

GAS TURBINE CONTROL SYSTEMS INCORPORATING CONDITION MONITORING AND FAULT TOLERANCE

by

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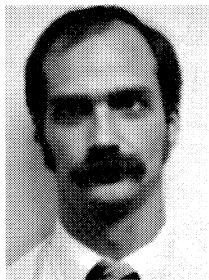
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Mr. Muster has authored and coauthored several publications on the dynamics of machine foundations, digital signal processing, and automated vibration data analysis systems.



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Since joining Boyce Engineering International, Incorporated, in 1988, Mr. Feinstein has been responsible for system design, development instrumentation and control (PLC) systems.

ABSTRACT

Novel concepts in gas turbine control technology incorporating condition monitoring and fault tolerance are described. Concerns with fault tolerance, system reliability, and users functionalities are discussed. The importance of incorporating mechanical and aerothermal analysis for optimum system reliability is discussed.

The thesis is presented that system reliability must be defined in terms that include the process controlled (i.e., the gas turbine) and not simply the controlling components. Fault tolerant considerations for both the instrumentation points and the control system can be addressed by means of an expert system coupled with a modelling system.

In the described system, an online, background running hybrid expert system compares real time input data from instruments to calculated thermodynamic and mechanical parameters. These calculations are then used to determine data deviations and component performance degradation. Further, a diagnostic system is able to make fault tolerant decisions based on prioritized rules. The paper describes how the integration of the hardware systems can be accomplished to maximize reliability. Concerns with fault tolerance of components are addressed with a practical approach to redundancy and hardware diagnostics on all subsystems.

Ways used to maximize the "usability and friendliness" of interface stations are discussed as it relates to system reliability. This is of special concern since the scientific functionalities of the system could potentially overwhelm an operator. Separate operator and engineer work stations are recommended to maximize the usefulness of the system.

INTRODUCTION AND NEEDS ANALYSIS

Combustion turbines for industrial applications were introduced almost 50 years ago. Since then, manufacturers, packagers and control system vendors have attempted to improve the reliability and safety of the system. Though many improvements have been made in metallurgy and thermodynamic efficiency, the greatest improvements to reliability and safety for operation can be accomplished by better controls and instrumentation. Controls have evolved from hydromechanical (fuel regulators) to

analog electronics to hybrid analog and digital systems to microprocessor systems, to redundant microprocessor systems, and now to microprocessor controllers that integrate expert systems for fault tolerant operation. The latter system optimizes safety and addresses fault tolerant concerns on the whole turbine train.

In 1980, the Electric Power Research Institute (EPRI) identified control system failure as the single most cause of lost availability in gas turbine generation [1]. Based on available data from the North America Electric Reliability Council (NERC) generating availability report and personal experiences, there are several factors that call for utilizing a system that would provide aerothermal and mechanical analysis and diagnostics of the turbo-generator systems. Thorough systems diagnostics (both control and turbogenerator) and a background expert rule based modeling system can be incorporated to achieve a reasonable approach to fault tolerance and to attain a fail safe type of operation.

The system would be microprocessor based with dedicated turbine control, operator interface, along with an engineer's interface. The system would include the basic control functions and condition monitoring capability.

Information obtained from the North America Electric Reliability Council [2] indicates that of the total combustion turbine plant availability factor, the turbine components have the lowest availability factor of all other systems. This report, based on statistical information for over 1600 turbine years of operation, indicated the following main causes of outages within combustion turbines:

- 52.2 percent — turbine hot end problem, deratings, inlet air problems, lube oil and vibration problems.
- 29.2 percent — turbine inspection and overhauls.
- 12.2 percent — other systems and/or operational decisions.
- 6.4 percent — control system failure.

In general, it has been the practice to view control system reliability as independent of the overall system involving both the gas turbine and the control system. In the authors' view, the proper perspective is to view the overall system reliability of which the control system is a subset.

It is the opinion of several users that high degrees of control system redundancy do not necessarily result in higher availability of the gas turbine. Some gas turbine users have found that triple redundant systems did not necessarily provide "high unit availability" even though theoretically they provide optimal "controller" availability. Several users have felt that the best approach is to provide limited physical redundancy but to build in fault tolerance within the software.

Six such control systems are under development, five of which will be for heavy duty gas turbine power generation operations. The sixth is a unique operation involving a rail gun that uses a large industrial gas turbine as the compulsator driver.

