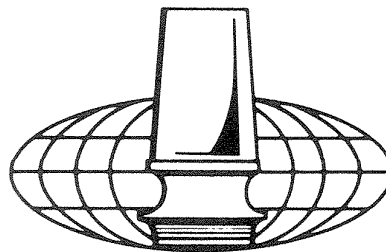


General Electric SPEEDTRONIC Control Systems



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INTRODUCTION

General Electric's gas turbines are controlled by the SPEEDTRONIC* electronic control system, which provides fully automatic control of the gas turbine and load system. This control system employs the latest electronic technology, including integrated circuits and microprocessors to carry out control, sequencing, and protective functions. The system includes sensors and servo actuators mounted on the turbine to provide input and output interfacing for the control system. Reliability is achieved through redundancy for key control functions, such as speed and temperature control. High performance, accuracy, and fast response, with virtually no deadband, is achieved by electronic computation and the use of high resolution hydraulic servos. The protective system is virtually independent of the control equipment and employs a high degree of redundancy to assure reliable and safe machine operation.

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GENERAL ELECTRIC
USA

The design of the present SPEEDTRONIC MARK II control is based on 10 years of experience with electronic controls for heavy-duty gas turbines. The first electronic control (SPEEDTRONIC MARK I) was developed in 1967, was commercially introduced in 1969, and was highly successful. MARK II SPEEDTRONIC was introduced across the product line in 1973, and employed solid state and integrated circuits for logic and computation functions for further performance and reliability improvements. Micro-processors were incorporated into the control system in 1976 and made such complex functions as combustion monitoring practical.

The control system design is employed across the product line from the LM2500 to the MS9001. Standard options are in place so that the control can be used for a variety of applications, such as remote, unattended utility peaking gas turbines, base-loaded industrial generator drives, remote pipeline pumping stations, etc.

Today users all over the world have General Electric gas turbines with SPEEDTRONIC control systems in operation and these units have accumulated millions of hours of operating experience since initial shipments in 1969. These units are in service in applications as varied as utility, marine, pipeline, process and combined cycles in ambients that vary from plus to minus 50 C. A significant number of these units are offshore with several hundred located in Russia, the Mid-East, Africa, Australia, South America and Asia. This experience has shown the SPEEDTRONIC control to be highly successful.

FUNCTIONAL DESCRIPTION

Control Arrangement

The two major areas that comprise the turbine control system are the turbine control panel, which contains the computational electronics, and the machine mounted sensors, devices, and actuators to provide input/output functions.

The turbine control panel also serves as the human/machine interface with the turbine. To meet the wide variety of possible applications, several arrangements for the location of the turbine panel are available. For peaking units, a control cab located at the front of the turbine as shown in Fig. 1, is used to house the panel. The cab also contains other equipment such as the generator panel, motor control center, and battery. When several units are located at one site, all the turbine panels may be packaged in a single control cab for operator convenience. Industrial units typically have the turbine panel located in a control room along with

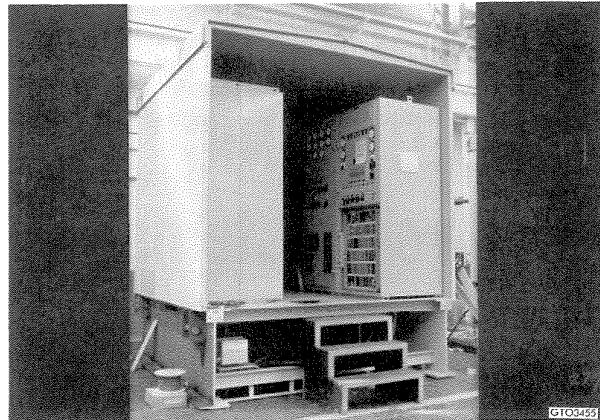


Figure 1

controls for other equipment. An arrangement used frequently for pipeline pumpers and platform installations is the Modular Electrical Control Center (Fig. 2). This assembly includes the turbine control, load control, and station control, all integrated in an enclosed assembly which has walk-in access for maintenance. A key advantage of this arrangement is that much of the interconnecting wiring and testing can be carried out in the factory, thus minimizing the field connection time. Although the control interfaces many systems, primary emphasis in this paper is on the turbine control panel.

The SPEEDTRONIC system performs the following functions:

1. Control of turbine output power over the load range.
2. Limits maximum output consistent with unit capability.

MODULAR ELECTRICAL CONTROL CENTER

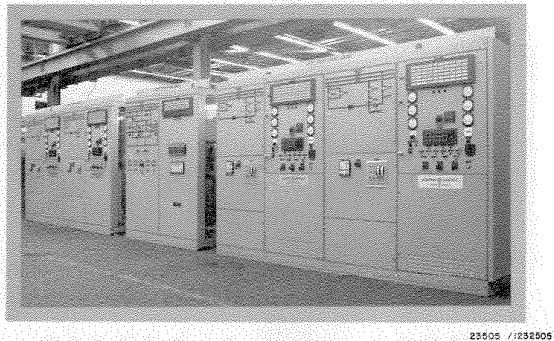


Figure 2

3. Sequencing of unit auxiliaries and turbine control parameters during gas turbine startup.
4. Protective shutdown of the gas turbine in the event of a non-recoverable system failure of the controls, turbine, or auxiliaries.
5. Monitoring and annunciation of malfunctions within the gas turbine, the auxiliaries, and the control system.

Primary control of the gas turbine is accomplished by controlling the fuel flow to the combustion system. On some units, fuel control is supplemented by varying cycle air-flow by means of changes in compressor speed or the position of variable inlet guide vanes to improve partload performance in applications involving exhaust heat recovery. Fuel flow, in turn, is controlled in response to the speed control system, the temperature control system, or the startup control, whichever of the three requires the least fuel.

Speed/Load Control System

The gas turbine speed control, or governor, controls the speed of the turbine output shaft.

The characteristics of the speed control can be either isochronous (speed precisely held to setpoint regardless of load), or droop (speed decrease with load). In generator drive applications, where the gas turbine operates synchronized to a large system, a droop governor characteristic is used, and the speed control inherently performs the load control function as illustrated in Fig. 3. While in this oper-

ating mode, the speed control function is still present and always active, except when the gas turbine is at maximum allowable exhaust temperature.

