase and still allow conventional indirect cooling to be used in the design of these units. These units have provided many years of reliable operation. However, to ensure future long-term reliability when they are rebuilt, the design of these units requires special design and process considerations.

Direct-Cooled Windings

Several different arrangements of direct-cooled windings have been used by domestic and foreign manufacturers to accomplish the conductor-cooling principle. The two primary methods currently used by GE for two-pole generators are radial flow cooling and diagonal flow cooling, as shown respectively in *Figure 6* and *Figure 7*.

Radial Flow Cooling

Radial flow cooling is used for small and medium sized two-pole units and for large four-pole units. The ventilation arrangement shown in the slot cross-section of *Figure 6* permits gas to enter the subslot in an axial direction. The gas then discharges radially through holes in the copper winding and through the wedges shown in the figure. This conductor cooling arrangement brings the cooling gas into direct contact with the copper conductors, eliminating the thermal drop through the insulation. The wedges are constructed with pre-drilled holes to allow for the passage of gas to the rotor surface.

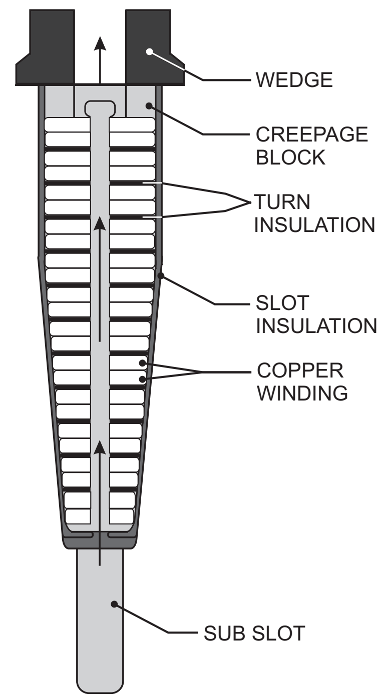


Figure 6. Radial cooled coil slot

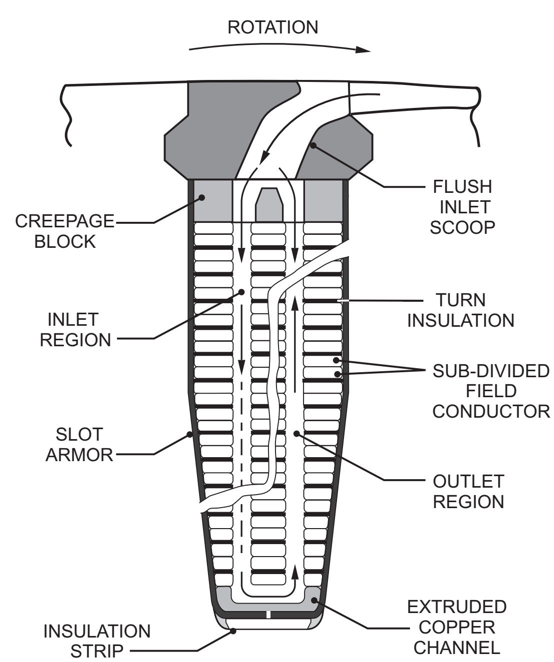


Figure 7. Diagonal cooled coil slot

The rotor slot in *Figure 6* may be tapered to provide an optimum balance between total copper area and rotor forging stresses. The size and contour of the subslot, along with the size and number of radial holes in the copper and wedges, are parameters designed specifically to keep the copper and insulation temperatures and rotor forging stresses within standard and material limits.

Four-pole rotor windings are subject to much less duty than those with two-pole designs. The four-pole rotor turns at half the speed, so the centrifugal loading of the copper winding against the wedges and retaining rings is considerably reduced. Much larger diameters of the large four-pole generators permit use of deeper and wider slots to accommodate a larger cross-section of copper winding. Increased rotor diameter also increases the available pumping head for forced convection cooling. All these factors ease the problem of designing the rotor cooling circuit

The radial flow direct-cooling arrangement was originally developed for large hydrogen-cooled four-pole generators. Once perfected, it was adapted to two-pole hydrogen cooled generators, and then to air-cooled generators. This is just one example of the development of technology for large generators that is then utilized to enhance smaller units.

Radial-Axial-Radial Cooling

This type of cooling system was GE's first proven design at gap pickup cooling. (*See Figure 8.*) The generator rotor and stator incorporated inlet and outlet sections along their axial lengths to achieve uniform cooling along the length of the generator field. This uniform cooling eliminated axial hotspots and allowed the ratings of the generators to be increased. The design was named radial-axial-radial because of the cooling flow which enters the rotor radially, goes in a radial direction into the winding, then proceeds in an axial direction and finally in a radial direction out of the winding. (*See Figure 9.*) This cooling scheme is accomplished by using extruded copper conductors that have been intricately machined to achieve the desired cooling pattern.

This design had been used very successfully and reliably for over 40 years. However, the design was replaced by diagonal flow design, which also incorporated a gap pickup. Diagonal flow

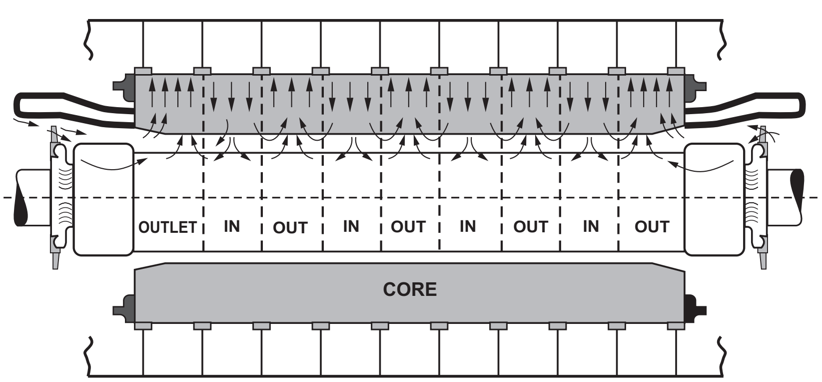


Figure 8. Rotor and stator cooling zones

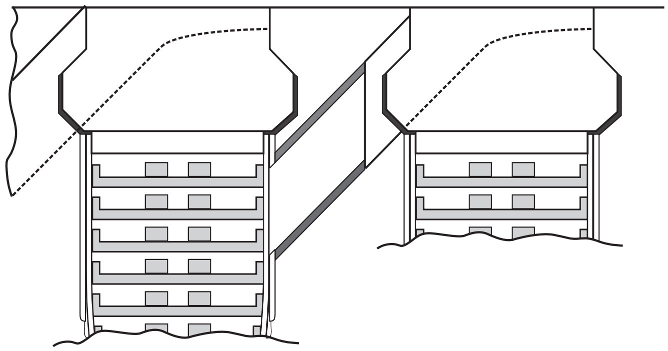


Figure 9. Radial-axial-radial cooled coil slot

offered the additional benefit of a simpler design that allowed it to be manufactured more easily, while increasing long term reliability without sacrificing performance. If a radial-axial-radial field requires a rewind, it is typically converted to a diagonal flow design or replaced with a new diagonal cooled rotor.