DESCRIPTION OF GAS TURBINE CONTROL AND CONDITION MONITORING SYSTEM

A fault tolerant control and condition monitoring system for gas turbines is complex, since it must incorporate aerothermal and mechanical computation techniques to check for instrumentation accuracy. It is truly a designer's dilemma. Such a system requires a number of measurement points on a machine. It would have the ability to provide the operator with status, alarm events, and control functions in a form similar to the one the operators are currently using. It would have the capability of dis-

criminating between good and bad sensor data and between useful and useless data. It would have a virtually infinite capacity for storing data, and would provide the operator with diagnostic information as to the cause of an abnormal condition. It would provide the operator with a list of corrective actions to be taken, and would have the capability of performing several analyses simultaneously, and displaying the results of the analyses in an appropriate form. Inevitably, this leads to design decisions influenced greatly by priorities and compromise. The conceptual design and configuration of the distributed microcomputer based fault tolerant gas turbine control system, described here includes four principal subsystems:

- Hardware and functional configuration
- Database configuration
- Turbine Analysis procedures
- Operator interface, display and report formats

The design of these subsystems is based on five interrelated considerations: data acquisition and control, data trending and storage, prioritized queueing of alarms, prioritized queueing of diagnostics, and fault tolerance rules for analysis. Each subsystem will be considered separately.

HARDWARE AND FUNCTIONAL CONFIGURATION

The gas turbine control system is a distributed intelligence based system. As such, it consists of multiple computers linked together via a network system. With the exception of the PLC and gateway, the operating system used by each computer is multitasking and multiuser via the local area network manager software. The multiuser multitasking operating system utilizes a preemptive task scheduler. The task scheduler switches to a new task every 32 milliseconds (or less).

The hardware modules of a typical system are enumerated below and presented in Figure 1.

- Turbine sequencer and controller (PLC).
- Turbine speed microcomputer
- Gateway communications manager and local operator station
- Turbine analysis microcomputer
- Engineer's work station
- Main operator station
- Turbomachinery vibration analyzer station

The control system incorporates diagnostics on the turbine and the control hardware. The system is designed to incorporate proven hardware and diagnostics software. A functional diagram is shown in Figure 2 of the suggested relationship of the controls and condition monitoring in the system. The shared I/O bus is shown in Figure 3 with the sequencer/controller and the condition monitoring system.

The chosen methodology for integration of condition monitoring to the system is by the utilization of a distributed I/O system to interconnect to the controller and the condition monitor. A reliable PLC based controller and distributed I/O bus system allows for a mini or microcomputer to tie into the I/O bus. The

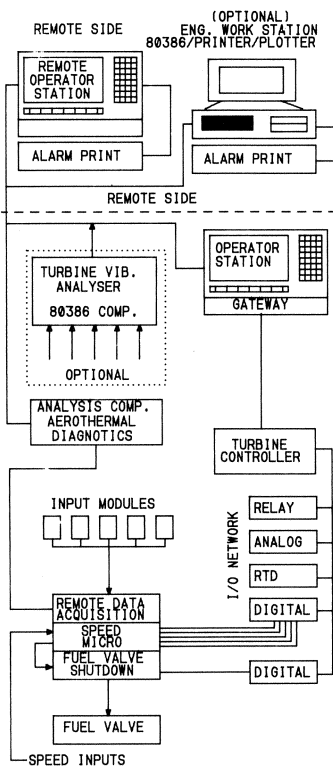


Figure 1. Hardware Configuration.

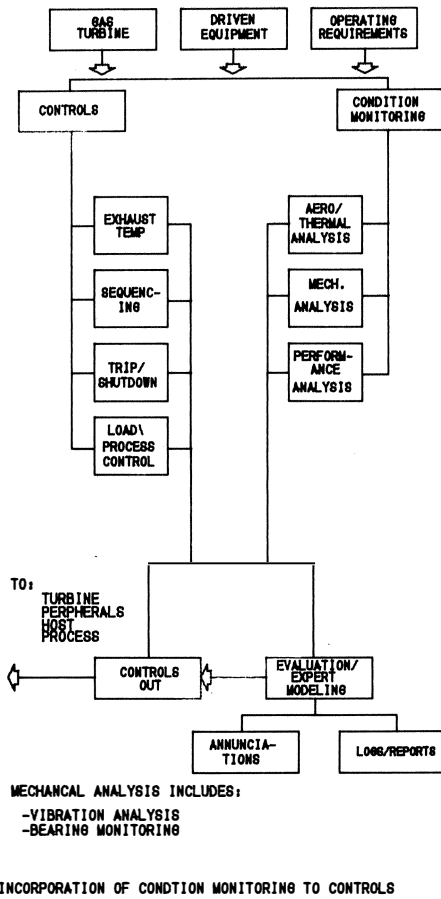


Figure 2. Functional Diagram.

