Today’s Discussion

I. Current CC Generator Issues

II. Generator Outage Planning

Note: Reference sections at the end
  • Generator 101 Review
  • Generator Maintenance Review

Current Generator Issues
Stator End Winding
Vibration, Looseness, & Resonance

- Causes:
  - Poor Design
  - Operational Aspects
  - System Event

- Identification:
  - Visual Inspection – Bore Scope
    - Broken ties and other components
    - Shifted components
    - Dusting and Greasing
  - Vibration Monitoring
  - Resonance
    - Bump Test

Stator End Winding
Vibration, Looseness, & Resonance

Dusting               Greasing

End Winding Vibration – Where Does It Come From?
Safe Levels of Vibration

- No definitive standards ..... (But many opinions)
- 5 mils safe, while 10 mils or higher may be too high for safe long-term reliability
- Phase leads, due to their geometry, may be a bit higher
- Trending of vibration levels is important
- A winding that trends up from 3 mils to 6 mils may be showing more signs of distress than a winding that starts at 6 mils and stays there

Stator End Winding - Looseness & Resonance

- Corse of Action
  - Visual inspection – identify dusting or greasing, broken ties, loose or missing hardware, wear of insulation, arcing or burning due to shorted turns
  - Evaluate the winding natural frequency and resonance by bump testing and by adding vibration transducers
  - Repair if broken or loose & Detune the winding if resonant. This can be done by changing the end turn bracing system. Make sure N=2 mode is outside the exclusion zone and phase leads are well damped
  - Bump Test confirmation of corrections

Vibration Monitoring

- The vibration transducer can be mounted anywhere in an end winding, phase leads or on the connection rings. It is nonconductive and immune to electromagnetic interferences.
- Typical installation includes 6 at each end of the generator
Resonant Exclusion Zones

- Exclusion zone for bump test: 115 to 135 Hz. for a 60Hz system for the N=2 oval mode of the end winding basket
- Skewed zone to prevent a high tuned winding from dropping down on 120 Hz

Repair and Detuning Options

- Red Eye Epoxy Coat the End Turns
- Correct any broken ties or spacers
- Install additional ties or spacers
- Install a nose ring and tapered series blocking
- Install a more advanced retrofit bracing system like NEC’s NECCO Brace System
- Rewind the machine with an advanced bracing system

Also - Keep Coils Tight In Slot

- Check that slot wedges are tight
- Loose wedges and loose coils in the slot will contribute to end winding vibration and the consequences mentioned earlier
Partial Discharge - PD
IEEE Standard 1434 - 2000

Partial Discharge - Corona

- Poor coil spacing
- Voids in coil internals
- Gaps between coil and slot

Areas of corona/partial discharge
Partial Discharge

- Causes
  - Voids
  - Poor Spacing
  - Poor OCP
  - Materials / Manufacturing?

- Testing / Monitoring
  - Slot and Bus couplers
  - EMI
  - Bore Scope

PD Corrections & Damage Repair

- Different methods depending upon the extent, depth, and location of damage.
  - Rewind
  - Repair
- Design, material and process considerations if rewind
- Repairs are normal clean and reapply semi-conductive, gradient, or non-conductive treatments.
  - Not generally considered permanent and should be inspected periodically
PD Corrections & Damage Repair

- Rewind Considerations

Emergence Of An Old Problem
Spark Erosion

Stator Spark Erosion (SE)
Unique to Mfr's Who DON'T Use Side Ripple Springs

- Flat side filler does not maintain side pressure on the coil
- Even if initially installed tight, insulation shrinkage creates additional gaps allowing spark erosion to occur
Spark Erosion

- Cause – Looseness in the slot eliminating the coil to core interface
- Severe deterioration in a relatively short period of time

Coil above failed in 33,183 hours

Stator Spark Erosion

- Identification of SE – Bore Scope Inspection

Level 2 SE Deterioration
Level 3 SE Deterioration

Stator Spark Erosion

- Operating Hours?
- Testing options:
  - PD Couplers
  - EMI
- Correction / Repair Options
  - Replace Top Side Filler
  - Injection Processes
  - Rewind
  - Design and Process Changes

Stator Core Issues
Rotor Pole to Pole & Main Leads

- Monitoring & Maintenance
  - Unit Cycles?
  - Bore Scope
  - Testing
  - Fleet History?
- Problems?
  - Identify
  - Analysis
  - Repair / Correction

New Design

- FEA Analysis
- Optimize material types, design geometry, and stress locations
- Improved processes and procedures for application

Rotor – Conductor Issues
Generator Rotor Thermal Sensitivity

- Causes - normally attributed to one or a combination of:
  - Insufficient or Unequal Clearances
  - Asymmetrical Coil Expansion
  - Bound Slot Wedges
  - Blocked Ventilation Passages
  - Shorted Turns