Diagonal Flow Cooling

The arrangement used in large two-pole generators is referred to as diagonal flow cooling. *Figure 7* shows a detailed cross-section of a typical diagonal flow field coil. Gas flows down through a series of slotted holes, offset in each layer from those in the previous layer. The bottom turn is a channel that redirects the gas to another series of slotted holes which force the gas upward in a diagonal progression to the top of the coil. The pumping action to provide gas flow is obtained in the configuration of the slot wedges, requiring little fan pressure to circulate gas through the rotor winding. The holes for gas inlet are inclined in such a manner that rotation of the field forces the gas through the wedge and down into successive turns of the coil. Discharge holes in the wedges have a raised section preceding the hole in the direction of rotation. This creates a pressure reduction at the hole with the lower pressure inducing gas flow by suction from the discharge end. There are several alternate inlet and discharge sections throughout the length of the rotor, providing multiple parallel paths through the winding (as shown in *Figure 8*). The stator core has corresponding inlet and outlet sections, matching those in the generator field.

Laminated Rotors

Until 1940 some older, smaller generator rotors were constructed with laminated steel (e.g., 5 MVA in 1935) in limited number. GE occasionally will get a request for spare parts, which we can generally support. Laminated rotors were constructed of a shaft forging and laminated full circle punchings shrunk onto the shaft with the collector end secured by a large nut to keep the punchings tight. A few of these units experienced vibration problems because the punchings shifted, causing a kink. Finding the kinked location and straightening out the punching package would usually fix the vibration. These laminated rotors were built with a stator bore of up to 23.75 inches. Beyond that, the rotor should be a solid design. The fields had a one- or two-piece coil slot wedge made of brass, and on some early units the wedges were actually insulated from the rotor laminations. The laminated rotors had radiating plates and sometimes holes in the retaining rings for end turn cooling. Generally such a rotor cannot be uprated, mainly due to flux density limitations of the original design.

Current 4-Pole Salient Pole Rotors

GE continues to produce state-of-the-art salient laminated rotors to support the GE 4-Pole Alterrex Excitation System (typical ratings are up to 4375 KVA). Of course vast improvements have been made in the design over the past 50 years compared to what was discussed in the previous paragraph. However, the rotors are limited in diameter and are most appropriate for machines in the smaller MVA ratings.

Problems Encountered With Generator Rotors

As a generator rotor ages, its insulation can be affected by temperature, mechanical wear and operating incidents. Rotor forging and other rotor components are also at risk. The most common problems occurring with generator rotors are shorted turns and breakdown in groundwall insulation. These two concerns will be discussed in detail.

Shorted Turns and Field Grounds

A short or ground occurs when the insulation in the field is damaged. A short results when the insulation between the copper turns is altered locally, allowing the adjacent turns to make contact. Although this is not desirable, generator fields have operated—and will operate—with a limited number of shorted turns without significant effect to the operation of the generator. Shorts can occur anywhere in the winding of the generator; however, they are most common in the endwinding area under the retaining rings.

Grounds occur because of a breakdown in the groundwall insulation. This can be in the slot portion of the field, under the retaining ring, at the main lead and terminals or collector and collector terminals, or in the bore copper region. However, unlike having a short, it is recommended not to operate a field with a ground. As the source of excitation is ungrounded, a single ground will not cause current to circulate in the field forging. Yet if a second ground should occur, current will circulate in the forging, and in a very short period of time melting and serious damage to the forging can result.

Figure 10 shows an example of both a short and a ground in the slot section of a generator field. It should be noted that the short only affects the insulation between the turns of copper windings, while the ground wall insulation is not affected. *Figure 11* is an example of a ground in the endwinding area between the top turn of the winding and the retaining ring.

The following conditions can lead to field insulation breakdown:

- **Time.** The longer a generator has been in service, the higher the probability that the soundness of the insulation has been compromised by mechanical stress or heat related damage.

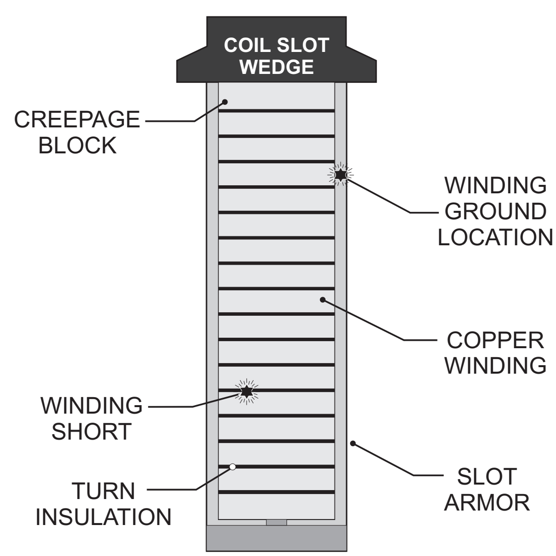


Figure 10. Coil slot insulation breakdown

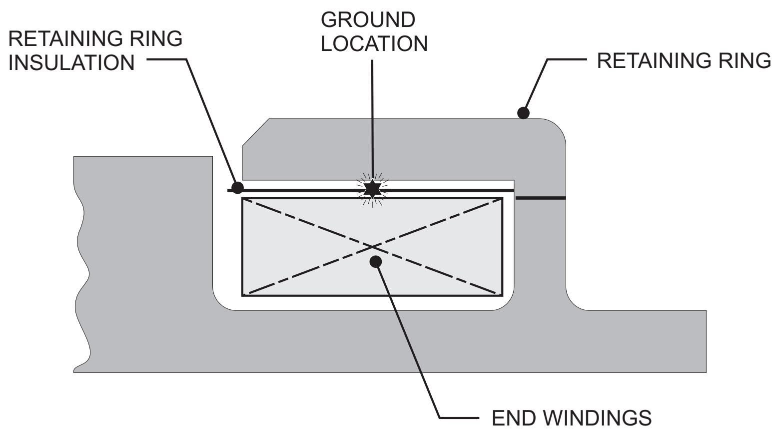


Figure 11. Field endwinding insulation breakdown

- **Type of operation.** A generator field that is subject to many start-stops and/or VAR cycling is more prone to a degrading of the insulation system than a field that is baseloaded.
- **Contamination**. The integrity of the insulation can be jeopardized if contamination has been introduced into the machine or if there has been any burning in the generator (which produces conductive material that can circulate inside the generator). This phenomenon is discussed in detail later in the paper.
- **Operating incidents.** Any operating incidents that induce heating, burning, arcing, high stresses, etc., can be detrimental to the insulation. This abnormal operation includes motoring, a negative sequence event (closing generator breaker at standstill or turning gear or single phase operation), burning within the generator or an overspeed incident.