SHARED I/O BUS

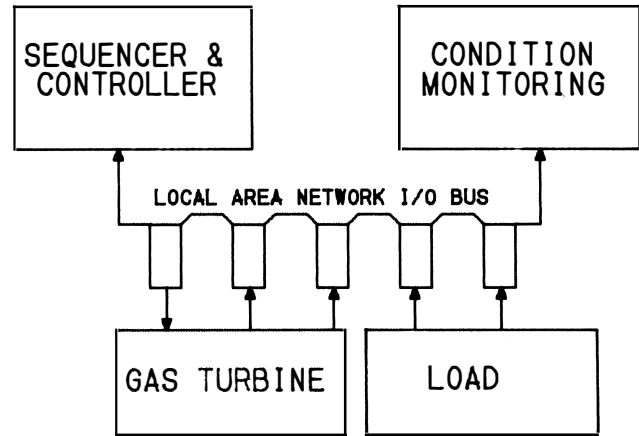


Figure 3. Shared I/O Bus.

condition monitor and interface systems incorporate a 32 bit microcomputer as an analysis computer and separate 16 bit microcomputer based operator and engineer's work stations. This supports all system analysis and diagnostic programs, and other data management programs. The advantages of this configuration as illustrated in Figure 1 are as follows:

- The I/O bus allows sequencer and controller, and condition monitor to communicate bidirectionally. Sequence and control functions can be affected according to condition, and a condition monitor can incorporate and relate to sequence and control modes.
- Condition monitoring system can back up controller at a derated level.
- Input information from modules is scaled in engineering units, calibration is exact in both systems, and software overhead is minimized.
- I/O modules can be located remotely (close to the transmitters) therefore simplifying the wiring burden.
- I/O modules perform diagnostics on themselves and I/O loops. Hardware diagnostics are communicated to controller and condition monitor via I/O network.
- Failsafe modes of I/O points are configurable to the individual module and point.

General Description of Turbine Sequences/Controller

The turbine sequencer/controller consists of a programmable logic controller with local area network tied to "smart" I/O modules. This system, though it intends to interface with the analysis microcomputer for protection and fault tolerance, was designed to be a stand alone system to continue running the turbine in the event that the analysis microcomputer or the condition monitoring were to fail. The PLC controller is designed so that if certain main control signals fail, fault tolerant data from the analysis computer will be used to keep the unit online.

The functions that the turbine sequencer/controller provides the overall system include, but are not limited to, the following:

- Provides sequence logic control and PID loop functions.
- Throttle processing

- Fuel metering valve position
- Fuel shutoff valve control
- Acceleration control
- Deceleration control
- Power control
- Speed control
- Starter control
- Turbine temperature control
- Generator performance monitoring
- Generator permissives
- Main breaker permissives
- Generator cooling system control
- Oil system control
- Oil cooling system control
- Air filter monitoring and control
- Enclosure ventilation control
- External trip system response

Functionalities of PID controls, sequencing, alarming, and protection reside within the turbine sequencer/controller module.

General Description of Turbine Speed Microcomputer

The turbine "speed micro" digitally counts pulses from two separate gears and magnetic pickups and performs a comparison of the highest readings and communicates them to the system. The speed micro also is used as an overspeed protection device. Overspeed conditions will be immediately sensed and an independent output of the speed micro will shut down the turbine via the trip valve.

The speed microcomputer monitors the various machine rotor speeds for stability, value, and rate of change. Of special concern is the detection of a runaway acceleration of the power turbine rotor due to loss of a coupling. This failure usually results in a catastrophic failure of the machine. The speed micro can shut the machine down under runaway acceleration conditions. The speed micro is designed to take data at a minimum rate of 60 points/second.

General Description of the Gateway Communications Manager and Local Operator Station

The gateway is the interface between the local I/O data network and the condition monitoring data network. Further, the gateway microcomputer contains control and protection functionalities that will backup (in manual) the PLC turbine/sequencer in the event of its failure. The gateway microcomputer is also a backup operator station.

The local operator station (gateway) provides the following functions:

- Gateway between the PLC bus and local area network software manager (operator station, engineering station, and analysis computer)
- Local operator user interface
- Automatic clearing of fault tolerant permission bits

General Description for the Turbine Analysis Computer

The turbine analysis microcomputer performs aerothermal analysis, and the expert rules analysis functions. A 140 MB hard disk resides within the analysis microcomputer for historical events retention. The system is used to automatically initiate the retention of raw and calculated data when triggered by a predetermined event (trip or startup). The analysis computer records and submits to the operator station printer all alarms and events with a time and date stamp. The analysis microcomputer

is responsible for providing estimated values for failed critical signals, and computing aerothermal performances of individual gas turbine components. Additional monitoring information (nonessential for controls) is made available to the system via the turbine analysis microcomputer from remote data acquisition units.