Turn Insulation Migration

Rotor End Winding Distortion
Vent Hole Visual Inspection

Partially Blocked Ventilation Passage

Generator Rotor Thermal Sensitivity
Maintenance & Correction

- Testing
  - Flux Probe – Shorted turns
  - Pole Balance – Shorted Turns
  - Impedance – Shorted Terms
  - Load & VAR swing – Vibration Change?
- Visual Inspection
  - Blocked Ventilation
  - Insufficient or Unequal Clearances
- Corrections
  - Repairs & Rewinds

Generator Outage Planning
Preliminary Planning

- "Go To School"
- Specifications
- Create a qualified "Bull Pen"
- Document basic emergency information

“Go to School”

- Know your machine and its specific issues
- Sources of Information
  - Past Outage Reports
  - Trended Information
  - Other Users
  - Users Groups
  - Vendors
  - Technical Papers
  - Exhibitions
  - IEEE
  - Web Sites
Specifications

- The purpose of the specification is to clearly define the expectations and requirements for the project.
- Overall Philosophy?
  - Process vs. Performance Specification
  - Clearly State Expectations and Requirements
- The best time to develop specifications is before you need them!

Primary Generator Specifications (Templates)

- Test & Inspect
- Stator Rewind
- Stator Coil Manufacturing
- Rotor Rewind

Test & Inspect Specification Elements

- Begin Spec Development by evaluating machine specific concerns
  - Consult past outage reports, findings & recommendations
  - Machine type or model specific items
  - How can concerns be best monitored and evaluated?
  - Maintenance function or planning for a rewind?
- Testing
  - Methods & Equipment
  - Levels
  - General Protocols
- Required documentation from Vendor
- Rotor in & rotor out variations
- Data collection opportunity?
Stator Rewind Specification Elements

- Basics from the test and inspect specification plus:
  - Stator Core Iron Evaluation
  - Key Elements for Quality Stator Coils
  - Stator Coil Side Packing
  - Coordinated Testing Program (manufacturing & at site)
  - Division of Responsibilities
  - Vendor to Attach Project Technical Proposal

Stator Rewind Specification Elements

ELCID Test

- Excite core to only 4% of rated flux density
- Search coil on trolley detects interlaminar circulating currents
- 100 milliamp action threshold
- Uses 110 vac – easy to set up and use
- 3 Tests - Before Stripping, After Stripping, and After Wedges Installed

Stator Rewind Specification Elements

Loop Test

- Test creates near full flux of the core and is viewed with a thermo graphic camera
- Requires high voltage power supply with adequate current
- Normally a one hour test but significant setup is required
Stator Rewind Specification Elements

Side Packing

- Side packing is a critical component to the corona protection system and to preventing vibration and coil abrasion.
- Flat side filler will not maintain side pressure on the coil.
- Even if initially installed tight, insulation shrinkage, can create gaps and increase the potential for slot discharge.
- Ripple side packing keeps constant pressure on the coil to minimize vibration and the potential for abrasion.

Stator Rewind Specification Elements

Testing Protocol

- Should be coordinated protocol from coil final test through in process testing to final machine acceptance testing.
- Final testing should at least include:
  - Megger & PI (PI of 2 or greater to HiPot)
  - AC or DC HiPot (2E + 1,000) for AC
    - DC most common, convenient, and easiest to perform
    - Most common AC level is 2E + 1 eq AC
    - For DC level multiply by 1.7
  - Per phase Resistance Test (balanced?)

Stator Rewind Specification Elements

Bump Testing

- Checks for local and global natural frequencies near the 120 Hz double operating frequency.
- If tests indicate a natural frequency near 120 Hz – Winding can be tuned.
Stator Coil Specification Elements

- Mica Based, Epoxy Resin Impregnated Insulation System
- Class F (thermal rating) Insulation System
- Qualified Insulation System
  - IEEE 1043 Voltage Endurance Testing
- Design Uprate?
- Design that Minimizes Losses

Stator Coil Specification Elements

**Losses**

- $i^2R$ Losses
  - inversely proportional to copper area
- Strand/Eddy Current Losses
  - proportional to strand thickness
- Circulating Current Losses
  - voltage potential differences between strands
- Spec should at a minimum request losses be minimized

Stator Coil Specification Elements

- Maximum allowable ground insulation voltage stress? Volts Per Mil – VPM
- Maximize Copper Content
- Superior Semi-conductive Slot Treatment and Gradient Treatment in the End Turns
- 100% Final Factory Test
  - AC Hipot $((2E + 1) \times 1.3$]
  - Power Factor Tip up
    - Set average value
    - Per coil target (less than 0.6% tip up)
  - Verify Slot Corona Treatment Resistivity
  - Fit
Stator Coil Specification Elements
Surface Resistivity

