ELECTRIC POWER RESEARCH INSTITUTE

Main Generator Excitation System Upgrade/Retrofit

Lessons Learned

Technical Report

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Lessons Learned

1011675

Final Report, November 2005

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Maintenance Reliability Group, LLC

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CITATIONS

This report was prepared by

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This report describes research sponsored by the Electric Power Research Institute (EPRI).

The report is a corporate document that should be cited in the literature in the following manner:

Main Generator Excitation System Upgrade/Retrofit: Lessons Learned. EPRI, Palo Alto, CA: 2005. 1011675.

PRODUCT DESCRIPTION

Upgrading or replacing even a portion of the excitation system of a generator can provide increased reliability and availability while simultaneously decreasing operational and maintenance costs. However, the upgrade or retrofit of an excitation system is a major cost involving some degree of implementation, installation, or performance risk. This report provides lessons learned, experiences, practices and solutions from plants that have installed excitation system retrofits and upgrades. This information will help electric utilities:

- Maximize their benefit-to-cost ratio by improving installation efficiency
- Help reduce possible difficulties and risks associated with the installation and operation of an upgrade or retrofit
- Ensure the best possible implementation and installation of upgrade/retrofit.

Results & Findings

The appendices of this report provide forty-five "Best Practices" and twenty-nine "Lessons Learned" from utilities that have performed excitation system upgrades and retrofits. The body of this report builds upon these "Best Practices" and "Lessons Learned" with additional information provided by utilities and manufacturers to guide power plants in the upgrade or retrofit of their excitation systems.

Challenges & Objectives

This project is intended to provide power plant utilities with a guide to performing excitation system modifications based on the experiences of other plants. A number of power plants have successfully implemented excitation system upgrades and retrofits. The experience and knowledge gained by personnel at these plants is a valuable resource for the entire electric utility industry. Equipment manufacturers, service providers, and other vendors have also amassed a wealth of information on performing excitation system modifications that will be valuable to the electric utility industry. This project and report makes the knowledge and experience of these plants and vendors readily available. In particular, excitation system engineers, design engineers, project managers and others directly involved with upgrading and retrofitting an excitation system will benefit from the "Lessons Learned," " Best Practices," and other information in this report.

Applications, Values & Use

This report serves to provide guidance in the upgrade and retrofit of main generator excitation systems. It will be beneficial to any utility considering implementing an excitation system modification. As equipment improves and changes with time, this report will remain a valuable tool. The guidance provided by this report and the “Lessons Learned” and “Best Practices” submitted by experienced plants will remain valid regardless of the excitation equipment involved in a modification.

EPRI Perspective

Previously published EPRI report 1004556 “Tools to Optimize Maintenance of Generator Excitation System, Voltage Regulator, and Field Ground Detection” discusses excitation system maintenance. This report and the project which produced it provides “Best Practices,” “Lessons Learned,” and additional information based upon the experience of power plants that are experienced with excitation systems upgrades and retrofits. Additionally, manufacturers and other vendors experienced with providing excitation equipment and services provided input into this report. A review committee of experienced personnel from seven utilities reviewed the report to ensure that this report will provide appropriate guidance to other utilities considering and implementing their own excitation system upgrade or retrofit.

Approach

The project team gathered information from power plants that have already completed an excitation system upgrade or retrofit. Ninety-one power plant units provided input through an initial e-mail survey. From the ninety-one units that responded to the initial survey, the team selected twenty-one companies that had reported extensive experience with excitation system modification to provide more detailed information. The team interviewed several of the companies that had the most experience to gain the maximum amount of their experience. The team also performed a literature search of standards, reports, and papers regarding excitation upgrades or retrofits and obtained further information from excitation system equipment manufacturers and service providers. Five manufacturers and service providers agreed to be interviewed and provide information from their vast experiences with excitation system upgrades and retrofits. A committee of representatives of seven utilities experienced with excitation upgrades and retrofits contributed their time and effort by reviewing the draft of this report and progress of the project. The review committee provided beneficial recommendations and additional information that are incorporated in this report.

Keywords

Main Exciter
Excitation System
Main Generator
Voltage Regulator
Upgrade
Retrofit
Lessons Learned
Best Practices

ABSTRACT

Power Plants with older rotating and analog excitation systems face the burden of maintaining their systems to be both reliable and economical, while reducing costs. Many plants have excitation systems that are 30 to 50 years old, and in some instances, even 80 years old. Obtaining replacements and having knowledgeable, experienced service personnel for these older systems can be difficult. Additionally, man-power requirements for operation and maintenance of these systems can take too large a share of limited and diminishing budgets. Efficiency, reliability and performance issues present problems to plants trying to stay competitive in today's deregulated market.

Newer state-of-the-art digital excitation equipment can provide increased reliability, efficiency and performance while reducing operational and maintenance costs. Increased functionality is provided by the digital system, incorporating many features that were previously performed by separate components or were not included at all in the older systems. These features can include: protective relaying; limiters; compensators; stabilizers; testing, tuning and calibration software; data-logging; self diagnostics; remote supervision and operation; and more.

Even when a company opts not to upgrade to a newer digital system, they may find it beneficial to replace their rotating exciter and/or voltage regulator. While not providing all the benefits of a fully digital excitation system, a new exciter and analog voltage regulator can offer significant improvements in reliability, maintenance, spare parts, efficiency and other areas.

This report serves as a guide to utilities considering implementing upgrades or retrofits to their excitation systems. A number of utilities which have already installed retrofits or upgrades to their excitation systems have provided much valuable information for this report. Furthermore, excitation equipment manufacturers and service providers have also provided information. The information provided by the utilities and vendors is incorporated into important considerations given in this report. Additionally two appendices to this report list the "Lessons Learned" and "Best Practices" that experienced utilities have developed from their own modification and have provided for this report.

ACKNOWLEDGMENTS

Special thanks to the review committee, who gave their time and effort to critique the draft of this report and provided valuable input:

- Michael Hoffer, Consumers Energy
- Gary Humphries, Duke Energy
- Tom Kordick, AmerenUE
- David Kral, Xcel Energy
- Mark Marcum, Tennessee Valley Authority
- Bob Smith, South Carolina Electric & Gas
- Jan Stein, EPRI
- Roger Stephens, DTE Energy

CONTENTS

LIST OF TABLES

1
INTRODUCTION

Power Plants with older rotating and analog excitation systems face the burden of maintaining their systems to be both reliable and economical while reducing costs. Many plants have excitation systems that are 30 to 50 years old, and in some instances, even 80 years old. Obtaining replacements and having knowledgeable, experienced service personnel for these older systems can be difficult. Additionally, man-power requirements for operation and maintenance of these systems can take too large a share of limited and diminishing budgets (reference 1). Efficiency, reliability and performance issues present problems to plants trying to stay competitive in today's deregulated market.

Newer state-of-the-art digital excitation equipment can provide increased reliability, efficiency and performance while reducing operational and maintenance costs. Increased functionality is provided by the digital system incorporating many features that were previously performed by separate components or were not included at all in the older systems. These features can include: protective relaying; limiters; compensators; stabilizers; testing, tuning and calibration software; data-logging; self diagnostics; remote supervision and operation; and more.

Even when a company opts not to upgrade to a newer digital system, they may find it beneficial to replace their rotating exciter and/or voltage regulator. While not providing all the benefits of a fully digital excitation system, a new exciter and analog voltage regulator can offer significant improvements in reliability, maintenance, spare parts, efficiency and other areas.

Many companies with older excitation system would find it worthwhile to study whether a system retrofit or equipment upgrade would be economically advantageous. A sizeable number will find that installing newer excitation equipment provides a high benefit to cost numbers, whether for a gas or steam turbine generator, or a hydro generator. This guide is provided to give assistance on the evaluation, selection and installation of excitation system upgrades and retrofits. "Lessons Learned" and "Best Practices" are presented to give the benefit of experience from other plants that have actually performed excitation system upgrades and retrofits.

Excitation System Upgrade/Retrofit Introduction

Utilities are faced with a number of options regarding the main generator excitation system. These options include: complete replacement or retrofit; retrofit of certain equipment, such as the voltage regulator; refurbishment and upgrade of components in the system; and maintaining the existing system without any upgrades and retrofits. The first option, complete replacement of the excitation system, has the highest initial cost, but the plant gains the functionality, performance, efficiency and reliability of a completely new and often a state-of-the-art system. In the long term a complete replacement can be the most economical option.

In plants with rotating exciters which are in good condition and do not have reliability or performance problems, an upgrade of the voltage regulator and other equipment may be the best option. Replacing the existing voltage regulator, pilot exciter, rotating amplifier (Amplidyne™), etc., provides most of the functionality and performance of a modern state-of-the-art system. On brushless exciters, transient performance gain from negative forcing is not usually available, although often this is not an issue. On all rotating exciters, the response time may still be longer than that realized by a completely static exciter. Some efficiency gains may be attained, although the exciter's frictional, windage, electrical resistance and other losses will still take away from system efficiency. However, the initial cost of a partial retrofit is less than that of complete system replacement, and may be the most long term economical option.

Refurbishment and component upgrades can be the best option where the performance and reliability of the existing system are not concerns. For example, if the only issue with an excitation system is part obsolescence, there are after-market products available which may solve the problem. With brushless exciters, problems with obtaining and maintaining rotating diode modules may be solved by after-market modules that provide improved reliability and maintainability.

Maintaining the existing system without any retrofits or upgrades is a viable option. If reliability, performance, functionality and maintenance are not large concerns, with zero initial cost in respect to the other options this option can be the best in the long term.

Maintaining the existing system can also entail overhauling and refurbishing the exciter and other components, including a rewind to restore the system to near new condition. Overhauling and rebuilding the excitation system component can be as costly as retrofitting the entire system with a completely new digital system.

A number of plants do go with overhauling and maintaining the system instead of a retrofit. Their reasons include: the operators are familiar with and experienced with operating the existing system; the maintenance technicians are familiar and experienced with the existing equipment; the existing equipment has provided several decades of good reliable service, and is expected after overhauling to provide similar service; and there are no other major issues with the system that the overhaul will not rectify.

The goal of this guide and of any decision making process regarding excitation system replacement is to provide the tools necessary to determine the most economical course of action. Other sources for help in the decision making process include the excitation system's OEM, other manufacturers and service providers, and other plants that have or had a similar excitation system.

Reasons to Upgrade or Retrofit

This section is intended to provide possible reasons to upgrade or retrofit an excitation system. These reasons are not all inclusive, nor will each reason apply to every excitation system. This section is to serve as a guide to the reader to aid in determining whether an upgrade or retrofit is necessary. The following section, "Reasons Not to Upgrade or Retrofit," provides guidance on the converse: situations in which an upgrade or replacement of an excitation system may not be feasible.

Modern excitation systems offer improvements in reliability, performance, operation, availability, efficiency and maintainability above those provided by older systems. Electro-magnetic and mechanical devices are for the most part eliminated; although, while reliable in their own time, these devices suffer from wear and often require more maintenance. Additionally, drift and other set point changes that can occur with the older devices can be eliminated with digital devices.

Other advantages of newer digital systems include:

- Better voltage regulation, down to ¼%
- Built-in redundancy, as an available option
- Auto-tracking between primary and backup or redundant regulators
- Soft-start capability
- Automatic synchronization
- Data-logging
- Built-in condition monitoring and diagnostics
- Human-machine interfaces (HMI) and graphic displays
- Built-in testing and tuning routines for quicker and more reliable set-up and calibration
- Serial and Ethernet communication capabilities
- On-line and off-line voltage limiters
- Built limiter, compensator, stabilizer and protective relaying functions
- Faster transient response with both positive and negative field forcing
- Expandability: add additional bridges as needed to increase field current capability

As mentioned previously, older excitation systems, although state-of-the-art in their time, may now be causing undue burdens for power plants seeking to remain competitive in today's market. These burdens can represent very valid reasons for upgrading or retrofitting. Various burdens and other reasons for upgrading or retrofitting can include:

- Maintenance costs
- Efficiency

- Part obsolescence
- Reliability
- Availability
- Generator uprate
- Poor transient response
- Need for data logging
- Need for remote operation
- Reduce demand on operators
- No knowledgeable system experts
- Available opportunity for excitation system outage
- Personnel hazards

Maintenance Costs

Older excitation systems inherently required more maintenance, even when they were brand new, than the newer digital systems. As these older systems age, wear and deterioration of components can lead to an increased requirement for maintenance.

Rotating exciters and other rotating components need to be aligned and balanced. Additional maintenance is required to measure, analyze and, if necessary, correct vibration of the rotating components. Couplings on rotating components typically require periodic inspection, cleaning and lubrication. The main generator lube oil system has to have added capacity for the excitation components, though this typically can be almost negligible, possibly adding slightly to the maintenance necessary for that system. Rotating excitation components will typically require insulated bearing, necessitating precaution with installation and maintenance, and creates additional failure points.

DC generator exciters and rotating amplifiers have commutators that require periodic maintenance. Brush length and brush pressure have to be checked periodically to ensure proper contact with the commutator. Brush dust build up on components creates a potential for electrical shorts, grounds and may prevent adequate cooling and has to be periodically cleaned from the machines. The commutator bars have to be periodically inspected and cleaned; the bar insulation may need to be milled down as the bar metal wears.

Dust and other debris have to be periodically cleaned from the machine to allow adequate ventilation and cooling. If build up is significant, a machine may need to be overhauled to satisfactorily clean the machine.

Older analog regulators require periodic maintenance to ensure they are in calibration and functioning properly. Calibrated set points often drift over time and require recalibration before they drift out of allowable tolerances. Temperature and other environmental factors can cause changes in set points that have to be accounted for in the allowable set-point range. Wear and mechanical failure can cause components such as motorized potentiometers to operate erratically or to fail completely. The various settings in the regulator and associate components, such as protective relays, limiters, power system stabilizers, etc., can be laborious to set properly, and often have to be rechecked and recalibrated every two to four years.

Belt driven equipment may require added maintenance to ensure proper alignment and tension. The equipment often requires periodic belt replacement due to wear and deterioration of the belts.

Additional maintenance manpower may be required to maintain the DC field breaker (reference 2). Being not as common as AC breakers, the DC breaker may require long lead times for certain replacement parts, if available. By interrupting DC current, the breaker is subjected to more severe duty than does an equivalently sized AC breaker, and because of this, may require more frequent inspections and maintenance.

Efficiency

Whether a rotating exciter is powered from the generator's shaft, a drive motor or a separate turbine, the plant's output is reduced by the energy needed to drive the exciter. Frictional losses in the bearings, and windage losses from the spinning rotor and fan, represent energy that is not available for output.

The windings of the exciter field and armature have ohmic losses that also represent energy that is unavailable as output. Additional loss may be due to cooling requirements for the exciter. Power requirements for providing lube oil to the rotating exciter are usually insignificant, though can represent some small loss.

Pilot exciters and exciter drive motors will have similar losses as given above for the main rotating exciter. Although the total loss from the exciters, pilot exciters and motors are just a small fraction of the total plant's output, it does represent actual value that cannot be realized and sold to the consumer.

Part Obsolescence

As with any older system and equipment, obtaining parts for an older excitation system can become difficult, if not impossible. Manufacturers often find it is not economically feasible to continue providing replacement parts for equipment that has been out of production for a decade or more. The low volume of orders for the parts may cause the production and the inventory of old parts to be cost prohibitive. Additionally, mergers, acquisitions, and business closures may hasten the unavailability of replacement parts.

Occasionally, after market parts may be available from other suppliers. However, the availability of after-market parts is based upon the need for the parts justifying the cost of manufacturing. As the age of a system increases, there will likely be less similar systems in service, and there will be less demand to justify continued manufacture and inventory of the parts by the after-market suppliers. Another possible source for spare parts could be other plants with a similar system. Although, the older the system, the less likely the exact same system will be in service at another plant that is willing to relinquish needed parts.

Part obsolescence can cause a significant cost to a plant if the part cannot be obtained or requires a long lead time. Plants have had to rent or borrow regulators and other components until a needed part could be acquired and repairs made. Although the cost of obtaining, installing and setting-up a temporary component is less than the cost of lost production, it still can be a significant expense.

System and component obsolescence can be a major factor in determining whether to retrofit or upgrade. Not only should the cost of obtaining parts be considered, but the impact on the plant as well, such as lost production.