As mentioned previously, in many cases the generator can operate satisfactorily with shorted turns in the field, whereas it is not recommended that a field be operated with a ground. While shorts are undesirable, they do not present any significant risk to the machine. Consequences of operating a field with shorts include the inability to reach the nameplate rating on the machine and the possibility of developing a thermally sensitive generator field. In the worst case, this would require a full field rewind in which all winding insulation would be replaced.

In the case of a single field ground, current will not flow in the field forging. However, if a second ground occurs, current will immediately start to flow between the two ground points. Within a matter of seconds this current could generate enough heat to melt the field forging, wedges or retaining ring. This could cause irreparable damage to the affected components, and in the worst case, result in the rotor bursting.

If a field ground occurs, the cause should be immediately determined and corrective action should be taken. Operating with a ground can lead to serious field damage and even to catastrophic failure should a second ground occur. Unfortunately, there is no way to determine if and when a second ground will occur.

As units age and experience many start-stop cycles, the turn insulation will degrade. In such conditions it is not uncommon for shorted turns to develop. Many units have operated for years with shorted turns without affecting the function of the field or the generator. It is only necessary to repair the shorted turns when the operation of the generator is unacceptably affected (i.e, the unit rating cannot be obtained, or unacceptable thermal sensitivity develops).

Regular inspection and testing of the generator field is the best way to ensure the integrity of the insulation system. If an insulation fault develops, a number of diagnostic tests can pinpoint the location and severity of the fault. This ability to quickly and accurately diagnose the problem minimizes the time required to implement corrective action, allowing the field to be returned to service in the shortest possible time.

There are a number of other concerns that also affect generator rotors.

Thermal Sensitivity

Thermal sensitivity is the term used to describe an excessive vibration of the generator rotor, induced by the heating effect of the field current. As field current flows in the winding, the copper heats up. Two things happen as a consequence:

1. The copper, having a greater coefficient of thermal expansion, expands more than the steel forging. This disparity in expansion results in the transmission of forces to the forging through the rotor slots, wedges, retaining ring and centering ring.

2. The heat generated in the copper dissipates into the forging and is drawn away by the cooling medium (air or hydrogen).

As long as both of these conditions occur symmetrically about the rotor centerline, there will be no forces that tend to "bow" the rotor. However, when the coil forces act unevenly, or when a temperature differential exists across the rotor, the rotor will tend to bow, causing an imbalance and subsequent vibration.

A thermally sensitive field will exhibit a change in vibration magnitude and/or phase angle with a change in field current. The circumstances that might cause a non-uniform distribution of forces are varied. Some of the more common factors that may cause thermal sensitivity (either singularly or in combination) include:

- **Shorted turns.** When a significant number of adjacent field turns are shorted, the pole with the greater number of turn shorts will have a lower resistance than the other pole. With the same current flowing, the higher resistance pole (the one with less shorts) will heat up and expand more than the other, causing a bow in its direction.
- **Blocked ventilation.** A blocked ventilation path may cause an uneven heat distribution in the rotor in much the same way that shorted turns can.
- **Insulation variation.** Non-uniformity in field insulation can result in binding of the field coils and an uneven distribution of friction forces, both in the slots and under the retaining ring. In this case, the coils with the greater binding or friction will transmit a greater axial load to the rotor, again causing the rotor to bow.
- **Wedge fit.** Uneven tightness of the field wedges can also result in non-uniform distribution of axial forces around the rotor. This situation is most prevalent when a portion of a field's

wedges are replaced and the fit of the new wedges is inconsistent with those of the existing wedges.

- **Endwinding blocking fit.** Similar to uneven wedge fits, unevenly spaced and fitted distance blocks can cause a non-uniformity of forces to be transmitted to the rotor, again resulting in bowing of the rotor and a change in its dynamic characteristics. This situation is most common in fields having spindle-mounted retaining rings.

While these are the most common causes of thermal sensitivity, there are other less prevalent causes such as misuse of adhesives, incorrect materials and certain types of misoperation.

There are two general types of thermal sensitivity: reversible and irreversible. As the name implies, reversible thermal sensitivity is characterized by its reversible and repeatable behavior. If a field's vibration increases and decreases as a direct function of field current, the thermal sensitivity can be considered reversible. However, if the field vibration increases with field current, but does not respond directly to a subsequent decrease in field current, the thermal sensitivity is considered irreversible, or slip-stick. The reversibility of a field's thermal sensitivity can be determined through a series of tests, the results of which will generally give some clues as to the most effective remedy. GER-3809 (Generator Rotor Thermal Sensitivity—Theory and Experience) covers generator field thermal sensitivity in great detail.

Contamination

The type and extent of contamination to be expected in a generator primarily depends upon its cooling configuration. A hydrogen-cooled generator is well sealed and should see very little contamination. A TEWAC (totally enclosed water to air cooled) unit will require small amounts of make-up air that can introduce particulates into the generator. An OV (open ventilated) generator is most likely to see large amounts of contamination introduced into the field.

Contamination of generator rotors can come from many sources. Carbon, which represents one of the more common contaminates, can come from collector brush wear or gas turbine exhaust. Other particulates likely to be found in a generator (such as silicon or petroleum by-products) can come from nearby operations or processes. While the inlet filters eliminate most of the contaminates from the air, the flow through the generator is so great that even a small percentage in the air stream equates to significant deposits over time. Other types of contamination can come from the generator itself. Worn insulation, blocking and wedges can introduce particulates into the ventilation stream that can accumulate in the field.

Liquid contamination may also be present and can compound problems by combining with the particulate contamination and sticking on all areas of the rotor. Generally, liquid contamination is limited to oil from the hydrogen seals and bearings. The oil can get drawn into the stator and coat both the stator and rotor ventilation paths. As a result, particulates in the ventilation stream that otherwise would proceed unimpeded will stick to the oily film and eventually create a significant build-up.

Problems that can arise from contamination build-up in a generator rotor include low meggar (resistance to ground) readings, overheating, creepage failures, and turn shorts.

