Best Practice Catalog

Excitation System

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1.0 Scope and Purpose

This best practice for the excitation system addresses its technology, condition assessment, operations and maintenance best practices with the objective to maximize performance and reliability. The primary purpose of the excitation system is to provide a regulated DC current to the generator rotor to induce and maintain a voltage in the stator at a set value under normal operating conditions while varying the generation or absorption of reactive power and supporting generator terminal voltage under fault conditions. The excitation system must respond to voltage and frequency excursions and this response must be coordinated with generator capabilities and protective relay functions to ensure continuous unit reliable generation. Due to its critical nature the reliability of the excitation system has come under the auspices of the North American Electric Reliability Corporation (NERC).

1.1 Hydropower Taxonomy Position

Hydro Power Facility → Powerhouse → Power Train Equipment → Exciter

1.1.1Exciter Components

Exciters and excitation systems have evolved from DC generators driven by the shaft of the generator or by an AC motor to the present solid state systems utilizing diodes or rectifiers. Many of the original systems are still in service today as a testament to their simplicity and reliability. The solid state systems may be brushless systems where the rectification takes place on the rotating shaft and field current is supplied to the rotor without going through brushes and collector rings. A very basic system is seen in Figure 1. Performance and reliability related components of the excitation system include the low voltage controls, the source of the field current (dependent on the type of excitation system, i.e. rotating or static), the power source (for a static system), current interruption or isolation devices (AC or DC field breakers), and the brushes and collector rings/commutator. For purposes of this best practice, the excitation system is considered to “end” at the collector rings or at the point of connection to the rotating field circuit.

