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RETROFITTING ADJUSTABLE SPEED DRIVES FOR LARGE INDUCTION MOTORS

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INTRODUCTION

Adjustable speed drives (ASDs) are used in many power plants to control process flow by varying the speed of synchronous and induction motors. In applications where the flow requirements vary significantly, ASDs reduce energy and maintenance requirements when compared with drag valves, dampers or other methods to control flow. Until recently, high horsepower ASDs were not available for induction motors. However, advances in power electronics technology have demonstrated the reliability and cost effectiveness of ASDs for large horsepower induction motors.

Emphasis on reducing operation and maintenance costs and increasing the capacity factor of nuclear power plants has led some utilities to consider replacing flow control devices in systems powered by large induction motors with ASDs. ASDs provide a high degree of reliability and significant energy savings in situations where full flow operation is not needed for a substantial part of the time. This paper describes the basic adjustable speed drive technologies available for large induction motor applications, ASD operating experience and retrofitting ASDs to replace the existing GE Boiling Water Reactor recirculation flow control system.

ADJUSTABLE SPEED DRIVES

ASDs use sophisticated solid-state electronics including diodes, transistors and silicon-controlled rectifiers (SCRs) or thyristors to change a constant frequency and voltage AC source input to a variable frequency and voltage AC output. All ASDs start out with an AC to DC converter followed by a DC link and then a DC to AC inverter.

The basic AC to DC converter has an arrangement of thyristors for the positive and negative portions of the input AC sine wave for each of the three phases. One switch or commutation is needed to rectify the AC power to DC, or 6 in all. This type of rectification is referred to as 6-pulse input. Each commutation produces stray harmonics that can inject into the source AC bus. Input transformers are usually used to reduce these harmonics. However, if the transmitted harmonics have an adverse effect on the supply bus, two solutions can be applied. The first is to provide a 12-pulse input that consists of two 6-pulse bridges connected in series so that two of the harmonics generated in one commutation are canceled. The second approach is to add a filter to the input source bus to absorb the unwanted signals.

Power between the converter and the inverter sections of the ASD is transferred by means of a DC link. This link acts as a power bridge between the two sections in the form of current or voltage, depending on the drive technology. If the DC link includes a capacitor, then it is acting as a voltage source where the capacitor smoothes the DC voltage and keeps it at the desired level. If the DC link includes an inductor in its circuit, the DC link smoothes the DC current to the inverter.

Thyristors are also used in the inverter to convert the DC signal to a variable frequency AC signal. There are two common types of AC drive inverters, current source inverters (CSI) and voltage source inverters (VSI). A VSI controls the voltage and frequency to the motor and a CSI controls the current. A VSI continually "forces" a wave form on the motor while a CSI senses the motor speed and changes its current output which helps steer the motor to the desired new speed.

CSI inverters are usually used for high horsepower and voltage motors since the large DC link inductor limits the fault current to the inverter and misfiring of the inverter power devices does not result in shutdown. The inverter, like the AC to DC converter, produces harmonics that can be fed to the motor. If the motor is not specifically designed for the ASD application, these harmonics can increase motor heating and may produce motor shaft, coupling or frame mechanical fatigue. For induction motor retrofits, capacitors are usually applied across the CSI output to filter the CSI harmonics and avoid derating the motor due to harmonic heating. However, these filters in parallel with the motor inductance create a L-C circuit with a resonance frequency that can be excited by the CSI harmonics. If this resonance frequency is present, harmonic currents can be amplified five to ten times. To eliminate this concern, three approaches can be used. The first is to produce a 12-pulse output by using two 6 pulse bridges. This approach eliminates the need for a filter but the additional bridge increases the cost of the ASD. The second approach uses Gate Turn-Off (GTO) thyristors to switch current on or off at any time during a cycle. This allows the inverter current wave form to be notched in specific patterns to eliminate selected harmonic currents. During acceleration, deceleration and continuous operation on or through these resonant conditions, the ASD control system turns the GTOs on or off at the time required to eliminate the harmonic currents. The third approach is to add inductors or transformers to the output to avoid these frequencies.

ASDs can be combined in many system configurations to provide the redundancy and horsepower required. Three ASD configurations are shown in Figure 1. The first configuration uses a bypass to allow continued operation if the ASD should require maintenance. The second configuration adds a spare ASD for redundancy. The last configuration uses two ASDs in parallel to supply the required load. This configuration allows low speed operation using one ASD if needed. A detailed 12-pulse input GTO ASD induction motor application is shown in Figure 2. Figure 3 shows the voltage and current outputs to the motor for a GTO induction motor ASD.

