Summary

Feedwater control systems are critical to the safe and efficient operation of a nuclear power plant. Existing control systems can be unreliable and hard to maintain due to the unavailability of spare parts. As a replacement, the Tricon TMR Digital System incorporates both high reliability and high availability as inherent attributes.

Aging feedwater control systems need to be replaced with high reliability, high availability modern digital control systems, so unnecessary feedwater system trips (and hence plant outages) can be prevented. The new systems must not only be easy to operate and maintain, but also be easy to upgrade and expand in the future.

Most monitoring, control and safety requirements are common to the feedwater systems for different boilers/steam generators in nuclear power plants. A feedwater control system must have the capability to handle both the common requirements and the vendor-specific requirements of all feedwater systems.

MAJOR REQUIREMENTS

Reliability, availability and maintainability

- High reliability and availability with no single point of failure for continuous plant operation
- Online diagnostics with over 99.9% coverage
- Online repair
- Easy to maintain, modify and enhance
- Easy to upgrade and expand - without affecting the existing field elements and wiring

Field interface

- Interface to existing field elements, as well as new field elements. Field elements include vessel water level, vessel pressure, steam flow, feedwater flow, first stage pressure, etc.
- Interface to other control systems in the plant
Control, safety and test
• Maintain water level in the vessel within a pre-defined range (setpoint ± a specified value) by maintaining steam flow out/water flow in mass balance under dynamic load conditions
• Implement existing automatic or manual operational procedures and control strategies
• Implement a combination of single-element/three-element auto control and manual control strategies, with bumpless switching between strategies. Single-element control uses only water level as an input; three-element control uses water level, steamflow and feedwater flow as inputs
• Detect unsafe plant conditions and safely shut the system down

Operator interface
• Easy to use operator interface for monitoring and control
• Enhanced visibility of critical feedwater parameters in real time
• Allow the operator to set the following control parameters: Setpoint for the vessel water level, Bypass for individual input signals, Reset for individual alarms, Auto/Manual control mode, Ramp Rate Hi/Med/Slow, etc.
• Easy to navigate between control, monitoring and maintenance screens

Communications
• Ability to interface with existing plant computer and DCS system
• Redundant, high speed, industry standard communication interfaces and protocols to transfer real-time data (feedwater system parameters, field status, alarms, trips, system status, field inputs and outputs, etc.) for control, monitoring, logging and trending for field diagnostic purposes

TRICON-BASED FEEDWATER CONTROL SYSTEM ARCHITECTURE
The Tricon-based feedwater control system architecture is shown in Figure 1 on the next page. This basic architecture can be adapted to satisfy existing plant-specific field elements and wiring requirements, any additional field element requirements, existing auto-manual feedwater control procedures and strategies and communication requirements.

A typical feedwater control system consists of:
• Triconex® Tricon TMR system
• Triconex TriStation 1131 application development station
• Feedwater control application software
• Foxboro I/A Series® System or Wonderware® HMI (Human Machine Interface)
• Maintenance/Engineering workstation
• TriLogger software

Tricon TMR system
The Tricon is a Triple Module Redundant (TMR) architecture-based digital safety and control system. The system is certified by TÜV (a world recognized, independent safety agency) at IEC (International Electrotechnical Commission) SIL (Safety Integrity Level) 3 to be used for safety and critical control applications in process control and other industries. The Tricon is also certified by the NRC (Nuclear Regulatory Commission) to be used for safety (1E) and critical control applications in nuclear power plants.

The Tricon has three independent channels from the input terminal to the output terminal. Each input is voted every scan by the three main processors (MPs), and the resultant voted input is provided to the same application running in the three MPs. The outputs from the application running in each MP go to the output modules where they are voted. The resultant voted output for each point goes to the output terminal/field device.

The TMR architecture and design allows the Tricon system to perform its intended safety and control functions in the presence of a single hardware fault. In addition, the design allows the Tricon to run in TMR, DUAL or SINGLE mode, thus providing high availability (99.99%).
The built-in online diagnostics provide more than 99.9% fault coverage and isolate a fault to a specific module. The faulted module can be replaced with a new module online without affecting the feedwater system operation. The Tricon combines technology and architecture features to provide safety and control functions with the high reliability and high availability required for the safety and critical control applications in nuclear power plants.

The Tricon can be expanded from a single chassis system all the way up to a 15 chassis system with a wide variety of I/O and communications (COM) modules. Most feedwater control systems require a main chassis and two to three I/O expansion chassis, depending on the number of field elements and spare slot requirements for future expansion.