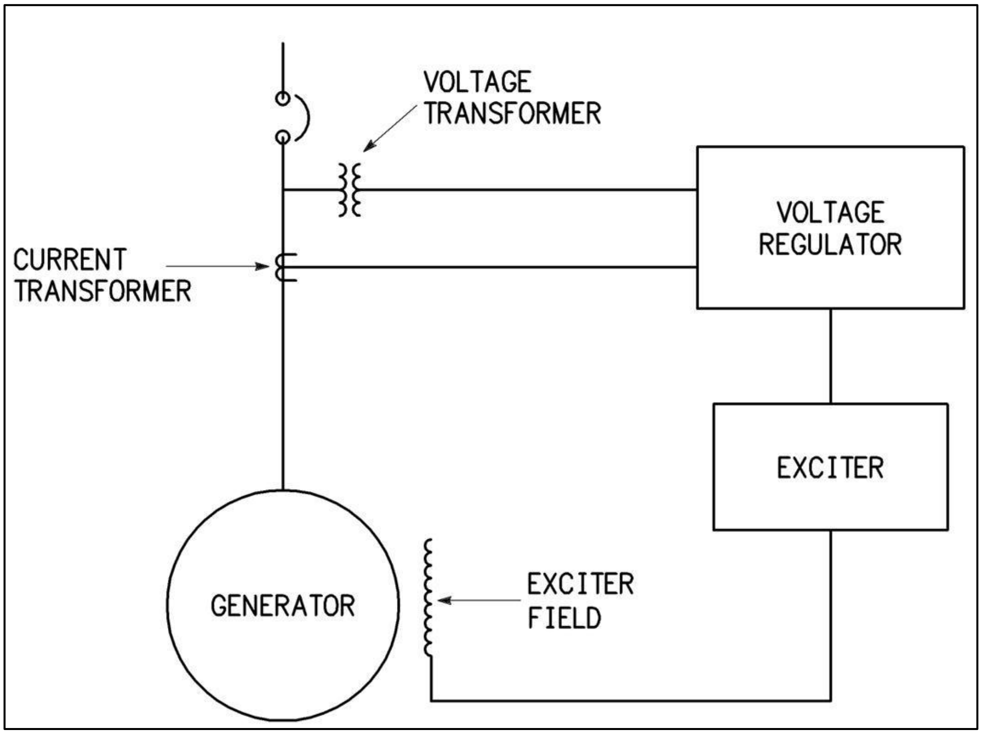

Figure 1: Excitation System Diagram

Low Voltage Controls: The low voltage controls portion, or regulators, of the excitation system provides the control and protective functions to regulate the DC field voltage and current supplied to the generator rotor. Field voltage to the generator is controlled by feedback from the generator instrument transformers. The information provided by these transformers is used by the "automatic voltage regulator" or AVR to control either the field of a DC exciter or alternator or the input to silicon controlled rectifiers (SCR's) which in turn determines the magnitude of the main DC field current. These instrument transformers are normally not provided with the excitation equipment however the voltage transformer is critical to operation of the AVR. Generally a "manual" regulator is also provided which functions as a field current regulator to maintain field current at a fixed value. In some critical facilities redundant regulators may be provided. On some older units a manual control rheostat is used that allows the AVR to be removed from service while the unit remains on-line under manual control.

Field Current Source: The primary field current sources will be either a rotating exciter feeding the main field of the generator or a static exciter using thyristor bridge rectifiers (SCR's). Another common excitation system is a brushless exciter with a rotating ac generator and rotating rectifiers

Power Source: For static exciters an AC power source must be provided for the bridge rectifier. This power source is generally a shunt supply transformer from the generator terminals but may also be any adequately sized AC supply from the line or load side of the generator breaker. For an exciter transformer, sometimes called a power potential transformer (PPT) or exciter power transformer (EPT), or any alternate supply, the rating must be sufficient to supply the field under all operating conditions, including faults on the generator terminals or the transmission system when connected, plus any losses in the conductors, convertor and transformer itself.

For rotating exciters the power source is usually a permanent magnet generator (PMG)

An alternative source of excitation power is a low voltage plant bus. This is not preferred due to the possibility of harmonic content from the exciter bridge having a deleterious effect on other equipment powered from the bus. This power source is not considered in this BP.

<u>Current Interruption Devices</u>: As the field current cannot change instantaneously for a close-in or internal generator fault fast suppression of the generator field is necessary to limit damage. As long as the unit is spinning and there is current in the rotor, energy will be fed to the fault. Depending on the type and vintage of the system a number of methods are utilized to dissipate and remove this energy. A field discharge resistor in parallel with the field winding provides a decay path for the field current when the resistor is placed in the circuit as the result of a unit electrical trip.

For a fully static system, the field voltage may be forced negative to result in rapid de-excitation.

For almost all systems field energy is dissipated in a field discharge resistor once the field breaker contacts open or a protective thyristor(s) is gated.

<u>Collector Rings, Commutators, and Brushes</u>: The brushes function to transfer field current from a stationary component, the brushes and rigging, to a rotating component. For a rotating exciter, the output of the exciter armature is delivered by the exciter commutator and brushes to the main generator field collector (or "slip") rings and brushes

Non-performance but reliability related components of the excitation system include the instrument transformers used to measure generator voltage and current.

<u>Instrument Transformers, Voltage and Current</u>: As the generator terminal voltage and currents cannot be directly measured a means for reducing these values to useful levels for the regulator is required. These transformers are normally not part of the excitation system regulator "package". Voltage transformers (VT's) reduce the generator stator voltage and current transformers (CT's) reduce the generator stator currents to useful quantities based on their transformation ratios. These transformers are normally housed in the generator switchgear and the secondary voltages and currents off any VT or CT may be used by multiple instruments, meters or relays. Inputs from the VT and CT are critical to both the controlling and protective functions of the regulator.

1.2 Summary of Best Practices

1.2.1 Performance/Efficiency & Capability - Oriented Best Practices

- Periodic performance testing to establish accurate current unit performance characteristics and limits.
- Dissemination of accurate unit performance characteristics to unit operators, local and remote control and decision support systems and other personnel and offices that influence unit operation and performance.
- Real-time monitoring and periodic analysis of unit performance at the Current Performance Level (CPL) to detect and mitigate deviations from expected performance for the Installed Performance Level (IPL) due to degradation or component failure.
- Periodic comparison of the CPL to the Potential Performance Level (PPL) to trigger feasibility studies of major upgrades.
- Maintain documentation of IPL and update when modification to equipment is made (e.g., re-insulation of field, exciter replacement).
- Trend loss of performance due to degradation of excitation system components. Such degradation may be indicated by increased excitation current required for a given load point or increased operating temperatures.
- Include industry acknowledged "up-to-date" choices for excitation system components and maintenance practices.