OPERATING EXPERIENCE

The US Electric Power Research Institute (EPRI) recognized the potential fuel conservation and reliability benefits associated with conversion of large constant speed induction motor applications to adjustable speed and initiated a program to evaluate ASD retrofits to existing induction motors. A field test program was initiated by EPRI in 1984 and completed in 1989 to evaluate ASD induction motor applications. This program developed guidance on ASD retrofit configurations, evaluated their economic and operational benefits, and gathered data concerning the impact of the ASDs on the electrical distribution systems (Ref. 1). The field test program included evaluation of ASDs that were installed in gas, oil, and coal fired plants for control of 2000 to 6300 horsepower boiler feed pumps and 5000 horsepower forced draft fans. The program verified the reliability of large ASDs and their potential for realizing operating cost savings. The following ASD features were recommended based on the field test program :

1. An input transformer to control converter harmonics and line to ground voltage at the motor.
2. An uninterruptible power supply (UPS) for the control system to eliminate adverse ASD performance effects due to line voltage spikes, dips, and interruptions.
3. Water cooled thyristors to simplify cooling of the ASD and provide more effective heat removal.
4. A ground between the inverter and motor to control line-to-neutral voltage at the motor.
5. Means to prevent resonance between the output filter capacitor and the motor.

The EPRI report also details the economics of each field test program ASD application and offers advice on how to calculate ASD benefits and implement a successful ASD retrofit. The most significant application issues identified by EPRI are the ASD input harmonics to the plant grid and the output harmonics to the motor. High total harmonic distortion (THD) levels transmitted to the plant grid can affect other equipment tied to the grid. Consequently, it is important to evaluate the grid and the effects that the ASD will introduce. An input transformer combined with filters or a 12-pulse input may be needed to reduce the THD to acceptable levels (e.g. Ref. 2). The output harmonics can cause eddy current heating of the motor windings and the torque pulsations can lead to shaft and frame vibration.