- Acceptable level ranges from 1,000 to 20,000 ohms/square

Stator Coil Specification Elements
Winding Fit-up Inspections

- Cross Over Clearance
- Coil Drop
- Proper lead alignment is critical to final brazing operations & good wind ability of coils
- End Turn Clearance

Rotor Rewind Specification Elements

- Conductor (New or Re-use?)
  - Reused Copper
    - Hardness Check
    - Cleaning and Reshaping Protocol
  - New Copper
    - CDA 107 Oxygen-Free Silver-Bearing Medium Hard 80-85 F
    - Qualified Brazing program
    - 100% Braze Inspection
    - Edge bend or Corner - build consistency verification
- Retaining Ring – evaluation or replacement?
- High Speed Balance?
Rotor Rewind Specification Elements

Retaining Ring Evaluation

Magnetic 4340 steel inspected by dye penetrant cracks due to High Stress from over-speed and corrosion

18.5 (non-magnetic) susceptible to SCC should be inspected or replaced Inspected by Zygo - NDT

Rotor Rewind Specification Elements

High Speed Balance

• Recommended after a rewind
• Verifies balance and overall "operability" in running condition
• Over-speed verifies mechanical integrity of the rotor
• Running electrical testing verifies the electrical integrity of the rotor through out the speed range.

Rotor Rewind Specification Elements

Other Considerations

• Forging evaluation
• Slot Wedge Evaluation
• Slot Wedge Material (non magnetic for flux probe)
• Axial Leads
• Radial Leads
• Collector Rings
• Coupling
• Coupling Bolts
• Seals
• Seal Fits
• Journals
Creating a Qualified Bull Pen

• Baseball teams (users) have Bull Pens for their Pitchers (vendors). Shouldn't we?
• How can you be sure Vendors have the "stuff" and are ready to pitch?
• What are some of the key considerations?

Vendor Selection Criteria

• Company Experience & Relations With Past Customers
• Safety Program & Record
• Cost / Value
• Engineering Resources
  – Facility Resources
    – High Speed Balance Pit
    – Machining
    – Cleanliness
    – Lifting Capacity
    – In-House Technology
• Capacity Capabilities
  – Shop Loading / Capacity
  – Performance to Schedule
• Commercial Terms
  – Coil Supply, Repair, and Manufacturing
    – Experience
    – Demonstrated Reliability
    – Testing & Fit Up – Representative sample vs. 100% verification
    – Delivery
• Personnel Resources
  – Background
  – Experience
  – Depth
• QA/QC Programs
  – Documentation and Archiving
  – Certification
  – In Process checks

Options Are Good – Accurate Winding Data Is Essential!

Data Taking & Banking
### Terms and Conditions

- A necessary evil for everyone in business today
- If handled before generator problems arise, the focus remains on the generator problem and not the T&C issues.
- Companies need Vendors & Vendors need business! Without a prior commercial understanding, they may not get together.

### Blanket Terms & Conditions

- The process usually takes an extended period to resolve
- Should emergencies arise, an absence of T&C's, with qualified vendors, can cause major delays and increased cost

### Blanket Terms & Conditions

- Four most common T&C sticking points:
  - Indemnification
  - Limitation of Liability
  - Warranty
  - Termination
It is a simple fact
Generators Fail

Forced / Emergency Outages
- No one plans to have a forced outage, but they happen.
- Total Cost Impact ???
  - Expediting
  - Lost Generation
  - Replacement Power
  - Contract Penalties
- Scheduled rewinds can dramatically reduce total costs if properly planned and implemented

Initial Emergency Communication
- Name plate information
- Digital pictures
- Nature of failure
- Location of failure
- Plant Contact names, phone numbers and location
- Machine design data
- Expectations
Outage Specific Planning

Developing a Scope of Work

• Start by reviewing existing information. Use the “Go to School information”.
• Prioritize desired work
• What are the schedule and duration constraints?
• Consider the Cost –vs.- Benefit of work options

Outage Specific Planning

Newer vs. Older Rewinds

Newer Vintage
• Rewind Cause – normally one or a combination of:
  − Design concern
  − Material concern
  − Operational concern
• What is the root cause?
  − Specific – not a symptom
  − How can it best be corrected?
• How can long-term reliable life best be achieved?