1.2.2 Reliability/Operations & Maintenance - Oriented Best Practices

- For any given load point the power into the exciter should be periodically measured and trended for degradation. For a static exciter the power into the exciter is from the PPT (or EPT). In a rotating system exciter field current and PMG output serve as indicators of power into the system. Shorts (shorted turns) or open or high resistance circuits in the components providing power to the exciter will result in increased losses and degraded performance.
- The power out of the exciter, i.e. the delivered field current, is determined by the AVR (or manual regulator). The amount of field current required for any operating point should be compared to the original manufacturer's curves.
- The brush rigging and collector commutator assemblies are most critical reliability components for both static and rotating exciters. The high temperature environment, brush dust generated, and wear of components due to relative rotating motion dictates increased focus on these areas. Brushes assemblies, collector rings and commutators should be inspected frequently. Establish a temperature profile for collector ring/commutator air temperatures. Trend for degradation and indication of brush/collector/commutator deficiencies. Periodic

infrared inspection of brushes under load can provide an indication of brush selectivity issues. On higher speed units brush vibration (and attendant wear, chipping) may be caused by excessive collector ring runout.

- Monitor field insulation resistance to ground
- Establish normal operating temperatures for other system components and trend for degradation (e.g., PPT's, rectifier bridge).
- Electronic and electromechanical (low voltage control) components should be maintained in a clean and preferably temperature controlled environment.
- Manual and motor operated rheostats should be periodically "wiped" (run through their limits), checked for smooth operation and visually inspected for arcing or overheating. Drive mechanisms should be inspected and lubricated as required.
- AC and DC breakers should be checked per vendor's recommendations.

1.3 Best Practice Cross-references

- I&C – Automation Best Practice
- Electrical – Generator

2.0 Technology Design Summary

2.1 Material and Design Technology Evolution

Early exciters were usually a DC generator driven off of the main generator shaft, by an AC motor or even an auxiliary water wheel. With the development of solid state devices, rectifier sourced exciters were developed evolving into the fully inverting silicon controlled rectifier (SCR) bridge(s) used in today's solid state exciters. Voltage regulators have changed from manual control of a rheostat in the field circuit of a DC generator to the present solid state digital regulators. The regulator will control either the field of a DC exciter or alternator or it may control the gating of the SCR's in a solid state exciter.

Performance levels for excitation systems can be stated at three levels as follows:

The installed performance level (IPL) is described by the unit performance characteristics at the time of commissioning. For excitation systems these performance levels are defined by the manufacturers provided guaranteed loss data and by the unit saturation (Figure 2) and "V" curves (Figure 3) which define the expected field current requirements for a given load condition. An explanation for the interpretation of these curves is found in IEEE 492.