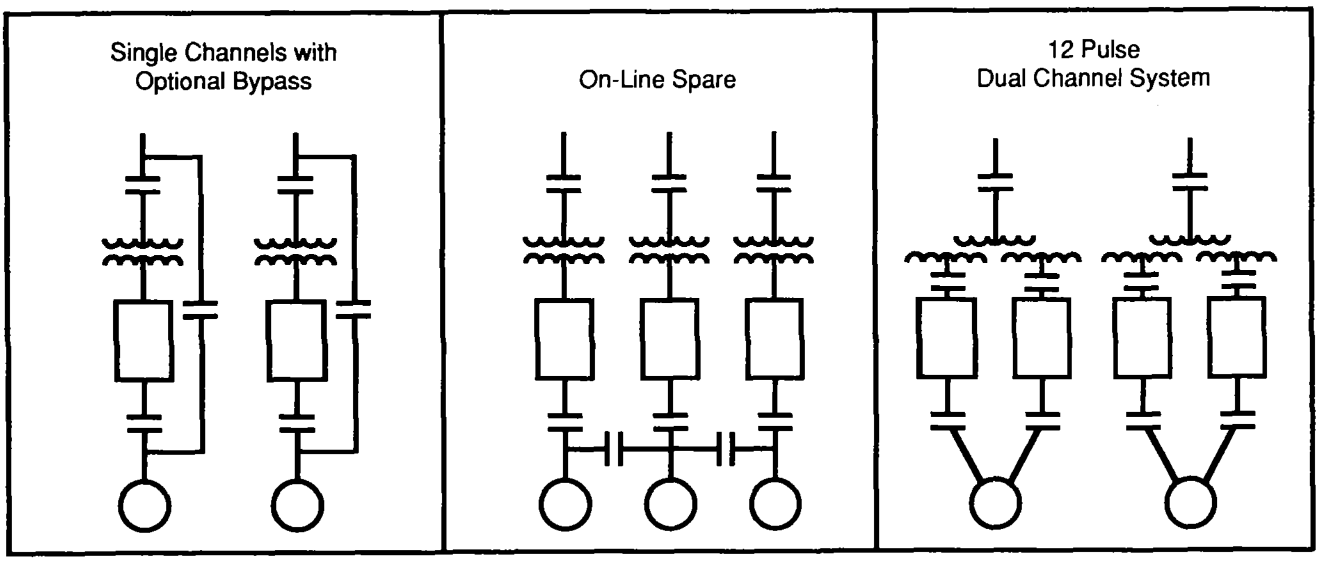

Figure 1. ASD System Configurations

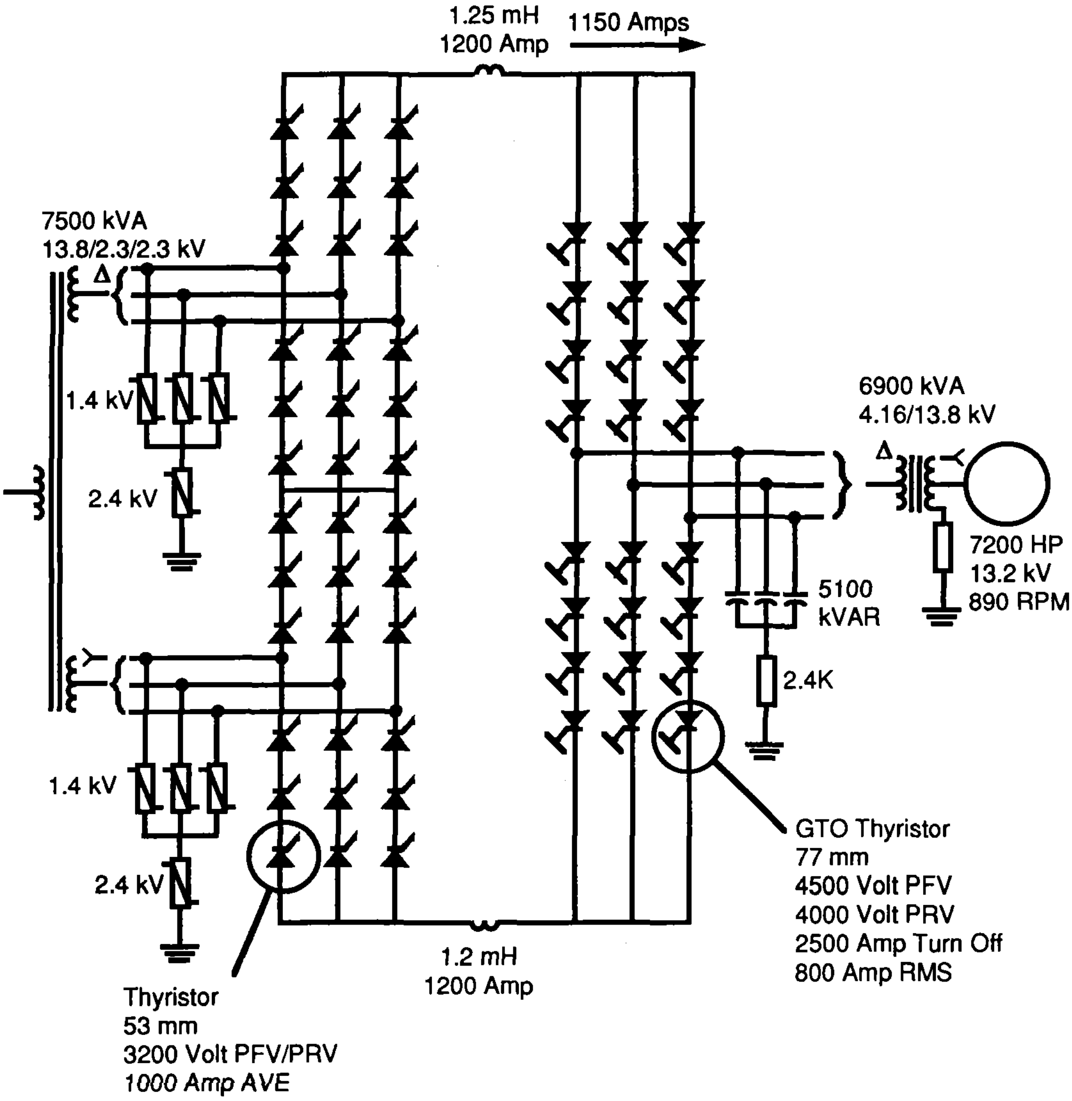

Figure 2. ASD Application (GTO)

BOILING WATER REACTOR RECIRCULATION SYSTEM APPLICATION

ASDs can be applied to systems in the Balance of Plant and Nuclear Steam Supply Systems (NSSS) of Boiling Water Reactors (BWRs). The primary NSSS applications being considered are the Reactor Recirculation System (RRS), to replace the existing flow control system, and the Residual Heat Removal System, to improve flow control during shutdown cooling and suppression pool cooling operation.

Most GE BWRs control recirculation flow by either a Flow Control Valve (FCV) or by varying motor speed using a Motor Generator (MG) set. Two typical configurations are shown in Figures 4 and 5. The recirculation pumps vary cooling flow through the reactor core and therefore change reactor power level. Consequently, recirculation flow control can be used to load follow and to avoid scrams by rapidly reducing power level during some operating transients. Flow control system transients are also analyzed in the Safety Analysis Report to assure that they do not cause unacceptable changes in reactor power.