Older Vintage
• Rewind Cause – normally age deterioration of components. Possibly machine characteristic change to support system needs.
• Were there any major technical deficiencies in the machine?
• Is an Up-Rate desirable?
• Incorporation of new materials and technologies
Outage Specific Planning

Replacement

- Replacement
  - Not as simple as it may seem unless swapping identical units
- Logistical concerns – Transportation & Lifting
  - Connecting to BOP – Cooling, Lubrication, Controls & Monitoring
- Has the root case of the problem been addressed by the replacement?

Outage Specific Planning

Timing

- Spring, Fall, Other?
  - Is there a best time?
  - Can the timing effect my price?
  - Vendor Availability
- RFQ process timing?
- NTP timing?
- Desired outage duration?

Outage Specific Planning

Other Issues

- Safety Issues & Expectations
- FME? (Foreign Material Exclusion)
  - Level
    - Process for access
    - Who can enter
- Vendor coordination on the generation deck
  - Lay-down space allotment – Plant Overhead Drawing
  - Facility restrictions?
  - Division of Responsibilities is crucial especially:
    - When multiple vendors are working
    - Utility requirements (Air, Water, Electric, Phone, Internet)
    - Lifting
  - Establish hard milestone interaction points with vendor(s) to review findings and limit wasted time in acting upon issues needing immediate intention.
### Outage Specific Planning

#### Division of Responsibilities List

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<th>Vendor</th>
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### Outage Specific Planning

**(Rotor Out)**

- Review special tools inventory and condition. Offer inspection by vendor.
- Crane condition and certification?
- Rotor support and protection based upon scope?
- Rotor Shipping preparation – Permits? Holiday restrictions?

### Venders

- Vender site orientation
  - Safety requirements
  - Coordination & Cooperation with other vendors and work being done at the same time
  - Lay down plan
  - Site support resources
- Vender – Plant contact points
- Vender Mobilization plan
Outage Specific Planning

Other Components

- Exciters
  - Brushless, Static, Conventional?
- Bushings
  - Spares
  - Testing & Evaluation
- Controls
- Iso-phase
  - Maintenance
- Cooling system?
  - Filters
- Lube system?
  - Filtering

Outage Specific Planning

Contingencies

- Back up’s to critical equipment
  - Induction heating / brazing, test set’s
- Specialty Tools on hand and in good condition
- Spares – on hand and qualified for use
  - Extra Consumables – resins, tapes
  - Emphasis on Long lead items such as Brushless Exciter Fuses and Diodes
  - Spare Coils?

Specialty Tools
Outage Specific Planning
Spare Bars

These spare bars may sit here on this shelf for 30 years and never be used. Then again, they may be needed next week.

Outage Specific Planning
Documentation and Trending

• Outage Reports
  – Should be kept together, organized by date, so they can be easily referenced
  – Electronic and paper files
  – Track recommendations, their completion and the details of completion (process, date)
  – Test Results – File by date
    • Normalize temperature and humidity
    • Trend

• Documentation should be a conscious intent as part of planning that carries through execution of the outage, rather than just gathering up the information after the outage is over.
• Documented information provides insight about where we have been and where we are.
• Trended information provides insight about where we are going. (Not a crystal ball but the next best thing!)
Final Thoughts

- Plan Early
- Utilize available resources in planning
- Planning for your next outage should begin while you are doing this outage
- Documentation is important for report requirements; but data trending is your best road map

Questions or Information

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Reference Sections

I. Generator 101 Review
   - Rotor and Stator
   - Capability Curve

II. Generator Maintenance Review
Generator 101 Review

Electro-Magnets, Sturgeon & Faraday’s Law

- Generator Rotor is an Electro-Magnet
- Invented in 1823 by William Sturgeon. Current running through copper wire wound around a piece of iron generates a magnetic field.
- Magnetic field is spinning at 3600 rpm from turbine.
- Faraday’s Law (1831) says that a magnet moving across a copper conductor will generate a voltage and current in that conductor
- Voltage and current is generated in the stator winding and taken out for distribution

Rotor and Stator

Induced Voltage in Stationary Conductors - Faraday’s Law
Turbo Generator Stators & Rotors

- Stator (Armature)
- High Voltage
  - 13.8 to 24 kVac
  - Stationary
- Rotor (Field)
- Low Voltage
  - 125 to 500 vdc
  - 3600 rpm – Turbo

Generator Cooling

- Importance of Cooling
  - Insulation Thermal Ratings
- Cooling Mediums
  - Gas
  - Air
  - Hydrogen
  - Liquid
  - Oil
  - Water
- Cooling Designs
  - Indirect
  - Direct

Generator Rotors

- Forged components (steel)
  - Shaft
  - Rings
  - Wedges
- Winding (copper)
- Insulation (glass epoxy/Nomex)
**Rotor Forging**