Collector, Bore Copper and Connection Problems

The collectors, bore copper and main leads represent a vital link in the excitation path. One problem encountered in this area is "collector flashover," in which the positive collector flashes to ground due to contamination. This creates a creepage path (a degradation of the collector shell insulation) that ultimately results in a forced outage.

As a rotor ages, loosening of components may develop in the rotor bore, bore copper, terminal studs, copper coils, retaining rings, terminal stud gooseneck, or mainlead 90° bend. The loosening may lead to increased relative motion between the stud/main lead and the #1 coil. This can result in low and high cycle fatigue, leading to breakage of the connection and a forced outage due to "loss of field current."

A large number of mechanical connections between the collectors and the #1 coils are in close proximity to ground potential. The insulation in these areas is designed with generous creepage paths, but over time the insulation can degrade, leading to a field ground and a forced outage. (*See Figure 12.*)

Copper Distortion

Distortion in the copper winding is sometimes found after a generator field has been in service for a period of time and maintenance work is performed on the rotor. (*See Figure 13.*) This condition most frequently occurs in the end-winding area. Distortion can occur due to the following reasons:

- The presence of soft or annealed copper
- Friction between the top turns and the retaining ring insulation
- Frequent cycling of the winding
- Overheating of the winding
- Coil foreshortening

Any damaged copper must be repaired or replaced prior to returning the generator rotor to service. Failure to do so can result in shorted turns or field grounds.

Forging Concerns

Generator rotor forgings should be inspected prior to a rewind to determine the long-term structural integrity. This is especially true if the rotor has been exposed to negative sequence

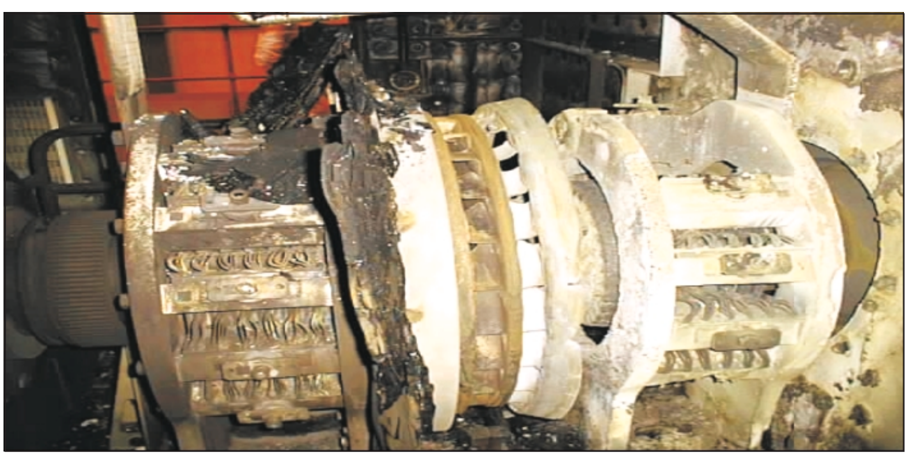


Figure 12. Collector and brush holder neglect

Figure 13. Moderate copper distortion

currents or a motoring incident, or if the forging was manufactured prior to 1959. Negative sequence currents can cause burning, hard spots and cracking on the surface of the forging. Rotors manufactured prior to 1959 tend to have significantly lower toughness than modern day forgings and the increased levels of impurities found in the forgings make many of them marginal for continued use.

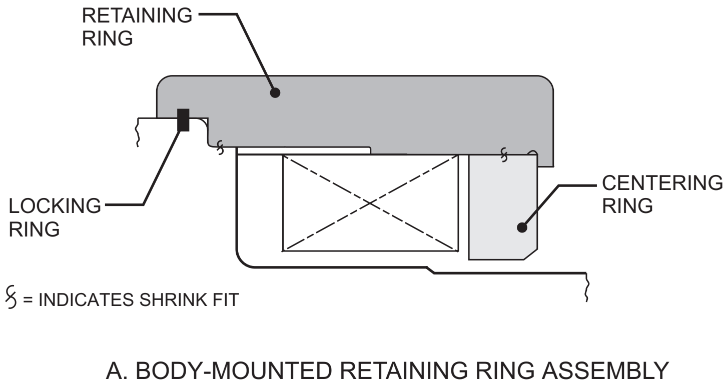
During inspections in the period from 1995 to 2001, three out of seventeen of our large steam turbine generators were found to have cracked generator rotor teeth. In two of these cases the rotors also had experienced in-service negative sequence events, which resulted in arc strikes on the rotor teeth, dovetail load surfaces, and on the mating surfaces of the slot wedges. The third generator rotor that experienced cracking had an operational history that included extensive turning gear operations (25,600 hours in an eight-year period). The cracks were detected during rewind inspections and were in the radial circumferential direction.

Based on the design of these fields and the low stress and original fatigue life calculations, it is not expected that generator rotor tooth cracking will occur through normal operation. However, if the generator rotor is subjected to significant negative sequence events, GE Energy Services should be consulted prior to the commencement of repairs or return to service. GE Energy Services can then determine the severity of such an incident and advise in the inspections that should be performed. Units with significant hours of turning gear operations (greater than 10,000 hours) should contact GE Energy Services regarding inspection recommendations.

Testing of the bore of the forgings is recommended for all of those manufactured before 1959 or if the generator is subject to frequent start-stops. Also, for those forgings manufactured after 1959 that have been in service over 25 years and 5000 start-stop cycles, it is recommended that the rotor bores of these forgings be inspected. Prior to 5000 start-stop cycles, the rotor teeth, dovetails and field wedges should be inspected using magnetic particle and fluorescent techniques.

Retaining Ring Concerns

Figure 14 shows the retaining rings used to restrain the centrifugal force of the rotor winding end turns. They require very careful attention during design and manufacture since they are the highest stressed components of the generator. The centrifugal load of the end winding contributes 5000 to 8000 pounds for each pound of copper under the ring. This produces a hoop stress, which attempts to stretch the ring during operation into a slightly elliptical shape for two-pole rotors due to the inherent non-uniform weight distribution of the end turns and the associated blocking. In modern generators the retaining ring is shrunken on a machined fit at the end of the body. This forces the retaining ring to remain cylindrical at full speed and



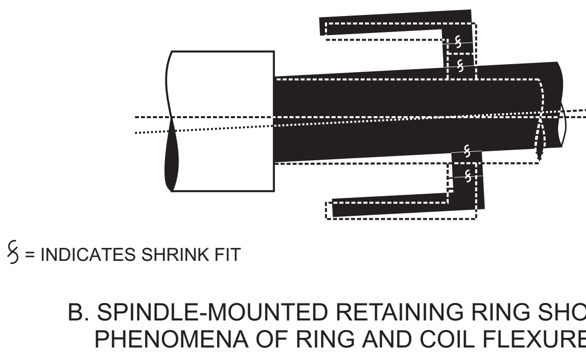


Figure 14. Retaining ring mounts

prevents differential movement of the ring with respect to the body.