Reliability

As the equipment ages and wears, system and component failures can become more prevalent causing more frequent forced outages. Not only is there a loss in production, but forced and unscheduled outages typically cost a utility more for replacement power than for a scheduled outage.

Other reasons listed in this section for upgrading or retrofitting the excitation system can have an effect on the system's reliability. Maintenance costs may limit the amount of work that can be performed on the system. Limited budgets may cause periodic maintenance outage intervals to increase and other necessary work to be deferred. With less maintenance, the possibility of decreased reliability may occur. Additionally, obsolescence may cause parts that should be replaced to remain in service, again potentially causing a decrease in reliability of the system.

Since electrical power production is dependent upon the proper functioning of the excitation system, the reliability of the entire plant is directly and adversely impacted by decreased excitation system reliability. Any measure, such as an excitation system retrofit, that improves the plant's reliability can typically be shown to provide a substantial benefit by reducing lost production.

Availability

While reliability is a measure of the system's ability to function properly when in operation, availability is a measure of the time the system can be in service. A system that requires frequent and lengthy periods of maintenance has low availability even though it might have high reliability. Low availability, like low reliability, represents lost production; although with low availability, the system down time may often be scheduled versus forced outages and unscheduled maintenance.

Aged components may require more frequent and longer duration maintenance, making the system, and the plant, less available for producing power. Even when the maintenance can be performed during scheduled outages, production can be lost if the excitation system maintenance becomes critical path.

Besides age-related failure and wear, part obsolescence and the loss of skilled experienced service personnel can adversely affect the system's availability.

Generator Up-Rate

Many companies are economically producing more power by taking advantage of design margins in the plant which may allow operation at higher levels of power. However, the excitation system may not have the design margin to be able to operate or respond to transients at a higher power level. In order to take advantage of the higher power levels, or plant uprate, certain limiting plant components and systems, possibly including the excitation system, will need to be replaced or upgraded.

The increase in revenue from uprated power production alone will likely provide economical justification to upgrade or retrofit the excitation system. Coupled with other reasons such as increased reliability and availability, reduced maintenance, and better performance, solid justification for upgrading or retrofitting the excitation system can often be had.

Poor Transient Response

Older excitation systems may not be able to react fast enough to a grid distribution, causing the generator to trip. Newer excitation systems may eliminate time constants associated with pilot and main exciter field windings, providing faster and better transient response. Higher excitation ceilings may be achieved and possibly two-quadrant operation (positive and negative field forcing) with modern excitation systems. A higher excitation ceiling and fast response allows for better coordination with electrical system protective relays. With better coordination, and by providing more time for protective relays to trip appropriate breakers to clear a remote fault, the newer excitation system can keep the generator on line during transients that otherwise may trip the plant.

Reliability council requirements may dictate accurate system models and certain transient response characteristics of excitation equipment. Some of the requirements for new and upgraded excitation systems may include: high initial response as defined in IEEE 421.1 (reference 3) and an excitation ceiling voltage of 150% with an external disturbance causing generator terminal voltage to drop to 70%. Although these requirements usually do not force an upgrade to an existing excitation system, they do represent desired performance, and may be required if significant work is to be done on the excitation system.

Data Logging

Digital excitation equipment typically provides some capability to record system parameter points and sensed or monitored points, such as generator terminal voltage and current. These points can later be retrieved in tabular or graphical format for assessment and analysis. Analysis and corrective actions for electric system disturbances can be facilitated by accurate recording of the transient. Periodic response testing, often required by reliability councils, can be simplified by the data-logging or oscillograph functions of the digital voltage regulator.

Remote Operation

Digital regulators are often equipped with communication ports that allow monitoring and control via a computer network. In an effort to improve efficiency, plants may need to be operated from a remote location or from a distance over which analog control signals cannot be effectively transmitted.

Smaller units at remote locations can be controlled from a central location. Multi-unit plants can be operated from a control room on the same site but situated relatively far from one or more units. Independent System Operators (ISO's) in the USA and similar organizations in other countries may require the ability to monitor and/or control generator VARs and other parameters to maintain electric system stability.

Monitoring and analysis also can be performed at locations remote from the plant. The performance of the excitation system can be checked and analysis of transients can be performed virtually anywhere in world with a computer and an appropriate network connection. However, in practice, network and computer security requirements will limit access. Still, the data recorded by the digital regulator can often be accessed as needed at key remote locations.

Reduce Demand on Operators

With older excitation systems, plant operators may have to spend a considerable amount of time monitoring the system and making adjustments as needed. One task commonly required is to periodically check the null meter to verify that the outputs of the automatic and manual regulators are the same, and make adjustment as needed. This is necessary to ensure that if the system were to transfer to the manual regulator due to a fault in the automatic regulator, the transfer will be bumpless and not cause a transient.

Plant start up and synchronization are other tasks which demand operator attention. Putting the system into service, flashing and energizing the generator field, monitoring generator voltage and system parameters, and finally, synchronizing and switching to the automatic regulator distracts the operator from other duties in the plant or may require an additional operator.

Modern digital excitation systems provide features that can relieve the plant's operators from many of the routine duties associated with start up of the excitation system. Commonly included features are:

- Self start - the excitation system on command will put itself in service, perform diagnostic checks and monitor its own performance.
- Field flashing and putting the regulator into service.
- Soft start with the regulator raising generator terminal voltage at a pre-determined rate and preventing voltage overshoot.
- Built-in volts/hertz and off-line and on-line voltage limiters ensure that generator and generator step transformer volts per hertz limits are not exceeded.
- Auto synchronization, as a possible option, automatically adjusts generator output and closes the generator output breaker at precisely the correct point.
- Auto-tracking between the automatic and manual regulators, or between redundant regulators, ensures that if a regulator transfer occurs it will be bumpless and without causing a disturbance.
- Backup control channels can extend the redundancy of the system by providing backup control of the excitation system.

Certain modern, completely digitally-controlled plants, such as combustion turbine plants, may operate with a single operator at times, who can solely start one or more units within minutes. The digital excitation system plays a big part in providing the lone operator the ability to start and place a unit on line. Plants that still require more than one operator still benefit from digital excitation systems. The operations staff can be reduced or the operators can devote their attention to other critical aspects of starting and running the plant.

No Knowledgeable System Experts

As specific excitation systems get older, the availability of knowledgeable service personnel with the skill and experience typically decreases. The original equipment manufacturer may have stopped supporting certain old equipment, or may no longer be in business. Service support companies likely will not have personnel who are trained and experienced with older, less common systems as the demand for such support does not justify the training or provide the experience. Personnel who have been testing, maintaining and troubleshooting the system for years may have retired, moved to other positions, or have become otherwise unavailable, taking their unique system knowledge and experience with them.

Some level of support can usually be obtained for any system, particularly from companies having personnel with a broad general knowledge of excitation systems and familiarity with the various excitation system schemes that have been used and put into service. However, intricate knowledge of the various components and interactions between the components and the rest of the system is often lacking. The modern digital systems being fairly new should have support for years to come, and as the systems become more common, the support availability may actually increase. Furthermore, the digital systems typically incorporate self diagnostics and troubleshooting features.

Available Opportunity for Excitation System Outage

Occasionally, a plant may need an extended outage to perform extensive modifications and repairs on systems and equipment other than the excitation system. An extended outage presents an opportunity to install and commission a new excitation system without the installation being critical path. While an opportune outage is not a valid reason in and of itself to retrofit a new excitation system, it does provide an economical incentive to install a new system earlier than otherwise necessary.

Of course the impact of installing a new excitation system on the outage would have to be analyzed. The ability of the plant to support the added work and provide sufficient manpower and resources needed would have to be verified. Additionally, at the end of the outage, the new excitation system will require start-up and some testing and tuning which could actually add a little time to the outage length. However, during a long outage, the new excitation system could be installed, commissioned, tested and pre-tuned to be ready at the end of the outage. Typically an excitation system upgrade or retrofit can be performed within an outage of a few weeks at most.

Personnel Hazards

Older electrical and rotating equipment does not have the designed and built-in safety features typically included with modern equipment. Present day requirements and regulations often dictate significant personnel safety features in electrical equipment. Older excitation equipment often has exposed bus bars, unguarded rotating elements, easily accessible electrical connections, and other potentially harmful items that present hazards to personnel working on the system. Additionally, older systems may contain asbestos and other materials that are now known to be harmful.

Modern day equipment is often supplied with built-in barriers and guards to protect personnel from inadvertent contact with energized components. Plexiglas shields allow visual inspection and are usually easily removable and replaceable to allow maintenance on the covered components. The following are real examples of hazards in older excitation equipment. The first two are actual electrical shock incidences and the third is a potentially fatal design flaw.

Electrical Shock Incidences

A maintenance electrician was in the process of inspecting the main generator exciter enclosure. During the inspection, the electrician began cleaning up an oil spill near the exciter brush rigging support. While wiping up the oil, the electrician's thumb came in contact with the rigging support and he received an electrical shock.

A plant was shutdown and the turbine generator on turning gear, when two machinists entered the generator alternator housing to view the location where run out checks of the generator rings were to be performed. A work group supervisor and an electrician were escorting the machinists. Without warning, one of the machinists reached out and touched the area where he would be mounting a mechanical indicator. As he touched the component, he felt a slight electrical shock in his forearm.

A well known and respected manufacturer had provided excitation cabinets with a potentially serious design flaw. The 480-volt feed cables were routed through the top of the cabinet, past the cabinet's main breaker to an exposed terminal block. From the terminal block, jumper cables ran back to the top of the main breaker. The safety hazard of this design is significant as a worker could easily and accidentally make contact with the exposed terminal block which was mounted at elbow height. Even with the cabinet's main breaker locked and tagged out, the terminal block was still energized. This is a design mistake that could have seriously injured a worker. Modern equipment is designed and supplied now with a much greater detail given to personnel safety. Though the risks cannot be totally eliminated usually there will a lowering of the risk.

Failure Incidences

The following are failure incidences that occurred with older excitation systems. The incidences may not have occurred with a modern static excitation, or may have been minimized or prevented with a modern digital regulator used with a rotating exciter.

With a unit operating at 88 percent power, vibration levels on the main turbine-generator alternator exciter bearings increased. Operator actions in correcting the vibrations were unsuccessful and the unit was manually tripped. The high vibrations occurred when oil deflectors for the vibration probe assemblies, installed at each exciter bearing, rubbed the rotor shaft. The oil deflectors were determined to have an insufficient bore to maintain clearance with the rotating shaft to prevent rubbing. The root cause of this event was that the vendor did not use the correct drawing and manufactured the deflectors with the wrong inner diameter.

A unit was operating at 50 percent power steady state when the generator tripped. Failure of the main generator exciter bearing caused the armature of the Permanent Magnet Generator (PMG) to grind into its stator. When this occurred, the PMG discontinued supplying voltage to the field of the main exciter. The event was caused by not performing a weekly generator exciter bearing ground insulation check. This allowed a prolonged ground resulting in the failure of the generator exciter bearing.

During a unit outage, the coupling between the main generator and the exciter was dropped while being rigged. The coupling weighs 350 to 500 pounds and was dropped approximately five feet. No injuries occurred as a result of the event. However, the coupling sustained some damage.

A nuclear unit was tripped when an undervoltage condition was sensed on the buses feeding the reactor coolant pumps. The unit safely shutdown and an investigation determined the undervoltage condition was caused by the main generator being transferred from the automatic voltage regulator to the manual voltage regulator. The transfer was initiated by a defective exciter field current limiter, and would not have caused an undervoltage condition if the manual regulator's set point was adjusted to match that of the automatic regulator. There was no auto-tracking feature between the regulators, and the station procedures failed to have the operator periodically monitor the null meter and adjust the manual voltage regulator as needed.

An incident at another plant involving a mis-operation caused a potentially dangerous transient. Because of historical problems with the GEN VOLTS ADJ (90P) potentiometer in the automatic voltage regulator,

> Operators were required to perform a weekly PM of transferring generator voltage control to MANUAL and wiping 90P by cycling it full scale in both lower and upper directions.
>
> Operator experienced a problem performing this PM. Generator voltage control was successfully transferred to MANUAL, but instead of taking 90P to LOWER, the Operator mistakenly operated the EXCITER VOLTS ADJUST (70P) potentiometer. Generator output voltage went to its minimum value, the Transfer Voltmeter indicated +2.5 V, and a Low MVAR alarm actuated. Believing that something had happened to the MANUAL Regulator, the Operator attempted to re-null the Transfer Voltmeter by operating 90P, but the Transfer Voltmeter remained at +2.5 V. Not realizing that this indicated maximum unbalance between the AC and DC regulators, control was shifted back to AUTO. This transfer resulted in generator MVAR transient from -230 MVAR to +775 MVAR (generator rating is 484 MVAR). Grid response and quick reflexes allowed the Operator to reduce MVAR load back to within the generator capability curve within the next 14 seconds before any serious core end heating or field heating occurred.

A fully modern excitation system cannot eliminate all failure modes nor prevent all mis-operations. However, safeguards built into the newer equipment can often help prevent or minimize many failures and mis-occurences.

Upgrade or Retrofit Alternatives

Just as there are reasons to upgrade or retrofit the excitation system, there are reasons not to upgrade or retrofit. It would be prudent to ensure that all alternative solutions have been eliminated prior to committing funds for an upgrade or a retrofit. This is not to say that an upgrade or a retrofit should be avoided or delayed, but that careful analysis should be performed so that the best possible solution to an excitation system problem can be selected. The goal is to select the most economical means to achieve the best possible reliability, efficiency and availability from the excitation system. Alternative to an upgrade or retrofit to solve excitation problems can include:

- Maintenance Program Enhancement
- Environmental Improvement
- Subcomponent Upgrade
- Limited System Upgrade

Maintenance Problem Enhancement

An improvement to the maintenance program may be the best solution. With various new technologies and techniques developed since the 1980s, certain problems can be identified and corrected before they become evident through failures and poor performance. For example, failures of electrical and electronic components may not be directly age related, but may be due to component overheating. A predictive maintenance technology such as thermography may be able to identify the overheating before it can cause additional failures.

Thermography can be used to identify overheating caused by poor or blocked ventilation, cooling subsystem problems, over-burdened components and numerous other causes. One instance was found where a modification located an external heat source near the excitation equipment. The excitation failures weren't age related or caused by defective components, but rather the components were being slowly cooked to failure. Identifying and correcting the ill-positioned heat source rectified the problem with the excitation system. An upgrade to newer excitation equipment would obviously have been a mistake in this case, as the problem was not with the old system and its components.

Environment Improvement

Environmental or external factors that may be affecting the reliability and performance of the excitation system can include: vibration from nearby equipment; changes in ambient temperature and humidity; activities creating dust and dirt; and components or structures blocking air flow. It is important to identify whether these or other possible causes are responsible for adversely affecting the system. In these cases, an excitation system upgrade or retrofit would be an unnecessary expenditure that may or may not eliminate system problems. Identifying and rectifying ambient factors having a detrimental impact on the excitation system could be the solution to reliability issues with the excitation system.

Subcomponent Upgrade

Another possible reason for wanting to upgrade the excitation system may be component failures which cause poor reliability. Maintenance may be troublesome on these components and obsolescence may make obtaining spare parts difficult. In cases where age-related failures are occurring and are not due to external factors, it may be possible to upgrade the particular component. Thereby the reliability of the excitation system can be restored and maintenance decreased without having to upgrade or retrofit the entire system.

An example of where a component can be replaced to restore reliability is on the diode wheel of a brushless exciter. Age failures of capacitors in the diode modules can short out the diodes. The module design prevents ready replacement of the capacitors, and part obsolescence makes obtaining spare modules difficult. After-market diode modules can be obtained and installed to replace the original manufacturer's modules. The new modules being of a heftier design and allowing ready replacement of subcomponents such as the capacitor can restore the exciter's reliability and reduce maintenance costs.

Limited System Upgrade

In other cases, upgrading a major component instead of the entire system may be the best solution to excitation system problems. When the rotating exciter is still in good condition and not causing operational and maintenance issues, problems with poor response, age-related wear of regulator components, lack of redundancy, excessive operator attention, and other factors can be relieved by just upgrading the voltage regulator. A new, modern digital-voltage regulator can provide much of the functionality, performance and reliability of a new excitation system at a fraction of the cost, provided that the rest of the existing system is in good condition and has many years of remaining life. Additionally, on those systems with pilot exciters, both the pilot exciter and voltage regulator may be able to be replaced by a new voltage regulator.