- Rotor forging machined from one piece of NiCrMoV steel
- Withstand torsional, lateral bending, vibratory and rotational stresses
- Torque from turbine is transmitted through coupling and shaft

**Empty Rotor Slot**

- Slots are machined in the rotor forging to hold the copper turns of the winding
- Wedge grooves (fir tree as shown or "T" shaped) allow wedges to hold copper turns in place during rotation
- Westinghouse often uses a "stepped" slot, along with a sub-slot for ventilation

**Retaining Rings**

Made from alloy steel non-magnetic forging
ASTM A-289 Class C (18Mn 18Cr)

Old Alloy 18Mn 5Cr susceptible to SCC
Types Of Retaining Rings

- Most modern design – Typical Westinghouse and newer GE
- Body mounted to shaft with a snap ring at nose of ring
- Cantilevered off the back end of the ring
- No contact with shaft at back end

Two Major Types

- Spindle-Mounted Retaining Ring
  - Usually 18.5 non-magnetic
- Body-Mounted Retaining Ring
  - Magnetic rings often have holes
  - Most non-magnetic don’t

Rotor Retaining Rings

- Magnetic ring – Holes are a good tell – Westinghouse or Electric Machinery – Body Mounted with snap ring to hold on
- Non-magnetic ring – normally no holes – this one is spindle mounted on the back end – GE style
Spindle Mounted Design

Rotor Windings

Conventional Indirect Cooled
- Older, conventionally cooled rotors use solid copper turns for carrying the current
- W design with fir-tree top wedge
- Often the rotor forging has many holes drilled through for cooling
Inner Cooled Conductors

- Newer, larger hydrogen cooled units have inner cooling in the rotor conductors
- Cooling gas is in direct contact with the copper
- More efficient cooling

Inner Cooled Coil & Insulation

- “C” shaped copper turn profile
- Nomex/glass epoxy slot liner or slot cell
- Glass melamine turn insulation bonded to the copper
- Top insulating filler
- Top wedge

GE Diagonal Cooled Winding

- On some large units, GE uses a diagonal cooled rotor winding cooling scheme
- Holes in copper are slightly offset with each turn
- Hydrogen gas travels up and out in a diagonal path
Rewound Rotor with Alum Conductor

End Turn Blocking

- End turn blocking:
  - supports the windings from distorting or shifting
- Blocks
  - typically positioned in a diagonal pattern
  - generally fit snug between coils, with additional clearance between the last row of blocks and the centering ring
- GE style blocks have tabs with rivets as shown

NEC Blocking Design

- GE units –
  - Metal rivets have come out and can catch on the RR liner
- NEC design:
  - improved design with a double tab arrangement fixed in place with a slot and dowel pins
- Nomex tabs:
  - maintain the block position within the end turn winding arrangement
Rotor Slot Wedges

• installed to hold the rotor coils against centrifugal forces
• also act as damper windings.
• Manufactured from magnetic steel, stainless steel, aluminum or titanium. Sometimes special brass/Beryllium copper is used for end wedges.

The wedges can have different geometries:
  – Standard
  – Pine tree type special
  – Vented

Cross Section of Wedge in Slot

• Slot Wedge radially supports coil in slot
• Wedges subject to high centrifugal forces due to rotation at 3600 rpm
• Coil should stay radially tight

Slip Rings/Collector Rings

• Rotating Member that:
  – collects D.C. excitation current from the carbon brushes and transports to the field winding via special connections.
  – Surface is usually grooved to even out the brush wear and reduce sparking.
  – Usually shrink fitted on the rotor shaft over an insulated sleeve.
Slip Ring Connections

Collector Rings
- Size and number can vary depending upon the amount of current to be supplied to the rotor.

Rotor Journals & Bearings
- Polished surfaces for bearings to support the rotor.
Rotor Journals & Bearings

Rotor Fans / Blowers
Circulate cooling gas, so that the rotor and stator windings stay at normal operating temperatures.

Squirrel Cage Fan
Axial Fan

Fans or Blower

• GE typically has two fans, one at each end of the rotor
• W typically has only one fan, mounted on the turbine end. W units often run hotter at the turbine end (i.e., WESTAC)
**Rotor Questions?**

**Generator Stator Components**

- Stator consists of the frame, core iron and coils
- Frame holds everything together
- Core iron provides a magnetic path for the flux
- Coils carry the current generated by the induced voltage
Generator Frame

- Frame holds hydrogen coolers
- Supports the bearing brackets that support the bearing, journals, and rotor
- Houses the "lead box" area where the main terminals exit

Looking Inside a Stator Frame

- Frame supports the core iron steel laminations
- Circular ribs add stiffness and rigidity
- Key bars or building bolts are welded to the circular ribs
- Core laminations are "located" by the key bars or building bolts