The COM modules provide the Tricon with the ability to interface to the existing plant computer, DCS systems, operator stations, etc. These COM modules provide the redundant, high speed, industry standard communication interfaces and protocols for transferring real-time plant data for control, monitoring, logging and trending for field diagnostics purposes. The I/O modules allow the Tricon to interface to different types of new and existing field devices. The I/O modules include: Analog Input, Analog Output, Thermocouple, Pulse Input, Digital Input and Digital Output.
TriStation 1131 Workstation
TriStation 1131 is a PC-based safety and critical process control application development workstation that provides a comprehensive set of development, test, monitor, validation and diagnostic tools for Triconex Programmable Safety Systems (Tricon and Trident). TriStation 1131 is compliant with the IEC 1131-3 International Standard for Programmable Controllers, Part 3: Programming Languages.

TriStation 1131 includes the following major features for application development:
• IEC programming languages: Structured Text (ST) language (textual language), Function Block Diagram (FBD) Language (graphical language) and Ladder Diagram (LD) Language (graphical language);
• IEC data types: Basic data types (BOOL, INT, DINT, REAL, DREAL, DWORD, STRING, TIME, TOD, DATE and DT) and user-derived data types (ARRAY, STRUCT, CONSTANT and ENUMERATION);
• Ready-made, thoroughly tested libraries for application development:
  – IEC standard library
  – Triconex library: system status and diagnostics functions, Scheduler functions, PID functions, Sequence Of Events (SOE) functions
  – Feedwater control libraries: Special feedwater control functions developed by the domain experts at Triconex, based on 20 years of experience in control system design and development
• User-defined libraries: Users can develop, test and archive their own libraries to be used in different applications
• Easy to use Windows-based graphical user interface
• A browser-based help system with help for TriStation 1131 operations, library functions and error messages
• Security features and audit trail
• Built-in application change control and version control
• Emulator for application testing prior to downloading to the Tricon system
• Project execution monitoring and control
• Comment boxes and variable annotation for in-line documentation

Feedwater Control Application Software
Critical control application software is developed using the TriStation 1131 workstation and associated standard, as well as feedwater control application specific libraries. See the critical application software architecture.

Foxboro I/A Series System or Wonderware HMI
The Foxboro I/A Series System or Wonderware InTouch® HMI provide a graphical, easy to use operator interface for the control and monitoring of turbine operation. In addition, they provide real-time data, alarms and event logging capabilities.

Standard feedwater control and monitoring screens are available for both workstations. The standard screens can be modified and additional screens can be easily developed to meet the nuclear plant’s operational requirements.

Maintenance/Engineering workstation
This is a commercial off-the-shelf ruggedized PC with the Tricon Diagnostic Monitor utility installed. This utility displays Tricon system and module status by mimicking the actual Tricon chassis and slots, so that the user can find the exact location (chassis number and slot number) of a module. This workstation may also include the TriStation 1131 application software and TriLogger software.

TriLogger
The TriLogger software provides the ability to record, display, playback and analyze the field data from the Tricon system. Data can be viewed in real-time, either locally or remotely. Data trending and analysis capabilities help diagnose field problems.
Critical application software architecture consists of standard, off-the-shelf software modules (programs, functions and function blocks) developed using TriStation 1131 and associated libraries. The flexibility of the feedwater control application architecture, combined with the TriStation 1131 programming facilities and the expertise and experience of the Triconex personnel, makes it easy to adapt the architecture to satisfy any plant-specific feedwater control strategy and procedures.

The software implements the feedwater operational states (modes) and the specific control and monitoring functions in each state, based on the feedwater system status received from the field and inputs from the operator station (HMI). Figure 2 shows the feedwater system states and state transition.

Figure 2 – Feedwater System States and State Transition Diagram

Figure 3 shows the major software modules and their interrelationships. These modules implement the field inputs processing, operator inputs processing, feedwater system states and control strategy.

Figure 3 – Feedwater Control Application Software Architecture
The Vessel_Water_Level, Steam_Flow and Feedwater_Flow modules process field and operator inputs. Each module scales the inputs, validates the inputs and selects median, average, single or zero value based on the number of valid inputs for each input type. The Feedwater System States and Control Strategy module implements the system states and associated control functions in each state:

**Field Manual State**
This state is entered on cold/warm start and when any one of the field auto_manual signals from the valves servo controllers or feedwater pump control system goes off. The operator controls feedwater flow manually from the servo controllers for the valves and the feedwater pump control system. In this mode, the application disables the demand signals to the field (i.e., sends zero to the servo controllers and feedwater pump control system). This state is exited when the field auto_manual signals from the servo controllers and the feedwater pump control system become true.