The speed control operates the turbine in response to the setpoint. On isochronous control, turbine speed is exactly equal to the setpoint. On droop control with the generator synchronized to the system, the setpoint determines turbine load. In addition, the rate of change of the setpoint determines turbine loading and unloading rates. Preselected load points and load/unload rates are provided. The input command to the setpoint controller comes from either the local switch on the turbine or generator panel, or from a remote raise/lower switch. For generator drive gas turbines, the load may also be set by a load limiter which has as its input a signal proportional to generator load. The load limiter normally has capability for three values of load limit; spinning reserve, an intermediate preselected load, and maximum load.

In most mechanical drive applications, gas turbine output is a function of the speed of the driven equipment. In this type of application gas turbine speed is not synchronized to any system, and an isochronous governor is used.

Temperature Control System

The temperature control system is designed to limit the firing temperature of a gas turbine to a maximum value, corresponding either to base or peak operating conditions. A typical temperature control characteristic is shown in Fig. 4. The slope of the temperature control lines is selected to maintain a constant firing temperature over the full operating range of ambient conditions. In addition, the exhaust

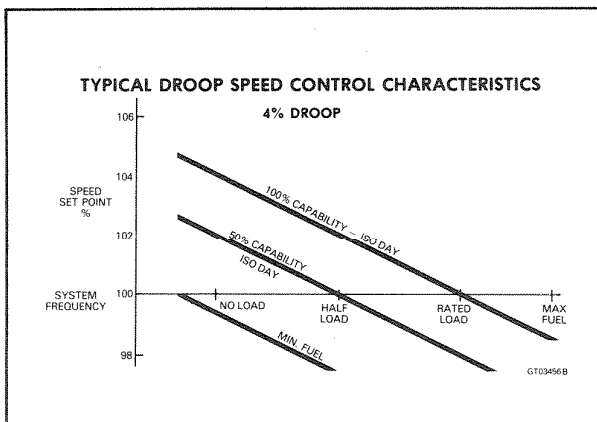


Figure 3

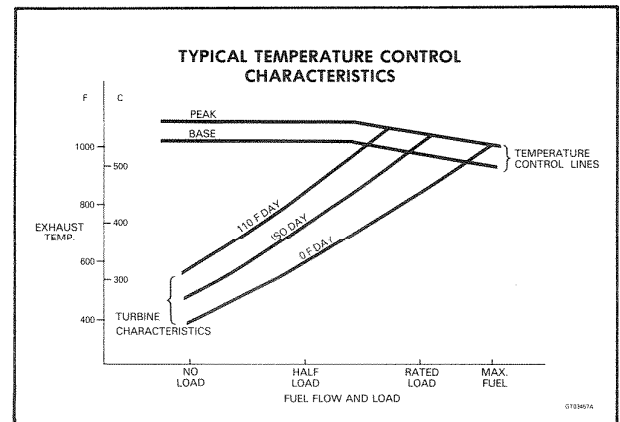


Figure 4

gases are limited to approximately 1000 F, under all operating conditions, to protect the exhaust system. The LM2500 temperature control limits the inlet gas temperature to the load turbine to a constant value.

The temperature control system on all single-shaft units employ an Integrated Temperature System (ITS) which will be described later.

Gas turbines, in applications associated with heat recovery, may be designed to operate with varying airflow over the load range to maintain maximum exhaust temperature for optimum heat-rate at part load. This change in airflow is accomplished in two ways; by varying compressor inlet guide vane angle, or by varying compressor rotor speed, or both. This latter method of varying airflow is unique to two-shaft gas turbines having variable area second-stage nozzles. In these gas turbines the axial flow compressor is driven by the first, or high-pressure stage, of a two-stage axial flow turbine. The second stage or load turbine is connected to the driven equipment. There is no mechanical connection between the two turbine stages, thus allowing them to run at different speeds. However, they are aerodynamically coupled by the variable area second-stage nozzles which vary the division of available energy between the two stages, thus allowing independent control of the compressor speed, and therefore cycle air flow. The resultant part-load characteristics are shown in Fig. 5. The LM2500, does not have the variable area nozzle and provides variable airflow over the load range by a wide speed range for the high-pressure set (5000 to 9800 RPM).

Startup Control & Sequential System

The startup fuel control is operated in conjunction with the sequential portion of the control system that operates

auxiliary devices during a unit start. The startup control provides a means of establishing scheduled fuel flow, as a function of speed and time, during the starting sequence when neither the exhaust temperature nor the unit speed are within range of their respective control systems. Prior to, and during the starting sequence, automatic checks are made to ensure that back-up auxiliary systems and the control system are operating properly. If these checks determine any abnormalities, the situation is alarmed, and the starting sequence is prevented from proceeding. A typical starting sequence for a single-shaft generator drive gas turbine is shown in Fig. 6. The startup of a two-shaft gas turbine is similar, except that in addition, the output shaft, or low-pressure turbine of the gas turbine begins to rotate at about 35-50 percent compressor speed.

Protective Systems

The basic gas turbine protective system is designed to detect abnormal operating conditions and safely shut down the turbine. This is accomplished through separate, redundant shutdown devices. The basic protective functions are: overspeed, overtemperature, lube oil pressure and temperature, loss of flame and vibration. Additional functions such as combustion system malfunction, compressor stall or fire may also be provided, if required by the specific application.

In most cases a protective system shutdown is preceded by an alarm at a lower level. An operator-initiated, manual emergency shutdown feature is also provided. High reliability is attained by a large degree of redundancy in the protective system. At least two means of shutting off fuel (two separate valves) are always provided, and redundant sensors are also provided to key functions.

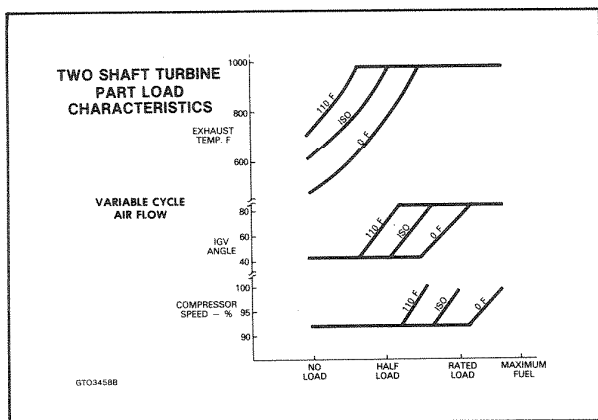


Figure 5

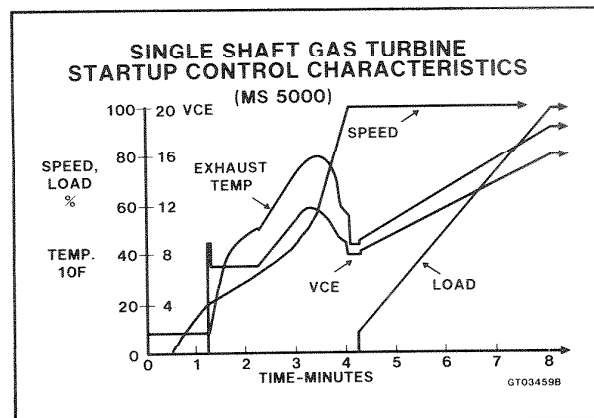


Figure 6

Monitoring System

The gas turbine control system is provided with a multi-point annunciator and supporting circuitry to detect and alarm abnormal conditions in the control system and turbine auxiliaries during startup and unit operation.