Looking Inside a Stator Frame

- Frame is designed to contain hydrogen explosion
- Building bolts in this photo vs. key bars
- Frames can vibrate, causing the core and then the winding to vibrate
Core Clamping

- Frame is also used as a bracing structure to clamp the core tight
- Core bolts are tightened, transmitting clamping force to pressure plate, finger plates, and then core
- Tension screws are sometimes used to stretch core bolt

Stator Core

Stator Core Lamination Style

- Two main types of core lamination design: key bar and building bolt
- Core is made up of thousands of individual laminations
- Each one is coated with insulation
- M-19, 29 Gage (0.014 inches thick) is most common
- Low losses
Core Lamination Type

- C-3 Organic coating
  - Lower temperature capability
  - Less die wear when punching laminations
  - More commonly used when punching lam's

- C-5 – Ceramic coating
  - Higher temperature capability
  - High die wear if punched
  - Always used when laser cutting
  - Franklin test of .5 amps

Core Lamination Tests

- Epstein Test – ASTM 343
  - Done to determine losses and expressed in Watts per pound
  - Late 1920’s – 2.65 W/lb – Now – 1.45 Watts/lb

- Franklin Test – ASTM 717
  - Verifies adequate interlaminar resistance coating on the iron
  - Test results shown in amperes, dependent on pressure (.06 A at 100 psi to .16 A at 1000 psi

Stator Core Iron

- Stator cores are usually stacked in vertical position
- Thousands of individually coated laminations form a solid iron structure
- Supports the coils
- Magnetic flux path
Final Stator Core Stacking

- Stator Core Stacking near completion
- Core is stacked lamination by lamination
- Core is hydraulically compressed at intervals to make sure it is compressed tight

Vent Ducts with “I” Beams

- The “I” beams form spaces in the stator core for cooling gas to pass through and cool the core

Stator Coils

- Cell
- Phase Leads
- End turns
- Connection End
Generator Stator Components

Stator Winding
- Stator winding is made of coils or bars
- Three main types of coil classification
  - Conventional air or hydrogen
  - Inner cooled air or hydrogen
  - Water or oil cooled
- Cell portion fits in the core iron slots
- End turn portion hangs over the end, outside the core
- Formed to an "involute" shape

Conventional & Inner Cooled
Design (L to R) – Air, Hydrogen & Water
Bar -vs- Coil

Loses?  
Manufacturing Cost?  
Winding Time?  
Maintenance?

Slot Cross-Section
- Core lamination
- Top coil
- Bottom Coil
- Cooling tubes
- Copper Strands
- Ground insulation
- Top fillers
- Side fillers
- Bottom breaker
- Top wedge

Optimize Coil Design
- I^2R Losses
  - inversely proportional to copper area – more total copper means lower I^2R losses – these losses are the highest percentage of total winding losses
- Strand/Eddy Current Losses
  - proportional to strand thickness – thicker strand means higher losses – slightly wider and thicker strand for Argentina – slightly higher Eddy Current losses but lower overall losses because of increase in copper cross sectional area
- Circulating Current Losses
  - voltage potential differences between strands
  - Roebel design eliminates

Conventional bar cross section
Stator Coil Bracing

- Diagram of simple bracing system with bracket and surge rings
- Decoupling system can be incorporated by allowing surge rings to slide on bracket surface

Fault Forces on End Turns

- Surge forces can occur during a fault, such as single phase operation, or a lightning strike on the bus
- The force is radial and distributed as shown
- Coil support brackets, or surge rings must handle

Stator Questions?
Capability Curve

Generator Maintenance Review

Generator Maintenance Review

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Generator Maintenance Review

- Purposes of Inspection & Testing
  - Monitor
  - Identify
  - Evaluate
  - Qualify & Quantify
  - Trend

Standard Equipment Monitoring

<table>
<thead>
<tr>
<th>Monitoring Activity</th>
<th>Purpose/Findings</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Over-temperature operation</td>
<td>Continuous</td>
</tr>
<tr>
<td>Ground</td>
<td>Failure of ground insulation</td>
<td>Continuous</td>
</tr>
<tr>
<td>Lube Oil Analysis</td>
<td>Contamination, bearing babbitt deterioration</td>
<td>Six Months</td>
</tr>
<tr>
<td>Vibration</td>
<td>Thermal sensitivity, loose component, imminent failure</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