MG Sets are used in the GE BWR 2, 3 and 4 product lines. A fluid coupler, located between the motor and generator, provides the slip needed to vary the speed of the generator which produces the variable frequency and voltage output to the induction motor. The motor and pump are located inside the primary containment and the MG Set is usually located outside both the primary and secondary containment. The motor and generator are air cooled. A water-to-oil heat exchanger in the oil circulation system removes the heat generated within the fluid coupler. A typical MG Set configuration is shown in Figure 4.

FCVs are used in the GE BWR 5 and 6 product lines. The pump motor operates at either 100% speed, using line voltage and frequency, or 25% speed using a low frequency motor generator (LFMG) set. The LFMG set is used during low power operation, heatup and cooldown since the net

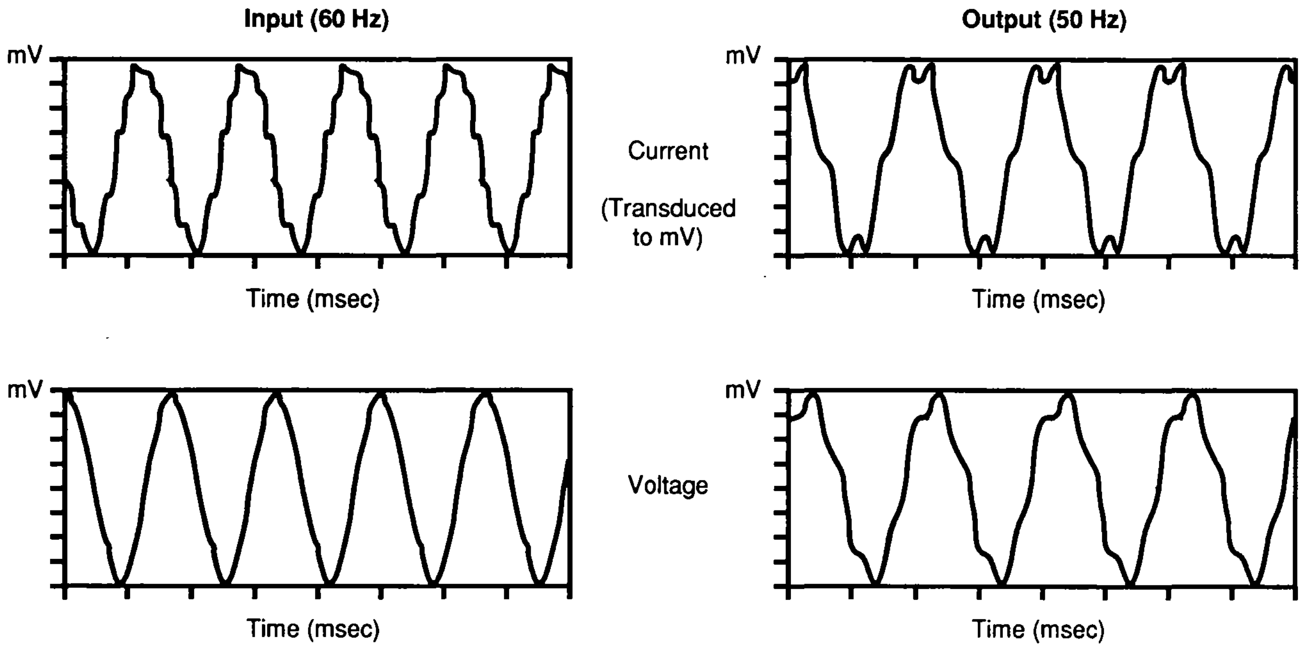

Figure 3. Voltage and Current GTO Inputs and Outputs

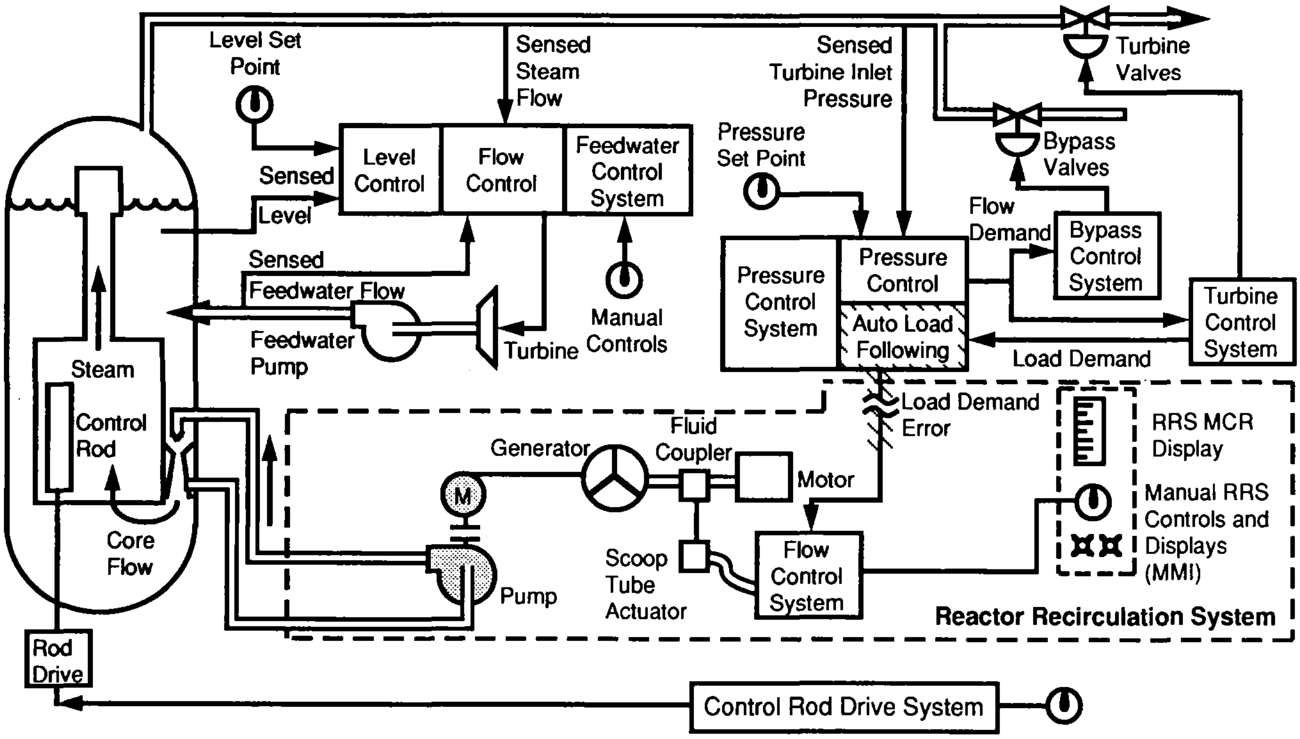

Figure 4. BWR 3/4 MG Set Configuration

positive suction head available in these conditions is not sufficient to avoid cavitation in the FCV. The motor, pump, FCV and its hydraulic operator are located inside the primary containment. A hydraulic power unit (HPU) is located outside the primary containment and controls the hydraulic fluid flow to the actuator. The HPU is in turn controlled by a microprocessor based system that senses various parameters such as FCV position, actuator position, and recirculation pump flow to produce the desired flow. A typical FCV configuration is shown in Figure 5.

Most cost effective ASD retrofit applications involve systems that must be operated at less than their design load for significant periods of time. The BWR RRS is such a system.