There are two types of retaining ring mounting schemes: spindle-mounted and body-mounted.

- **Body-mounted.** A retaining ring mounted on the field body is subject to high circulating currents during certain unbalanced loading conditions that produce negative-sequence currents in the rotor body. The current circulates in a closed loop pattern: first along the length of the field body, then entering the retaining ring and flowing circumferentially around the ring for a short distance before returning to the field body. Unless good electrical contact exists at the junction between the retaining ring and the rotor body, excessive heat may occur and possibly damage the ring.
- **Spindle-mounted**. Spindle-mounted retaining rings allow flexure between the rotor body and retaining ring, which can lead to insulation and coil failure at this location. This is particularly true for units that operate with frequent start-stops and/or load cycling.

Two classes of materials are used for retaining rings: magnetic and nonmagnetic. Nonmagnetic rings are used for higher-rated generators to minimize leakage flux and to reduce losses.

The older generator rotors in the GE fleet use retaining rings that were manufactured from magnetic forging materials. These rings have provided reliable service and have not been a problem when well maintained. However, some magnetic rings that were exposed to extensive moisture have developed severe corrosion and rusting and have required rework or replacement. Magnetic retaining rings were replaced with those made from nonmagnetic materials. Two of the most common materials were Gannalloy and 18 Manganese-5 Chromium (18Mn-5Cr). Both of these materials have been recognized to have problems that arise from their operating environment. Gannalloy has been found to be subject to embrittlement when operated in a hydrogen environment. As a result, it is recommended that those type rings be replaced.

Across the industry it has been found that retaining rings made from 18Mn-5Cr are subject to stress corrosion cracking (SCC). Because of the high incidence of SCC on these rings, it is recommended that all utility and industrial 18Mn-5Cr retaining rings be replaced with an 18Mn-18Cr material which is highly resistant to stress corrosion cracking. Since the generator rotor must be removed from the stator to replace the retaining rings, this is most often done when the generator is on a major outage and when the rotor is being rewound. Failure to properly maintain retaining rings could result in a catastrophic failure. (*See Figure 15.*)

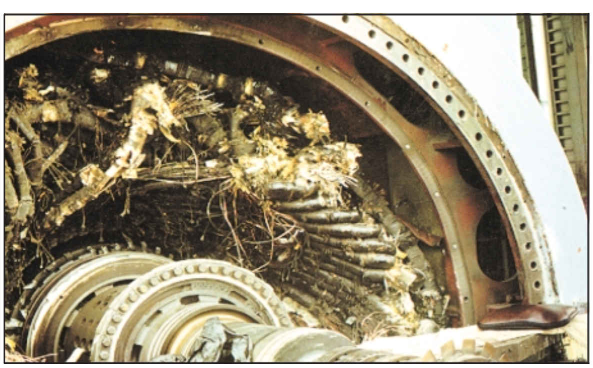


Figure 15. Catastrophic retaining ring failure

Misoperation

There are various modes of generator rotor misoperation. While some are rather benign to the rotor, some are catastrophic to the rotor and can cause secondary damage to the generator stator as well as to the prime driver. Misoperation of the rotor can occur due to a number of reasons including: internal generator failure, auxiliary equipment failure, abnormal system conditions, and operator error.

The most common modes of misoperation that can affect a generator rotor are shown in *Table 1.*

■ Field overheating	■ Abnormal frequency and voltage
■ Loss of excitation	■ Breaker failure
■ Rotor or stator vibration	■ Voltage surges
■ Synchronizing errors	■ Transmission line switching
■ Motoring	■ Electrical faults
■ Reduced seal oil pressure	■ High speed reclosing
■ Unbalanced armature currents	■ Subsynchronous resonance
■ Loss of synchronism	■ Accidental energization

Table 1. Common modes of misoperation

Generator Rotor Reliability and Life Expectancy

Generator Rotor Life

The life expectancy of a generator rotor depends upon mode of operation, rotor design and operating incidents. Generators that are operated as peaking units with many start-stops and also with high var loads (high field currents) generally will have a lower life expectancy—much shorter than a base load unit with few start-stops and operating near unity power factor with lower field current. More frequent start-stops tend to induce more mechanical wear on the insulation and will lead to more long term distortion on the copper conductor. This is because the insulation and copper are subject to extremely high "g-forces" every time the generator is accelerated to speed. When the unit is at speed and high field current is applied to the copper winding, high forces are developed in the axial direction. This can cause copper deformation and distortion and also can cause abrasion on the insulation, which can lead to premature failure.

The older conventionally-cooled rotors have higher "hot-spot" temperatures. If operated at high field currents they would tend to have shorter life expectancies than a direct-cooled field, which tends to distribute heat removal more evenly. Generator rotors with spindle-mounted retaining rings tend to require maintenance and repair work more frequently than those with body-mounted retaining rings. This is due to the relative motion between the spindle-mounted retaining rings and the field body caused by start-stops and once-per-revolution bending. This may lead to top turn breaks and other operational problems such as thermal sensitivity.

Operating incidents such as motoring or negative sequence operation can lead to rotor forging and retaining ring damage. Other incidents of high voltage spikes have caused insulation failures that have led to shorted turns and field grounds. Minimizing operational incidents can prevent premature maintenance work on a generator rotor and can prolong its useful life.

Generator Experience

Generator rotors that operate primarily at base load duty and have minimal operating incidents can expect to have an average useful life of approximately 30 years. This approximate lifespan, of course, applies to the forging. The insulation and the copper may need to be repaired or replaced during this time. On the other hand, rotors that see frequent start-stops and load cycling can be expected to have a much shorter useful lifespan. Older rotors with forging issues and/or spindle (flush) mounted retaining rings are more prone to accelerated life degradation. Although there is no exact formula, stop/start application does significantly reduce service life. A unit operated in a frequent start/stop mode can expect the insulation life of roughly 30% to 50% of that of a base load unit. If longer life expectancy is required, a modern-designed field with body-mounted retaining rings and direct conductor cooling may yield a significant improvement.

Knowing the life expectancy of a generator rotor is very helpful in planning future maintenance and minimizing forced outages. Frequent inspections, and electrical and flux probe testing can help diagnose insulation deterioration and assist in decision making for future repairs and rotor rewinds.