Testing Summary

BE SURE ALL CIRCUITS ARE DE-ENERGIZED

<table>
<thead>
<tr>
<th>Maintenance Activity</th>
<th>Purpose/Findings</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>Dielectric Absorption</td>
<td>Winding cleanliness</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Polarization Index</td>
<td>Winding cleanliness/moisture</td>
<td>Major and Minor Outage Cycle</td>
</tr>
<tr>
<td>Power Factor</td>
<td>Insulation integrity</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Partial Discharge</td>
<td>Coil tightness; insulation integrity</td>
<td>On-line or Outage Cycle</td>
</tr>
<tr>
<td>Megger</td>
<td>Integrity of insulation</td>
<td>Major and Minor Outage Cycles</td>
</tr>
<tr>
<td>Blackout</td>
<td>Corona suppression integrity</td>
<td>Rewind</td>
</tr>
<tr>
<td>Resistance</td>
<td>Integrity of joints and connections</td>
<td>Major and Minor Outage Cycles</td>
</tr>
<tr>
<td>Flux Probe</td>
<td>Rotor winding shorts</td>
<td>On-line, Rewind</td>
</tr>
<tr>
<td>Rotor Impedance</td>
<td>Rotor winding shorts</td>
<td>Rewind</td>
</tr>
<tr>
<td>Ground Fault</td>
<td>Rotor Ground</td>
<td>Continuous</td>
</tr>
<tr>
<td>Split Voltage</td>
<td>Location of rotor grounds</td>
<td>As Needed</td>
</tr>
<tr>
<td>Voltage Drop</td>
<td>Presence of shorted turns</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>El Cid</td>
<td>Integrity of stator core</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Core Loop</td>
<td>Integrity of stator core</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Bolt Torque</td>
<td>Stator core looseness</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>Cracks, defects in forgings</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Temperature Monitoring</td>
<td>Normal/abnormal operation</td>
<td>On-line and Continuous</td>
</tr>
<tr>
<td>Dye Penetrant</td>
<td>Cracks, defects in forgings</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Eddy Current</td>
<td>Cracks, defects in forgings</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Magnetic Particle</td>
<td>Cracks, defects in forgings</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Wedge Mapping</td>
<td>Stator winding tightness</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Hi-Pot</td>
<td>Insulation integrity</td>
<td>Major Outage Cycle</td>
</tr>
<tr>
<td>Vibration</td>
<td>Rotor imbalance</td>
<td>Monthly and On-line</td>
</tr>
<tr>
<td>Visual Inspection</td>
<td>Normal/Abnormal Performance</td>
<td>As Available</td>
</tr>
<tr>
<td>Oil Chemistry and Count</td>
<td>Bearing oil contamination</td>
<td>Twice Yearly</td>
</tr>
</tbody>
</table>
### Visual Inspection

<table>
<thead>
<tr>
<th>Maintenance Activity</th>
<th>Purpose/Findings</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator Winding</td>
<td>Dusting, greasing, oily, broken ties, discoloration, foreign object damage, &amp; contamination</td>
<td>Before every minor and major outage to help determine scope</td>
</tr>
<tr>
<td>Stator Core</td>
<td>Damaged iron, loose iron, discoloration, foreign objects, &amp; contamination</td>
<td>Major outage with the rotor out</td>
</tr>
<tr>
<td>Rotor</td>
<td>Discoloration from overheating, loose or shifted blocks, arcing &amp; contamination</td>
<td>Before every minor and major outage to help determine scope</td>
</tr>
</tbody>
</table>

### Visual Inspection – Bore Scope

- Less intrusive
- Technology continues to improve
  - Probes have been getting smaller to gain greater access in tighter areas
  - Improved optics are yielding improved clarity
- While it is a very beneficial tool and can provide valuable insight, there are limitations to what can be adequately seen and evaluated. Data interpretation and conclusions must be done by experienced personnel.

### Contamination
Contamination Failure
GE; 18,824 KVA; 12,500V

Inspection & Testing References
Electrical Tests - Stator

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<tr>
<th>Maintenance Activity</th>
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<tr>
<td>Insulation Resistance or &quot;Megger&quot; with PI</td>
<td>Determines presence of contamination</td>
<td>Minor and Major Outage</td>
</tr>
<tr>
<td>Winding Resistance</td>
<td>Integrity of brazed connections</td>
<td>Minor and Major Outage</td>
</tr>
<tr>
<td>Hipot</td>
<td>Proof test to &quot;stress&quot; insulation</td>
<td>Major Outage</td>
</tr>
<tr>
<td>D.C. Ramp</td>
<td>Determines insulation condition / strength</td>
<td>Major Outage</td>
</tr>
</tbody>
</table>

Insulation Resistance Testing

- 2500 vdc for stator
- 500 vdc for rotor
- PI (Polarization Index) -
  Compare 1 minute and 10 minute
  - One Min. (100 Megohms)
  - Ten Min. (300 Megohms)
  - PI = 300 / 100 = 3.0
- PI > 2.0 is good
## Winding Resistance - DLRO