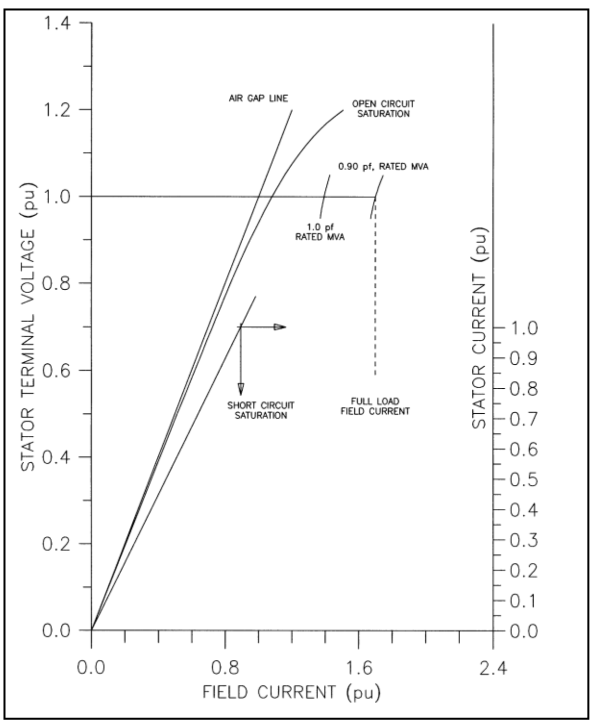

Figure 2: Typical Saturation

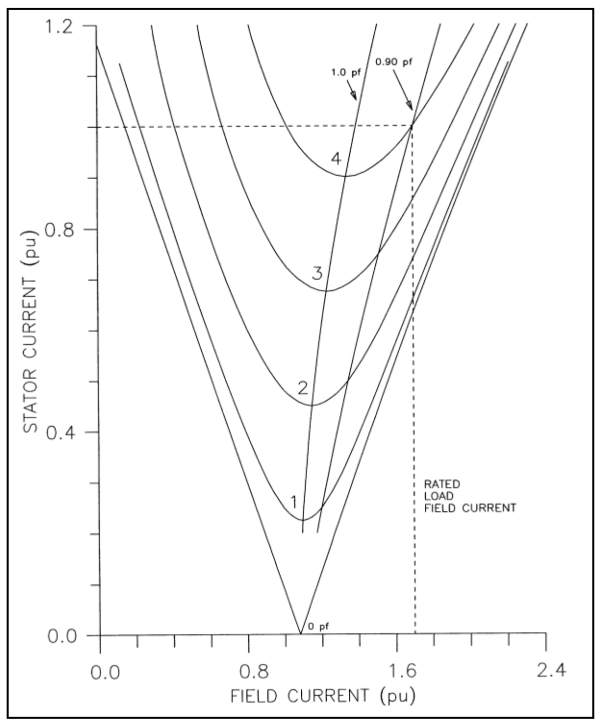

Figure 3: Typical "V" Curves

The Current Performance Level (CPL) is described by an accurate set of excitation system performance parameters. While current performance can be compared to the IPL curves and loss data, additional data points (not provided for by the IPL) for temperature measurement of system components should at some point be collected for baseline and trended over time.

Determination of the Potential Performance Level (PPL) for excitation system will entail system improvements that provide minimal reduction of losses and non-performance related improvements such as improved response times offered by solid state systems. For a given generator, rating improvements in excitation performance can only be expected to restore the original IPL relative to field current required at a particular load point.

2.2 State of the Art Technology

Excitation system efficiencies, as a measure of losses, are the sum of the electrical and mechanical losses in the equipment supplying excitation. This will include losses in exciter field circuits, manual and motor operated rheostats, voltage regulators, PPT's, collector and commutator assemblies, motors used in the system, switchgear and any electrical connections in the power circuit. These losses are directly correlated and vary based on the amount of field current which is directly correlated to the operating power factor and load.

For a state of the art excitation system with a fully static exciter and digital voltage regulator the total excitation losses may approach 4% of the total generator losses at rated load condition. For a 33 MVA unit this total may be 15 to 30 kW. In older systems which include manual and/or motor operated rheostats, main exciter field windings, a pilot exciter and commutators not found in a state of the art system these losses may approach 10%. Here the value may be 40 to 60 kW. In both cases these IPL values are generally provided as calculated data by the manufacturer and very difficult to determine empirically as independent test for the exciter.

The more significant gains as defined by the PPL are in the area of reliability, improved exciter response time (transmission system stability, minimized fault damage), reduced maintenance requirements and improved flexibility and integration with modern control and protection systems. Reduction of losses is not a prime consideration in the decision to replace an existing system.

3.0 Operation & Maintenance Practices

3.1 Condition Assessment

USACE Hydro Plant Risk Assessment Guide [1] provides a methodology for assessing the condition of a system based on its age, operation and maintenance history, availability of spare parts and service support, and test performed on both the power and control circuitry. Some of the factors considered in this assessment follow.