Generator Rotor Refurbishment and Replacement

Generator Rotor Rewind

Reasons For Rewinding

Experience has shown the rotor to be the generator component requiring the most maintenance. This is not surprising considering that it operates under very high centrifugal load, and that typical operating incidents have the greatest impact on the field (motoring, contamination, etc.). Rewind of the field normally focuses on re-insulation of the field winding. However, the owner should not lose sight of other considerations. It is common for older units to be operated at lower power factors to carry more reactive power. This places greater duty on the field leading to accelerated wear and, at times, field current sensitive vibration (thermal sensitivity). GE has developed several component modifications to the designs, including a patented "slip plane modifications" to improve the field vibration stability at high thermal loads. These modifications are available for retrofit or as part of a rewind.

The first step in considering a generator rotor rewind is to define its intended use. For example, what are the service life, reliability requirements, outage interval requirements, load requirements (MW and MVAR) load and performance requirements (such as change in power factor, terminal voltage, etc.). Realistically defining these parameters will establish the extent of the rotor rewind necessary. GE can produce several options with various levels of risk for future operation.

Types Of Insulation

When a new winding is being provided, the three basic decisions the designer must make are number of turns per slot, turn cross-section, and method of cooling. Normally, the method of cooling the new winding will be the same as the original winding. However, there are cases where an improved cooling scheme should be evaluated to facilitate an uprate or for reliability considerations. The number of winding turns and turn cross-sections is determined through analysis, in conjunction with the selected turn and ground insulation systems.

There are three types of turn insulation systems. The first is a system of taped turns where every other turn is taped, including the end turns, with a mica mat tape. This system is the least costly but most labor intensive (hand taped) since the turn insulation is applied prior to winding and provides the most protection against contamination. The disadvantage of this system is that it requires narrower copper in the slot section because tape adds to the coil width. (*See Figure 16.*)

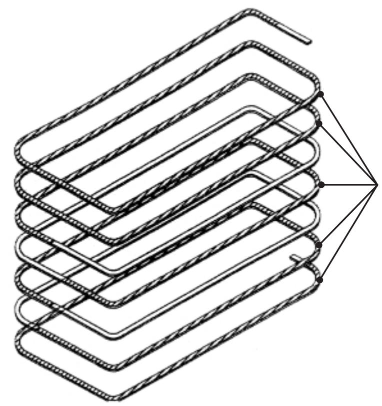


Figure 16. Taped insulation system

The second system consists of strip turn insulation in the slots and taped ends. This system allows for wider copper in the slots, yet still provides for contamination protection in the end region since every other turn is taped with mica mat tape. The third system is an "all strip turn insulation" system and it utilized when improved endwinding cooling is required. The strips can be either Nomex or a glass laminate as shown in *Figure 17.*

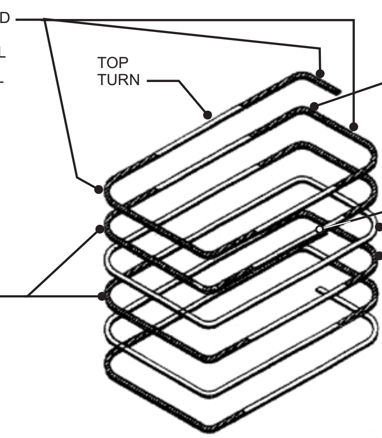


Figure 17. Taped and strip insulation system

There are two types of ground insulation (or slot armor) material that are currently used in the slot section. The first type is a rigid armor that has high mechanical strength. This material has a glass base and may contain a film layer. In addition, in higher-voltage fields this material has a grading applied to prevent creepage failures at the top and bottom of the slot. The other type of material is Nomex, which is both flexible and tough.

Ground insulation in the end region is provided by the retaining ring insulation, shown in *Figure 18*, and by the designed creepage paths at the slot exit and centering ring. The retaining ring insulation must be mechanically strong to withstand the centrifugal loading, yet flexible enough to absorb the discontinuities of the endwinding's outer surface. It also has to allow for movement of the end turns due to thermal expansion. An outer layer of glass and an inner layer of Nomex typically provide these features. The inner surface is also treated with a low friction coating to allow more uniform movement of the winding.

The endwinding blocking must support the winding to prevent permanent distortion, yet also allow for thermal expansion. (*See Figure 19.*) The blocking materials that are currently utilized are epoxy glass laminates. It is important to employ a service-proven blocking pattern that is compatible with the specific endwinding geometry being used, since it is the blocking pattern which allows for thermal expansion movement and ventilation. Also, special consideration must be given to the blocking and support of pole-to-pole, coil-to-coil and terminal connectors. It should be noted that asbestos was used extensively in older generation distance blocks and rotor insulation; maintenance/repair processes must take this into account.

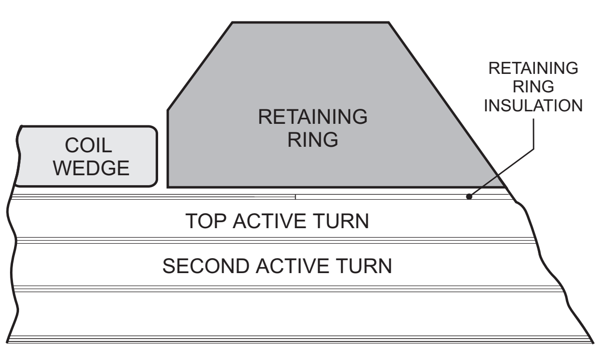


Figure 18. Retaining ring insulation

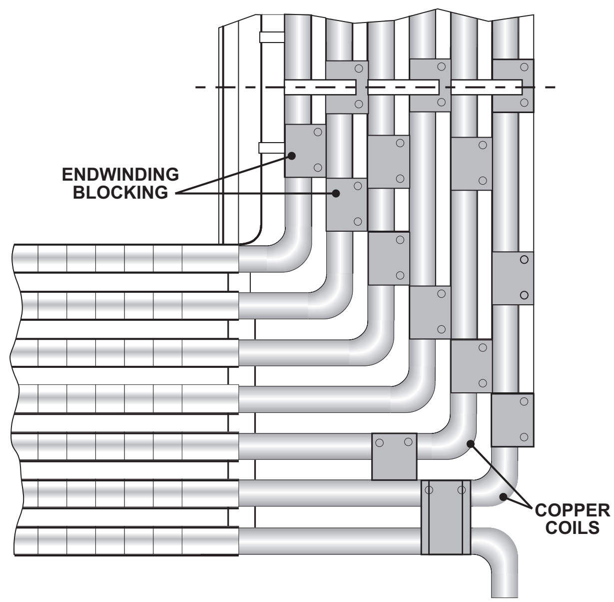


Figure 19. Endwinding blocking

Some design features are added when high cyclic duty is anticipated. These include reliefs in either the copper or body at the end of the coil slots to prevent armor damage, reliefs between the slot armor ends, and the blocks just outside the body when rigid armors are utilized.