The annunciator is provided with a "first out flashing" feature, which causes the first registered fault to flash as an aid to the operator in troubleshooting.

Optional Features

The gas turbine control system is designed to allow the incorporation of special features required by the application. Typical options would include: various fuel combinations, black start, remote operation, deadload pickup and variable air flow control for exhaust heat recovery applications.

Standard control designs are also available for water or steam injection for limiting NO_x emissions. In these cases, a monitoring and recording system that shows operational compliance with EPA requirements is included as part of the control system. Many other features, such as fast start, fast load, automatic load control, black start, power augmentation and inlet heating are available options for the turbine control system.

Operation

Completely automatic startup of the gas turbine plant is initiated by simply giving the gas turbine a start signal with the Master Start/Stop Switch (Fig. 7). Status of the gas turbine, its auxiliaries, and its controls is provided by status

lights on the panel throughout the starting sequence, from a "ready to start" condition through to "complete sequence." Manual startup is provided only to the extent that the automatic sequence can be stopped at preselected points such as "crank" and "fire" (with the operation selector switch) and typically is used only during system checkout. Selection of fuel, for dual fuel units, is accomplished at the panel using the fuel selector switch.

Synchronization and loading of generator drive units is accomplished automatically up to a small load level for spinning reserve. Initiation of a second start signal will cause the gas turbine to load up automatically at a pre-determined rate to the base or peak temperature control point, depending on which was selected at the panel. Provisions are also available for manually synchronizing the generator and manually loading it to any desired level. Monitoring of gas turbine conditions during normal operation is readily accomplished from the various meters mounted on the turbine control panel. In addition, on units with ITS, all measured operating temperatures and all key turbine control parameters can be read out on a current basis by calling for the appropriate listing.

Shutdown from any condition of generator output is accomplished by initiating a stop signal using the Master Start/Stop Switch. Again, unloading and shutdown of the gas turbine is accomplished completely automatically through the end of the gas turbine cool-down sequence. The shutdown sequence can be interrupted, and reversed, at any point prior to opening the generator breaker. An emergency trip push button is also provided for use under abnormal conditions requiring immediate tripping of the gas turbine.

Troubleshooting is greatly aided by use of a 40, 50 or 60 point annunciator, which indicates preselected unit malfunctions, plus those which would cause a normal shutdown or turbine trip. The first annunciator drop will be flashing to distinguish it from subsequent drops that will be indicated by a steady light. Rectification of the malfunction causing the annunciator drops will allow resetting all lamps. Lamp test provisions are also provided to ensure identification of defective indicator lights. On units with ITS, additional information, including historical data of varying age, is frozen in the memory and can be called up in the event difficulty is encountered. Finally, several categories of starts, stops, and operating times are monitored by counters and clock meters, as an aid in planning scheduled maintenance.

In addition to local control at the turbine panel, options are available for remote control by means of the Remote Master Control Panel. Control location selection is accom-

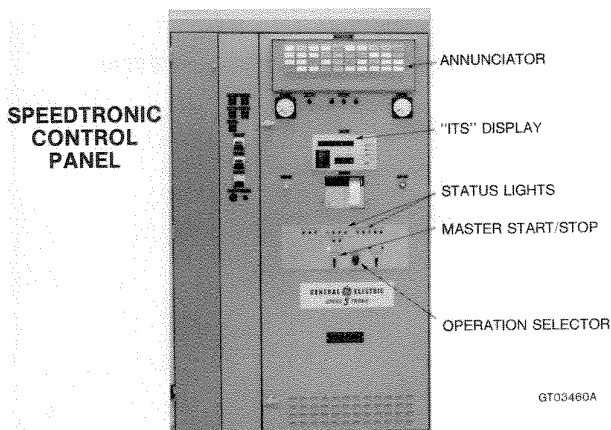


Figure 7

plished at the Gas Turbine Control Panel, thus allowing turbine panel location to take priority of control during abnormal conditions.

SYSTEM DESIGN

The system is comprised of three distinct areas: the control, the protection system and the sequential system as described below.

Control System

The basic philosophy in designing the SPEEDTRONIC control system has been to minimize machine shutdowns resulting from control system failures. Thus, to enhance running reliability, a large degree of redundancy has been employed. In general the failure of one of the redundant systems will provide annunciation, with the unit remaining in operation. Further, in areas where full redundancy is not practical, one functional system serves as a backup for others. For example, the temperature control will control the turbine should the speed control fail. The basic goal in the design of the control has been to maintain turbine operation in spite of control failures, recognizing that process interruptions and shutdowns can be costly.

The fundamental concept in the turbine control is that of a speed governor which commands the fuel control to provide proper fuel flow to the turbine as shown in Fig. 8. The speed control operates through a minimum-value gate together with inputs from the temperature limit and the startup schedule such that the output of the gate, VCE (variable control electronic), is at all times the minimum

fuel command from any one of these four inputs. Thus if the speed control requires more fuel than the temperature limit, the minimum value gate selects the temperature-limit value as the VCE command. The VCE output of the gate drives the fuel control, which in turn delivers fuel to the turbine. The range of the VCE signal is 4 (zero fuel) to 20 (maximum fuel).

Speed Control Loop

When the speed control is in command, the control system appears as the loop illustrated in Fig. 9. The output of the speed control is selected by the minimum value gates to produce the VCE signal which, through the fuel control, provides the required fuel flow to the turbine. The turbine speed is sensed by the speed pickups and compared to the speed command. The speed control adjusts the fuel flow until the desired (command) speed is achieved. On two-shaft units the LP set speed loop controls fuel flow to control low-pressure turbine speed, while the HP speed loop controls the second stage nozzle.