Upgrade or Retrofit Concerns

A complete upgrade or retrofit of the excitation system as described in the previous section may not be the best solution to reliability and other system issues. Furthermore the upgrade or retrofit may cause new issues or concerns which will need to be addressed in the design, installation and commissioning of the modification. Some of these other issues and concerns are:

- Additional failure modes may be introduced by new equipment and circuit configurations.
- Infant mortality failures of circuit cards and other components can adversely impact initial reliability of new system.
- New and increased skill levels may be required of craftsmen and technicians in order to maintain, test, troubleshoot and repair the new system.
- A greater reliance on vendor support may be needed to service new equipment.
- Lateral and torsional vibration characteristics of generator can be altered by removal of old excitation equipment and installation of new equipment.
- New power sources may be required to supply excitation system.
- New cabinets and other components, such as a power potential transformer may require significantly more floor space than what is made available by removal of the old equipment.
- Heavy components, such as the power potential transformer, may require structural modification to facility in order to support the added load.
- New electronic components may require special environmental features, such as air conditioning.
- Operators, technician and other plant personnel will require training on the new system.
- Power electronics components may cause harmonic distortion on electric lines, and possibly cause radio frequency inference.
- Longevity of specific models may impact the length of time new excitation equipment will be serviceable. Specific models of digital exciters have had only six to ten years of manufacturing runs, before the manufacturers switch to newer models. Spare parts and OEM service may only be available for limited number of years after the manufacturing run.

There are other issues and concerns with a complete upgrade of the excitation system; some may be particular to one type of system and not to others. However, all the issues and concerns are not insurmountable and can be dealt with in a properly designed and implemented modification.

If the entire excitation system is antiquated and causing operational and maintenance problems, the utility should not be discouraged from upgrading or retrofitting the entire system. This may be the best cause of action, producing the highest reliability and availability, and being the most economical solution. However, it is a decision which cannot be rushed into and implemented hastily. In many cases, the best economical decision can be improved maintenance or simple component modifications. The cost-benefit section in Appendix D of EPRI Report 1004556 "Tools To Optimize Maintenance of Generator Excitation System, Voltage Regulator and Field Ground Protection" can help analyze problems with the excitation system and determine the best course of action to take.

Excitation Systems

A number of sources on-line and in literature provide excellent descriptions of excitation systems and components. It is not necessary to reproduce this information in this guide, nor the intent for this to do so. The IEEE 421 standards (references 1, 3, 4, 5 & 6) provide information on various excitation systems and their models. An overview of various excitation systems can be found in the EPRI Report "Tools to Optimize Maintenance of Generator Excitation System, Voltage Regulator and Field Ground Protection" (reference 7).

2
UPGRADES AND RETROFITS

There are numerous varieties of excitation equipment and schemes used today in electric power production; some of the equipment dating back eighty years or more. For each excitation system there are several different ways to upgrade or retrofit the system. As discussed in the previous chapter, the system can be partially upgraded by replacing minor or major components. An entire retrofit of the system can be performed by replacing the whole system with a completely new and different system.

The different combinations of excitation systems and upgrades are too numerous to discuss each in detail in this guide and would not serve much benefit. This section is to provide a general overview that will cover different ways an upgrade or retrofit can be accomplished. From this general overview, an idea can be formed of which upgrades and retrofits will be beneficial.

Component Replacement

In some cases, system reliability can be enhanced by replacing or upgrading minor components in the system, such as diode modules on a brushless exciter as mentioned in the previous section on Reasons Not to Upgrade or Retrofit. Certain components, such as surge capacitors, may have a limited lifetime, and need to be replaced on a periodic basis to prevent in-service failure. A ten-year replacement of electrolytic capacitors is not uncommon and does not require extensive maintenance expenditure. Additionally, items such as capacitors are common place and not typically obsolescence issues. Although the exact same make and model may no longer be available, another make and model with the exact same ratings can usually be easily obtained.

Besides capacitors, other items that might require periodic replacement to maintain system reliability can include diodes, thyristors, and relays or relay coils. Replacement parts for all items will not necessarily be as easily obtainable as capacitors. If a routine replacement program is established, adequate lead should be available to obtain sufficient replacements of the exact item or to evaluate and obtain sufficient equivalent replacements.

When replacing minor components it is important to ensure that there is not an external factor that is adversely affecting component life. Excessive heat, humidity, electrical surges, contaminants and vibration can cause components to prematurely fail. Identifying and correcting these external factors, if present, can reduce or possibly eliminate the need for periodic replacements.

Upgrading minor components that are sources of decreased system reliability or part of a periodic preventive maintenance replacement program can improve reliability and extend the component replacement period. Capacitors, diodes and other items which are designed and manufactured to better withstand temperature, voltage spikes, overcurrent and other factors may be obtainable and offer longer service life.

Even more complex items such as circuit cards may be reversed engineered and replacements provided by companies that offer this service. The reversed engineered after-market boards can offer improved performance and reliability by taking advantage of materials and technology which may not have been available at the time the original boards were manufactured. When obtaining reversed engineered boards and other components, assurance should be obtained from knowledgeable parties that the original equipment manufacturer's rights are respected. Patents and other rights may have expired by the time a replacement is necessary, and may not even be applicable in all cases; however, this guide does not intend to and cannot provide assurance of such. A company's legal department or purchasing department may be able to provide the needed assurance, or the original equipment manufacturer may provide such assurance if they consider the part obsolete.

An equivalency evaluation should be performed to ensure that the upgraded and replacement components meet all the requirements of the original components and that the replacements will be economically beneficial. Most plants, or their parent companies, have in-house procedures and processes for evaluating replacement components, usually through their engineering or purchasing departments. Additionally, the excitation system's original equipment manufacturer may be able to recommend, or even provide an upgrade component.

The periodic replacement of minor components are a continuing expenditure, though are likely only a fraction of the cost of replacing a major component such as the voltage regulator or the entire excitation system. However, if there are other problems or issues with the excitation system, the periodic component replacement and the upgrade of minor components can represent an expense that is not beneficial to the plant's overall reliability. A common theme presented throughout this guide is that a careful cost benefit analysis and system evaluation will ensure that the best and most economical solution is used to address excitation problems and issues. The best solution may be simple, minor component replacement, and in other cases with other plants the best solution may be an upgrade to a major component or a system retrofit. In some cases an improved version of an original component may be available. Examples include solid state devices to replace motor operated potentiometers (a frequent source of reliability problems) and pneumatic timing relays.

Major Component Replacement

Major components such as a pilot exciter and the voltage regulator may require upgrade or replacement in certain instances. Replacement and upgrade of major components is not always the best solution to excitation system problems and issues. Bearing failure, winding faults and other problems with a pilot exciter may be repairable, though costly and could reduce the reliability of the pilot exciter. Failures and trouble with multiple components and with components that do not have available replacements may require change out of a major component. Parts for items such as motor driven potentiometers and rheostats, particularly with old or less common systems, may be impossible to obtain and may be too difficult or expensive to have a single unit fabricated. Furthermore, replacing one component does not offer increased reliability of other potentially faulty components in the system. It will not be worthwhile to expend an amount of money and effort to obtain a replacement for one component when other components in the system are likely to fail or cause decreased system reliability.

Other issues with the excitation system besides the reliability of minor components may necessitate a major component replacement. Performance issues may necessitate an upgrade. A higher excitation capacity and faster response time, both to better handle transients, may be desired and needed to improve plant reliability and aid electrical system stability. Reliability enhancements such redundant or back-up regulators with auto-tracking may be essential not only for improved reliability, but for increased availability of the system. Operations and maintenance man-power requirements are usually reduced with the new voltage regulators. Modern digital regulators can offer soft start and auto synchronization, along with the previously mentioned auto-tracking between regulators, all which reduce the attention needed from the operators. On-board diagnostics and test features, as well as simplified tuning requirements, aid in reducing maintenance requirements.

If the main exciter is in good condition and has years of predictable remaining life, it can be economically reasonable to keep the main exciter in service and only upgrade the voltage regulators, and pilot exciter if applicable. Though the main exciter will still require more maintenance than that required for a completely new modern static exciter, the benefit of reducing the continued maintenance may not outweigh the cost of a complete static exciter. Additionally, by keeping the main exciter, a new electrical power source for the generator field is not needed. Problems or predictable potential problems with the main exciter may eliminate the advantage of keeping the exciter. Again, a cost benefit analysis that includes the actual maintenance costs and a reasonable prediction of future maintenance requirements will aid in determining whether to keep the main exciter.

In systems with a pilot exciter, the pilot exciter may be retained or replaced along with the original voltage regulator. There are advantages and disadvantages to either option. In retaining the pilot exciter a separate feed is not needed to provide the power necessary for the main exciter's field. As with the main exciter, the pilot exciter has to be in good condition with years of remaining predictable life. Often, it is better to replace the pilot exciter, eliminating potential problems and required maintenance. Typically, a power source for the main exciter's field can be made available in most plants, eliminating the need for a pilot exciter.

Exciter Replacement

Obviously with a complete excitation system replacement the benefits of an entirely new system are realized. If the original system had performance issues in which transient response was insufficient, or if the excitation system was a limiting factor in up-rating the plant, a new system can eliminate these issues. Reliability and maintenance concerns with the original system can also be eliminated. In most systems, only the collector rings and generator field will remain, possibly with some of the old control elements.

Old excitation systems having separately driven exciters provide a relatively clean retrofit of a static exciter into the system. In somewhat oversimplified terms, the retrofit consists of connecting the new static exciter's output to the generator's brush rigging, in place of the old exciter's output. The old exciter may be left in place, or removed to make floor space available and for possible salvage value.

Retrofits of direct driven exciters with a static exciter can also be thought, in oversimplified terms, as connecting the new static exciter's output to the generator's brush rigging in place of the old exciter's output. There is usually no technical reason to remove the old exciter as long as it is decoupled and adequate clearance prevents expansion of the generator shaft causing the generator (collector) shaft to contact the exciter shaft. The existing collector rings, shaft, bearing, brush rigging, enclosure and cooling can be retained. If the original exciter has to be removed, possibly for floor space, modification to the collector enclosure and the cooling system may be required.

A retrofit of an older static exciter to a new static exciter is perhaps the simplest to make. The existing Power Potential Transformer (PPT), field breaker, power bridges and power cables may be retained if in good condition of the necessary capacity. If negative field forcing is required, the power bridges will also have to support a two quadrant operation. In many cases the static excitation system may just need an upgraded voltage regulator.

A brushless exciter is more complicated and costly to upgrade to a static system. The rotating exciter has to be removed, collector rings and brush rigging installed, adding bearing(s) and lube oil supply/drain for the stub, and enclosure for the rings fabricated. Other major issues can include maintaining hydrogen cooling system integrity and providing ventilation and cooling for the rings. Still, replacing a brushless system with a static system can often be economically desirable and be installed during a routine maintenance outage.

The new static exciter, whether for a brushed or brushless original system, will require space in which to be installed and have field power and control power circuits supplied to it. Larger units may require cooling for the bridges, though many are simply air cooled. Interfaces to existing controls, protective relaying and other circuits will need to be made.

Most static excitation system retrofits will require a new power source to supply the generator's field. A PPT connected to the generator's output, or a station bus, is used to feed power to the static exciter for the generator field current. It is usually preferable to use the generator output, making a tie at the generator breaker, unit auxiliary transformer, or if necessary, by tapping into the isophase bus. A station bus is often easier to connect into, however, considerations regarding the effects on the exciter from bus switching, large motor starts and other bus transients have to be made. Additionally, the effect on the bus from the exciter, particularly when responding to a generator transient, will also have to be considered.

Not all excitation system upgrades are to install digital static systems. Some plants may prefer an analog voltage regulator and a rotating exciter. Some reasons for these preferences are: familiarity with analog regulators, availability of a rotating exciter, maintaining similarity between equipment in other units at the plant and other company operated plants, a preference for discrete analog components over a nearly all-inclusive digital processor, and keeping a resemblance to the original system. Installing a new analog regulator and/or a rotating exciter is not usually less complicated nor less costly than a digital static system, and could in fact be more complicated. The set up, testing and tuning of the regulator can be more difficult and lengthy. Lubrication and cooling for the rotating exciter will likely have to be altered to match the new fittings. The new exciter will need to be balanced and aligned, and may require foundation rework.

Regardless of whether the retrofit is to install a static or rotating exciter, the voltage regulator and other parts of the system will need to interface with control and relaying circuits. The control circuit may be entirely replaced, with digital operator controls and touch screens, or tied into an existing DCS system. Another option includes maintaining the existing controls and meters by having the new excitation system equipped with appropriate interfaces. A variation of this option may retain portions of existing controls, such as metering, while the actual control devices are upgraded to digital devices,. If retaining the existing controls, or installing a separate digital excitation control system, consideration should be given to providing for possible future tie-in to a plant DCS system. Even if the plant does not currently have a DCS, a number of plants have upgraded to a DCS system and many will likely do so in the future. It should be a relativity simple matter to specify the new excitation system providing for a DCS interface.

More detailed discussion on the various options and types of retrofit is presented later in this guide. Considerations on the decision to upgrade or retrofit and the issues and various factors involved in the specification, design, installation and commissioning will be covered in more detail than in this introductory section.

An important last note in this section is to make sure that the operators are aware of the differences in operation that they will see with the new excitation equipment. One difference that has caused concern at first with operators was noticeable fluctuations in VARS due to a more accurate and faster acting regulator. Although a new system is performing correctly, and better than the previous system, differences in exciter and generator performances should not be allowed to create a concern with the operators or cause them to question if the system is performing correctly.

3
INITIAL PROCESSES

As with any major project a detailed and deliberate process for developing and implementing the modification has to be followed to ensure that issues are properly addressed and that the modification is as cost effective as possible. Most plants have detailed procedures and processes for developing and implementing modifications. This chapter is intended to provide guidance particular to excitation systems that only supplements existing procedures and processes. Information for consideration during the initial processes in excitation system upgrade or retrofit is provided in this chapter. A basic outline of the initial processes is as follows:

- Identify major and minor issues with the existing system, and required and desired features of the new system with consideration for potential future unit uprates
- Assess condition of existing equipment and circuits
- Evaluate and determine initial scope of modification, whether to replace minor component, upgrade a major component, or retrofit an entire new system
- Ensure accurate complete documentation of the modification process

The above outline and the detailed description that follows are not necessarily in sequential order. Certain items may be performed simultaneously or out of the order shown. For example, ascertaining the condition of wiring and existing equipment may add a major issue to those already identified for the existing system.

Existing System Issues

Obviously the need to upgrade or retrofit the excitation system must start with problems or issues with the original system. The upgrade or retrofit will be a major expenditure and the benefits of the new system must be clearly shown. By identifying all the problems and issues with the original system, the new excitation equipment can be chosen with the features that are needed without expending more funds than necessary. While there may be one or a few primary issues that a new system is required to address, secondary and smaller issues should also be addressed. It is much better to identify all the desired features for a new system up front than trying to add more features later in the process. Starting with a complete list of all desired features and requirements will allow items which are not cost effective or practical to be eliminated, while ensuring the inclusion of items which are needed.

Issues and Problems

Problems and issues to be addressed by the new system can include:

- Equipment failure/system reliability
- Equipment and system availability
- Condition of existing equipment
- Inadequate transient response time
- Need for two quadrant operation, negative field forcing
- Lack of capacity/Power uprate
- Excessive maintenance
- Excessive operator burden
- Lack of auto-start and auto synchronization
- Lack of soft start capability
- No redundancy of components
- No auto-tracking between regulators
- Lack of remote operation capability
- Lack of self and remote diagnostics
- Lack of data logging capabilities
- Poor operator interface
- No built-in testing and tuning features

Some of the features may seem to be, and can be redundant to other listed features. For example the items for auto start and synchronization, auto-tracking, remote operation and operator interface can be included in the item for reduced operator burden. However, listing them separately ensures that these items stand out and are identified as not all new systems may include them. If desired, these items could be listed as sub-items under reduced operator burden. Similarly items relating to maintenance, reliability and other areas can be listed as sub items of their specific areas. It is important to realize that the above list is not complete and should not be considered all inclusive. Each plant is unique in certain aspects and issues, and features important and applicable to one plant may not be so for another.

