The Tricon Turbine Control System
A Field-Proven Triple Modular Redundant (TMR) Digital System
for Turbine Control and Safety Application in Nuclear Power Plants

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1. Abstract

The Triconex® Tricon™ is a Triple Modular Redundant (TMR) digital system for turbine control and safety application in nuclear power plants (NPPs). The steam turbine is a critical element in the continuous operation of NPPs. When a turbine goes offline, the entire plant goes down. Poor reliability of the existing obsolete control system is one of the major causes of turbine trips. A single component failure can result in a turbine shutdown, causing unscheduled plant outages that cost hundreds of thousands of dollars per day in maintenance costs and lost revenue. The Tricon is a high reliability and high availability (99.99%) turbine control system with no single point of failure. It provides an economical solution to the obsolescence, reliability and availability problems, while improving the operational efficiency of NPPs.

2. Introduction

Turbine control systems are critical for the safe, efficient and continuous operation of an NPP. Existing control systems are old, obsolete, unreliable and hard to maintain due to the unavailability of spare parts. The staff at NPPs should not spend time trying to keep antiquated control systems running. The design and architecture of a critical control system should incorporate high reliability and high availability as inherent attributes. This type of control system allows the plant operator to focus on the plant behavior, monitoring field parameters critical to maintaining the plant and quickly perform corrective actions when necessary.

Aging turbine control systems must be replaced with high reliability and high availability, modern digital control systems, so unnecessary turbine trips and plant outages can be prevented. New turbine control systems must be easy to operate, maintain, upgrade and expand in the future.

Nuclear power plants have various types of turbines from different vendors. Many turbines are reheat steam turbines that vary in size from a few hundred megawatts (MWs) to over 1000 MWs. Most monitoring, control and safety requirements are common to all turbines from different vendors. A turbine control system must have the capabilities and flexibility to handle common requirements and vendor-specific requirements for all turbines.

3. Major Requirements

Reliability, Availability and Maintainability
• High reliability and high availability with no single point of failure for continuous plant operation
• Online diagnostics with more than 99.9% coverage
• Online repair
• Easy to maintain, modify and add future enhancements
• Easy to upgrade and expand in the future without affecting existing field elements and wiring

Field Interface
• Interface to the existing and new field elements for the turbine, if required.
• Interface with other control systems throughout the plant

Control, Safety and Test
• Implement existing automatic or manual operational procedures and control strategies
• Implement manual or automatic turbine chest and shell warm-up, turbine generator synchronization
• Perform online valve tests (main control valves, main stop valves, reheat stop valves and intercept valves) and over speed detection test under operator control
• Detect and safely shut down the system when unsafe plant conditions arise. Unsafe conditions include: turbine overspeed, loss of lube oil pressure, bearing temperature, vibration abnormalities, power load unbalance (PLU)
• Automatic switching between speed control state (mode) to load control state, depending on the plant conditions
• Droop control for speed and/or load stability
• Automatic switching between full arc and partial arc (single valve mode and sequential valve mode) operation
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Operator Interface
- Easy to use operator interface for monitoring and control
- Enhanced visibility of critical turbine parameters in real-time
- Easy navigation between the control, monitoring, maintenance and test screens

Communications
- Ability to interface with existing plant computer and/or DCS system
- Redundant, high-speed, industry standard communication interfaces and protocols to transfer real-time data (such as turbine parameters, field status, alarms, trips, system status, field inputs and outputs) for control, monitoring, logging and trending for field diagnostics purposes

The Tricon satisfies the above requirements for turbine control in NPPs. The Tricon overall architecture is presented in Figure 1. This basic architecture can be adapted to satisfy existing plant-specific field elements and wiring requirements, additional field element requirements, existing auto-manual turbine control procedures and strategies and communications requirements.

4. Tricon Architecture

A typical Tricon system consists of the following:
- Tricon™ TMR system
- TriStation 1131™ application development station
- Turbine control application software
- I/A Series® or Wonderware® HMI (Human Machine Interface)
- Maintenance workstation
- TriLogger software

A brief summary of the Tricon system components is provided below.

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

The Tricon has three independent channels from the input terminal to the output terminal. Each input is scanned and voted 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 can isolate a fault to a specific module. The faulted module can be replaced with a new module online without affecting the turbine 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 NPPs.
The Tricon can be expanded from a single chassis system to a fifteen chassis system with a wide variety of I/O and Communications (COM) modules. As shown in Figure 1, most turbine 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 with the existing plant computer, DCS systems and operator stations. 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 with various types of existing and new field devices. The I/O modules include: Analog Input, Analog Output, Thermocouple, Pulse Input, Digital Input and Digital Output.
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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). The 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, LREAL, 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
  - Turbine Control Libraries: Special turbine control functions developed by the turbine control domain experts at Triconex, based on the last twenty years of experience in turbine control systems design and development
- User-defined libraries: Users can develop, test and archive their own libraries to be used in various applications
- Easy to use Windows-based graphical user interface (GUI)
- A browser-based help system with extensive 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

These features allow users to develop and test application software in a systematic and modular fashion.

Critical Turbine Control Application Software
Critical control application software is developed using the TriStation 1131 workstation and associated standard, as well as steam turbine control application specific libraries. Please see the critical application software architecture section.

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

Standard turbine control and monitoring screens are available for both workstations. The standard screens can be modified and/or additional screens can be easily developed to meet the nuclear plant's operational requirements. Please see Section 6, Operator Screens.
**Maintenance/Engineering Workstation**

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

**Trilogger**

The TriLogger software provides the ability to record, display, play back and analyze the field data from the Tricon system. Data can be viewed in real-time (locally or remotely). Data trending and analysis capabilities assist in diagnosing field problems.