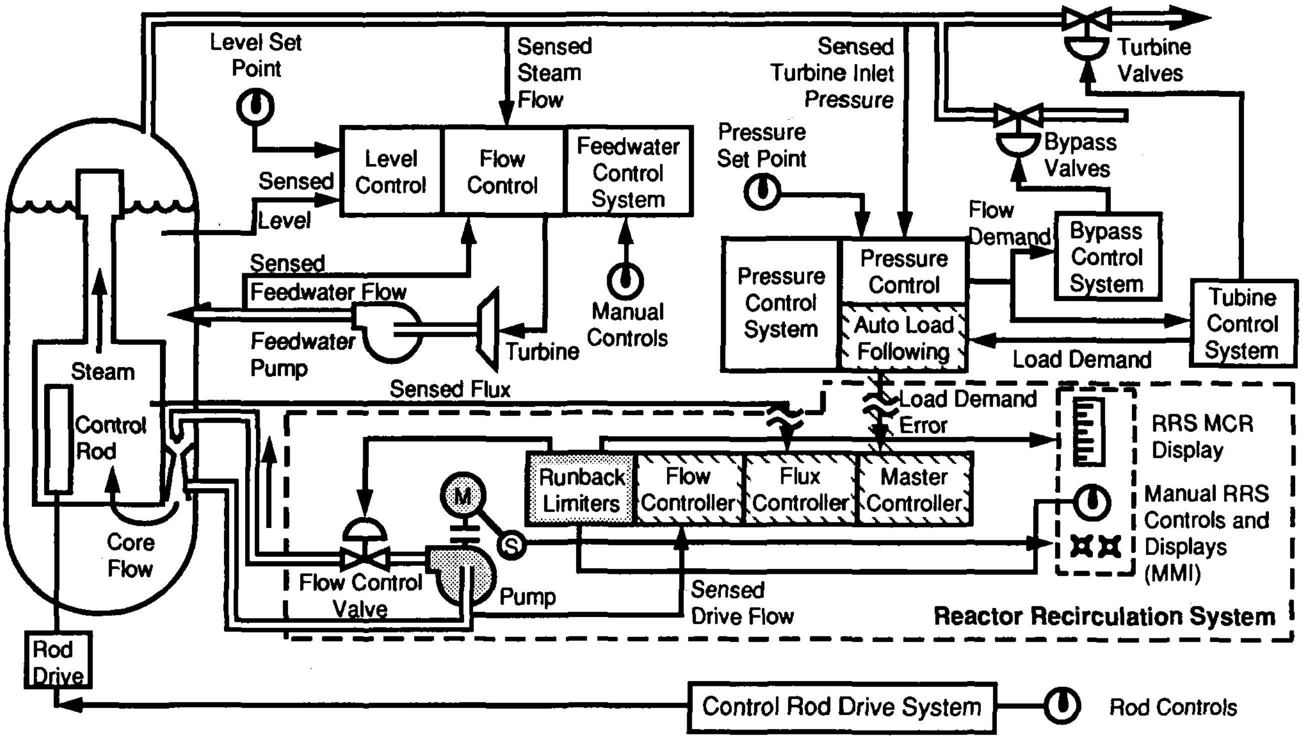

Figure 5. BWR 5/6 Flow Control Valve Configuration

To maximize the fuel cycle, BWRs are usually operated at 100% power at low core flow at the beginning of the cycle and at maximum core flow at the end of the cycle. The core flow range can vary from 75% to 85% at the beginning to 105% to 110% at the end of the cycle. Since a significant part of the input energy is wasted across the FCVs and in the MG Set fluid couplers during operation at low core flows, applications of ASDs to replace the FCV and MG Set systems are being considered. Current industry incentives to reduce fuel, operation and maintenance costs, maximize plant capacity factor and reduce exposure to personnel also contribute to ASD benefits. Some of the other factors that are considered in evaluation of ASDs are :

1. Reliability and Maintenance Frequency
   The current flow control systems, FCVs, HPUs and MG Sets have contributed to forced outages due to failures. Low power operation also occurs when it is necessary to shut down one recirculation loop for maintenance. ASDs have high reliability and require infrequent maintenance.
2. Location of Equipment
   Monitoring RRS FCV performance and diagnosing problems during operation must be performed using the sensors available inside the containment. Radiation exposure to maintenance and in service inspection personnel during outages is also significant for these plants. The ASDs, like the MG Sets, can be located outside both the primary and secondary containment.
3. Fluid Leaks
   Fluid coupler oil leaks present a significant fire hazard due to the high temperature of the oil. The HPU hydraulic fluid has a high flash point but leaks inside the containment are likely to spray adjacent equipment and create messy cleanup efforts. Both fluids must be periodically replaced and are considered hazardous wastes.
4. Self Diagnostic Capabilities
   The MG Set equipment generally has limited instrumentation. Diagnosis of the cause of system trips due to spurious electrical problems is based on the experience of the maintenance personnel. In some cases, it has taken several trips to find the source of the problem.
5. Motor Lifetime
   Both the FCV and MG Set systems use full voltage to start the pump motors. The thermal and mechanical surges created by the high inrush currents decrease motor lifetime. An ASD can start the motor at current levels of 100% or less versus the 500% to 700% levels encountered during across the line starting. This is usually referred to as the ASD "soft start" capability. For FCV plants, operation at lower speeds will also extend motor lifetime.

Once the economies have been studied and determined to be favorable, it is necessary to assure that there are no adverse affects to the existing equipment. Analyses of the electrical grid and NSSS components are needed to assure the installation will be acceptable. The grid analyses are needed to assure that the harmonics created by the ASD are acceptable. If not, mitigation devices are designed to reduce these harmonics to acceptable levels. The recirculation pump motor, pump, piping and reactor internals must also be evaluated to assure that ASD does not cause excessive heating of the motor windings and the torque pulsations do not adversely affect the motor, pump, piping and reactor internals.

The reactor internals respond to the pressure pulses generated by the centrifugal pump blades as they pass the pump cutwater. FCV plants are only analyzed for 25% and 100% speed blade passing frequencies. These pressure waves are transmitted down the suction and discharge piping to the reactor vessel. Application of an ASD allows operation at blade passing frequencies between 25% and 100% speed. A blade passing frequency in this range may excite reactor internals and require additional vibration mitigation modifications in addition to the ASD modification. The torque pulsations transmitted to the pump may also result in pressure pulses that must be evaluated.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM WNP-2 RETROFIT

The 1150 megawatt (MW) WNP-2 nuclear plant is the first ASD retrofit project for a BWR-5 recirculation system. The WNP-2 RRS has two recirculation loops with a 8900 HP, 6.9 kV induction motor, centrifugal pump and FCV in each loop.