Identification of the issues that have to be addressed is the first step to the upgrade or retrofit process. The first three listed items of failures, reliability and availability may be addressed by simple replacement or upgrade of minor components. Though some of the other issues and features listed may be desirable, they may not be cost effective if the major issues are only with minor components. Obviously, if the major issues are not addressable by handling problems with components, then the cost effectiveness of including desired features improves with a larger scope.

Having identified the major issues with the existing system and desired features in the new system, the type and scope of the system modification can be evaluated and determined.

Depending on the scope of the modification, desired features can be included or eliminated from the change based upon whether they can be cost effective.

Experience from Other Plants

The value of the experience from plants that have performed an excitation system upgrade or retrofit cannot be overstated. Other plants may have had issues with their excitation system similar to those at one's own plant. Talking with and obtaining information from personnel at other plants which have performed a similar modification will aid in determining if a project to upgrade or retrofit the excitation system upgrade or retrofit should be implemented.

Additionally, studying their lessons learned will prevent having to learn the lessons through one's own trial and error process. Of course the purpose of this guide is to provide a compilation of "lessons learned" and "best practices" based upon the experiences of plants that have performed the retrofit and upgrades. Still unique and specific experiences can be garnered by communicating with experienced plants.

If possible, a visit to one or more plants with a new excitation system will provide even more help with developing and implementing one's own modification. Especially when the experienced plants are very similar to one's own plant, information regarding the issues that were addressed, the benefits that were achieved, the type of equipment which was installed and processes to develop and implement the modification can only help and improve one's own modification development and implementation process.

System Condition Assessment

Equipment

The condition of the main exciter, pilot exciter, if present, and other components should be assessed and a determination made of remaining life. If components are in good condition and can reasonably be expected to have significant life, it may be desirable to retain some or all of the components if an upgrade or retrofit is performed (reference 1). Ascertaining the condition of the equipment will aid in the determination whether to uprate or retrofit; and will aid in determining the scope of the upgrade or retrofit if one is to be performed. Additionally, equipment determined to have faults, or is failing, can provide economical justification for a modification.

Data from previous testing and maintenance of the exciter and other components can be used in lieu of, or in conjunction, with the preliminary testing if that data is sufficient enough for making a well based decision on the equipment's condition.

The condition of the main generator, including the field and collector rings, should also be assessed, especially with older machines, to ensure that potential generator problems will not negate the expected benefits from upgrading the excitation system. Generator condition testing may not be necessary, as with the exciter, if it is known that the generator is in good condition based upon previous test data and maintenance overhauls

Circuits

The condition of control and power cables should be assessed early in the project. This will aid in determining the scope of the modification and if wiring problems could be become an issue during implementation of the modification. In older plants the existing wire insulation may have become brittle and so deteriorated that the wiring should be replaced. For circuits that would be retained, such as those that would be used to tie existing controls and metering to the new equipment, the wires and cables may need to be replaced during the modification if they are in poor condition.

Additionally, wire diagrams and other drawing may not accurately reflect the current configuration, or the drawings may no longer exist. Wire labels in the equipment may be missing or have become unreadable. Tying the new equipment into existing interfaces will be more difficult and add to the scope of the modification if wiring details are incomplete or inaccurate. Identifying and correcting wiring issues early in the modification process will allow for better and more effective implement of the upgrade or retrofit.

Upgrade/Retrofit Scope

Having identified the issues and concerns with the existing excitation system and its components, and having evaluated those with desired features for the new system the exact scope of the modification can be developed. The process to determine the scope and type of modification to be implemented should select that which will address the major issues and provide the most benefit with the minimum possible expenditure of funds. A cost benefit analysis of various scopes and schemes will identify which will provide the best return of the funds spent. Utilities typically have their own processes to evaluate modifications and performing cost benefit analysis, though Appendix D of EPRI Report “Tools To Optimize Maintenance of Generator-Excitation System, Voltage Regulator and Field Ground Protection” (reference 7) can help provide an overview of a typical process.

A brief synopsis of the scope selections is shown below. A detailed discussion of the sections follows the synopsis.

- For reliability and availability issues due to one or a few minor components, a component replacement program or upgrade is usually the best selection.
- For issues beyond the reliability of a minor component, but where the main exciter is in good condition, an upgrade of the voltage regulator is usually the best selection.
- Where excitation system issues cannot be adequately handled by component or voltage regular upgrades, a retrofit of the entire excitation system can be the best selection

As previously mentioned, when a replacement program or upgrade to existing minor components can address the major issues with the existing excitation system this will probably be the best course of action. The cost of periodically replacing or upgrading minor components can be a fraction of what could be spent to upgrade the voltage regulator or to retrofit the entire system. Performing an upgrade or retrofit could have no or negative value if nearly the same reliability and other benefits can be achieved through a problem addressing the minor components.

The next step in increasing scope is replacing the existing voltage regulator. If components in the regulator need replacement but are too expensive, too difficult to obtain or too numerous to begin replacing to achieve the desired reliability an upgrade or retrofit of the voltage regulator will begin to be the best choice. Other factors as previously mentioned in this guide such as: better performance and transient response, improved functionality, higher power (if the regulator is the limiting factor) and reduction of operator burden, can lend themselves to making the regulator upgrade the better selection to address issues with the excitation system.

Other major components such as a pilot exciter, power potential transformer and power current transformers may be eliminated or upgraded with the voltage regulator. The condition of these other major components and the configuration of both the existing and the upgraded system will determine whether to include these components in the modification. The initial cost of the modification may be reduced by using an existing power potential transformer to provide excitation power, in those existing systems that have one. However, the long term cost benefit of the modification could suffer if the PPT is in poor condition or is under-rated.

Replacement of the entire excitation system and retrofitting new equipment in its place has the highest initial cost of the possible modifications; however this typically also has the highest benefit value. The evaluation process and cost benefit analysis should favor a complete retrofit if the cost-to-benefit ratio is better than those of the other choices. Also failure or poor condition of the main exciter will push the analysis in favor of this choice to replace the entire system. Other issues such as increase excitation power for plant uprate and demand for better transient may also push the analysis towards this choice.

An alternative to a complete retrofit is to overhaul, rewind and refurbish the existing exciter and other components, possibly replacing some components such as the AVR. The existing exciter may have given 30 or more years of dependable service. A complete refurbishment may provide a similar level of service. Plants may opt for refurbishment for a number of reasons, including keeping the same system with which the operators and technicians are familiar and experienced. Of course a refurbishment will not be able to resolve all the issues with the excitation system, such as a need for higher performance or a power up-rate. The benefits of a modern digital system will not totally be realized with a refurbishment, which may be acceptable based upon the needs of the plant.

The following table provides a comparison of the various choices for addressing excitation system issues.

Table 3-1
Excitation System Options

Feature	Do Nothing	Replace/ Upgrade Minor Components	Upgrade AVR	Refurbish Exciter and Rest of System	Retrofit New Excitation System
Initial Cost	Zero	Minimal	Moderate	High	High
Response	Slow	Slow	Good	No Improvement	Best
Transient Response	Poor	Poor	Good	No Improvement	Best
Regulation	Fair	Fair	Best	No Improvement	Best
Reliability	Poor	Possibly Better	Improved	More Improved	Most Improved
Reduce Operator Burden	Poor	Poor	Good	No Improvement *	Best
Reduce Maintenance	Poor	Poor	Improved	No Improvement *	Most Improved
Power Uprate	No Improvement	No Improvement	Somewhat Improved	No Improvement	Most Improved
Efficiency	No Improvement	No Improvement	Somewhat Improved	No Improvement *	Most Improved

* Refurbishment may eliminate certain equipment problems and work-arounds that may provide some improvement in the areas of operator burden, maintenance and efficiency.

Documentation

Throughout the entire project it is essential that accurate and complete records be maintained. Having good records serves a number of purposes. First, the records should show the issues and features that were evaluated, and the decisions made regarding them. As the modification process continues, the why and how the modification was developed and implemented will be clearly shown. The same modification on another unit or at another plant can more easily and efficiently be performed based on the records. Issues and concerns that arise later in the process or after the completion of the modification can be more readily addressed. The documentation will best begin with the initial processes of the project.

4
CONCEPTUAL DESIGN

The conception design phase lays the foundation for the entire project. It is important that sufficient detail is given to this phase to ensure that modification begins successfully and to prevent costly redesign and errors later in the project. As most every utility has their own procedures and processes for modifications, this guide will not attempt to provide a complete detailed description of the conceptual design process. Not only would attempting to describe the process be unnecessarily redundant, the possibility of conflicting with an established process or procedure is best avoided. What this guide will provide are items that should be considered and addressed during the conceptual design process for the excitation system. Most of these items have been given by utilities and service and equipment providers as “Good Practices” and “Lessons Learned.” Consideration and addressing of these items will lay a foundation of developing a specification, a cost estimate and the actual project design.

Industry Experience

As mentioned in the previous chapter on the “Initial Processes”, talking with and visiting other plants that have performed an excitation system modification can greatly aid the development of the conceptual design. Information for the conceptual design is best obtained from a plant which incorporated at least a similar modification to the one being considered. Thus, if the scope of the modification is known or anticipated during the evaluation process, conceptual design information and suggestions should be requested at that time from plants with similar modifications.

Personnel with experience with excitation upgrades and retrofits need to be involved in the project as early as possible. Supplement contract personnel may need to be hired if in-house expertise is not available.

Preliminary Data on New Equipment

Obtain lead times, costs, dimensions and other equipment information. These items are fairly standard to any conceptual design process. Typically, utilities will have design processes that will cover this topic and/or have experience with obtaining this information, so not much detail will be spent in this guide on these items. The basic intent is to obtain an idea of the types and models of equipment available for the desired modification, get a feel for how much it will cost, and determine the space, environmental and structural requirements for the modification.

Another concern that should be addressed is the expected length of time spare parts and OEM service will be available after installation. A number of digital exciter models have had production runs of only six to ten years. OEM cannot reasonably be expected to indefinitely provide support for equipment that has been long out of production. Plants have report that they reasonably expect to have OEM support for the digital excitation equipment they installed for ten to twenty years.

Whether the plant expects to operate the new excitation equipment beyond this support periods and possibly be willing to install newer equipment should be considered. Certain components, such as the power potential transformer and collector assembly, will likely not need to be replaced. However, the regulators, possibly the bridges, and other electronic component may be obsolete in one or two decades. The cost of replacing the components becoming obsolete though will be less than a complete retrofit as transformers, collectors and other components will likely be retained.

Power Requirements

The new excitation equipment will require different power sources. First is the source for excitation power; the source that provides the power to drive the generator field current. On older systems, the rotating exciter provided the power, whether driven directly coupled to the generator or separately driven by a motor or turbine. Modern static excitation systems obtain electrical power from the generator output or a station bus as the source of excitation power.

The necessary voltage for static exciter is obtained through a power potential transformer (PPT). Power is preferably taken from the generator output for stability and less inference from and on the station buses. Often a connection to the generator output is made at a transformer fed directly from the generator output, or at the generator output breaker if one exists and is directly connected to the generator. However, a station bus is sometimes the most practical supply to tie-in to for excitation power. Sufficient capacity must exist on the bus not only for normal operation, but for surges due to exciter transient response. Analysis should be performed to ensure that large motor starts, bus switching and other bus transients will not have a detrimental effect on the excitation system.

Additionally, there will be other power requirements, typically 120 volt sources for control, cooling system, equipment heaters, etc. DC power may be required for controls and monitoring. A field flashing source may be required for start-up of the generator; an adequate DC source may need to be available with sufficient capacity. Instead of a DC source, some exciters may require 480 volt power, which is rectified to provide the field flashing DC current.

At this point it is probably too early to specify the exact power requirements for the new system. However, knowing what the new equipment will likely require will provide direction to determine if additional power sources have to be provided; or impose limitations that the new equipment has to use the available supplies.

Interfaces

Even with the most extensive retrofit, there will be points where the new equipment must tie into existing plant equipment and wiring. These include existing controls, power circuits, protective relays, monitors and the generator's field circuit. Additionally, a network interface may be desired or needed for remote operation and/or monitoring. It is important to identify and itemize the different interfaces the new equipment will require and the voltage, current, frequency and other characteristics that must be met. The vendor will need to provide equipment that will meet the interface requirements, or interface circuitry must be provided by the vendor, the utility or a third party to ensure proper function.

Control Circuits

Various control schemes may be desired for the excitation equipment. These include existing operator controls in the control room, a digital control system, tie-in with a DCS system, remote control through a network connection, local control at the exciter or AVR mainly for maintenance and tuning. Many plants prefer to keep their existing control schemes with which the operators are familiar. The types of signals used for control and monitoring will need to be specified to the bidders.

The new excitation equipment must be able to connect with the control scheme or circuit interfaces must be provided. These interfaces often can be produced by the equipment provider or through a third party provider. Whether a direct connection or a circuit interface is used, care must be taken to specify all the required connections and their parameter such as voltage levels, polarity, range, time duration, etc (reference 1).

One problem reported with using an existing control and monitor scheme was that the operators noticed indication activity was different from what their experience had been with the old excitation system. The new AVR had better regulation and faster response than the old AVR, and the field amps and generator VARs changed more quickly than before. It is important that the operators are aware of system differences that will occur with the new equipment; otherwise concern may develop as to whether the new equipment is functioning properly.

Specifying provisions for tying the new equipment into a DCS system is a recommendation for most plants, whether they have a DCS system or not. Many plants may add DCS eventually, and having the excitation system ready for it will save future expense and trouble.

Relaying and Metering

The new exciter or new AVR will need to tie in with the existing relay and metering scheme for the generator. Much of the excitation-related protective relay functions can be contained in a modern digital exciter or AVR. Tie-in with existing relay and metering circuits can be accomplished through dry contacts and analog input/output terminals. Ethernet, optical fiber or other digital connections may be necessary on some newer equipment. The exact type and signal requirements should be specified to have the prospective bidders be able to propose the correct configurations for the upgrade or retrofit. The exact signal levels and scaling factors, such as 0 to 120 volts AC with 480 V / 120 V, for each input and output should be specified. Equipment suppliers may require or recommend additional inputs and outputs other than what is specified. They should be require to include all the required and recommended connections in their proposals.

Obstacles, Interferences and Hazards

Identify structural components, piping, conduits, and other equipment which may interfere with or block installation of the new equipment. The new equipment may have to be designed around such inferences or the interferences moved. New excitation equipment that is to be installed in existing cabinets, or at least within the space occupied by the old equipment, will obviously not have as much problems with obstructions or interferences. Access to equipment location may still be a problem, particularly when the old equipment is being removed and bringing in the new equipment. Additionally, existing or potential interferences with cabinet doors and other accesses should be identified and addressed in the modification. Hazards which may have a detrimental effect on the new equipment, such as heat sources, piping leaks, etc., need to be identified and addressed.

Generator Testing

Ensure that generator excitation data is available, accurate and complete. This data may be from generator documentation or from preliminary tests as previously described in this guide. Exciter data will also be required if the exciter is to be retained. Testing may be required to obtain excitation levels and time constants. Information regarding exciter testing, parameters and modeling can be found in the IEEE 421 standards (references 1, 3, 4, 5 & 6); particularly IEEE 421.2-1990 (reference 4), 421.4-2004 (reference 1) and 421.5-1992 (reference 6).

Many modern digital regulators provide a wide range of easily made adjustments so that testing for levels and time constants may not be necessary prior to commissioning. Older regulators may require hardware alteration, such as varying capacitors, to make substantial parameter changes. Consult potential vendors to determine if testing for limits and time constant might be needed. With the modern digital regulator the parameter changes often can be readily made through keypad or keyboard entry during commissioning. Additionally, vendors with a broad history of providing excitation system retrofits often have records of the limits and time constants for many machines on which they have worked.

Redundancy

Redundancy should be built into the new design (reference 1). Most systems have a back up regulator, typically the manual regulator. A fully redundant automatic voltage regulator can provide desirable system capabilities in the event of failure in the primary automatic regulator. Many modern digital regulators do provide redundancy built into the same cabinet. Whether opting for a redundant automatic voltage regulator or just the manual regulator as a back up, ensure that auto-tracking is included to ensure smooth transfer in the event of primary failure.

Often overlooked is redundancy for smaller components. Having redundant power feeds for cooling system fans is a simple feature to design into the system, though without it the equipment may overheat and trip if fan power is lost. Ensure redundancy to the extent practical for critical components and items, such as cooling fans, control power, bridges, etc., in order to increase system reliability. The concept of the saying, "For the want of a nail, the shoe was lost. For the want of a shoe, the horse was lost…" applies to excitation equipment as much as it does to anything else.