The speed sensors produce an AC voltage with frequency proportional to speed. The sensor is an electromagnetic device located adjacent to a toothed wheel on the turbine shaft and produces a pulse with each passing tooth. The output of the sensor is converted to an analog signal so that voltage level is proportional to speed. In addition to providing feedback for the speed control loop, this analog voltage drives a speed indicator and is used for input signals to the speed relays. The use of this relatively high frequency signal permits the use of a high gain loop having fast response and high transient accuracy. The speed control can be provided with either isochronous or droop characteristics, or as a fur-

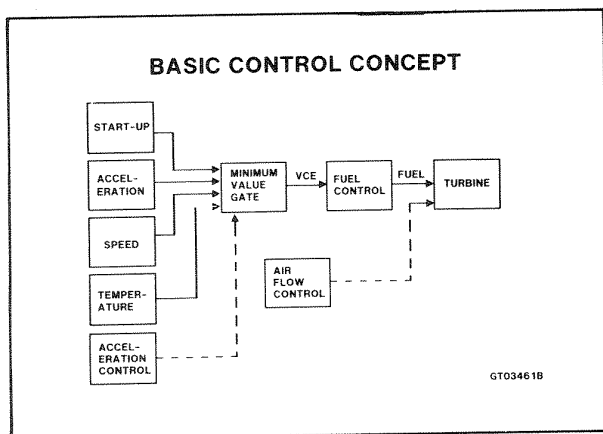


Figure 8

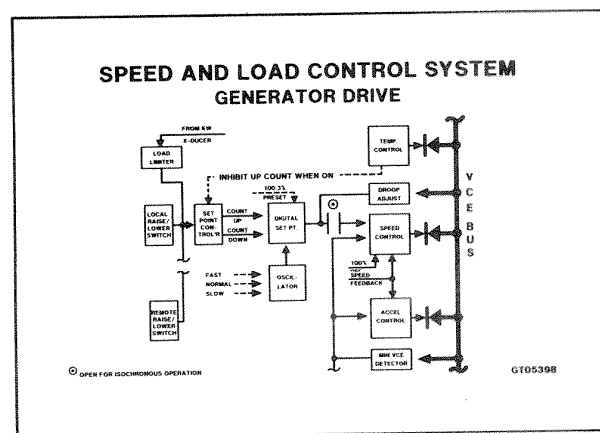


Figure 9

ther option, these can be interchanged by input command. Utility units generally are operated in the droop mode (4 percent typical) but may be isochronous for isolated systems. Mechanical drive units typically are operated in the isochronous mode.

The setpoint for the speed control utilizes an oscillator-driven digital counter. The output of the setpoint provides a DC analog voltage proportional to the count level in the counter. The raise/lower control enables the oscillator to drive the counter up or down, thus varying the voltage of the setpoint. This concept provides an accurate, stable vernier control of the setpoint. Loading and unloading rates are controlled by the frequency of the oscillator, and several rates are available.

Redundant speed pickups are employed and failure of one will not shut down the turbine but will alarm. The integrity of the sensors is checked by continuously measuring the impedances of the sensor with a small DC signal current.

Startup Control

During startup, fuel flow to the turbine is determined by a startup schedule. Since both the speed control and the temperature control during this period will permit higher fuel flows, the minimum value gate selects the startup schedule as shown in Fig. 10. During the initial phase of the startup, VCE is held at zero to prevent fuel flow while the turbine accelerates to firing speed, and purges the gas path. When firing speed is reached, VCE is set at the "fire" level (Fig. 10). When ignition is sensed by the flame detectors, VCE is lowered to the warmup value to minimize thermal shock to hot-gas-path parts. At the end of the warmup period (typically 0 to 1 min) VCE is gradually increased, or

ramped, to a value which will accelerate the turbine to full speed. The VCE ramp, however, can be overridden by an exhaust temperature suppression removal rate limit (typically 2.5 to 5 F/sec) and by a rotor acceleration limit (typically 0.2 percent to 2 percent/sec).

Temperature Control

This control loop limits fuel at startup, or during operation when maximum safe operating temperatures are reached. When the temperature limit is active, the control loop is as shown in Fig. 11. The turbine exhaust temperature is sensed and compared to the setpoint temperature value, and the difference between these values is amplified, and drives the fuel control to achieve the setpoint value. The temperature setpoint is generated by biasing the exhaust temperature with a compressor-discharge pressure to calculate the allowable exhaust for a constant firing temperature as shown in Fig. 11. This setpoint has an upper limit (approximately 1000 F) to protect the exhaust system hardware. The LM2500 temperature control concept differs slightly since temperature is sensed between the gas generator and load turbines and a constant temperature limit is imposed.

The temperature control system is implemented with analog electronic circuits for two-shaft turbine control systems. Single-shaft turbine control systems employ a microprocessor-implemented temperature computation system identified as the Integrated Temperature System (ITS). This computation system carries out the temperature control function in addition to several other functions (combustion monitor, water injection and modulated IGV's) as described later.

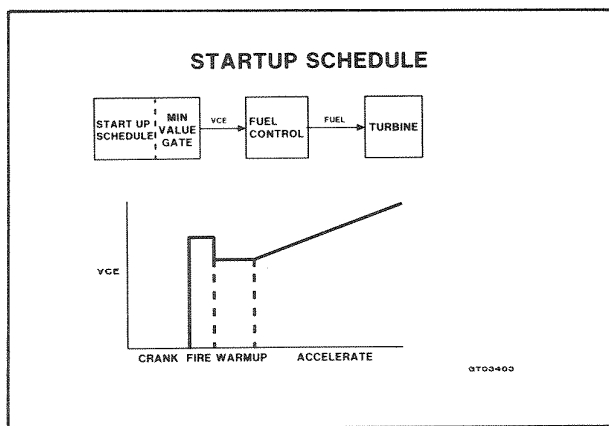


Figure 10

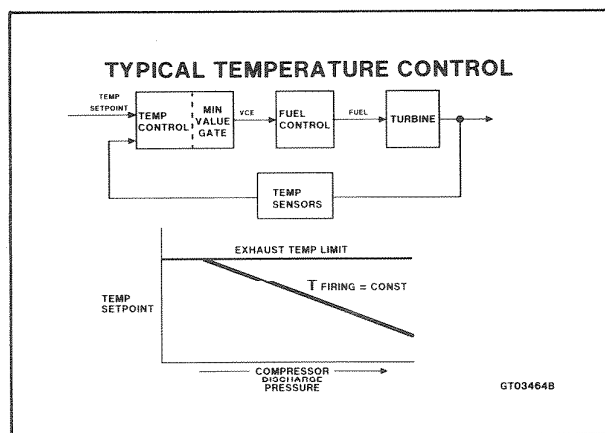


Figure 11

The temperature feedback signal for all turbines is obtained by averaging the output signals from multiple exhaust thermocouples (13 to 22 depending on the turbine). Cold junction compensation is employed to obtain an accurate signal.