**Local Automatic/Manual**
This state is entered when the current state is Field Manual and the field auto_manual signals from the servo controllers and the feedwater pump control system are true. This state is also entered when one of the following occurs:
- The Local Auto mode flag is set by the operator
- A loss of feedwater flow is detected in single-element or three-element control mode
- A loss of vessel water level is detected in single-element or three-element control mode

The operator controls the feedwater flow from the HMI through the Tricon system. From the HMI, the operator can set the system in a remote mode by setting the remote mode flag on. This state is exited when any one of the field auto-manual signals goes off or when the remote mode flag is set by the operator and the prerequisites (field conditions) for the single-element control mode are satisfied.

**Single-Element (Water Level)**
This state is entered when the current state is Local Automatic/Manual, the remote mode flag is set by the operator and the prerequisites (field conditions) for the single-element control mode are satisfied.

In this mode, the water level target (setpoint) is compared to the actual vessel water level to generate an error signal. This error signal is processed by the Proportional-Integral-Derivative (PID) function to generate the demand signal (setpoint) for the feedwater flow controller's PID. Gain and integral settings for the PID are derived from the adaptive tuning parameters across the full spectrum of power band for optimum level control. The single-element control is used for low load condition (power level less than 16% of full power). The first stage pressure input is used to estimate the current power level. Refer to Figure 4 for an example of single-element and three-element control strategies.

This state is exited when any of the following occurs:
- One of the auto-manual signals goes off
- A loss of vessel water level or feedwater flow is detected
- The Local Auto mode flag is set by the operator
- The power level is greater than or equal to 16% and the prerequisites (field conditions) for the three-element auto mode are satisfied

**Three-Element (Water Level, Steam Flow and Feedwater Flow)**
This state is entered when the current state is Single-Element and the prerequisites (field conditions) for the three-element control mode are satisfied.
In this mode, the water level target (setpoint) is compared to the actual vessel water level input to generate an error signal. This error signal is processed by the Proportional-Integral-Derivative (PID) function to generate the demand signal. This demand signal is combined with the steam flow input to generate a setpoint for the feedwater controller’s PID. This setpoint is compared to the feedwater flow input. The resultant error signal (feedwater flow error) is the demand signal for the field control elements. The gain and integral settings for the PIDs are derived from the adaptive tuning parameters across the power band for optimum level control.

The system automatically switches between single-element and three-element control mode depending upon the plant conditions. Once in three-element control mode, the system remains in that mode as long as there is at least one valid input for the water level, steam flow and feedwater flow. Figure 4 shows one of the various ways of implementing control strategy. Invensys has implemented different strategies for different nuclear power plants, based on plant-specific control requirements.

This state is exited when any of the following occurs:

- The auto-manual signals goes off
- A loss of vessel water level, a loss of steam flow or a loss of feedwater flow is detected
- The Local Auto mode flag is set by the operator
- The power level is less than 14% of full power

![Figure 4 – Detailed Single-element and Three-element Control Strategy](image-url)
OPERATOR SCREENS
The feedwater control and monitoring screens listed below are available for both the I/A Series workstation and the Wonderware workstation. These standard screens are provided with programmable security levels and can be modified to meet a particular nuclear plant’s operational requirements. Additional screens can also be easily developed.

- Feedwater Overview screen
- Control screen
- Alarms screen
- Maintenance screen
- Field I/O screen

SUMMARY
The Tricon is a high reliability, high availability (99.99%), digital feedwater control system with no single point of failure. The built-in features (high reliability, high availability, low maintenance, self-calibration, built-in online diagnostics, online repair, easy to expand and upgrade) help reduce life cycle operations and maintenance costs.

The online diagnostics provide more than 99.9% diagnostic coverage, providing a basis to reduce periodic surveillance testing between refueling cycles. Online repair increases availability even further.

When you install the Tricon, you get the experience and knowledge of the Triconex feedwater control domain experts. You also gain Invensys’ experience in design, development, installation and support of the feedwater control system, efficient project execution and integration capabilities, round-the-clock customer support and customized training for the I&C and plant operation personnel.

Any future expansion and upgrades can be performed in a day or two without changing existing cabinets, terminal panels or field wiring. This means not having to perform continuity tests, loop checks or recalibrations. The overall result is a tremendous savings in expansion or upgrade costs, less project management effort and reduced outage duration.