The hard motor starts and the vibration inherent during partial flow operation of the RRS resulted in an inordinate amount of on-going system maintenance at WNP-2. In 1985, the plant experienced a failure of one of the pumps due in part to system vibration. The repairs, implemented in both coolant loops sequentially, forced the plant into single-loop operation for 19 months. The huge loss of revenue and the repair costs inspired WNP-2 engineering personnel to examine the feasibility and benefits of using ASDs to eliminate the FCVs. The following plant benefits were identified from their study :

House Load Reduction
The house load savings due to low speed operation during part of the fuel cycle were estimated to be 7500 MW hours per year provided the FCVs were removed.

Fuel Cost Reduction
An ASD could operate the pump at greater than rated speed allowing higher core flow operation at the end of the fuel cycle. This would optimize the fuel cycle and reduce fuel costs (estimated to be $52,000 per percent core flow increase per fuel cycle).

Improved Operation
An ASD would improve plant capacity factor by allowing operation in regions prohibited by the experienced pump and FCV problems, improve control capability, support non-nuclear heatup similar to the earlier MG Set plants and improve the operator interface.

Mitigate Pump Design Related Failures
The cause of the previous pump failures was not corrected but the pump design was hardened and restrictions placed on operation. This however did not assure that failures would not reoccur in the future. ASD variable speed operation and the reduction in system vibration were expected to prolong pump service life by reducing service duty.

Personnel Radiation Exposure Reduction
The RRS was historically the highest single dose contributor due to inspections, surveillance, and maintenance of the equipment inside the containment. The ASD would allow removal of the most maintenance intensive equipment from the containment with the attendant reduction in dose to personnel.

System Reliability Improvement
System and plant reliability were hampered by vibration related failures of branch piping, FCV position sensors and hydraulic lines. Vibration was also thought to be a contributor to premature isolation valve wearout. The ASD would reduce system vibration, eliminate the FCV and HPU and reduce duty on the pump, motor and piping.

Maintenance Frequency Improvement
The ASD soft start capability would reduce motor starting duty and extend the motor refurbishment cycle. The ASD would also be accessible during operation for maintenance and repair if needed without shutting the plant down. HPU maintenance would be eliminated along with ASME Section XI testing of the HPU hydraulic line containment penetration valves. The potential for hydraulic fluid organic contamination of drywell equipment and the threat to hydrogen control capability during an accident would also be eliminated.

Given the significant benefits identified by this study, the WNP-2 staff proceeded to identify an ASD retrofit concept and perform a detailed cost and benefit analysis. The EPRI work (Ref. 1) and their preferred large induction motor ASD configuration played a significant part in this evaluation. WNP-2 engineers traveled to California to evaluate the highest horsepower application of the EPRI concept at the Southern California Edison Ormond Beach Units where ASDs are used to drive 7200 HP boiler forced draft fans (Ref. 3). Several ASD vendors were evaluated by the Supply System and the GE GTO induction motor drive was selected since the GE drives had performed flawlessly at the Ormond Beach Units for over three years. In addition GE is the WNP-2 designer and is intimately familiar with the RRS design.

Prior to specific plant ASD design, the following studies were performed to validate ASD application at WNP-2 :

1. Torque pulsation analysis of the motor, pump and piping. The significant harmonics transmitted by the ASD were 3, 6 and 12 times the line frequency for 6-pulse operation and 2 and 12 times the line frequency for 12-pulse operation.
2. Pump blade passing frequency vibration analysis of the reactor vessel internals for the 25 to 106% speed range required. The blade passing frequencies for this range were 75 Hz to 318 Hz.
3. Analysis to determine whether the pump and motor could be upgraded to operate at higher than their design speeds

4. Evaluation of the existing 6.9 kV breakers to determine their suitability for use in this application.

These studies concluded that the equipment could be operated up to 106% speed, some electrical protection schemes needed modification to accommodate the new equipment configurations and some jet pump sensing lines required stiffening to accommodate the new operating speed range. Based on these results, WNP-2 selected the ASD design shown in Figure 6 with the following features :

Dual GTO (12 pulse) induction motor drive trains in both loops
Redundant thyristor cooling systems
Dual HVAC building cooling
N+1 GTO inverter thyristors
Single train operating capability
Three levels of overspeed protection
Off line self diagnostic capability
Redundant digital process control systems giving a mean time between failure of 40 years
Retention of most existing operator benchboard control features