Nozzle Control

The variable area nozzle on heavy duty two-shaft units is controlled to provide optimum energy division between the high-pressure and low-pressure shafts. For regenerative units this control loop maintains constant exhaust temperature, by decreasing compressor speed, as load is decreased as shown in Fig. 12. In the upper half of the load region, the nozzle closes with decreasing load to slow down the compressor. At about half-load the minimum permissible HP speed is reached, and further decreases in load result in lowering exhaust temperature since air flow now remains constant. In this region the nozzle must open with decreasing load to maintain constant compressor speed. Near rated load the exhaust temperature is biased downward by compressor discharge pressure to provide constant firing temperature. For simple-cycle units the compressor speed is held constant over the entire load range since there is no advantage in maintaining constant exhaust temperature. A block diagram of this control loop for a regenerative unit is illustrated in Fig. 13.

Inlet Guide Vanes

The inlet guide vanes for heat recovery units are modulated to provide optimum overall cycle efficiency. This control loop adjusts the IGV angle, which varies air flow through the turbine, to provide constant exhaust temperature within the IGV control range. The control system is

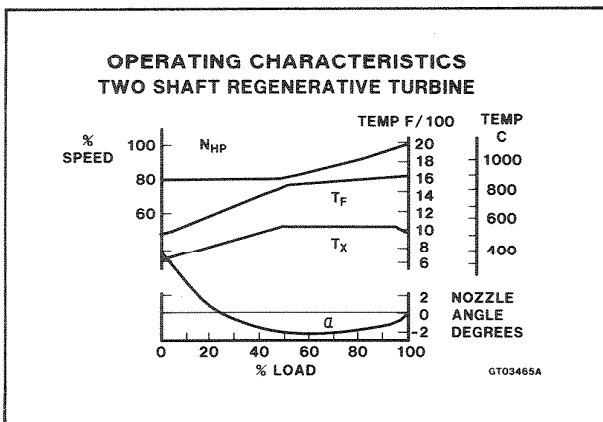


Figure 12

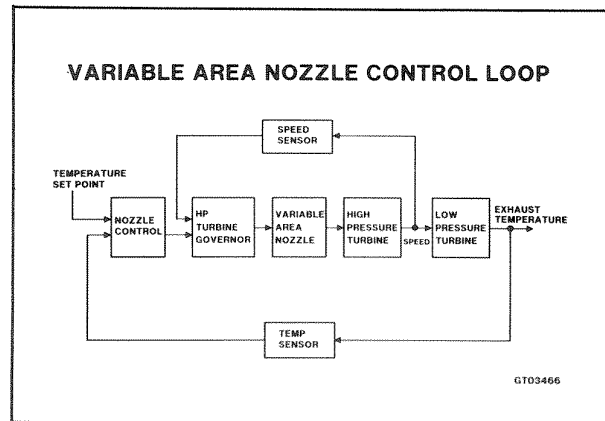


Figure 13

similar to that for the nozzle as shown in Fig. 13 except the control actuates the IGVs. During startup the IGVs are held fully closed (low air flow position) to avoid possible compressor pulsation.

Water Injection (NO_x Control)

The controls for the water injection system perform two functions: 1) control of the water according to a pre-established schedule, and 2) continuous monitoring of the quantity of water injected to assure compliance with requirements at all times. A typical water injection schedule is illustrated in Fig. 14. The schedule establishes water flow as a function of fuel flow. US Federal Regulations require that this curve be established by test for each turbine at the time of installation. The control system for the water injection

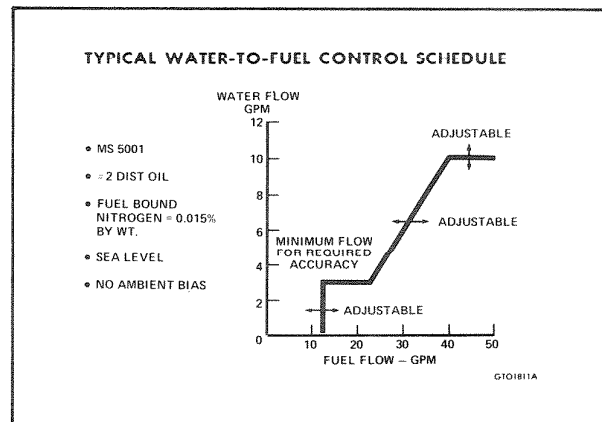


Figure 14

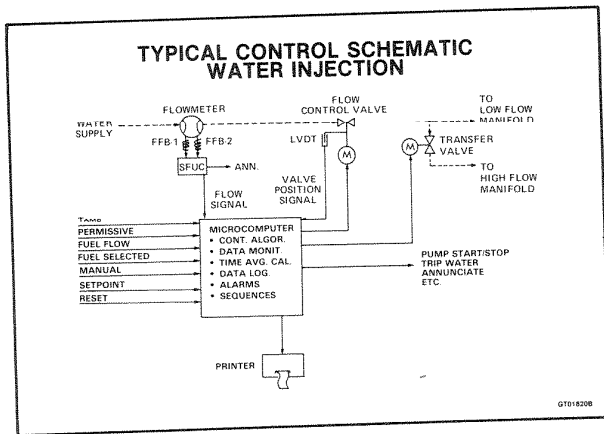


Figure 15

tion equipment, illustrated schematically in Fig. 15 includes a flow meter to sense water flow rate and a micro-computer which compares the sensed flow with the required flow (as determined by the schedule and fuel flow) and generates a command signal to the flow-control valve. A position transducer is attached to the water injection valve to sense valve position. This position signal serves as a backup, to determine water flow rate, should the water flow meter fail.

The micro-computer also provides the monitoring function, with the required water flow computation based on a separate, permanently-stored schedule, as the basis for determining if the proper amount of water is being injected. For the monitoring function, the actual water-to-fuel ratio is computed, compared to the required ratio, and added to a time-averaged calculation for a required one-hour time period. This process is accomplished on a roll-over type basis with new data continuously added (one per minute), and data older than one hour removed from the calculation. Should the time-averaged ratio (water-to-fuel) fall below the required ratio, an alarm occurs with automatic printout of all pertinent data (60 state points) for the previous hour. In addition to this printout, periodic logging occurs at an operator selectable-time period of one hour or less. An operator demand readout at any time is also available. This output information is provided on a standard printer.