The turbine analysis computer provides for the following functions:

- Engineering unit conversion
- Alarm status comparisons for analysis points only
- Analysis point calculation
- Turbine and turbine subsystem diagnostics
- Diagnostic message generation
- Turbine control fault tolerance permission bit setting
- Aerothermal calculations
- Data Capture trending file generation
- Main storage for trend and data capture files

General Description of Engineer's Work Station

The engineer's work station is the diagnostics window into the online operating system. Shift diagnostics and status reports can be generated from the engineer station. The engineer station will further allow for the authorized modifications and additions to expert rules and operator graphics to the system. The engineer's work station can also be used as a backup operator station if located in the control room. The engineering station provides the following functions:

- capability to change database parameters
- view current point values, status, and trends
- review alarm history
- view vibration data collected by the turbomachinery vibration analyzer
- capability to change PID and sequence tuning parameters

General Descriptions for Main Operator Station

The main operator station will provide the operator with all the necessary information for running of the turbine in a user friendly manner via a standard graphical user interface (GUI). Soft keys, membrane keyboard, and optional track ball pointing device are used to enhance the simplicity of operation.

The operator station provides the following basic capabilities to the operator:

- Primary user interface for operator control of analog setpoints for speed, load, etc., and digital push buttons for start, stop, etc.
- View current point values, status, and trends
- Review alarm history
- Primary alarm annunciation and acknowledgement

General Description for Turbomachinery Vibration Analyzer (TVA)

It is possible for the system to incorporate a turbomachinery vibration analyzer (TVA), which provides the analysis microcomputer with additional mechanical turbine information. The turbine vibration analyzer ties directly into the condition monitoring network.

The eight or sixteen channel TVA provides for the following vibration analysis capabilities that can be obtained on demand [4]:

- Time waveform snapshot
- Fixed frequency span spectral snapshot
- Order tracking spectral snapshot

- Order tracking unfiltered orbit
- Order tracking filtered orbit
- Fixed frequency span transient capture
- Order tracking transient capture

When the optional TVA is present, the results of analysis of vibration, and dynamic exceptions are sent to the Turbine Analysis Computer for trending. The Analysis Computer sends specific requests for analysis information to the TVA. Requests for on demand vibration data will be directly from the engineer's station to the TVA and responded to the engineer's station via the local area network.

The vibration data analyzer utilizes a 32 bit, microcomputer based, dynamic data acquisition system which has the capability of "order-tracking" spectral amplitude and phase measurements to one of four key-phaser inputs. The vibration data analyzer hardware specification includes eight or sixteen programmable low-pass, antialiasing filters (digitally programmable from 20 to 20,000 Hz in 1-Hz increments), eight or sixteen gain ranging amplifiers (gains of 1, 2, 4, and 8), an integral four-channel, key phaser or rotating speed sensor interface (1 to 150,000 pulses-per minute) with software programmable division for multiple-pulse-per-revolution speed signals, and an integral A/D pacer clock, eight or sixteen separate but simultaneously triggered 12 bit analog-to-digital converters with integral dual 128 Kilobytes on-board RAM buffers, 16 bit parallel input/output port (IEEE-488), and 10 Mbit/sec local area network interface.

DATABASE CONFIGURATION

The database for such a system must be uniquely designed to incorporate relevant turbomachinery related facets which require database components to be related to each other. For example, an abnormal rise in bearing temperature may result in accelerated spectral data taken on that point.

The database of information used by the fault tolerant gas turbine control system consists of the following separate databases:

- Analog input database
- Digital input database
- Analog output database
- Digital output database
- Vibration probe database
- Vibration analysis group configuration database
- Diagnostic map database
- Trend group database
- Summary chart database
- Bar chart database
- Panel layout database
- Mimic database
- Mechanical component identification database
- Combined mechanical diagnostic rule database
- Diagnostic rule group database

The information contained in the group of databases cited above include descriptions of analog, digital, and vibration inputs from a rotor system (both measured and calculated), descriptions of the groups of inputs for processing and the analysis procedure configuration for each group, descriptions of the expected mechanical or performance response or limiting responses for various severity indices via maps. Mechanical component identification is provided of vibration sources and associated frequencies or orders, descriptions of expert diagnostic rules to process and diagnostic messages to present to the operator, expert diagnostic rule groups to process when a specific event occurs. A description of the calibration parameters for the analog and dynamic data recording system is also included.

Analog Input Database

The analog input database provides the system with a description of measured "control" and "analysis" analog inputs and calculated analog input variables. Measured control analog input variables are passed to the gateway computer from the PLC analog input blocks. Measured analysis analog input variables are passed to the system via the serial port from a separate remote data acquisition Unit (RDAU). Measured analog input variables are typically of 12-bit resolution and represent 4-20 ma DC or 0-10 Volt DC. These are proportional to specific engineering variables such as turbine load, exhaust gas temperature, compressor discharge pressure, peak-to-peak (pk-pk) displacement, root-mean-square (rms) displacement, acceleration in rms g's, velocity in in/sec rms, turbine load, average exhaust gas temperature, bearing metal temperature, lubrication oil flow and lubrication oil temperature, and pressure drop across air and oil filters. Calculated analog input variables include variables such as average exhaust gas temperature, exhaust gas temperature spreads, aerothermal parameters, vibration time-domain statistics and running-speed order related harmonic spectral peak amplitude and phase, variables algebraically related to other analog inputs, and variables algebraically related up to three diagnostic maps. The analog input database also includes the validity, alarm, and danger limits and the number of a diagnostic rule group to process, if the analog input limit status changes. Analog inputs including the numerous conversion types including linear conversions, integration, thermocouples and RTD conversions etc.