**5. Critical Application Software Architecture**

The critical application software architecture consists of standard, COTS software modules (programs, functions and function blocks) developed using TriStation 1131 and associated libraries. The flexibility of the turbine control application architecture, combined with the TriStation 1131 programming facilities and the expertise and experience of Triconex personnel, makes it easy to adapt the architecture to satisfy any plant-specific turbine control strategies and procedures.

The software implements the turbine operational states (modes) and specific control and monitoring functions in each state. This is based on the turbine status received from the field and inputs from the operator station (HMI). Figure 2 displays the turbine states and state transition diagram.

Figure 3 displays the major software modules and their interrelationships. These modules implement the turbine control strategy (states and associated functions in each state).

**Shutdown (State 0)**

This state is entered upon cold/warm start and when a turbine trip occurs (such as overspeed trip, master solenoid trip, loss of oil pressure, all speed pickups failed). The following operations are performed:

- Close all valves
- Initialize field mechanical trip solenoid and master trip solenoids
- Initialize target speed setpoint, speed reference, target load setpoint, load reference, controllers’ logic
- Energize turning gear
- Perform valve-stroking test if requested by the operator and the prerequisites for the test are satisfied
This state is exited when there is no active trip and the trip reset signal from the HMI is activated.

**Ready to Start (State 1)**
This state is entered when one of the following conditions is true:

- Current state is Shutdown (State 0), there is no active trip and the trip reset signal from the HMI is activated
- Current state is Speed Control (State 2) or Overspeed Test (State 5) and the close valves signal from the HMI is activated

This is usually the turbine “Warm Up” mode during which the following operations are performed:

- Perform the shell warming or the chest warming if requested by the operator and the prerequisites for the warming are satisfied
- Check conditions for starting the turbine: all valves closed, generator breaker open, field power OK and no active turbine trip
- Latch the turbine and check that the oil pressure is established
- Set the ready to start flag

This state is exited when the ready to start flag is set and the target speed setpoint is selected from the HMI.

**Speed Control (State2)**
This state is entered when one of the following conditions is true:

- Ready to start flag is set, the target speed setpoint is selected from the HMI and all valves are closed
- Current state is Speed Sync (State 3) and the speed sync signal is de-selected (speed sync aborted) from the HMI
- Current state is Overspeed Test (State 5) and the overspeed test signal is de-selected (test aborted) from the HMI
- Current state is Generator Online (State 4) and the generator breaker opens

The following operations are performed:

- Open all main stop valves, reheat stop and intercept valves and LP turbine valves
- Ramp speed reference to the target speed setpoint using the ramp rate selected from the HMI
- Modulate the control valves using the speed PID (Proportional, Integral and Derivative) controller, Demand multiplexer and the valve control module
- Use preset critical band ramp rate to avoid sustained operation in the critical speed bands
- Allow operator to adjust speed setpoint for manual synchronization when the turbine reaches the speed close to sync speed
- When this mode is entered from the Generator Online state when the generator breaker opens, enable the Load Drop Anticipatory (LDA) module. LDA helps protect the turbine from overspeed

This state is exited when one of the following is completed:

- Generator breaker is closed
- Overspeed test flag is set by the operator
- Speed sync flag is set by the operator

**Speed Sync (State 3)**
This state is entered when all of the following conditions are true:

- The current state is Speed Control (State 2)
- The auto speed sync signal is activated from the HMI
- The turbine speed is within sync speed ± specified value (RPM) and the generator frequency is within 60 ± specified value (Hz)

The following operations are performed:

- Calculate the target speed setpoint from the generator frequency
- Small bias is added to the target speed setpoint to attain desired phase rotation in the positive direction
- Set the auto sync complete flag and close the generator breaker

This state is exited when the generator breaker is closed, or the auto speed sync signal is deactivated from the HMI.
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6. Operator Screens

The following standard turbine control and monitoring screens with security levels are available for both the I/A Series workstation and the Wonderware workstation. These standard screens can be modified and/or additional screens can be easily developed to meet nuclear plant operational requirements.

- Main Menu Screen
- Turbine Overview Screen
- Turbine Start-up Screen
- Normal Operation Screen
- Turbine State (mode) Screen
- Valve Tests Screen
- Alarms and Trips
- Maintenance and Diagnostics

Example 1

Example 2
7. Summary

Invensys is a customer-centric company that provides a complete solution to the nuclear industry for safety and critical control. Invensys has installed more than 1,500 turbine control systems in plants all over the world, including NPPs.

The Tricon is a high reliability, high availability (99.99%), digital turbine control system with no single point of failure. The built-in features of the Tricon (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 built-in online diagnostics provide more than 99.9% diagnostic coverage, providing a basis to potentially reduce periodic surveillance testing between refueling cycles. Online repair increases availability even further, as turbines are not required to be shutdown to perform repairs.

The Triconex Tricon solves the obsolescence, reliability and availability problems of NPPs, while improving the operational efficiency of the NPP.

With a Tricon installation, you not only receive proven TMR technology, but the experience and knowledge of the Triconex turbine control domain experts spanning over a quarter of a century in the industry. Triconex experts have seen and resolved many problems associated with the installation and operation of turbine control systems. If you experience problems with the installation or operation, it is highly probable that Triconex experts know about the problem and are ready to help you solve it. With Invensys you gain experience in design, development, installation and support of the turbine control system, efficient project execution and integration capabilities, round-the-clock customer support and customized training for the I&C and plant operation personnel. The Tricon will be the last system you will ever have to install for turbine control. Future expansions and upgrades can be completed in one or two days, not weeks. Existing cabinets, term panels, or field wiring do not need upgrading. This means you don’t have to perform continuity tests, loop checks, or recalibrations. The overall result is tremendous cost savings in expansion or upgrades, project management efforts and reduced outage duration.