The digital computations for the water injection control function is implemented in the ITS micro-computer for single-shaft gas turbines, for the two-shaft units (non-ITS turbine panels) the computations are performed by a micro-processor housed in a small cabinet separate from the turbine control panel.

Fuel Control System

The fuel control modulates the fuel flow to the turbine in response to the VCE command signal. The standard fuel systems are designed for operation on liquid, gas or both.

On heavy-duty gas turbines the liquid fuel system utilizes a positive-displacement fuel pump with a bypass valve around the pump to modulate fuel flow as illustrated in Fig. 16. Closing the bypass valve forces more fuel flow into the turbine. The flow divider assures equal flow to each combustion chamber. The flow division is accomplished by mechanically coupled free-wheeling gear pump/motor elements (one set for each combustion chamber) having identical displacement for each element. In operation, some elements serve as motors to drive other elements functioning as pumps, where required nozzle pressure to result in equal flows through each nozzle are slightly higher. The rotational speed of the flow divider is used as a flow feedback to the fuel control loop.

On the LM2500, fuel flow to the gas turbine is modulated by the fuel control valve. A bypass valve maintains a constant pressure drop across the fuel control valve making fuel flow directly proportional to the control valve position command. Because of the annular combustor and the use of thirty fuel nozzles, a mechanical flow divider is not required.

The gas fuel system (Fig. 17) uses two valves in series to control gas fuel to the turbine over the required range. The speed-ratio/stop valve is controlled to provide an inter-stage gas pressure, P_2 , that is proportional to turbine speed (main air compressor speed on two-shaft units). This control loop

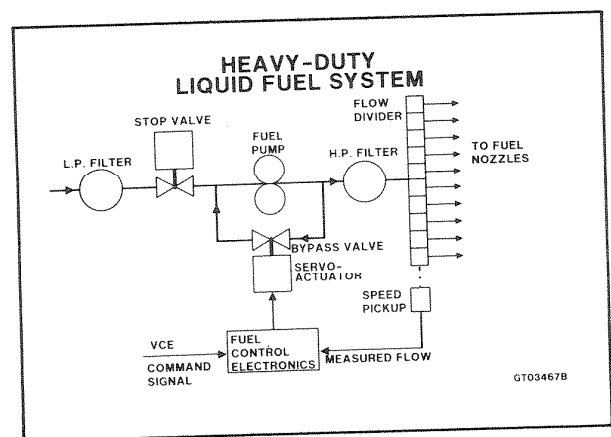


Figure 16

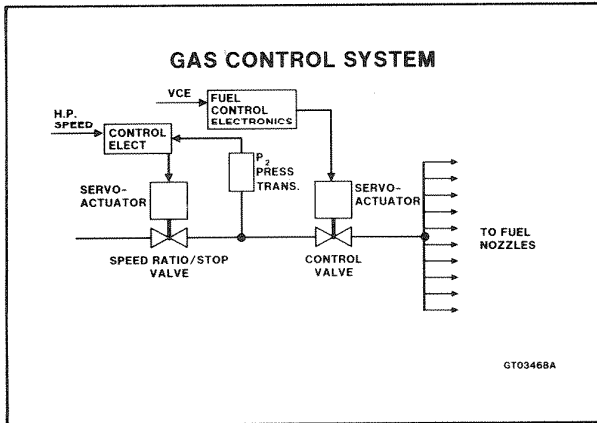


Figure 17

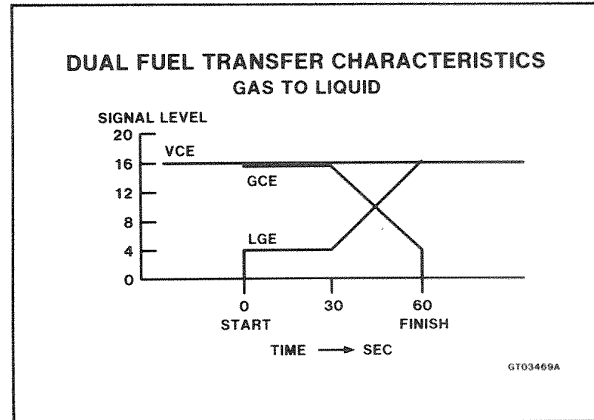


Figure 18

utilizes a pressure transducer to sense P_2 . The transducer output signal is compared to the command signal (proportional to turbine speed), and the error drives the servo actuator to maintain P_2 proportional to speed. This control arrangement provides increased accuracy over the needed turndown ratio from minimum (startup) fuel flow to maximum fuel flow. Thus it provides low upstream pressures at the control valve at startup where low flow rates are being controlled. The gas fuel control valve is operated by the servo actuator in response to the VCE command signal. On the LM2500, an additional stop valve is provided downstream of the control valve.

Dual Fuel

For dual fuel operation a "VCE splitter" is used to develop two modified VCE signals for the liquid and gas systems. These signals are identified as "LCE" and "GCE" for the liquid and gas signals respectively, and their sum equals the VCE signal; i.e. equal to the total fuel command. Transfer to either fuel while the unit is running or operating on a mixture (minimum of 10 percent for either fuel) is possible. A typical transfer from gas to liquid is illustrated in Fig. 18. At the initiation of the transfer, the LCE signal is increased to provide a small fuel flow (slightly above 4.0 which corresponds to zero fuel) to fill the liquid fuel lines. This LCE level is held for 30 seconds while GCE is maintained equal to VCE. At the end of the 30 second period, LCE is increased linearly with time. GCE is reduced while maintaining the sum equal to VCE. When LCE reaches the VCE command and GCE reaches 4.0 (0 percent fuel), the transfer is complete. GCE is then dropped to zero to assure positive shutoff.