Digital Input Database

The digital input database provides the system with a description of both measured and calculated digital variables of BOOLEAN (TRUE or FALSE) format. Measured variables are passed to the system from the gateway computer via the local area network. Calculated digital inputs include the outputs from 16-input gates, data latches, one shot multivibrators, Schmidt triggers (analog input comparator with hysteresis). Typically one digital input or a group of digital inputs (via a gate) may indicate when the rotor system enters an abnormal or transient condition. A status change of a digital input variable can also be associated with a diagnostic rule group. The measured or calculated digital input variable status change can then be used to schedule a group of mechanical diagnostics or fault tolerant rules for processing.

Analog Output Database

The analog output database provides the system with a description of up to 16 PID loops. This description includes, PID loop tagname and description, associated feedback, and setpoint tagnames, setpoint alarm limits, and PID loop tuning parameters. In addition, this database defines the scaling for the display of the setpoint control windows.

Digital Output Database

The digital output database provides the system with a description of digital output variables. This is similar to the digital input database but includes pushbuttons for operator controls for on/off start/stop operations, with up to 15 permissives per button.

Multiple Trends Database

This permits multiple trends for visual display. Up to eight points may be viewed simultaneously. This is a very valuable feature during startup.

Vibration Probe Database

The vibration probe database provides the system with a description of variables measured via the eight or sixteen dynamic data acquisition channels and 4 speed sensors. Variables in this database include, but are not limited to, tagname, description, probe type units, conversion factor, default data analysis settings, associated speed sensors, associated analog points and spectral envelopes.

Vibration Analysis Group Configuration Database

When an automated vibration data analyzer unit is being used to capture data that characterizes a transient condition of a gas turbine, spectral data can be acquired and stored in the computer's RAM using the following quantitative criteria defined in a vibration analysis group database file established by the user by means of a Vibration analysis group dynamic database form. Parameters defined in the vibration analysis group database include 16 probenames, speed sensor channel, data acquisition mode (fixed span or order tracking), delta time, delta speed, and delta amplitude.

A unique feature of the vibration analysis and trending system is its ability to acquire spectral data conditionally based on the criteria encoded in the delta speed, delta time and delta amplitude parts of the vibration analysis group database. These instructions to the computer trigger the acquisition of data at relatively short time intervals whose length is adjusted according to the apparent suddenness of the sensed changes. When a transient is initiated, the instructions of the delta parameters in the configuration database enable the system to capture automatically the detail of the transient response of a rotating machine in a waterfall display. During steady state operation, the system permits data to be acquired at only preset time intervals of the operator's choosing.

Diagnostic Map Database

Each map in the diagnostic map database consists of a set of ten x, y pairs for one to ten z values. This data is used to generate the coefficients required for three-dimensional interpolation of the described function or "map." Given the analog input variables x and z, the resulting y value may be obtained via interpolation techniques and stored as another analog input or used in conjunction with a vibration or combined mechanical diagnostic rule. The x variable could represent variables such as time from startup, running time, running speed, etc., the z variable could represent ambient temperature, load, severity index, etc., and the y variable could represent analog variables load, exhaust gas temperature, etc., or analog variable related to vibration deflection, velocity, acceleration, or phase, etc., at any selected ratio to the running speed.

Mechanical Component Identification Database

Each mechanical component of the rotor system described in the mechanical component identification database may have up to 16 fixed or order tracking frequencies defined as potential excitation sources. Each excitation source has an associated iden-

tification code and identification message. This database is used in conjunction with the vibration probe spectral envelopes in the generation of diagnostic messages and are also used by the display programs.

Combined Mechanical Diagnostic Rule Database

Each combined mechanical diagnostic rule consists of 20 subconditions (comparisons), "weights" for each subconditions, a diagnostic message, and eight qualifiers. When a combined mechanical diagnostic rule is processed, the result of each subcondition test is weighted and combined via the logical AND, OR, NOR, NOT, and NAND operations. The result of the combined mechanical diagnostic rule analysis procedure is a number whose range is 0.0 to 1.0, which can be divided up into eight ranges. Each range has an associated diagnostic message qualifier.

The types of comparison possible for each subcondition include the following:

- Single value comparison
- Comparison to 2-D map
- Comparison to 3-D map

Each rule may be used to schedule another rule or list of rules. Each rule may be used to set a digital output (fault tolerant rule).