The NEMA insulation class (B, F, H, etc.) will determine the operating temperature limits. The electrical insulation integrity of this insulation and the system is reduced with increasing age. All electrical insulation deteriorates over time due to increased exposures to the cumulative effects of thermal stress and cycling, vibration and mechanical damage, and deleterious contaminates. Age also determines obsolescence status and availability of vendor technical support and spare parts. A variety of electrical tests may be performed to aid in assessing insulation condition.

Obviously, these condition assessment factors are closely related. The evaluation should also consider the failure and forced outage history. It is likely, however, particularly for older units, that there may be a lack of history, maintenance records, and design documentation to supplement the assessment.

Infrared thermography can be used to monitor deterioration of bolted electrical power connections, collector/commutator performance and rheostat performance. Winding resistance and system insulation resistance should be measured periodically to detect deterioration. Field insulation resistance may be continuously monitored online and trended.

Brushless systems should be inspected stroboscopically for blown fuses if applicable. In some cases a blown fuse can cause a cascading overload of remaining fuses. Collector ring/commutator and brush rigging condition should be evaluated. Ring film condition, commutator condition and overall cleanliness have a significant effect on reliability. A typical collector ring, brush rigging assembly, commutator assembly is seen in Figure 4.

Bridge temperature, transformer temperatures, cabinet air temperatures and collector ring temperatures can provide an early indication of deterioration. Figure 5 shows a typical solid state system cabinet.

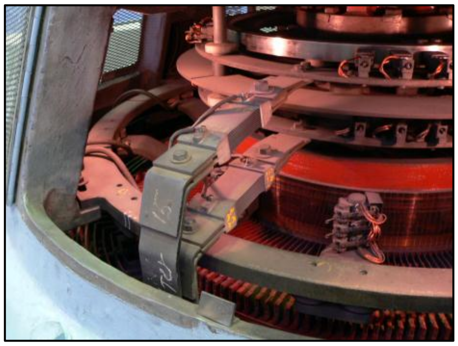

Figure 4: Collector/Commutator/Brushes

Figure 5: Typical Solid State Cabinets

3.2 Operations

It is critical that the design and capacity of the exciter match the operational requirements. Operation of the exciter and generator must be maintained with the manufacturer's capability curve. An example capability curve can be seen in Figure 6. For the excitation system critical operation is in the over excited region of the curve where field current is a maximum and temperature limits may be reached. Operation outside these limits results in increased heating and rapid deterioration of insulation and reduction of service life. Temperature limits for the field are determined by the NEMA insulation class.

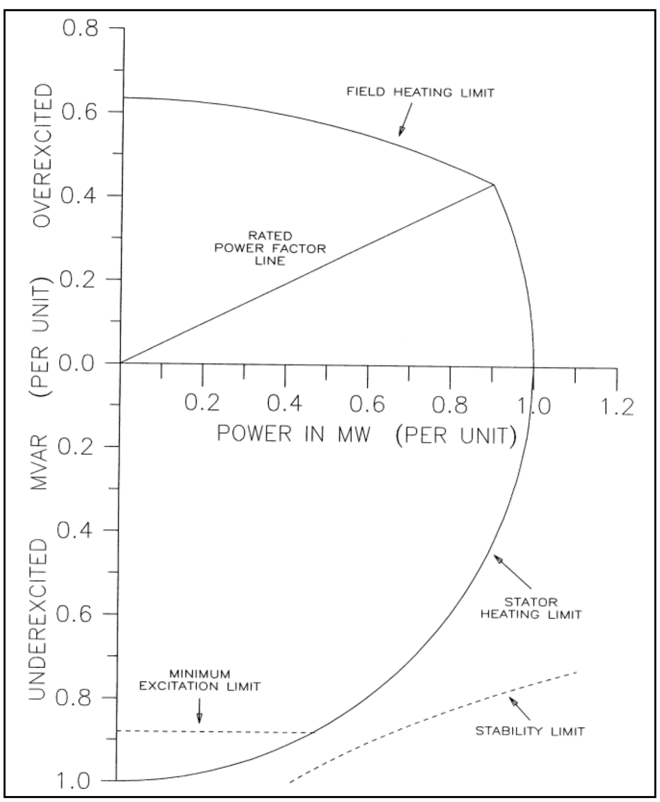

Figure 6: Typical Generator Capability Curve

For generating units whose capacity (output) has been uprated without exciter replacement consideration should be given to the number of collector ring brushes required by increased field current, the change in the generator short circuit ratio if applicable, and operating temperature limits.