Protective Systems

High reliability for the protective system is achieved by employing a high degree of redundancy. At least two independent means of shutting off fuel are employed. The shut-off valves are operated hydraulically utilizing redundant electronic circuitry and multiple sensors. In addition, the heavy-duty units utilize a hydromechanical trip system for overspeed, loss of lube oil, and manual trip. The redundant arrangement for the protective system elements is illustrated in Fig. 19. The sensors for the electronic protective system, operate through dual routes to redundant electronic trip systems. The outputs from the redundant elec-

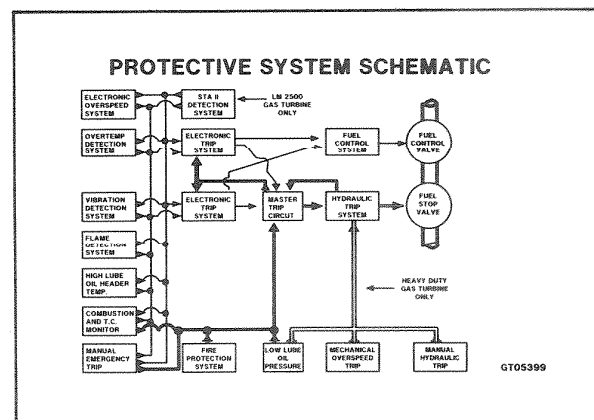


Figure 19

tronic trip systems drive the stop valve and the control valve directly to shut off fuel flow and, in addition, provide a signal into the electronic control system and to drive the control valve to the closed position.

The system is designed to be self checking. For example, at startup, the systems such as the flame detectors, overspeed, and overtemperature are checked and startup is aborted if one of the redundant systems has failed. If failure of one of the redundant protective channels occurs while running, an alarm will occur but the unit will not be shut down. Failure of both protective channels will cause a shutdown. In this way high running reliability is attained, yet safety is not compromised in the event of a total failure. In addition to the turbine protective functions, the driven load has protective requirements such as vibration, low lube pressure, electrical relaying (generator drives), high gas compressor temperature (compressor drives), etc. The control system is also protected for failures, such as a control system power supply failure, which will result in a safe machine shutdown.

Overspeed

The overspeed protection utilizes a two channel factory adjusted electronic system. Both channels are checked at shut down and again during start-up to ensure they are operating properly. In addition the heavy-duty units have a mechanical overspeed bolt, and the LM2500 has a third electronic channel with two out of three tripping logic.

Overtemperature

The concept for overtemperature protection is somewhat different between control systems having the ITS, and those that do not.

Non-ITS systems utilize two separate overtemperature channels which are totally independent of each other, and independent of the temperature control system. Each channel has three dedicated thermocouples, and their signals are averaged to provide an input to the particular overtemperature channel. The system provides an alarm level above the temperature control line (usually 20 F) and a trip level at a higher temperature, (typically 40 F above the control line). If either channel indicates an alarm level, an annunciator drop will occur. If the trip level is indicated by either channel, the unit will be tripped.

The non-ITS system also incorporates a self-monitoring feature. If a failure of either channel is detected, it will be alarmed. A failure of both channels will result in a turbine trip.

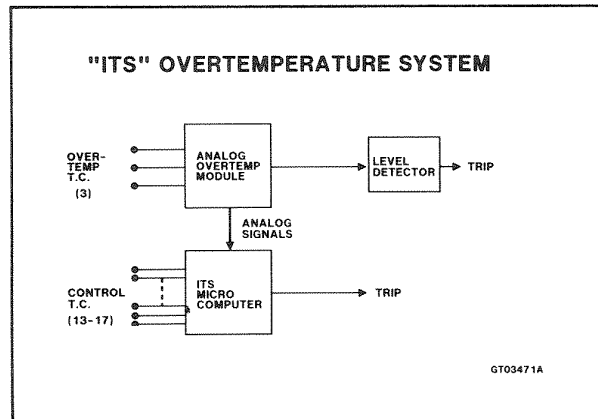


Figure 20

The ITS overtemperature system involves an analog overtemperature module, monitored and backed up by the microcomputer, as shown in Fig. 20. The analog overtemperature module is independent of the microprocessor, and will trip the turbine if the microprocessor malfunctions and the exhaust temperature exceeds the trip level. The module derives three output signals from the three overtemperature thermocouples and selects a median signal from these three. All four of these signals are monitored by the computer, which alarms if there is some malfunction of the analog module. The analog module generates a trip based on the median signal.

The computer also generates a median signal from the 13-17 control thermocouples. It further generates an overtemperature alarm and trip based on the median signals.

One of the advantages of the ITS system is that an overtemperature or a control thermocouple can fail and full protection is maintained; yet the probability of false trips caused by malfunctions is reduced.

Vibration

The vibration protection system utilizes velocity type sensors on the turbine and load equipment (load compressors with high stator to rotor mass ratio often employ displacement sensors). This system is used specifically for protection, and is not intended to serve as diagnostic vibration equipment. The sensors are monitored for failures so that if a ground, open circuit, or short occurs in any channel, the annunciator will indicate that a problem exists.

Flame Detection

Two flame detectors are used with each combustion system (two on all units except the MS3002 which has four detectors). The flame detectors are utilized in both the startup sequence and during operation. During operation, loss of flame indication on one sensor will alarm only but, should both sensors indicate flame loss, the unit will trip. During startup, indication of flame by one sensor will permit the starting sequence to continue. The detectors are checked prior to startup to assure they are indicating "No Flame" as a system failure check. A shorted or an open flame sensor results in a "No Flame" indication.

Combustion Monitor

Large single-shaft units are now shipped with a combustion monitor as standard protective equipment. This device samples the output from the control thermocouples at one second intervals. The temperature data obtained from each sample is analyzed in a microcomputer to predict developing combustion problems. The device also indicates failed thermocouples and failure of the microcomputer itself.

The criteria for developing combustion problems, based on exhaust thermocouple data, has been established through extensive testing and analysis of test data. The data shows that various models of one machine size and of course different machine sizes, respond quite differently to combustion system malfunctions. This, coupled with improvements in thermocouple reliability have required various algorithms to be optimized for each particular machine and verified through extensive field testing. If the microcomputer fails, it will alarm, but a unit shutdown will not occur.

The monitor also provides protection for the water injection system to avoid flame-out from excessive water injection. Should any of the exhaust thermocouple indicate a low temperature (such as would occur from combustion chamber flame-out with excessive water) the water injection system is tripped (and alarmed), but turbine operation is maintained. The extinguished chamber typically relights, and the operator can manually re-initiate the water injection system. The monitor sampling and computations functions are carried out by the ITS microprocessor.

Lube Protective Functions

Low lube oil pressure is a key protective function. Generally two or more pressure switches are employed and both alarm and trip levels are standard. The primary trip path for low lube pressure is through the electronic trip system. On heavy duty systems a sufficiently low lube-oil pressure will trip the hydraulic system as shown in Fig. 19.

High lube oil temperature also is an alarm and trip function although for continuously manned stations, a design option is available to prevent a trip on high lube temperature.