Diagnostic Rule Group Database

The diagnostic rule group database is used to define a related group of diagnostic expert rules to process conditionally based on a change in status of an analog input, digital input, analog output, digital output, or vibration probe. Each diagnostic group consists of a group name, description, and list of up to 16 diagnostic rules.

Analog Analysis Database

This contains the information and procedures for the exhaust gas temperatures analysis procedures and for aerothermal analysis. This database is used to construct a model of any given compressor turbine configuration for the purpose of performance analysis. Typical models include single or twin spool turbines with or without load compressors. A list of analog points related to the given machine train is defined by the engineer.

Report Generation Database

This permits the choice and formatting of printed reports.

Mimic Display Database

This permits the generation of mimics by the user using standard graphical picture generation software.

TURBINE ANALYSIS PROCEDURES

The control system described herein is intended to provide operators and engineers with thorough information on the health and performance of the turbomachinery. By having this improved visibility, users can make informed decisions to improve maintenance scheduling, improve safe operational performance, and reduce mean time to repair.

Aerothermal Analysis Procedures

The analysis and diagnostics functionalities of the system involve aerothermal performance analysis, mechanical analysis coupled with rule based diagnostics. Performance analysis is based on the current ambient conditions, fuel intake, and the operating load or speed. Aerothermal performance analysis will consist of efficiency presentations of the compressor and turbine

sections based on corrected conditions. Results of the analysis include compressor and turbine adiabatic efficiencies and power, temperatures, pressures, and flow rates at different sections in the machine train, thermal efficiency and heat rate. The results are presented based on corrected conditions and compared with the performance maps for the machine. Operators, maintenance personnel, and engineers will be able to monitor performance degradation and deduce the best maintenance schedules for compressor cleaning, inlet air filters maintenance, turbine cleaning, and nozzles changes. Some rule based diagnostics are based on these comparisons.

Mechanical analysis will provide for lube oil systems, bearings, auxiliaries, and vibration analysis. In addition to the traditional monitoring capabilities, items such as oil drains, water cooler inlet and outlet temperatures (on both oil and water), thrust bearings, babbitt temperatures, lube oil tank (level and temperature), control oil, and torque converter pressures may be monitored.

Diagnostics Rule Analysis Procedures

The authors believe that expert rules based diagnostics to be one of the most important features of a future control system. An expert rule base can be the foundation from which the system could announce problems and required corrective actions, automate fault tolerant actions, and restrict actions (permissives) or loading. The expert rules should be expandable and allow the ability to incorporate additional "rules" as experience on turbine operations and performance. Rules have to be tailored for each application.

The expert rules generate messages or actions based on the "IF-THEN" approach. Up to 10 parameters (subconditions of "if" statements) can be compared to formulate a single rule. Results from up to 10 rules can be used to further formulate an additional rule. Rules are also "weighted" (prioritized) to allow for decisions of higher significance to prevail. The system being designed can accommodate approximately 100 rules, but expansion will be possible.

As rules get formulated, they will be presented on the operator screen with a tag name of up to 15 characters. This will prompt the operator to press the "Help" soft key which will provide detailed information on the problem and required corrective action. With the operator and technician knowing which piece of equipment failed (e.g., pump or breaker), the mean time to repair can be reduced.

Predictive Maintenance

A 1983 EPRI study indicated the annual maintenance cost per horsepower on turbomachinery was \$7 to \$9 dollars for predictive means, \$11 to \$13 dollars for preventive means, and \$17 to \$18 dollars for corrective means [3].

Predictive maintenance optimizes inspections and overhauls schedules through the use of "condition directed" maintenance. Turbine components, that under normal preventive maintenance procedures are replaced on an empirical time schedule, would now be replaced on a more cost effective basis. The following examples of "expert rule diagnostics" shows features that help make maintenance decisions. All such rules have to be tailored to particular machines and operational conditions.

Clogged Air Filter Diagnostic Message

Differential pressure transmitters across the turbine inlet air filter and generator air filter could note the proportional pressure drop through the filters, and be able to diagnose the most economical maintenance schedule.

Compressor Fouling Diagnostic Message

Compressor fouling is indicated by the decreasing axial compressor discharge pressure, mass flow and an increase of exhaust

temperature. It is possible to optimize the most economical cleaning schedule based on a trade off between cleaning costs, downtime costs and penalty cost of degraded operation.

Seal Leakage Problems Diagnostic Message

Increases in fuel flow, compressor discharge pressure, and turbine temperature will most likely indicate seal leakage problems which need to be corrected.

Foreign Object Damage Diagnostic Message

Reductions in ratio pressure or PCD and shaft horsepower, coupled with increases in turbine inlet temperature would indicate damage or fouling to the compressor, or foreign object damage.