Shorted rotor turns may increase excitation requirement for a given generator load, kVA. Rotor insulation class may limit kVA output due to temperature limits. Deratings of the excitation system may also impact kVA output of the unit.

3.3 Maintenance

The frequency of maintenance will best be determined by consideration of manufacturer's recommendations, the age of the unit, the operating mode of the unit, environmental conditions and the failure history of the unit. No one frequency recommendation will be applicable to all units. The maintenance of excitation system components is also a significant factor in its performance capabilities. Manufacturer's recommendations provide a basis for items necessary to maintain. These recommendations should be adjusted based on the actual age, operating conditions and operating environment in order to maximize life expectancy. Cleanliness is required to minimize potential for electrical tracking and grounds as well as to prevent degraded cooling or heat transfer.

The collector ring/commutator and brush rigging assembly are probably the most maintenance sensitive component of the system when it comes to reliability. The generation of carbon brush dust due to the relative motion between the rings/commutator and the brushes provides opportunities for field grounds and flashovers, including fires. Brush condition (length, freedom of movement, leads discoloration) should be visually checked frequently depending on how the unit is operated. The collector ring film should be visually inspected and run-out measured to be within manufacturer's tolerance. If necessary the ring may be required to be trued, in situ or removed. The ring film may need to be removed and re-established. In either case the ring finish should be within manufacturer's tolerance. If necessary as indicated by insulation resistance measurements the brush rigging should be cleaned.

Inspect the commutator and ensure that the commutator insulation does not protrude above the copper bars. If so, undercut per manufacturers recommendations.

Rheostats should be inspected, cleaned to ensure uniform, low contact resistance and lubricated for free movement. A typical rheostat is seen in Figure 7.

Figure 7: Motor Operated Rheostat

Excitation system AC and DC breakers and contactors should be tested, inspected, and maintained per the manufacturer's recommendation. Particular attention should be given to DC breaker and contactor contacts for wear and electrical erosion.

Equipment enclosures should be cleaned and any vent filters replaced as necessary. Vents should not be obstructed. For solid state systems with force cooled bridges verify operation of bridge fans, lubricate as required.

Both solid state dry type and oil filled PPT/EPT's should periodically meggered and have turns ratio tested. If fitted with fans they should be cleaned and operation tested. Oil filled PPT/EPT's should be inspected for tank and bushing leaks. Transformer bushings, if applicable, should be cleaned and oil level checked. If fitted with oil pumps and motors their operation should be tested. Transformer oil should be checked for dissolved gases and quality.

4.0 Metrics, Monitoring and Analysis

4.1 Measures of Performance, Condition, and Reliability

Excitation system losses (rheostat, brushes, transformers) and excitation system availability are all measures of condition and reliability. Losses associated with the exciter may include rheostat losses, brush contact losses, brush friction losses, and windage losses. These losses may approach 15-30% of the unit full load losses. Generator rotor I^2R losses are included with the generator and not considered in the excitation best practice.

Any I^2R loss, which is a waste heat loss, may be reduced by reducing R. "R" is the resistance which is a function of temperature and physical properties of copper in the excitation system components. R varies but not significantly with the temperature changes in operation. "I", the current, may vary significantly. The amount of current, the most significant factor in the loss equation is dictated by the load. Exciter losses are the total of the losses in the equipment supplying excitation. This equipment is minimized with a static system, thereby reducing these losses.

Rheostat losses are the I^2R losses of the rheostat if used. This is eliminated when using a static system.

Brush contact losses are the electrical losses in the collector ring brushes. Prudent maintenance of collector ring, commutator (eliminated with static system) and brush rigging minimizes these losses.