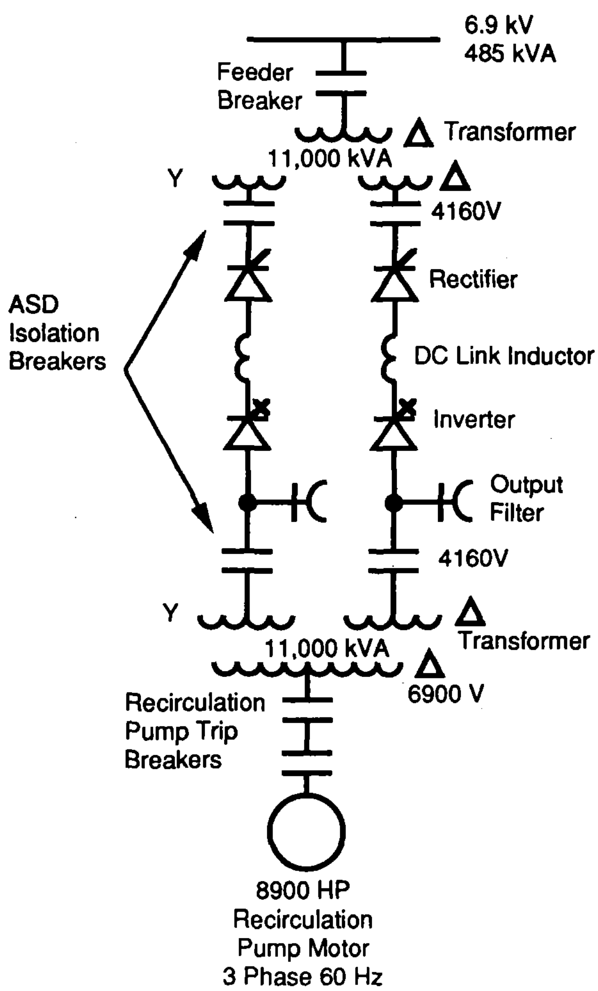

Figure 6. WNP-2 ASD Configuration

Redundant UPS
Control Room ASD Video Display.

Controlling the ASD output frequency from 15 to 63 Hz will vary pump flow from 25% to 106% and permit large reactor power level changes if needed. A manual controller on the main bench board permits either ganged or single loop operating modes. The speed rate of change is limited to plus or minus 5% per second and the existing RRS trips are maintained.

Under transient conditions, the loss of a feedwater pump, with subsequent or coincident low reactor water level will initiate rapid runback of the recirculation pumps to the power level that can be supported by the remaining feedwater pumps. The ASD output frequency will automatically lock at its last value upon loss of the control signal. Upon receipt of a pump trip signal, the ASD will run back prior to a circuit breaker trip.

Installation of the drives and their associated equipment required 3000 square feet near the turbine building. The drive building occupies about two thirds of this area. The remainder accommodates the input and output transformers, the eight link inductors and the dual heat exchangers. The drive controls, rectifiers, inverters, filter capacitors, supporting circuit breakers, UPS, power panels, etc. are located in the drive building. This installation and connection to the plant auxiliary power sources were completed while the plant was operating.

The control room panels, cabinets and benchboard inserts were prefabricated and tested to minimize outage work in the control room. The remaining outage work will consist of installing jet pump instrumentation sensing line vibration mitigation devices, inserting the drives between the 6.9 kV breakers and the pump motors, removing the obsoleted equipment and controls and startup testing. Due to the large amount of work involved, current plans are to leave the FCV in place and lock it in the full open position.

The major lesson learned from this project to date is to carefully design the ASD equipment to optimize the power factor of the system for the expected system loads throughout the fuel cycle. Conservatism in the design values led to over specification of the equipment for maximum load operation whereas the system will spend a significant part of its operating life at less than design capability. Consequently, utilities considering ASD retrofits should determine the expected operating duty and work with the ASD vendor to optimize the power factor for the overall range of operation.

SUMMARY

ASD retrofits can be cost beneficial in situations where full flow operation is not needed for a substantial part of the time.

Operating experience has shown the reliability of ASDs. EPRI has completed a field test program to provide guidance on how to implement large induction motor ASD retrofits successfully and evaluate the energy savings achieved from various ASD applications.

Emphasis on reducing operation and maintenance costs and increasing the capacity factor of nuclear power plants is leading some utilities to consider replacing their BWR flow control systems with induction motor ASDs. The Washington Public Power Supply System is currently retrofitting an ASD to power and control the flow of the RRS pumps at WNP-2. This modification will eliminate the need for the FCV and its associated equipment. The major benefits are an increase in core flow capability, increased control system reliability, and reduced radiation exposure to plant maintenance staff. The ASDs are housed in a new building outside the turbine building and will be connected to the existing recirculation pump switch gear. Detailed analyses of the recirculation pump and motor, on site distribution system, control system design and reactor vessel internals were required to assure that the retrofit would be acceptable. In addition to these analyses, the expected operating conditions of the system should be evaluated in order to optimize the power factor of an ASD retrofit.

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