Bearing Failure Diagnostic Message

Bearing failure on a bearing can be forecast by monitoring changes of bearing metal temperatures and vibration overtime. This evaluation would consider lube oil temperature as a reference. If oil whirl exists, there would be a vibration frequency corresponding to one half the running speed, noting specific degradations of bearings can be utilized to help establish the most cost effective schedule to replace them before rotor damage occurs.

Plugged Nozzles Diagnostic Message

Plugged nozzles can be found by noting an increase in combustion unevenness. Fuel pressure to the nozzles should also be monitored as a further possible indication of plugging. Effectively diagnosed, fouled nozzles can allow for safe derated operation of the machine until maintenance can be scheduled to correct the problem.

Combustor Related Problems Diagnostic Message

Combustor problems normally result in large spreads in the exhaust gas temperatures and possibly an increase in vibration readings. The preceding subsections outline some of the bases by which expert rules can be developed for predictive maintenance and avoidance of catastrophic failures. Users will be able to gain efficiency and improve maintenance scheduling by having information readily available from the control systems presentations. Users will further improve on the time taken for overhauls by knowing the exact components to be replaced or repaired, so that proper parts and manpower resources can be scheduled in advance.

Diagnostics Rule Processing for Fault Tolerant Considerations

Turbine systems can be analyzed by using complex relational aerothermal modelling techniques information to determine overall deterioration, and to determine what specific components (or sets of components) causes the deterioration. The system uses relational aerothermal performance information and expert rules to determine the health of components as well as fault tolerant considerations for failed transmitters. Typical transmitter failures which can be backed up with relational performance or aerothermal information are presented in the following subsections. Fault tolerant and fail safe considerations are summarized in Table 1.

Exhaust Temperature Sensor Fault Tolerance

Depending on the turbine type, the system incorporates 12 to 18 exhaust temperature thermocouples for monitoring, the average of which can be used as a calculated setpoint for controls. The calculated average will take all failed or high spread signals from the averaging equation. The system can incorporate two exhaust temperature thermocouples for fault tolerance. These reside within the controller hardware.

Table 1. Systems Fault Detections & Reactions Matrix.

	FAULT	FAULT TOLERANCE	FAILSAFE
1.	Exhaust Temperature Monitoring Thermocouples	Back up with average of 2 control thermocouples	N/A
2.	PCD Pressure	Estimated from Aerothermals	N/A
3.	Turbine Speed	When on-line monitor gen. frequency for protection	If generator breaker opens initiate operator action
4.	Load Signal (KW)	Use calculated from current & voltage. If PT's or CT also fail control on EGT.	N/A
5.	PLC Controller	Gateway microcomputer will allow manual control of turbine.	N/A
6.	Analysis Microcomputer	Will continue running but cannot incorporate further fault tolerance	N/A
7.	Gateway	Will run "blind" on load control, protective systems still o.k.	N/A
8.	I/O "Local Network"		I/O modules programmed for safe shut down
9.	Main Operator Station	Backed up by "local operator station" & engr. workstation	N/A
10.	Condition Monitor Network	Operate from "local operator station"	N/A
11.	Engr. Workstation	Not necessary for control, condition monitoring operation	N/A
12.	Analog Output to Fuel Throttle	Redundant outputs to fuel throttle valve	N/A

Axial Compressor Discharge Pressure (PCD) Sensor Fault Tolerance

If the PCD signal is lost, PCD pressure may be estimated from aerothermal information based on inlet air conditions and speed/load.

Turbine Speed Sensor Fault Tolerance

The system may be designed to operate online with lost speed reference if tied to the bus. A generator load signal must be present, and if the generator load breaker is lost, the controller will drop speed for a preset minimum valve limit and stay steady state as long as EGT is within range. The operator would then initiate corrective action(s) and go back online or initiate a controlled shutdown. This system will not support isochronous operation if the speed signal is missing.

Load Signal Sensor Fault Tolerance

The load signal may be backed up by calculations based on separate current and potential transformers coming into the system. In the event that these fail, the turbine can operate on exhaust gas temperature control.

Turbine Controller Fault Tolerance

The controller algorithm and needed protected systems will also reside in the "gateway" microcomputer, which is tied to the I/O bus network. This allows the gateway to be a backup manual controller, once the system is on line. Automatic startup sequencing would not be supported by this configuration. The PLC based turbine sequencer/controller can also operate as a

stand alone unit in the event of a failure of the gateway and/or analysis/diagnostics microcomputer.

As it is essential to maintain reliable operation of the turbine generator system, the aforementioned fault tolerant schemes are incorporated into the system. Further, several failsafe modes are incorporated to maintain maximum safety of the systems. To accomplish fault tolerance and failsafe modes of operation, an important design consideration is that of diagnostics of both turbine system and controller hardware. The following diagnostics will ensure that each critical subsystem is carefully monitored and diagnosed.