Brush friction loss is a mechanical loss due to rubbing friction between the brushes and collector rings and/or commutators. Elimination of the commutator brushes with a static system reduces these losses.

Friction and windage losses are the power required to drive an unexcited machine at rated speed with the brushes in contact (excitation system contribution to this loss is typically minimal and unavoidable).

The key measurements include field current I_f, field winding resistance R, temperature T, and brush voltage drop in volts.

4.2 Data Analysis

The CPL, relative to losses, is described by an accurate set of unit performance characteristics determined by unit efficiency testing, which requires testing per IEEE 115 methods. The CPL relative to field current requirements of the unit is made by comparison to the saturation and "V" curves. Failure to meet the IPL for field current may be due to shorted rotor turns.

4.3 Integrated Improvements

Reliability issues, obsolence issues or impending unit uprate may warrant complete replacement of the existing exciter. The preferred option is a completely solid state unit which offers the following advantages [4]:

- Eliminates high maintenance and obsolete components
- Eliminates time constants associated with exciter field components and provides fast system voltage recovery and transient stability
- Provides data recording capability for trending and troubleshooting
- Offers an opportunity to increase original field excitation and uprate the unit.
- Provides digital communication capability that facilitates remote control and monitoring.
- Provides option of backup regulators
- Enhanced control features such as a power systems stabilizer, power factor and VAR control.
- Eliminates losses associated with commutator brushes and rheostats
- Facilitates validation of system dynamic performance for conformance with NERC standards.

It may not be necessary to replace the rotating exciter to restore unit reliability. Replacement of the pilot exciter/voltage regulator with a digital system may be sufficient to improve unit reliability; however, the response time of the system will not be optimized as with a full static system. While replacement of the voltage regulator only is a reasonable compromise, replacement with a full static excitation system is the best solution.

NEMA class F or H insulation (maximum operating temperature 155 or 180 C, respectively) should be used for rotor pole windings. For unit uprates brush capacity should be evaluated for additional field current requirements. Constant pressure brush springs should be used for collector and commutator brushes.

Location and placement of a new solid state system and PPT (EPT) is often a challenge in existing plants. Once locations for new equipment have been determined, consideration of the operating environment may indicate the need for additional cooling for reliability of the low voltage electronics.

5.0 Information Sources

Baseline Knowledge:

1. USACE – *Hydro Plant Risk Assessment Guide, Appendix E4 Excitation System Condition Assessment*
2. EPRI –EL-5036, Volume 16, *Handbook to Assess the Insulation Condition of Large Rotating Machines*
3. IEEE 115 – *Guide for Test Procedures for Synchronous Machines*

State of the Art:

4. Basler Application Notes – *16 Reasons to Replace Rotating Exciters with Digital Static Exciters*
5. EPRI 1004556 – *Tools to Optimize Maintenance of Generator Excitation Systems, Voltage Regulators and Field Ground Detection*

Standards:

6. IEEE Std 492 – *Guide for Operation and Maintenance of Hydro-Generators*
7. NERC GADS – *Top 25 System/Component Cause Codes*
8. IEEE Std 421.1 – *Standard Definitions for Excitation Systems for Synchronous Machines*
9. IEEE Std 421.2 – *Guide for Identification, Testing and Evaluation of the Dynamic Performance of Excitation Control Systems*
10. IEEE Std 421.3 – *Standard for High Potential Test Requirements for Excitation Systems for Synchronous Machines*
11. IEEE Std 421.4 – *Guide for the Preparation of Excitation System Specifications*
12. IEEE Std 421.5 - *Recommended Practice for Excitation System Models for Power System Stability Studies*
13. IEEE Std 1147 – *Guide for the Rehabilitation of Hydro Electric Power Plants*
14. EPRI Report 1011675 – *Main Generator Excitation System Upgrade/Retrofit, Nov 2005*

It should be noted by the user that this document is intended only as a guide. Statements are of a general nature and therefore do not take into account special situations that can differ significantly from those discussed in this document.

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