Generator Rotor Modifications, Upgrades and Uprates

An uprate often can be realized while performing a rewind, modification or replacement to a generator rotor. For example, a rewind could be an opportunity to install new Class F temperature-insulating materials. Running at a higher temperature from higher field amps can produce more flux and more MVAR and/or MW. The same applies to a direct-cooled conversion or a replacement rotor with perhaps more uprate capability.

It has been common to support a gas turbine or steam turbine uprate by taking advantage of the existing generator margin (i.e., just operate the generator at a higher power factor than originally designed). An example of this would be to operate at 0.95 lag rather than the original 0.9 lag, while recognizing a reduction in MVAR capability. Assuming the generator is in "as-new "condition, this requires no changes to the generator hardware or performance curves, as long as it operates within the existing reactive capability curve.

With recent energy shortages causing brownouts and blackouts, this practice of uprating generators at the expense of existing MVAR capability—along with projected reinforcements of NERC Planning Standard Section G30 (.9 pf lag minimum) uprates to rotors—should be strongly reconsidered.

Impact on Other Components

When any change in the rating of a generator is contemplated, a coordinated examination of all the generator components is necessary. This can best be understood by referring to *Figure 20*.

As shown in *Figure 20*, Area 1 indicates the increased capability that is potentially available if the stator is rewound. Area 2 shows additional capability that is potentially available if the field is also rewound. Notice that if the stator alone is rewound, the power factor in the lagging region at the new maximum rating is increased unless the rotor has a margin that was unused at the previous rating. Similarly, unless there is unused temperature capability in the core end region, the leading power factor capability becomes more restrictive. To control core end heating, some cases may require changing from magnetic to non-magnetic retaining rings

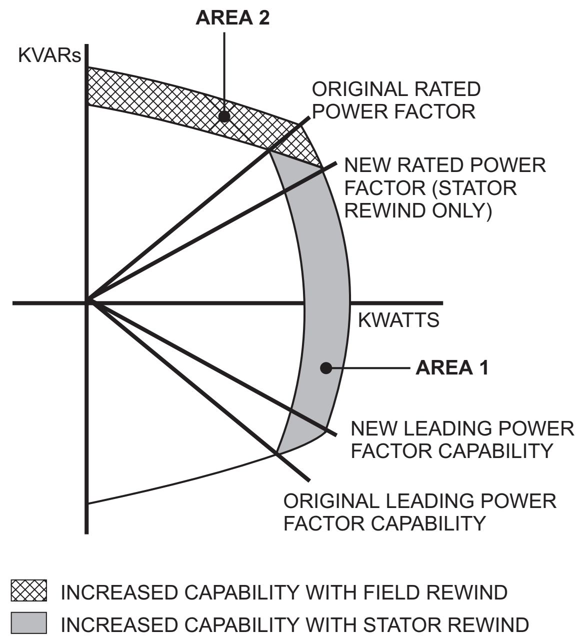


Figure 20. Uprating capability curve

These changes also require a design study and possible upgrade/replacement of the coolers and excitation system. For this reason, rewinds can best be addressed by the original equipment manufacturer who has the knowledge of the unit's electromagnetic design and is in a position to make the necessary design studies and capability assessments.

The magnitude of the performance improvement that can be achieved varies widely from machine to machine. In a conventional hydrogen-cooled generator, uprate potential can range from 10% (with a new armature winding) to as high as 35% (with a new armature winding, new direct-cooled field and new exciter).

Generator Rotor Replacement

It is often possible to repair/refurbish an existing rotor to satisfactory working condition. However, in certain circumstances, it may become necessary to replace the existing rotor. The following situations are instances when replacement is preferable to repair:

- When outage duration is critical, the differential cost between a rewind and a replacement may be offset by potential loss of revenue.
- A significant uprate, or other benefit such as increased efficiency, may be achievable with a replacement field, but not with a modification to the existing field.
- An operational, or other, incident may have damaged the rotor forging sufficiently to make further operation impossible or unsafe.

There are generally two choices to obtaining a replacement field: a newly manufactured field or an exchange field. These are discussed in the following sections.

Exchange Field

GE has implemented an exchange field program for some of the more numerous generator models, where the customer will receive a completely refurbished field as a replacement. The existing field is removed and returned to GE for refurbishment for another customer. The benefits include a shorter outage and lower cost than a new replacement field. The original design of the field remains the same, though the retaining rings are upgraded to 18Mn-18Cr.

New Field

In addition to the benefit of a short outage duration, a new field would incorporate the latest design features such as:

- Direct-cooled coils, either radially or diagonally cooled
- Body-mounted retaining rings (for larger units)
- Creepage blocks
- "State-of-the art" insulation system

In some cases, a new field will allow for more efficient operation and will also permit the generator to be uprated.

Rewind, Refurbishment and Replacement Recommendations Versus Risk

Below are listed recommendations to repair rotors, in order of risk.

New Replacement Rotor

The best technical option is to uprate to a new Class F rotor with a body-mounted, 18Mn-18Cr retaining ring and a direct-cooled winding with a state-of-the-art high quality forging). It extends life the most, offers the most additional uprate capability, allows for the quickest outage and will address TILs. Though it is initially the most expensive option, it may ultimately be the most cost effective when considering potential back-end costs such as replacement rotors and downtime.

Exchange Field

Currently there are exchange fields for the more numerous gas turbine generator models. Additional exchange fields are being added as the fleet ages. Other than a new replacement field, an exchange field is the best technical option since it replaces most hardware while reusing another NDT rotor forging for economy. Cost is less than a replacement field but higher than a rewind with new copper. The exchange fields are balanced.

Rewind With New Copper

This is the next best repair. It consists of a new copper field winding, field winding turn and ground insulation, slot filler, blocking, and retaining ring insulation. New copper should strongly be considered if the rotor is more aged, as the copper can soften and distort over a period of time (approximately 15-30 years). The decision to replace or reuse existing copper is somewhat subjective. It is best to inspect the copper at an outage and make the decision to order new copper for rewinding at the next outage. Unlike the previous two repair options, this repair does not renew the collector ring insulation, the bore copper insulation, collector stud insulation or main lead and terminal insulation. These options should be ordered if the field is to be completely renewed. A high speed balance is strongly recommended with new copper. The risk of this option is not replacing the collector ring insulation, the bore copper insulation, collector stud insulation or main lead and terminal insulation and not addressing any pre-existing conditions with the forging or retaining rings, etc.