- DLRO – Digital Low Resistance Ohmmeter
- Should be capable of 4 or even 5 significant digits
- Compare all three phases of the stator winding – if not balanced within about 3% maximum, strand breakage or joint failure may be occurring
- Rotor value should be consistent outage to outage when corrected

## Hipot Testing

- Hipot testing – high potential or overpotential testing - used as proof test
- Preferable to have a failure during a controlled test, during an outage, rather than at some unknown time, possibly when the unit is badly needed
- \[ AC \text{ kV} = (2E + 1) \]
- Multiply by 1.7 for the DC value
- AC equipment, as shown at right, is large and heavy

## Hipot Testing

- AC testing is more demanding than DC
- AC has higher risk of coil failure
- DC more commonly used as maintenance test (1.2 to 1.6 times (2E+1))
- AC more commonly used as commissioning test for new winding
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<th>Purpose/Findings</th>
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<tr>
<td>ELCID – Electromagnetic Core Imperfection Detection</td>
<td>Shorted laminations</td>
<td>Major outage</td>
</tr>
<tr>
<td>Core Loop</td>
<td>Shorted laminations</td>
<td>After rewinds or core repair</td>
</tr>
<tr>
<td>Wedge Tightness</td>
<td>Loose wedges</td>
<td>Major outage</td>
</tr>
<tr>
<td>Partial Discharge</td>
<td>Insulation deterioration, coil tightness in slot</td>
<td>Yearly</td>
</tr>
<tr>
<td>Bump test</td>
<td>Detects resonant frequencies</td>
<td>Major outage</td>
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</table>

**ELCID Test**

- Excite core to only 4% of rated flux density
- Search coil on trolley detects any interlaminar circulating currents
- 100 milliamp action threshold
- Uses 110 vac – easy to set up and use

**ELCID Test Plot**

- ELCID test plot shows multiple locations with significant hot spots and “areas under the curve” as shown at the right
- 100 milliamps or greater requires further investigation
Core Loop Test

- Excite core to rated flux density
- Wait one hour for heat to soak through
- View with infra-red
- Locations 10°C above average core temperature should be corrected
- Need High Voltage – 4160 volts
- Higher safety precautions

25-Year-Old Stator Core – Loop Test

- Original Core loop test shows a 111.3 degree C core hot spot a few minutes into the Core Loop Test. Another area, as shown, is at 78.4 degrees

Core Tightening

- Check core clamping bolt torque
- Every 5 years or major outage
- 80% to 100% of original OEM recommended values - 150 – 200 psi
Wedge Tightness Tester

- Loose stator wedges can allow the coil to vibrate due to double operating frequency slot pounding forces.
- This vibration can cause stand breakage, or insulation damage on the ground wall insulation.
- Loose wedges can be located by an Adwel Wedge Tapper – shown at right.
- If ripple springs are used to keep the slot tight, deflection can be measured through gage holes in top wedge.

Wedge Tightness Tester

- Operator places “wedge tapper” over each wedge.
- Tapper determines natural frequency of wedge.
- Computer stores values and compares to all other values.
- Can compare against preset data, new calibration data, or a floating calibration.
- Consistent results versus old method of “hand tapping” and listening.

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<td>Integrity of brazed connections</td>
<td>Minor and Major Outage</td>
</tr>
<tr>
<td>Flux Probe</td>
<td>Rotor shorted turns (running)</td>
<td>Yearly</td>
</tr>
<tr>
<td>Pole Balance</td>
<td>Rotor shorted turns (stationary)</td>
<td>Major Outage</td>
</tr>
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</table>
Rotor Flux Probe Test

- Detects presence of rotor winding turn to turn shorts at rated speed
- Identifies Pole and Coil Number of shorted turns
- With current applied to rotor while spinning, test picks up slot leakage flux as each slot passes probe

Inspection & Testing References

<table>
<thead>
<tr>
<th>Specialty Rotor Tests</th>
<th>Purpose/Findings</th>
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<tbody>
<tr>
<td>Boresonic Inspection</td>
<td>Forging Material Integrity</td>
<td>Rewind and based on past assessment</td>
</tr>
<tr>
<td>NDE – Retaining rings and other components</td>
<td>Detect cracks, corrosion and material deterioration</td>
<td>Major Outage and Rewinds</td>
</tr>
<tr>
<td>High Speed Balance</td>
<td>Qualify rotor mechanically &amp; electrically and dynamic balance</td>
<td>After major rotor work and Rewinds</td>
</tr>
</tbody>
</table>

Running Electrical Tests

- Recommended after a rewind
- Verifies presence or absence of shorted turns
- Verifies balance and overall “operability” in running condition