The control circuit, as well as relaying circuits, may require redundancy in critical portions of the circuits to minimize circuit failures, whether to run or to trip. Interlocks, permissives, trips and other functions may need to be parallel or serial redundancy to ensure correct operation in event of failure in a single circuit component. More complex circuit configurations, such as a one-out-two-twice configuration, may be required to prevent unnecessary actuation but still ensure proper operation with a single component failure.

Verify Existing Configuration

Ensure that connection diagrams, wiring drawings, and other documentation accurately represent plant configuration. Ensure that the existing wiring is labeled or otherwise easily identifiable. Delays and added expense in installation may occur from unidentified wiring problems. The design should identify and correct inaccurate documentation and configuration problems. The condition of the wiring should also be verified. Wiring that is deteriorated or in poor condition should be replaced by the modification.

Verify Regulatory Requirements

Various codes and regulations may have changed or come into effect since the original excitation system was placed into service. New OSHA requirements for the U.S. reflecting changes in NFPA 70E (reference 8) and other safety issues may require protective barriers and features that were not commonly used in past installations. Health and safety agencies in other countries may have adopted similar requirements. Most equipment manufacturers are aware of and comply with national regulations and codes, though the buyer must ensure that the equipment supplied will comply with the requirements.

Regional reliability councils or other similar organizations require more features to help maintain the stability of the distribution system in their areas. Appendix D has a list of typical requirements proposed or adopted by several U.S reliability councils; similar measures may be required or are being considered by councils or similar agencies in other areas.

Preliminary Drawing and Diagrams

Develop block diagrams, connection diagrams, layouts and outline, and schematics. Depending on the extent that a plant will be performing the design or having a vendor do the design, drawings and other documentation should be prepared to show at least a preliminary design for the new system. This will aid the utility staff in several ways: preparing a budgetary estimate; determining actual extent of the modification; providing an accurate scope of work for the vendor; ensuring completeness of the modification; determine fit of new equipment – both physically and electrically; verify functionality and performance of the conceptual design.

Preliminary Calculations

Perform preliminary calculations, electrical loads, mechanical loads, cooling loads (air and water if necessary), power system harmonics, vibration, etc. An assessment should be made to determine that the new equipment will be adequately supported by existing systems in the plant, and also that the equipment's weight will be structurally supported by the existing floor. Particularly, a new power potential transformer may require additional structural members to adequately support its weight. If existing systems and structures are found not to be adequate, enhancements must be included in the design to ensure sufficient capability to support the new excitation equipment.

Future Considerations

It is important to consider future requirements of the excitation system when developing the specification for the retrofit. If within several years after the excitation system is retrofitted it is decided to uprate the plant's output, the new excitation equipment should be capable of supporting the uprate. By designing in capacity for a future uprate, the need to retrofit the system again or not perform an uprate is avoided. Possible design considerations for a potential uprate include an oversized PPT. Care must be exercised so as not to utilize too large of a transformer due to short circuit current capacity.

Another consideration is to utilize power bridges with higher capacity, or to install modular equipment which allows additional modules to be added when needed. Other items to consider for possible future uprates are power cabling – both exciter feed and field cables, power potential transformer feed source, cooling subsystems.

Coordination

Coordinate with all disciplines from the start of project, as this will not just be an electrical project. Various disciplines will need to be involved in the project. Civil and structural will be required for verifying floor loading capability, mechanical for the cooling systems, and others as needed. The extent of involvement of these other disciplines will vary, depending on the type of upgrade or retrofit being performed.

An upgrade consisting of replacing the voltage regulator may require minimal involvement from non-electrical disciplines. On the other hand, the complete retrofit of a rotating exciter with a static exciter could require extensive involvement such as: the floor and structural members may need to be strengthened for the power potential transformer; supports for conduits and other components will need design and installation; fire seals may need to be added; equipment and piping may need to be relocated; floors and walls may need to patched; and numerous other non-electrical areas requiring work. It is important to the success of the project to involve the non-electrical disciplines early in the project in order to ensure that all the necessary work and requirements are addressed.

Cooling

Cooling may be necessary for the power bridges, PPT, brushes and other components. The means to provide cooling can be ventilation, water to air heater exchangers, water to water heat exchangers.

On systems which were brushless that have been retrofitted to a static system, a new ventilation system will be needed to provide cooling for the brushes and collector rings. Typically a shaft mounted fan will draw or push air over the rings and brushes, though external fans and ducts may be used instead. Depending on environmental conditions, air conditioning and filtering may be needed to ensure minimal brush wear.

On systems which already have brushes and collector rings, the ventilation may have to be redesigned due to changes in configuration of the collector enclosure with removal of the rotating exciter. Due to various existing systems in use and different configurations of upgrades and retrofits, each modification will be somewhat unique; however, it is important to ensure that adequate cooling and ventilation is provided for each modification.

Power SCR bridges will require cooling; often air is used. However, water may be required to for higher capacity components. The cooling may be taken from stator cooling or may be a close loop system utilizing a water-to-air or a water-to-water heat exchanger. Typically there is no compelling need to specify a preferred method of cooling. The equipment manufacturers should be allowed to specify the cooling requirements and include the cooling method in their proposals.

Control and Auxiliary Power

Power for control and operation of the excitation equipment may be provided by using the power that is installed for the existing system. However, the new system may require additional power or a different type of power – such as DC instead of AC. Additionally, power may be required for cabinet fans, lighting and utility receptacles. Different manufacturers will typically have somewhat varying requirements for control power and can usually configure their equipment power requirements to match what’s available in the plant. It is not necessary or practical to specify exact power requirements; though prospective bidders should be given the types of power that is available.

Collector and Brush Assemblies

Installation of a stub shaft and bearing for the collector rings will require lubrication and vibration monitoring instrumentation. The existing systems for the turbine generator will likely be used. Supply and return lines from the existing pipes will need to be designed and run to the new bearings, or lines for the old exciters will need to be modified to fit the new bearing. The new bearing will need vibration instrumentation with the instrumentation tying into the existing turbine vibration monitoring system. Input points for the old exciter's bearings will probably be best used for the new bearing. Additional instrumentation may be added when replacing an existing brushless exciter; added instrumentation can include field voltage, current and temperature (derived from voltage and current). Even when the old excitation had collector rings, the retrofit may still require a bearing change that could necessitate lube oil and vibration monitor modification.

5
GENERAL CONSIDERATIONS

This chapter provides some general considerations for use throughout the project. Many utilities have procedures and processes that provide generic guidance and instruction on the general project considerations. This guide cannot replace or supersede those procedures and processes. This chapter is intended to augment the generic guidance and instruction with general considerations that, while not just particular to the excitation system, can have a significant impact upon and are possibly more likely to cause concern with an excitation system upgrade or retrofit project.

Size and Weight

Static excitation system cabinets and the Power Potential Transformer (PPT) can require a significant amount of space. The availability and access to space for mounting the component should be verified. Care should exercised not to take space required for laydown during turbine maintenance or other work. The PPT's weight can be significant; the strength of the floor and structural members should be verified to ensure that the weight can be properly supported. Additional support may be necessary for the existing floor.

Field Breaker

An AC field breaker has several advantages over a DC breaker, including less contact wear and more availability of parts. Consideration should be given to using an AC breaker to interrupt power to the excitation power bridges, instead of using a DC breaker in the field circuit. With removal of the field breaker, a crowbar circuit or similar circuit should be installed to limit field overload during a trip.

Shaft Voltage Suppressor

High frequency harmonics from the SCR bridges on the field circuit can induce high frequency onto the generator shaft. This high frequency that may not be bled off sufficiently and arcing in the shaft bearing may occur. Even though the bearings are typically insulated from ground, the capacitance of the insulation can allow the higher frequencies to pass through the bearing. A shaft voltage suppressor with resistance capacitance values for passing the higher frequencies can be used to bleed the high harmonics to ground before they can result in damaging shaft currents.

Fire Seals

The fire rating of walls and other structure can be compromised by openings for cables, conduits, bus work, cooling line and other components. It is necessary to ensure that the fire ratings are maintained by installing adequate fire seal in all openings made or uncovered by the project.

If the installation of the cables, conduits, bus, cooling lines, etc., is to be performed by the contractor, the fire seals will need to be included in the specification. The specification should include the fire rating of the wall and other structures that may be breeched, and provide the composition installation details for the fire seals. Though unlikely, if conduits must enter a Class I or II location as defined in Articles 500, 501 and 502 of the National Electric Code – NFPA 70, the necessary requirements such as sealing fittings should be called for in the specification.

Foreign Object Exclusions

The excitation system cabinets and components must have screens and seals to prevent dust, dirt, debris and small animals from entering. Conduits and raceway openings should also be sealed to prevent foreign matter and moisture from entering the cabinets and components.

Multiple Units

Cost savings may be realized by a one-time purchase for multiple units. If several units at the same plant or even at different plants are to have excitation system upgrades or retrofits, several benefits can be derived by one purchase of the equipment for all units. Manufacturers may give a volume discount, particularly if they can produce and ship the equipment over a period of time.

Additionally, the specification and design for all the units will be simplified, even if the units have different existing excitation system configurations. While the specification and design may actually be more complex that those for a single unit, the total amount of work and documentation will be less than developing a separate specification and design for each unit.

Another benefit will be the similarity between the units. Having the same make and model equipment will reduce the training needed for technicians and engineers to support all the units, and experience levels will increase more quickly by working on the same equipment at the various units.

Control Interface

A primary consideration is how to implement the controls for the new equipment (reference 1). The existing control scheme can be replaced with a digital scheme utilizing touch screen displays and computer keyboards for control and monitoring. Or, the existing control scheme can be tied into the new equipment so that the operators will have familiar devices for controlling the excitation system. Many manufacturers can supply their modern excitation equipment with input and output that utilizes dry contacts. Hand switches and other existing control devices can then be used to operate the system.

There are advantages to either installing a new control scheme or utilizing the existing devices, with the plant operators' preference being a major factor in determining the advantages. By keeping the existing control devices, the operators have familiar switches, lights and other items for running the system. Additionally, there can be some cost saving by utilizing the existing controls and the associated wiring. By replacing the existing control scheme with a digital scheme plants typically find that operator burden is somewhat lessened and that the system is easier to operate. This is particularly so in plants which have implemented a digital control system (DCS) for most of the other systems in the plant (reference 9).

Relay and Metering Interface

As with the control circuits, the new excitation equipment will have to tie into the existing relaying and metering circuits. While some relays may be replaced by components of the new equipment, the new equipment will have to be connected at some points to existing circuits. Voltage, current, trip and other signals should be identified for which the new equipment shall have an input or output connection. These will include mainly those of the generator protective relaying and metering schemes. Interface circuits and modules may have to be designed or procured later, depending upon the new equipment that will be purchased; though most excitation equipment will conform to standard signal current and voltage levels used for relaying and metering.

Collector Rings

Retrofitting a brushless exciter with a static exciter will require installation of collector rings and brush rigging. Even refitting a brushed exciter may require modification to the collector assembly. With a brushless to static exciter retrofit, installation of the collector rings typically consist of the rings mounted on a stub shaft. All but small rings require a stub shaft and bearing to support them. Small rings may be mounted overhung on the generator, but typically these are not on the size generator found in power plants. Vertical generators in hydro-electric plants may be small enough, and being vertical not need a support bearing.

The collector rings mounted on the stub shaft usually will have axial field leads running to butterfly connecters on the end of the shaft, which will join to similar connectors on the generator shaft. When the field connections are made, the stub shaft is coupled to the generator shaft. A small number of brushless exciters employ radial leads; for these, the radial leads will need to be connected to the radial leads in the generator shaft over the coupling.

A steady rest bearing is used to support the end of the stub shaft. Lubrication lines and vibration monitoring instrumentation will need to be connected to the bearing. A bed plate or support is often used under the bearing and stub shaft to provide solid support. Shimming and probably grouting of the bed will need to be done to hold the stub shaft in alignment.

Collector rings and brush rigging can be provided for any size generator. A number of OEMs and after market suppliers can supply large rings, having banks of brushes along their lengths that can carry thousands of amperes of field current. Additional brushes and brush holders may be required for increased capacity due to unit uprate if the existing collector rings can be, and are, retained.

Vibration

With a retrofit of the rotating exciter with a static, a good amount of mass is removed from the end of the generator shaft. This may change vibration characteristics of the generator and prime mover. Significant modifications to the rotor have the potential to affect the rotor's balance. The generator will require a balance check after the modifications, including the addition and removal of balance weights, if necessary. A detailed vibration analysis will need to be performed. Data from operation, run up and coast down of the generator may need to be collected to model the generator for vibration analysis and to verify analysis model of the generator.

With consideration of machine vibration, torsional analysis is necessary when the rotating mass of the generator, exciter, prime mover, etc is changed (reference 30). Modifications which change remove components, add components or do both will to some extent affect the torsional dynamics of the generator train. Replacement of a direct-driven rotating exciter with a static exciter generally results in a more torsionally rugged machine as usually one sub-synchronous mode is eliminate and a vulnerable shaft span is removed.

The Generator OEM should be consulted to ascertain the unit's natural torsional frequencies and that modes do not adversely change as a result of eliminating exciter shafts and/or couplings. Certain structural data on the generator rotor may be considered proprietary by the generator OEM; however, experienced suppliers of collector rings and generator service companies may have records from similar generators and be able to supply the missing mechanical data.

Three factors need to be considered in the process for analyzing the torsional effects of replacing a direct-driven rotating exciter with a static exciter. Other types of excitation system modifications may have some or all of these factors for evaluation the torsional effects of the modification.

1. The removal of an exciter rotor for instance will retune all of the torsional modes of vibration to some degree. This is especially important in four-pole turbine-generators and even some two-pole units where the last-stage blade-rotor modes of the LP turbine may well be retuned as a result. This could be good or bad but regardless it is necessary to know the outcome to avoid resonance during operation.
2. This issue in this regard is in the consideration of what remains or what is added to the shaft. Typically a steady-rest bearing and shaft is added; however, a slip-ring ventilation fan remains. This new shaft extension with the existing rotors may now be tuned to create transient torsional response in the collector region that is far greater that the original design configuration.

3. The final issue is the excitation control itself while this control may work well for voltage control it may cause torsional stability problems especially when power system stabilizers are involved. Such instability may be conditional on loading and may go unnoticed until large fatigue cracks appear in the main generator shaft. Power system stabilizers should not be applied without consideration of the design for torsional stability.

In addition to machine vibration associated with the generator and exciter, vibration in other areas of the plant can be a concern. Vibration at the locations where excitation system cabinets and other components are to be placed may cause detrimental effects to the system. Electrical connections and component mountings can become loose, or components may fail prematurely due to vibration. A low level of vibration on the floor can be amplified at the top of a cabinet. Care must be exercised to ensure that placement of excitation system components does not subject them to undue vibration. Vibration and seismic requirements, if any, should be incorporated within the specification.

6
SPECIFICATION CONSIDERATIONS

This chapter provides topics to be considered for the specification. Obviously not all of this chapter will apply to a specific upgrade or retrofit, though the topics should help in ensuring completeness of the specification requirement. Issues regarding legal, safety, insurance, etc are typically handled by a utility's purchasing procedures and processes, and are not part of this guide.

Many vendors can only provide a portion of the equipment for a complete excitation system retrofit. Companies may only supply the static exciter and voltage regulators. Other companies only provide the assembly consisting of collector rings, shaft, bearing, brush rigging and collector enclosure. Consider separate specifications for the different portions of the retrofit, or if preferred, require the bidders to partner with or subcontract to vendors who supply the needed equipment and services.

Regulatory Issues

IEEE specification 421.4 (reference 1) provides guidance on excitation system specification and should be consulted.

Specify an IEEE 421.5 model (reference 6) – require that the new excitation system has a transfer function conforming to an IEEE 421.5 model. Reliability councils or similar agencies will often require an accurate excitation system model for power studies. The following is an extract from a specification, provided courtesy of Duke Power:

> X.X.X Control Model Block Diagram - Supplier to provide a control model block diagram in accordance with IEEE Standard 421.5-1992 "Recommended Practice for Excitation System Models for Power Stability Studies" and provide the appropriate parameters (or constants) that represent the as-left calibration. Supplier to provide the necessary conversion equations so that the equipment settings can be converted to the above referenced IEEE model or Power Technologies Inc. PSS/E model. For each adjustable setting variable, supplier to provide the range of adjustment. The AVR System modeling shall also satisfy the applicable requirements of NERC Planning Standards (and associated Compliance Templates) section II.B.
>
> Control models are required for Unit 1 and Unit 2 AVR Systems, if different. Two (2) copies of the control model block diagram with parameter tables shall then be submitted to Owner for review and approval. After Owner approval, six (6) copies of the final control model documents and two (2) CDs containing the documents in electronic format shall be provided to the Owner.