Rewind Reusing Original Copper

This is perhaps the most economical repair but carries commensurate longer-term risk and is not recommended for older aged rotors, as its repair scope is limited. The scope of material is basically field winding turn and ground insulation, slot filler, blocking and retaining ring insulation. The original copper is cleaned but reused. This repair does not normally renew the collector ring insulation, the bore copper insulation, collector stud insulation or main lead and terminal insulation. A high speed balance is not normally recommended as there is not the significant change in mass introduced that would require a balance. This repair has greater risk in the long run because it does not normally replace the original copper, collector ring insulation, the bore copper insulation, collector stud insulation or main lead and terminal insulation. Nor does it address any pre-existing conditions with the forging or retaining rings, etc., although these components may need replacing at any time after the basic rewind repair. Any of these repairs can be added to the workscope if higher reliability is desired.

High Speed Balancing

In addition to the obvious benefit of maximizing dynamic stability, a high speed balance allows for a comprehensive evaluation of the generator rotor's overall suitability for service. The quality of work performed on the rotor can be fully assessed, which minimizes the potential for a costly outage extension. A fully equipped high speed balance facility can perform each of the following:

High Speed Balance

In most cases a high speed balance, under stringent acceptance criteria, will eliminate the need for subsequent "trim" balancing on site—a process that can be extremely time consuming due to the extent of disassembly and reassembly of the generator necessary to gain access to the rotor.

GE recommends a high speed balance whenever the rotor is rewound with new coils. However, experience has shown that a rewind with existing copper does not require a high speed balance to successfully return to service with acceptable vibration levels.

Flux Probe Test

A flux probe test can be performed if the facility is equipped with a static excitation system to energize the rotor coils. A flux probe test can then be conducted to determine whether any shorted turns exist. The field is spun up to operating speed and excitation applied to the collectors. The flux probe then measures the relative magnetic flux from each coil. If there are one or more shorts in a coil, the relative flux will be lower in that coil compared to its corresponding coil. The number of shorts and number of turns per coil determines acceptability.

Thermal Sensitivity Test

In some GE balance facilities sufficient power is available from the excitation system to perform a thermal sensitivity test and a related test—a prewarming test. The thermal sensitivity test involves first running the rotor up to operating speed and establishing a stable state prior to applying excitation. Excitation is then applied. With current through the coils, the temperature increases gradually during which time vibration magnitudes and phase angles are recorded at regular intervals. Once a target temperature is reached and maintained for 20 minutes, a final set of data is recorded. From the hot and cold vibration data a thermal vector can be calculated. The field passes thermal sensitivity if the thermal vector is below a threshold value, generally 3 mils.

If the field fails the thermal sensitivity test, a prewarming test can be performed to aid in diagnosing the cause of the thermal sensitivity. To perform a prewarming test the rotor is brought to operating temperature by spinning at low speed with excitation applied. After operating temperature is reached, the rotor is spun up to operating speed and vibration data taken. A comparison of the vibration levels from the prewarming test with those of the thermal sensitivity test can help in pinpointing the cause of the thermal sensitivity.

Conclusion

The average age of the GE generator rotor is approaching the limit of the original intended life. The integrity of the insulation systems can be monitored using flux probe and other electrical testing. As the generator rotors age, it should be expected that rewinds, modifications or replacements will be necessary, especially following an in-service operating incident. Many options are available to the user in which the rotor can be restored to the original condition, modified to present day design condition or replaced with a new, upgraded design. Modifying or replacing the generator rotors also gives the user the possibility of uprating the generator.

Frequently Asked Questions

1) Q. What is the typical lifespan of a generator rotor?

   A. The life is dependent upon mode of operation, in-service operating incidents and misoperation. Generator rotors are typically rewound, upgraded or replaced in the 10-30 year time frame. Those used in stop/start mode can expect a shorter lifespan.

2) Q. What are the most common causes of a generator rotor insulation breakdown?

   A. The degradation in insulation is caused by heating and/or mechanical wear and/or operating incidents. A breakdown in the insulation will cause shorted turns between conductors or a ground between the conductor, and the field forging or retaining ring.

3) Q. When can a flux probe test be performed on a generator rotor?

   A. The test can be performed under no-load with the stator short-circuited or during operation at load. When the test is performed at load, it must be done at various load points to test all coils in the rotor.

4) Q. If a generator rotor is a conventional (indirect-cooled) design, can the rotor be converted to a direct-cooled winding?

A. Depending on the design of the rotor, in some cases it is possible to convert to a direct-cooled winding. Converting involves machining subslots in the rotor forging below the coil slots. Because of rotor geometry and size, this modification is not possible on all rotors.

5) Q. Is there asbestos in generator rotor insulation and blocking materials?

A. On older units, each GE generator rotor that is being rewound or modified will have all components with asbestos identified, while new non-asbestos materials will be included in the rewind materials package.

6) Q. Why should a generator rotor not be operated with a field ground?

A. While a single breakdown in groundwall insulation will not damage the rotor or its components, should a second ground occur, high current will pass through the rotor forging which can cause melting, wedge and ring damage and in the worst case, a forging failure.

7) Q. What uprate potential does my generator have if it is rewound?

A. It depends on the particular design. GE Generator Engineering can do a quick proposal design and offer several options with various uprates and possibly even increases in efficiency.

8) Q. Can just changing out a magnetic retaining ring to a non-magnetic retaining ring uprate my rotor?

A. Yes. For example, for a small air cooled generator (say 20 MW), 2–5% uprate in field capability is possible.

9) Q. Should a field be high speed balanced following a rewind?

A. GE recommends a high speed balance following a rewind with new copper. If copper is re-used, the field will generally not require a balance.

10) Q. Can thermal sensitivity result in a forced outage?

A. Generally, thermally sensitive fields will exhibit high vibrations that may limit output, but it is very rare for thermal sensitivity to force an outage. GE fields have had only one such incident

11) Q. When should a replacement field be considered?

A. A replacement field is worth considering when the customer is looking for:

- A very short outage duration
- Uprate potential
- Replacement of a bad forging
- Improved efficiency
- Extended life

12) Q. Is there a GE Technical Information Letter on rotor cracking ?

A. Yes. It is "TIL 1292", issued December of 2000 and is titled "Large Steam Turbine Generator Dovetail Inspection Recommendation." It briefly cites several recent dovetail cracks in older generator forgings and recommends inspection for those cracks.

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