I/O Modules Fault Tolerance

The I/O modules have self diagnostics and loop integrity diagnostics features. Output modules are also programmable to a failsafe mode if all else fails (local area network, or analysis and turbine/controller modules). Each output point on each module, whether discrete or analog, is individually programmed to a failsafe mode to maintain maximum safety of the system.

PLC Controller Fault Tolerance

The PLC turbine controller/sequencer performs self diagnostics of its CPU, memory systems, and communications systems. In the event of a failure, this failure is communicated to the condition monitoring and interface systems via a local area network (I/O bus) to allow the gateway communications microcomputer to operate as a backup controller.

Analysis Diagnostics Microcomputer Fault Tolerance

The system's software makes it possible for all of the microcomputer systems on the network to operate with full visibility of the health of every other subsystem. The failure of the analysis microcomputer is communicated to the PLC via the I/O bus, to allow the controller to continue running the turbine systems and bypass the above mentioned expert rule diagnostics.

Operator Station Fault Tolerance

A backup local operator station can be installed in the system directly off the I/O bus network. This allows for a backup mode of operation in the event of the failure of the main operator station. The engineering workstation (microcomputer) should be designed to be used as a backup to the operator station. The engineering workstation could be used by engineers to develop special reports and for modification of rules and databases.

Turbomachinery Vibration Analysis Procedures

The turbomachinery vibration analysis unit has the capability of performing the following analysis functions which follow those of Muster and Muster [5]:

- Vibration analysis group data acquisition scheduling
- Vibration analysis group data acquisition processing
- Vibration analysis group engineering unit conversion
- Time domain segment statistical analysis
- Synchronous time domain segment averaging
- Time domain windowing
- Transformation from time domain to frequency domain
- Single channel spectral analysis
- Two channel cross spectral analysis

- Single-input single-output transfer-function analysis
- Frequency domain averaging
- Synchronous single channel phase response
- Ensemble averaging
- Order tracking harmonic amplitude and phase analysis
- Frequency domain spectral data comparison
- Mechanical system expert rule diagnostic analysis

Computational details of the above can be found in the Muster and Muster article [5].

OPERATOR INTERFACE, DISPLAY AND REPORT FORMATS

The operator interface consists of 16 groups of sixteen panels. Each panel consists of one screen presented as a matrix (six rows by four columns) of windows in a format similar to an annunciation panel. Each window represents an object such as an analog input, analog output, digital input, digital output variables, trend groups, summary charts, bar charts, mimics, diagnostic rules, etc. The specific mode of operation of the workstations is enabled via the function keys and main menu. The various modes of operation selected via the function keys include the following:

- Help
- Alarm acknowledge
- Select next panel
- Select last panel
- Display mode
- Database add
- Database edit
- Delete output
- Output control enable
- Enable menu

The database add, edit, and delete function are enabled by default at the engineering workstation, whereas the output control function is disable. At the operator workstation, the database operations are by default disabled, whereas the output control function can be enabled by the operator.

In both workstations, the main menu enables the operator to select the group and panel desired for display. Each panel and group has a 40 character title associated with it to simplify operation for the user.

The groups of panels facilitates both selection and display functions for each object defined in the system. If the workstation is in display mode, the operator simply moves the cursor to a specific window, via the membrane keypad cursor keys or trackball, and then selects the window for full screen display, via the enter key. Possible full screen displays include, but are not limited to, the following:

- EGT polar plot and EGT spread bar chart
- summary charts
- bar charts
- trends of analog input variables
- XY diagnostic maps
- status change event log
- diagnostic message log

In addition, vibration displays are also available as enumerated in Muster and Muster [5].

CLOSURE

Analysis indicated that availability improvements for combustion generating plants should focus on:

- Incorporation of fault tolerance to instrumentation and controls.
- Optimizing of inspection and overhaul schedules.
- Avoidance of catastrophic incidents.

The system outlined herein intends to accomplish the above, incorporating expert rules and performance analysis and a condition monitoring system. Inspection schedules and overhauls constitute over 20 percent of all outages in combustion generating plants. The scheduled inspection and overhauls are necessary to prevent catastrophic failures which result in extended downtime (sometimes in excess of three months), in addition to the direct cost of repairs.

Instrumentation and controls have improved significantly in reliability and capabilities. Proven 16 bit PLC based controllers and "smart" I/O modules offer complete control and sequencing functionalities at greatly enhanced speeds from previous technologies. These controllers also feature hardware diagnostics and annunciation, even to the point of certifying output loops. Maintainability is further improved with the ease of replacement of modular components and minimal calibration requirements.

Computer hardware is becoming faster and more sophisticated and capable of storing ever larger quantities of data. These developments have had a synergistic effect on algorithms and analytical methods that, when they were conceived, were viewed as impractical, theoretical curiosities. In today's technical environment, they have taken on new life as decision-support tools for operating engineers and, in turn, they have resulted in the true integration of control systems and real time, online health analysis.

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