> All additional functions installed (current compensation, V/Hz, over/under excitation limiters and protection, power system stabilizer, etc.) must also have the parameters stated. In the case of a power system stabilizer, a standard model must be provided along with the necessary conversion equations, as described above for the exciter.

Require regulatory compliance – provide requirements of the ISO, the regulatory council and other agencies, and ensure compliance with the requirements. Compliance may include requirements such as a minimum excitation ceiling voltage of 150 percent with 70 percent degraded generator terminal voltage, and a high initial response excitation system as defined in IEEE Standard 421.1 (reference 3)

Require documentation on transfer function accuracy – the transfer function of the digital voltage regulator or exciter may be limited to certain operational conditions and also is a discrete digital representation of a continuous analog model. Require the vendor to provide documentation on how accurately the digital transfer function fits the model and on any limitation to the function's variables.

Design Issues

Specify a proven design – specify that proven design of excitation equipment is to be installed. Require information of past installation and proven success of the model and type of equipment being proposed by the bidder.

Require standard nomenclature – require that software variables and constants are displayed with names corresponding to real quantities. Values should be displayed in engineering units (Volts, Amps, MVar, etc.). This should apply to both operator and technician's displays, and to any remote terminals.

Specify preferred units of measure – require bidders to use a specific measure system such as English, metric or a combination of both.

Specify exact dimensions – if existing cabinets are to be used, or if the new equipment is to fit in the same space, provide accurate dimensions of the cabinets, any openings, mounting hardware and other components.

Require standard digital communications – specify that the digital communication capability of the equipment should conform to standard method and protocols, such as Ethernet and Modbus™. Non-standard communication protocol can make difficult or impossible future needs to tie in other equipment and networks.

Specify A/D and D/A interfaces – require interfaces that allow analog test signals to be applied and analog output signals to be measured and monitored with test instruments. This can allow on-line testing such as a terminal voltage step response test to verify performance of exciter and PSS.

Specify variable lengths and sample rates of data – specify that the lengths and sample rates of the individual fields being logged can be changed as needed to match the parameters being stored. This will minimize the memory requirements for the logged data.

Specify redundancy – require redundancy for critical components on which failure of any could cause the excitation system to fail. Redundant items can include voltage regulators, power bridges, cooling system, and control power. The redundant voltage regulator can be a manual regulator, though a redundant automatic voltage regulator would provide better performance. The requirement for redundancy though has to be tempered with practicality. For example, a redundant power potential transformer may not be practical or economical.

Require redundancy in critical control circuits. Interlocks, permissives, trip and other circuit component which are crucial should possibly be redundant to minimize circuit failure. Parallel or series components, or a one-out-of-two-twice configuration, depending on component circuit function may be necessary.

Specify brush polarity change capability – require that the polarity of the brushes and collector rings be readily changed by swapping leads or bus links. Though a number of utilities no longer perform routine polarity swaps, having this capability built into the equipment can prevent future difficulties and expense if it is determined a polarity swap is needed.

Specify future uprates – specify if the excitation equipment shall have sufficient margin to handle possible future uprates of the plant.

Specify allowable harmonic content – specify the allowable total harmonic distortion on the primary of the power potential transformer. Vendors should best be able to select the transformer's K factor to match their equipment without being excessively over rated. The K factor does not represent the means to reduce harmonic content, but rather the designed capability of a transformer to withstand harmonics. Vendors should select a transformer with a K factor which can withstand the allowable harmonic content.

Require successful bidder to evaluate ambient condition at location for new equipment and propose cooling, filtering, conditioning, etc. to correct if needed. Bidder should take into account the heat load from the new equipment, such as the power potential transformer, and the impact on both the new excitation equipment and other equipment in the area.

System Features

Specify auto-tracking for manual regulator – require auto tracking between the automatic and manual voltage regulators, or between the primary and back-up automatic voltage regulators. Auto-tracking will help ensure a bumpless transfer upon failure of the primary voltage regulator. Additionally, it will ease operator burden by not requiring an operator to make periodic manual adjustment of he backup regulator.

Specify auto-start and sync - the auto-start, soft start and synchronization features reduce the probability of generator voltage overshoot on start up and lowers likelihood of synchronization errors. Operator burden is reduced by having the functions performed automatically

Require built-in limiters and compensators – for digital voltage regulators and exciters require limiters, compensators, protective relays and power system stabilizers (that are determined to be necessary) be incorporated into the design. These components will not typically be individual components, but part of the hardware and software of the digital voltage regulators and exciters. The digital equivalents of these components can often be implemented as computational models, and can provide more reliable service and easier set up than the individual analog versions.

Require a DCS interface – even if a plant does not have a Digital Control system installed, the cost of having the necessary network connection is minimal. Then, if in the future the plant upgrades to a DCS system, the excitation system is ready. Many digital voltage regulators and exciters come equipped with the necessary connections anyway.

Require self-diagnostics and testing – digital voltage regulators and exciter should have built-in diagnostic routines that monitor the performance of the equipment and that can be used to troubleshoot problems with the equipment. Bidders should list in their proposals the diagnostic tests and test routines that will be included in their equipment. Built-in test functions and simulated inputs can greatly facilitate testing and tuning of the exciter. As with diagnostic routines, the bidders should provide a listing of the built-in test functions.

Require data-logging – most digital excitation equipment provide some data-logging capability. The data-logging and the display of the stored data can help investigate problems and faults in the excitation system, the generator and out on the grid. Specify points that need to be recorded, the sampling rate and the storage duration. Instead of specifying points, the bidders could be required to provide in their proposals the data-logging capabilities offered with their equipment

Require computer security – the input terminals should be password or key-lock protected. Remote network connections should be password protected and should incorporate an authentication scheme for remote users. Different levels of access and security should be provided for different user functions, such as monitoring, system control, and configuration changes.

Require logging of calculated values – specify that calculated variables, such as terminal voltage, watts and VARs, are logged as actual values. This will facilitate display and retrieval of these values by not having to re-calculate them from the original variables.

Equipment Considerations

Include all required interfaces the equipment will require and their specifications, including small signal control, current loops, indication, data bus and annunciators.

Specify field flashing requirements – provide the voltages and currents available to supply the field flashing circuits.

Specify available voltages – provide the available voltages for control and auxiliary power.

Specify excitation power source – specify the voltage for providing excitation power and whether generator or bus fed.

Require isophase connections to generator output – for exciters fed from a generator with an isophase output, require isophase bus or at least single phase cables to minimize phase-to-phase fault potential.

Specify maximum allowable harmonic distortion (THD) on power systems and control circuits from new equipment (reference 10).

Specify black start requirements of new system, if desired, and whether station batteries are to use or if vendor is to supply.

Require burn in of circuit cards and other applicable electronics at the factory prior to shipment to minimize infant mortality failures. Require at least 24 hours, preferably 72 hours, of burn in time for all cards including spares.

Project Processes

Detail responsibilities - delineate responsibilities of the vendor and what will be the plant's responsibilities. These should include equipment, material, personnel, engineering, analysis, demolition, disposal, installation, commissioning, training and documentation

Detail obstacles, limitations and interferences – include in specification problem areas that the vendor may have. Examples may be lack of an overhead crane, limited ceiling height, obstruction by other equipment.

Specify major equipment and tools – list the equipment and tools the vendor is responsible for, such as cranes, hoists, test equipment and simulators, alignment instruments, etc., and what equipment and tools the plant can and will supply.

Considered replacement cabinets – if desired to have the new regulator mounted in the existing cabinets, consider having the regulator installed in new cabinets that match the existing cabinet. This way the new regulator can be factory tested in its cabinet and shipped as a unit. Installation time will be reduced and the possibility of installation problems is lowered by having the equipment pre-assembled and tested.

Include repairs and wiring changes – ensure that problems with existing wiring and equipment are listed in the specification and whether the vendor is to correct the problems. Wiring problems can include deteriorated insulation, mislabeling, and undocumented changes. The equipment and wiring that will be retained should be walked down, inspected and tested prior to specification issue so that problems that the vendor will need to correct can be identified to the bidders.

Specify any necessary requirements for hazardous material handling and disposal. The project may involve hazardous materials such as asbestos and lead paint.

Specify milestone dates – require vendor to supply draft drawing, actual drawing, equipment and material, final drawings and personnel to the plant by specific milestone dates in order to meet the plant's scheduling requirements.

Require spare part lists – require vendor to supply a recommended spare parts list, and to provide the initial supply of spare parts.

Require special tools and instruments – specify vendor is to supply special tools and instruments needed to test, repair and maintain the equipment.

Combine Units – if several will require similar upgrade or retrofits, cost saving may be realized by a one-time purchase for multiple units. Additionally, identical equipment can be obtained for the multiple units by a one-time purchase, perhaps providing a volume disconnect and providing consistency between the units.

Equipment Testing

Require burn-in testing – specify vendor to perform a burn-in run of equipment, to include all supplied spare cards and other components, in order to minimize "infant mortality" failures.

Require factory testing and tuning– require that the new equipment be assembled and tested at the factory to the extent possible. Simulated inputs and outputs will be required, but performing the initial testing and tuning at the factory will help reduce commissioning time and prevent possible trouble during the outage.

Require site testing similar to factory testing prior to installation. Upon arrive on site, new equipment should be assembled and tested to the extent possible. Simulated inputs and outputs will be required, but performing the initial testing and tuning on site prior to the outage will help reduce commissioning time and prevent possible trouble during the outage.

Documentation

Successful bidder should perform verification of existing documents and plant configuration at beginning of project to include all interface points between existing and new equipment. Discrepancies and missing information should be rectified.

Require documentation on settings – require vendor to provide the range and limitations on the settings and adjustments that can be made to the equipment.   Future plant changes may require re-adjustment of exciter or voltage regulator; this requirement will help ensure that present and future needs of the plant can be met.

Require documentation on terminal displays – require bidders to provide documentation on the operator and technician display screens and how well these screens incorporate human factors into them. Bidders probably will not be able to provide an exact design of screens, but they should be able to describe interface screens and provide a representation of how the screens should appear.

Require complete documentation to include all drawings and manuals by certain milestones dates. Bidder should supply preliminary documents early in project. At conclusion of project must supply final revision of all drawings, manuals and other documents to include markups and field changes.

Training

Require vendor supplied training – specify on-site training for operators, engineers and technicians. The training for each category of student – operator, engineer and technician – must be tailored for their specific jobs functions, and should provide the necessary instruction for the student to be fully able to operate or maintain the equipment. Additionally, the vendor should provide necessary training documentation and materials to be incorporated into the plant's training program.

Include training simulators – specify vendor to provide a training simulator of the digital exciter or voltage regulator. The training simulator may be computer software that runs on a personal computer or a separate piece of hardware. Technicians should be able to train and familiarize themselves with testing, setting up, and tuning the regulator or exciter using the simulator.

7 PROJECT CONSIDERATIONS

Project Team

Many projects within power plants are not the sole province of a single discipline. The upgrade or retrofit of the excitation system is not an exception. Though the excitation upgrade or retrofit is mainly an electrical project; mechanical, civil and other disciplines will be needed. Since operators will be the end users of the new system, their input or involvement is critical for a successful upgrade or retrofit. Other groups that may not be directly involved with the actual upgrade or retrofit, such as training and stores (purchasing, material management), will need to participate to a limited extent in the project.

A utility may not have the in-house expertise for an excitation system modification, unless they have had experience with modifications at several plants. The project team needs to have individuals with excitation system modification expertise for the best possible implementation of the modification. If in-house expertise is not available, vendor or supplemental contract personnel having the necessary expertise should brought in to assist with the project as early as possible.

The project team should be composed of representatives from all groups that will be involved with and/or affected by the project. Only a certain portion of the team, a core team, will actually devote a major portion of their time and effort to the project and be mainly responsible for directing the project to success. The rest of the team is needed to provide input for their areas of expertise and to keep their groups up to date with the project. It is important to keep the same people on the project from start to finish, to the extent possible. Discontinuity created by members moving off and on the project team can be obstructive to the success path for the project.

Management Sponsor - a senior level person at the plant, or in the utility, who is kept cognizant of the progress of the project and provides management level support to the project team.

Project Manager – coordinates the entire project, interface between the vendors and plant, coordinates the various groups, and should be a power engineer or have a working knowledge of the excitation system. Smaller projects may have the lead engineer serve as the project manger, while the larger project should have an individual experienced with project management.

Operations – end users of the excitation system and one of the groups most affected by upgrade. Operator input and acceptance of the proposed upgrade or retrofit is crucial to the project. Also, operations will be involved with releasing equipment for work and applying clearances.

Maintenance – including I&C, another group that is significantly affected by the upgrade or retrofit. Electricians, mechanics and technicians need to have group representatives involved from the start of the project. The number of craft personnel and technician will vary depending on the scope of the project and whether the project is conducted in-house or as turn-key. Some maintenance and I&C personnel definitely should be involved with all projects, even turn-key work, so that they gain knowledge and experience with the new equipment.

Electrical Engineer – one electrical engineer should be the lead engineer on the project. Other electrical engineers may be involved depending on the scope of the project. Design, preparation of specification, review of vendor drawings and documents, protective relay coordination, and drawing mark-ups are among the tasks for which electrical engineers are needed. A small component replacement project may only require one electrical engineer, while a complete retrofit of the excitation system may require the contribution of up to four or more.

Mechanical Engineer – one mechanical engineer will be needed for design, specification preparation, vendor drawing and document review, drawing mark-up for rotating equipment; and for work involving lubrication, cooling and other mechanical systems. One or two additional mechanical engineers may need to be involved for large scope retrofits.

Civil/Structural Engineer – a civil/structural engineer is needed to review floor loading, layout and design of supports and other civil work activities. Additional civil engineer may be required for design and review structural modification if needed to support the new equipment or to add more space.

Welding Engineer – a welding engineer will be needed for the welding of supports and other structures. Many plants have standard welding procedures and may only need a welding engineer for review and possibly specification of non-standard welds. Additionally, the welding engineer services may be incorporated into the civil engineering section at many plants, so that a separate welding engineer is not required.

Drafter/Designers – drafters/designers will be needed to revise drawings, create new drawings and incorporation of vendor drawing and documents.

Planner/Scheduler – a planner/scheduler is needed to lay out the timeline of the project, detail the projects implementation paths, identify milestones and critical paths, and arrange coordination of the various activities. Depending on scope of project and individual plant practices, some of the planner/scheduler activities may be done by the project manager.

Construction or Installation, whether in-house, contract or vendor personnel craft people will be needed to perform the actual installation. Electricians will obviously perform a large part of the work; millwrights/machinists, pipe fitters, sprinkler fitters, iron workers, riggers, cement workers, carpenters, laborers, painters, sheet metal workers, insulation workers and other crafts may be needed depending on the project. Foremen, and possibly general foremen, particularly for the electricians, will likely need to be assigned to the project. For large projects, craft superintendents may need to be assigned as well. Work planners or field engineers will be needed to develop work orders and packages.

Stores/Materials – materials, purchasing, stores personnel will need to be involved with the project to acquire the equipment and materials, receive and provide storage for the equipment and materials, and create a spare parts inventory. For major scope projects such as a complete retrofit a materials/stores representative may need to be directly involved with the project team.

Training – the training department will need to update lessons, develop new training, instruct personnel on the new equipment, and document the training and qualifications of personnel. Training will likely not need direct involvement with the project, though need to be cognizant of modification, receive training material from the vendor and likely attend vendor training courses.

Vendors – Once a vendor's proposal is accepted, the vendor representative should be part of the project team. On a major project, the vendor's project manager, engineers and superintendents should be directly interfacing with others on the team. Smaller projects, such as minor component replacement, probably do not require a vendor representative. Third party vendors supplying a small portion of the project may have direct involvement, but if the portion being supplied is critical or complex then that vendor may have to be directly involved.

The project team's size and composition will vary greatly with scope of the project. Supplemental and contracted personnel may be used to fill a number of positions in lieu of in-house personnel. Most of the above groups should attend important project meetings such as a project kick-off meeting; other meetings and routine day–to-day contact may be required for core team members. Additionally, participation may vary depending on the project schedule; craft typically will be more involved during the installation than the design phase. This is not to say that craft, or other groups will not have some involvement during design, but just that the levels of involvement is lower.

A project team composition for a complete retrofit of a rotating exciter with a static exciter may consist of the following:

- 1 Management Sponsor
- 1 Project Manager*
- 1 Lead Electrical Engineer*
- 2 to 3 Electrical Engineers*
- 1 to 2 Mechanical Engineers*
- 1 to 2 Civil Engineer*
- 1 Operator*
- 1 Electrical Designer
- 1 Mechanical/Civil Designer
- 1 Scheduler*
- 1 Electrical Planner*
- 1 Mechanical/Civil Planner*

- 1 Parts/Materials Buyer
- 1 I&C Foreman/Supervisor*
- 2 I&C Technicians
- 1 Contact Labor Superintendent*
- 1 Electrical General Foreman
- 2 Electrician Foremen – 1 per shift
- 16 Electricians – 8 per shift
- 1 Millwright Foreman
- 4 Millwrights

* Core Team

Other groups not assigned to the project provide support as needed. The actual scope of the project, whether the project is performed in-house or turn-key, and a plant's own processes will determine the actual composition of the project team.

Project Schedule Considerations

Complete as much work prior to outage as possible. Conduit runs and supports can often be installed prior to the outage. Some cables may be pulled in prior to the outage, other cables may be cut to length or slightly longer and staged for pulls during the outage. Some demolition work might be able to be performed pre-outage, such as removal of redundant components, though there will be a risk if the primary component fails. Fabricate and assemble cabinets to the extent possible before the outage. Structural supports and floor modifications may be possible to perform pre-outage.

Specify layout areas, assembly areas, work areas for the different activities. Pre-stage material, equipment and tools so that they will be readily available when needed.

Perform a rehearsal walk-through of critical work activities to be performed. Verify there are not obstructions and other problem that will interfere with the activity. An example of activity that may benefit from a rehearsal walk-through is the rigging and placement of the collector enclosure for a new static system.

Have vibration modeling done well before outage. Balancing and vibration testing times can be minimized by ensuring that a complete accurate model analysis is performed and any identified problems are corrected.

Have the excitation system's transfer function modeling complete before final acceptance of design.

Evaluate the risks of certain milestones not being met due to failures or problems with plant equipment, tools, materials, etc. Develop contingency plans to ensure project remains on schedule in spite of potential problems or failures.

Project Design Considerations

The goal of this section is to provide the reader with good practices for designing an excitation system retrofit or upgrade. It is not to specify standard design practices for modifications in general. Power companies have their own procedures and practices for developing and designing modifications. It is not the intent of this guide to supersede or modify any established procedure or practice. Rather, the intent is to augment those procedures and practices for the specific instance of an excitation system upgrade or retrofit by providing suggested guidance and good practices regarding excitation system upgrades and retrofits.

Do not assume anything regarding a vendor design. Verify the design against the specification. The vendor, though doing their best to perform a quality job for the plant, may not realize all of the plant's expectations. If there are details missing in a proposal or the design, request clarification from the vendor.

Verify all interface signal levels, polarity, type, grounding, isolation, etc between new and existing equipment, and between separate pieces of new equipment. Develop and design converter and/or isolator circuits as necessary to ensure correct signals. Coordinate with all vendors on required interfaces for the equipment they are supplying.

Obtain equipment size and weight data from the vendors and verify that it is acceptable for the location were the equipment will be installation.

Ensure there or no hazards from steam, water, oil, etc. impinging on the new equipment. Modify impinging source or design shields and barriers if necessary. Ensure proper ventilation is available for the new equipment, and that there are no heat sources, especially those that may currently be off, which will impact the new equipment. Identify obstructions to removal of old equipment and the movement and installation of the new equipment. Modifications, whether permanent or temporary, may be necessary to remove obstructions.

Verify that the installation of equipment, conduits, bus work, supports will not obstruct, block or otherwise interfere with other equipment and other work, including possible work in the future or work that is performed on a long period - such as removal of a large pump motor for overhaul. Also ensure installation will not block access to a pipe or cable chase, prevent vehicle traffic, block a walkway or a ladder, etc. Check with other engineers and designers in other disciplines, and particularly with plant craft supervisors and foremen. The craft supervisor and foremen can provide valuable feedback on work that is, can, and may be performed in the area. It is not unusual to find that one small pipe or conduit had been inadvertently installed so that it blocks a future major work activity.

Ensure that components of the new equipment will be laid out sensibly, with consideration for future activities. Do not unnecessarily take 18 feet of space for a 6 foot panel. If there are no constraints on locating a panel within a given area, leave as much contiguous space as possible for possible future placement of other panels and equipment. Also for conduit and other lines, try to leave as much space as possible and practical for future work. For field run or placed items, specify that space must be used to allow for future installations. Symmetry and appearance are not one of the main goals, but efficient practices should be.

Equipment and components should be inspected upon arrival on site for completeness and for possible damage. Items not being immediately installed should be stored in a dry controlled environment. Manufacturers usually provide short and long term storage requirements which should be followed to maintain condition of the components and to preserve warranties.

Commissioning and Startup Considerations

Plant engineers and technicians should be involved in installation and commissioning of the new excitation equipment. Even if the upgrade or retrofit is being performed as a turn-key project, having plant personnel as observers or inspectors, and assisting the vendor, will provide valuable experience with the new equipment. After the new equipment is installed and commissioned, the plant‘s technician and engineers will have to maintain the equipment and troubleshoot problems. Outside support may be costly and delays could be encountered waiting for the service representative to arrive on site. Though the new digital systems are highly reliable, having plant personnel trained and experienced with the equipment is important in maintaining high reliability and availability.

The new excitation system’s equipment should be assembled and tested at factory to the extent possible. Simulated inputs and outputs will be required, but performing the initial testing and tuning at the factory will help reduce commissioning time and prevent possible trouble during the outage. Have a plant representative witness factory testing and tuning, and also verify compliance with specification. Third party interface modules and other components should be supplied to the vendor to be assembled with the excitation equipment and tested to verify functionality and provide burn-in.

At the factory test, verify the terminal displays for usability and human factors. Verify the different screens, dialog and messages boxes, user commands, help functions, confirmation and other items the plants considers necessary. If the software can be supplied separately to the plant, verification of the software should be performed before the factory tests.

Collect base line vibration, electrical and thermographic data at start-up of the new equipment. Thermography should include new components; such as bridges and panel wiring, transformer connections, brushes and rigging, bus work, etc.

Predictive maintenance tests, such as vibration and thermography should be performed more frequently on the new equipment for the first year of service. Typically these tasks will be performed at the first, second, third, sixth and twelfth month. A plant’s engineers and technicians should determine the actual test schedule based upon their experience and training. The vendor may recommend other tests and a different schedule. The vendors recommendations should be followed; though they can be added to, no vendor recommendations should omitted without the vendor's concurrence.

Realized Costs and Benefits

The costs of the upgrade and retrofit projects vary greatly. The actual costs are determined by scope of the project, the original equipment, the modification performed and the new equipment installed. The cost for a minor component upgrade is minimal, while the cost for retrofitting a brushless exciter with a digital static exciter may run upwards to $3,000,000 (US).

The brushless to static exciter retrofit on average is the most expensive due to need for collector rings, stub shaft, brushing rigging and a collector enclosure which can add $500,000 to $600,000 (US) to the project. Retrofits with digital static exciters were found to cost from $1,500,000 to $3,000,000 regardless of the type of the original exciter. The payback periods for plants that implemented static exciter retrofits were between 4 and 8 years.

The benefits realized were found to be consistent with those expected. These include improved reliability, better efficiency, reduced maintenance and operating costs.

A

GOOD PRACTICES

Table A-1
Good Practices

PRACTICE	DESCRIPTION
1	Assemble and test all components to the extent possible at factory, prior to shipment (FAT – Factory Acceptance Test).
2	Assemble and test all components to the extent possible on site prior to outage (SAT – Site Acceptance Test), this allows for training and helps find equipment infant mortality problems through extended burn-in. The SAT should closely mimic the Factory Acceptance Test.
3	Perform initial tuning of voltage regulator at factory, prior to shipment
4	Coordinate with all vendors on required interfaces between existing and new components, and between components from different vendors
5	Pre-test interface components and software prior to outage. Have third party interface components shipped to AVR/exciter vendor for factory tests.
6	Maintain same crew from start to finish including engineers, technicians and craft personnel.
7	Perform preliminary testing of generator with excitation system vendor.
8	Ensure specifying exact cabinet dimensions, door swings, openings and cable/conduit entry for cabinets and other components.
9	Cost saving may be realized by a one-time purchase for multiple units, as well as having exactly identical equipment in the different units.
10	Complete as much work prior to outage as possible.
11	Specify lay-down areas, assembly areas and work areas for the different activities.
12	Perform a rehearsal walk-through of work to be performed.
13	Incorporate future unit uprate in design.
14	Pre-stage material, equipment and tools.
15	Involve plant technicians as much as possible in project to provide experience with the new equipment.
16	Have plant personnel thoroughly trained by vendor, to include operators, I&C technicians, electricians and engineers.

PRACTICE	DESCRIPTION
17	Specify a proven design, one that has been successfully installed and operated at other power plants.
18	Design in redundancy for all critical components, including redundant power for auxiliaries such as cooling fans.
19	Specify auto-tracking for manual regulator.
20	Do not over specify Power Potential Transformer unnecessarily.
21	Ensure ISO and reliability council’s requirements are met by the design.
22	Layout component sensibly, with consideration for future activities.
23	Ensure sufficient excitation ceiling voltage for degraded terminal voltage.
24	Ensure sufficient power to drive fault for proper breaker coordination.
25	Coordinate with all disciplines from start of project
26	Have vibration modeling done well before outage.
27	Provide for brush polarity swaps at rigging
28	Incorporate auto sync feature
29	Talk with and visit plants that have made similar upgrade.
30	Include PdM tests, whether by plant or vendor in project.
31	Complete modeling before final acceptance of design.
32	Specify an IEEE 421.5 model.
33	Maintain good documentation of project for future reference.
34	Take advantage of built-in limiters, compensators, PSS and other components in digital AVRs and digital exciters.
35	When purchasing a new system, ensure that the range of settings offered is adequate to meet their present and future requirements.
36	With digital systems, specify direct digital storage of calculated terminal voltage, field voltage, field current, real and reactive power and regulator/limiter outputs
37	With digital systems, specify step change and sinusoidal test signals which can be injected throughout the control logic.
38	Specify A/D and D/A interfaces which allow analog signals to be applied as test signals or measured on external recording equipment.
39	Specify adjustable data storage record lengths and sampling rates to accommodate different types of tests.
40	Ensure security of AVR and exciter network connections with password and/or key-lock protection to prevent unauthorized access and software changes. Both remote and local access should be restricted and protected.

PRACTICE	DESCRIPTION
41	Ensure new digital equipment conforms to standard communications protocols accepted by utility.
42	Purchase training simulators from vendor supplying AVR or static exciter to train technicians, operators and engineers.
43	If excitation level and time constant data for the main generator and/or exciter is missing, it is suggested that testing to obtain the missing data is performed prior to finalizing the specification for the excitation system upgrade retrofit. Preliminary discussions with similar plants and possibly prospective vendors, prior to finalizing the specification, may help determine if testing will be necessary or beneficial for vendors to submit proposals for a specific update or retrofit.
44	An AC field breaker typically has advantages over a DC breaker, including less contact wear and more availability of parts. Specify an AC breaker at input to power bridge instead of a DC field breaker.
45	A shaft voltage suppressor should be used to avert bearing damage form high frequency electrical harmonics from SCR power bridges.

B
LESSONS LEARNED

The following table consists of "lessons learned" from utilities who have successfully implemented an excitation system upgrade or retrofit. Some of the "lessons learned" may duplicate "best practices" provided by other utilities in Appendix A.

Table B-1
Lessons Learned

LESSON	DESCRIPTION
1	Redundancy is needed for all critical components, including power for auxiliaries such as cooling fans.
2	Verify proposed design against specification. If there are details missing in the proposed equipment specification, seek clarification from vendor.
3	Verify interfaces are compatible with existing circuits. Verify signal levels, polarities and ground references.
4	Design equipment modifications as needed prior to outage. Identify and design modifications needed for both existing and new circuits and components to the extent possible, prior to installation.
5	Train plant personnel on set-up, testing and maintenance of new system and components prior to placing new system in service. Costly vendor support may be needed if plant personnel are not trained to maintain equipment.
6	Have plant personnel involved in commissioning and tuning. Even if vendor is to perform set up commissioning, plant technicians and engineers need to be involved in process to gain experience and understanding of the new system.
7	For multiple units have plant personnel learn to commission and tune system from involvement in first unit.
8	Have plant personnel who are knowledgeable on the system and trained to troubleshoot and repair the new equipment.
9	Ensure the proper interfaces on new equipment; ensure that all vendors involved with project use a common standard interface and the same nomenclature. Interfaces and nomenclature should conform to plant specifications.
10	Be aware of differences in nomenclature when comparing equipment from different vendors. In their proposals different vendors may use different nomenclature; this may add difficulty in evaluating the proposal. Ensure vendor conform to plant specified nomenclature in the supplied system and components.
11	Hardware and software trouble in digital regulators and exciters can exhibit unexpected symptoms that may not be diagnosed using familiar analog systems troubleshooting techniques and experience.

LESSON	DESCRIPTION
12	Self diagnostics of digital systems will not identify all problems that occur in the excitation system. Though greatly useful, the self diagnostics of a digital AVR or exciter may not cover the auxiliary components and circuits of the excitation system.
13	In purchasing a new system, ensure that all current and future needs are satisfied by the vendor's proposal.
14	Ensure the new AVR or exciter has a transfer function that corresponds to an IEEE 421.5 model
15	Ensure vendor documents limits on AVR or exciter settings.
16	Ensure vendor documents accuracy of the exciter model for the entire range of settings and operational frequencies. Any differences between the IEEE model and real-life performance of the exciter should be documented as well.
17	Ensure vendor utilizes ergonomics, human factors in the design of the system and equipment. This should include the use of engineering units (V, A, MVar, etc.) for data values.
18	Have familiar, industry-accepted nomenclature and acronyms used in operators' and technicians' interfaces.
19	Ensure functions and tasks given on local and remote interfaces to the AVR or exciter are clear, user-friendly and readily understood. Have actual operators and technicians verify control and maintenance interfaces
20	Review software to ensure suitability. Review design of user screens, boxes, error messages, help screens, system messages, verifications, alarms, warnings and other aspects of the user interface.
21	Ensure equipment is supplied with a design that has all the required built-in diagnostics, test and tuning features and data-logging capabilities.
22	Test model's transfer function using an analog input signal and verify the analog output response.
23	Verify and document the wiring configuration prior to issuing specification to ensure that wiring changes do not need to be included.
24	Ascertain condition of wiring and equipment prior to issuing specification to ensure that wiring replacement or equipment repairs do not have to be included.
25	Ensure proper fit and mounting of new equipment and interfaces prior to actual installation. Allow sufficient time in case modification to new equipment or mounting adapters have to be made.
26	Coordinate regulator limiter settings with unit protective relaying during commissioning.
27	Ensure equipment is shipped in the required sections and is delivered on trucks compatible with the receiving location.
28	Ensure the riggers who will be handling and setting the new equipment understand the sensitive and delicate nature of the equipment.
29	Ensure adequate cooling is provided to all equipment and cabinets, especially with micro-processor based systems.

C
CONTRIBUTORS

The following manufacturers and excitation system equipment and service providers have contributed to this report. Their time and resources provided for completion of this report, along with that of the power plants that have also contributed to this report, are of much benefit to the electric utility industry.

- Basler Electric Company – www.basler.com
- E Squared Power Systems, Inc – www.e2psi.com
- ElectroMechanical Engineering Associates (EME) - www.emeassociates.com
- Excitation System Services, Inc - www.excitationservices.com
- Siemens Power Generation, Inc (formerly Siemens-Westinghouse) - www.powergeneration.siemens.com

The following power plants have contributed to this report regarding excitation system upgrades and retrofits for the benefit of the electric utility industry.

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- IPL - Petersburg Unit 2, AES
- IPL - Petersburg Unit 3, AES
- IPL - Petersburg Unit 4, AES
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- Edwards Unit 3, Ameren
- Rush Island Unit 2, Ameren
- Rush Island Unit 1, Ameren UE
- D. C. Cook Unit 1, American Electric Power
- D. C. Cook Unit 2, American Electric Power
- Cholla unit 2, Arizona Public Service Company
- Laramie River Unit 1, Basin Electric
- B.C. Cobb 4, Consumers Energy
- B.C. Cobb 5, Consumers Energy
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- J.C. Weadock 8 , Consumers Energy
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- Wallerawang Power Station, Delta Electricity
- Salem Harbor Station 1, Dominion
- Salem Harbor Station 2, Dominion
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- Millstone Unit 3, Dominion Nuclear Connecticut
- Catawba, Duke Power
- Baldwin Energy Complex Unit 1, Dynegy Midwest Generation
- Baldwin Energy Complex Unit 2, Dynegy Midwest Generation
- Baldwin Energy Complex Unit 3, Dynegy Midwest Generation
- Havana Power Station Unit 6, Dynegy Midwest Generation
- Arkansas Nuclear One, Entergy
- Seabrook, FPL Energy
- Huntly Power Station , Genesis Energy
- Coal Creek Station, Great River Energy
- Intermountain, Intermountain Power
- Gentleman Station Unit 1, Nebraska Public Power District
- Gentleman Station Unit 2, Nebraska Public Power District
- St. Lawrence - FDR Power Project, NYPA
- Rawhide Energy Station, Platte River Power Authority
- Boundary Dam Power Station Unit 3, SaskPower
- Boundary Dam Power Station Unit 4, SaskPower
- Boundary Dam Power Station Unit 5, SaskPower
- VC Summer, South Carolina Electric & Gas
- Plant Vogtle Unit 1, Southern Company
- Plant Vogtle Unit 2, Southern Company

- Hatch Unit 1, Southern Nuclear
- Hatch Unit 2, Southern Nuclear
- CORONADO Unit 1, SRP
- T. H. Wharton, Texas Genco
- Craig Station, Tri-State Generation and Transmission Association
- Browns Ferry Unit 2, TVA
- Browns Ferry Unit 3, TVA
- Sequoyah Unit 1, TVA
- Sequoyah Unit 2, TVA
- Watts Bar Nuclear, TVA
- Torrens Island Power Station, TXU Australia
- Big Brown Unit 1, TXU ENERGY
- Martin Lake Unit 1, TXU ENERGY
- Martin Lake Unit 2, TXU ENERGY
- Monticello Unit 2, TXU ENERGY
- North Lake Unit 1, TXU ENERGY
- North Lake Unit 3, TXU ENERGY
- North Main Unit 4, TXU Energy
- Parkdale Unit 1, TXU ENERGY
- Stryker Creek Unit 1, TXU ENERGY
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- Blue Lake 2, Xcel Energy - North Region
- Blue Lake 3, Xcel Energy - North Region
- Blue Lake 4, Xcel Energy - North Region
- Hennepin Island 1, Xcel Energy - North Region
- Hennepin Island 2, Xcel Energy - North Region
- Hennepin Island 3, Xcel Energy - North Region
- Hennepin Island 4, Xcel Energy - North Region
- High Bridge 5, Xcel Energy - North Region

- High Bridge 6, Xcel Energy - North Region
- Inver Hills 1, Xcel Energy - North Region
- Inver Hills 2, Xcel Energy - North Region
- Inver Hills 3, Xcel Energy - North Region
- Inver Hills 4, Xcel Energy - North Region
- Inver Hills 5, Xcel Energy - North Region
- Inver Hills 6, Xcel Energy - North Region
- Riverside 8, Xcel Energy - North Region
- West Faribault 2, Xcel Energy - North Region
- West Faribault 3, Xcel Energy - North Region
- Wilmarth 1, Xcel Energy - North Region
- Wilmarth 2, Xcel Energy - North Region

D
RELIABILITY COUNCIL REQUIREMENTS

The following were extracted from actual or proposed requirements of several reliability councils in the U.S. These extracts do not cover all the requirements of every reliability council, and are mostly minimum requirement for connecting the main generator to the power grid. Typically an existing plant will not have to comply with a requirement that would necessitate an equipment modification. New plants and those existing plant performing an excitation system upgrade typically have to comply with all the requirements.

- All synchronous generators shall have excitation systems with continuously acting automatic voltage regulators.
- The main generator's excitation shall be controlled by the automatic voltage regulator at all times when connected to the power grid Exceptions to this rule are for: Maintenance and testing; and during failure of the automatic voltage regulator, provided repairs or replacement are proceeding in a timely manner.
- A high initial response excitation system, as defined in the current revision of IEEE 421.1 (reference 3), shall be installed on new generators rated at or greater than 30 MVA. Existing generators will comply with this requirement upon replacement of the main exciter.
- The new excitation systems shall have a ceiling voltage of at least 150 percent of the rated generator field voltage when a system disturbance results in 70% of rated generator terminal voltage. Existing generators will comply with this requirement upon replacement of the excitation system. If an existing excitation system is upgraded, but the main exciter is retained, the ceiling voltage shall be at least the previous level with a system disturbance resulting in 70% of rated generator terminal voltage.
- The excitation system shall be capable of producing an output current no less than the main generator field winding's short time thermal overload capability.
- The automatic voltage regulator shall maintain the main generators terminal voltage between 0.5 percent above and below the set point during normal operation.

E
REFERENCES

The following are end notes which are references specifically called out in the text of this report.

1. IEEE 421.4-1990, "Guide for the Preparation of Excitation System Specifications"
2. ANSI C37.18-1979, "IEEE Standard Enclosed Field Discharge Circuit Breaker for Rotating Machinery. Rev C, January 1996"
3. IEEE 421.1-1986, "Standard Definitions for Excitation Systems for Synchronous Machines"
4. IEEE 421.2-1990, "Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems"
5. IEEE 421.3-1997, "Standard for High-Potential Test Requirements for Excitation Systems for Synchronous Machines"
6. IEEE 421.5-1992, "Recommended Practice for Excitation System Models for Power System Stability Studies"
7. EPRI Report 1004556, "Tools To Optimize Maintenance of Generator-Excitation System, Voltage Regulator and Field Ground Protection"
8. NFPA 70E, "Standard for Electrical Safety in the Workplace"
9. IEEE 1046-1991 "IEEE Application Guide for Distributed Digital Control and Monitoring for Power Plants"
10. IEEE 399-1997, "Recommended Practice for Power Systems Analysis - Brown Book"

The following are general references not called out in the text of this report, but which may be of benefit to the reader considering an excitation system upgrade or retrofit.

11. EPRI CD 1006780, "Guidelines for Reducing the Time and Cost of Turbine Generator Maintenance Overhauls and Inspections. Repair Procedures"
12. EPRI NP-7502, "Electric Motor Predictive and Preventive Maintenance Guide"
13. EPRI Power Plant Electrical Reference Series, Volume 1, "Electrical Generators"
14. EPRI Power Plant Electrical Reference Series, Volume 2, "Power Transformers"
15. EPRI Power Plant Electrical Reference Series Volume 16, "Handbook to Assess the Insulation Condition of Large Rotating Machines"
16. EPRI TR-101140 "Adjustable Speed Drives Applications Guide"

17. IEC 60276, "Definitions and Nomenclature for Carbon Brushes, Brush-Holders, Commutators and Slip-Rings"
18. IEEE 43-2000, "Recommended Practice for Testing Insulation Resistance of Rotating Machinery"
19. IEEE 67-1990, "Guide for Operation and Maintenance of Turbine Generators"
20. IEEE 95-2002, "Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and Above) with High Direct Voltage"
21. IEEE 115-1995, "Guide: Test Procedures for Synchronous Machines Part I-Acceptance and Performance Testing Part II-Test Procedures and Parameter Determination for Dynamic Analysis"
22. IEEE 118-1978, "Standard Test Code for Resistance Measurement"
23. IEEE 500-1984 "Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations"
24. IEEE 519-1992, "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"
25. IEEE C37.102-1993, "Guide for AC Generator Protection"
26. IEEE C57.13-1993, "Standard Requirements for Instrument Transformers"
27. IEEE C57.13.1-1981, "Guide for Field Testing of Relaying Current Transformers"
28. NEMA CB 1, "Brushes for Electrical Machines"
29. Reactor Operational Experience Results and Databases http://nrcoe.inel.gov/
30. EPRI Report 1011679 "Steam Turbine-Generator Torsional Vibration Interaction with the Electrical Network: Tutorial"

F
GLOSSARY

AC Regulator - *see* Automatic Voltage Regulator.

AVR - *see* Automatic Voltage Regulator.

Alternator - an AC generator, typically refers to small AC generator used to supply excitation power to the main generator field.

Amplidyne - *see* Rotating Amplifier.

Armature - the AC windings of a generator or motor.

Automatic Generation Control - the system that allows a load dispatcher or other party to control generation at a plant from a remote location.

Automatic Voltage Regulator - controls main generator field current to produce the required generator output.

Brush - typically a carbon based block used to transfer electrical current between the stationary and rotating components of a generator. Also *see* collector and commutator.

Brush Pressure - the pressure on a brush that forces the brush against the rotating collector or commutator to maintain electrical contact. Equal to the spring force applied to the brush divided by the brush's cross-sectional area.

Brushless Excitation System - an excitation system that employs an alternator with a stationary field and a rotating armature, so brushes are not required to contact the alternator's output to the generator's rotating field. Shaft mounted diodes rectify alternator's output to DC for the generator field.

CBA - *see* Cost Benefit Analysis.

CT - *see* Current Transformer.

Collector - a component in many generators and alternators for transferring current between stationary and rotating elements. The collector consists of rotating slip rings and stationary brushes that provide low mechanical friction and low electrical resistance.

Commutator - a component of DC generators and motors that transfers current to and from the rotating armature. The commutator in generators converts the AC armature current to a DC output current, and in motors converts the applied DC current to an AC current for the armature.

Controlled Rectifier - a component that converts an AC voltage to a DC voltage, and controls the level of DC by varying the conduction time (firing angle) of each applied AC cycle.

Cost Benefit Analysis - the process of determining the net economical results of implementing a particular maintenance task or plan.

Crowbar - a component used to limit the voltage across the field winding. Works by conducting at a set voltage value to bleed off current through a discharge resistor.

Current Density - the number of amperes of current through a specific cross sectional area.

Current Transformer - an instrument transformer used to accurately measure current flow. Typically selected to operate in a range of 0 to 5 amps of secondary current for the entire range of primary current.

DC Voltage Regulator - *see* Manual Voltage Regulator.

Dynamic Testing - a test performed while the component and system are in service and under load.

EPRI - Electric Power Research Institute.

Excitation Transformer - *see* Power Potential Transformer

Exciter - the alternator or DC generator that supplies the electrical power for the excitation system to produce the main generator's field current. Generally, any component that supplies the electrical power to produce the main generator's field current.

Field - the DC winding of a generator; produces the magnetic field for generator excitation.

Field Breaker - a DC circuit breaker that interrupts the field circuit of a generator or exciter.

Field Discharge Resistor - a resistor that is applied across the generator's field circuit to rapidly de-energize the field winding during a generator trip.

Field Flashing - a momentary application of DC current to an exciter field to provide initial excitation to an exciter during startup.

IEEE - Institute of Electrical and Electronics Engineers.

IRT - Infrared Thermography, *see* Thermography.

Insulation Resistance Test - an electrical test that assesses the condition of electrical insulation by applying a fixed DC voltage across the insulation.

Intangible Benefits - in cost benefit analysis, the benefits that do not have an obvious monetary value, such as regulatory compliance and personnel safety.

Interturn Short - an electrical short between adjacent turns of a winding.

Leakage Current - the surface current flowing from the insulation, which is constant over time. Insulation damage, defects, moisture, and other conductive contaminants can greatly increase the leakage.

Limiter - a component or circuit that functions to prevent the system from operating in a prohibited mode.

Manual Voltage Regulator - controls and maintains main generator field current at a specified value.

Maximum Excitation Limiter - prevents the excitation system from causing the generator to operate in the over-excited mode. May permit some over-excited operation for short durations for transient response.

MEL - *see* Maximum Excitation Limiter.

Minimum Excitation Limiter - prevents the excitation system from causing the generator to operate in the under excited mode.

Motor Operated Potentiometer - a potentiometer that is adjusted by an electric motor to allow remote operation from the control room.

MXL - *see* Maximum Excitation Limiter.

NEMA - National Electrical Manufacturers Association.

NMAC - Nuclear Maintenance Application Center, organization established by EPRI in 1988 as part of the general industry effort to improve plant maintenance.

Noncontrolled Rectifier - a component consisting of diodes that rectifies AC voltage into DC voltage, does not control the level of DC voltage. Also see Controlled Rectifier.

Null Voltmeter - a voltmeter that measures the difference between two voltages. Typically used to ensure that the outputs of the automatic and manual regulators are equal.

OEL - Over Excitation Limiter, *see* Maximum Excitation Limiter.

OEM - Original Equipment Manufacturer.

Ohm's Law - the relationship between voltage, current, and resistance: voltage across a component is equal to the current flow through the component multiplied by the resistance of component (V=IR).

Open Loop Test - a component functional test that is performed without normal system feedback.

Over Excitation - the generator operational mode in which too much field current is applied. Causes the generator to operate above its design limits.

PdM - *see* Predictive Maintenance.

PM - *see* Preventive Maintenance.

PMG - *see* Permanent Magnet Generator.

PSS - *see* Power System Stabilizer.

PT - Potential Transformer.

Pilot Exciter - a small alternator or DC generator used to produce excitation power for the main exciter.

Permanent Magnet Generator - a pilot exciter that uses permanent magnets to supply its excitation field, instead of relying on a field winding and an external power source.

Potentiometer - a continuously variable resistor.

Power Potential Transformer - a power transformer that supplies the electrical power for the excitation system to produce the main generator's field current.

Power System Stabilizer - a component or circuit that automatically alters voltage regulator output to oppose power system oscillations.

PPT - *see* Power Potential Transformer

Predictive Maintenance - test and inspection techniques and technologies that are performed to assess component condition and predict possible future failure or malfunction of the component. The intent of predictive maintenance is to forewarn equipment deterioration early enough that corrective actions can be planned and implemented prior to an actual failure or malfunction.

Preventive or Preventative Maintenance - time-based maintenance tasks that are performed to prevent malfunction or failure of a system or component, prior to any actual indication of trouble.

Regulatory Testing - testing and calibration required or strongly recommended by regulatory agencies, reliability councils, insurers, manufacturers, etc.

Rheostat - a continuously variable electrical resistor used to regulate current.

Rotating Amplifier - a rotating machine similar to a DC generator, except the brushes are shorted together, and a second set of brushes are added at the location where output from the resultant armature reaction field produces a large current. Produces a large current that is controlled by a relatively small field voltage.

Rotor - the rotating element of a generator or motor.

SCR - *see* Silicone Control Rectifier.

Silicone Control Rectifier - a semiconductor, similar to a diode except that it has to be electrically turned on (gated) to conduct. Used to control level of DC voltage produced from an AC voltage, *see* Controlled Rectifier.

Stator - the non-rotating magnetic core of a generator or motor.

Thermography - the science and technique of obtaining and analyzing thermal images of components.

Torsional Vibration - oscillations in the rotational speed of a component.

UEL - Under Excitation Limiter or minimum excitation limiter.

Under Excitation - the generator operational mode in which too little field current is applied. Causes the generator to operate beyond its lower design limits. May cause generator to slip out of synchronism.

URAL - Underexcited Reactive Ampere Limiter or minimum excitation limiter.

Vibration Analysis - the techniques and technology for collecting and analyzing vibration data. Used not only to determine if accepted vibration limits are exceeded, but also to determine the location and cause of vibration problems.

Vibration Monitoring - routine monitoring of vibration levels of a component to determine if acceptable levels are exceeded or if an adverse trend is developing.

Volt per Hertz - the ratio of voltage to frequency. If frequency decreases, the voltage must decrease proportionally to avoid saturating and overheating the magnetic core in generators and transformers.

Voltage Regulator - a component that controls the field current to the generator. *See* Automatic Regulator and Manual Regulator.

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