Hydromechanical System

The hydromechanical protective system is illustrated in Fig. 21 for a single-fuel, single-shaft unit. During operation, hydraulic pressure exists in the system and holds the fuel stop-valve in an open position. If the overspeed trip mechanism is operated by the overspeed bolt or by the manual valve, the hydraulic system is opened to drain and the resulting pressure drop causes the stop valve to close by spring force. System redundancy is obtained with a pressure switch, which operates the electronic trip system when the hydromechanical trip system is operated. Further trip system redundancy is provided with the solenoid valve which is operated by the electronic trip and/or master trip circuit.

Other Protective Functions

In addition to these primary turbine protective functions, the driven load (generator drive and its system, or load compressor) will have associated protective functions and are typically incorporated into the protective system. The turbine electronic control system also incorporates protective functions. For example, if fuel at startup exceeds a pre-established limit, indicating fuel system failure the startup will be aborted. Total power supply failure will always trip the unit so as to result in a safe shutdown. In general, however, such trips are minimized to enhance running reliability.

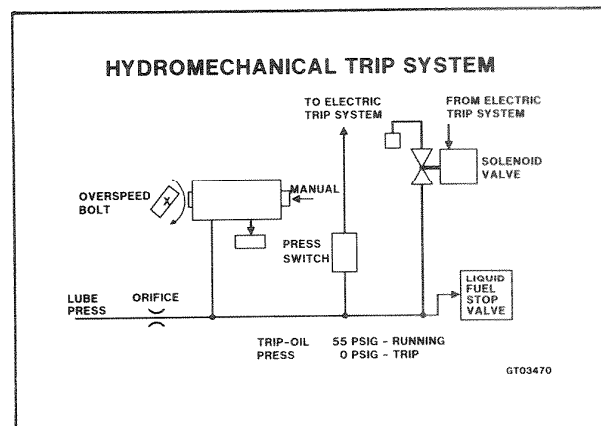


Figure 21

The Sequential System

The sequential system provides the logic for automatic startup, loading, and shutdown of the turbine. The system not only provides sequencing of turbine devices, but also initiates turbine auxiliaries such as auxiliary lube pumps, the fuel forwarding system, etc. A fail-safe philosophy has been used in designing the system so that in the event of most malfunctions which preclude further operation the turbine will be safely shut down. High reliability of the sequential system has been achieved by careful attention to the design and selection of electronic and hydromechanical components.

Components that make up the system include input devices such as pressure and temperature switches and output devices, such as solenoid valves, motor starters, etc. The logic functions, timers, speed relays, etc., are implemented with solid-state electronic devices. This system provides fully automatic sequential operation of the turbine and its load and auxiliaries. For example, for a generator drive the sequential system:

- (1) activates the auxiliaries
- (2) engages the clutch
- (3) cranks the unit
- (4) turns on fuel and set proper amount for firing
- (5) turns on ignition and detects flame
- (6) sets-up the warm-up time and warm-up fuel flow
- (7) determines key speed points
- (8) detects complete sequence
- (9) initiates synchronizing
- (10) closes the generator breaker and
- (11) loads the unit to the desired level

A feature provided by the sequential system to enhance starting reliability is a multiple start attempt, typically employed on generator drives. After the unit has been given a start signal, the failure of the sequence to progress will automatically revert the sequence back to the initial stage. As soon as the turbine coasts down to starting device recoupling speed, a restart will be attempted. This sequence is repeated until the turbine start is successful, or after attempting to start for twenty minutes, the system is shutdown.

COMPONENT DESIGN

The major components that make up the turbine control system are the turbine control panel, the sensors (primarily

on the turbine base), and the servo-actuators which provide control inputs to operate the turbine. The design of these major components is reviewed below and maintenance features are outlined.

Electronic Design

The electronics for the control are contained primarily in the turbine control panel and include major items such as the page, power supplies, interfacing relays, the micro-computer for the ITS and terminal trip wiring terminations.

The page is mounted in a roll-out rack, shown in Fig. 22 and is basically a set of receptacles for the individual cards to plug into. The interconnecting wiring is attached at the back side of each socket with wire-wrap connections. The wire-wrapping is done on a computer-controlled machine, using a computer-generated wiring pattern. The same computer generates the elementary diagram to provide correspondence between the elementary and this backplane wiring.

Power supplies use unregulated DC power from the station battery, and convert it to the precision regulated outputs for the electronic cards. These supplies are designed and constructed with large margin to assure a cool running, long life system. Critical supplies have short-circuit and overvoltage protection to prevent failure propagation. Considerable care has been taken to control current and voltage transients that might damage components or cause noise problems in the control electronics. Most of the power supplies are switching-mode regulators, although some have follow-on series regulators for precision voltages.

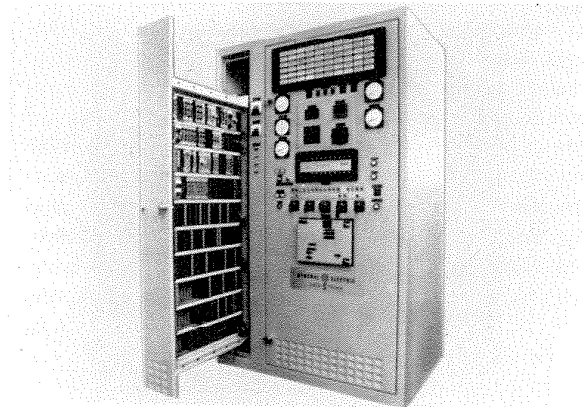


Figure 22

The microcomputer for the ITS has three principal parts:

1) The small electronics module that holds the computer, memory expander, digital to analog and analog to digital converts,

2) The low level thermocouple "input stick." This device has the connection points for terminating the thermocouple wires. It amplifies and multiplexes (switches in one at a time, according to instructions from the computer) the signals, and passes them to the analog-to-digital converter.

3) The power supply required by the microcomputer.

Figure 23 shows the microcomputer card along with the expander card. The microcomputer card uses an Intel 8080 microprocessor chip and four 2708 erasable memory chips. Extensive quality control measures and careful manufacturing techniques are used in assembling these cards. Every component part is given a thorough power-on test at parts receiving. All of the computer chips are heat cycled before the test. The satisfactory devices are then prepared for automatic insertion machines.

All electronic cards (microprocessor, analog, and digital) are made in a ultra-modern facility including automatic computer-controlled component insertion and receive a seven-day burn-in with power on, as shown in Fig. 24. Following burn-in, they are completely tested on automatic testers and after the cards are inserted in the page with others they again receive testing. When the page is assembled into the turbine control panel it is functionally tested, and receives a final test during the cab or Modular Electrical

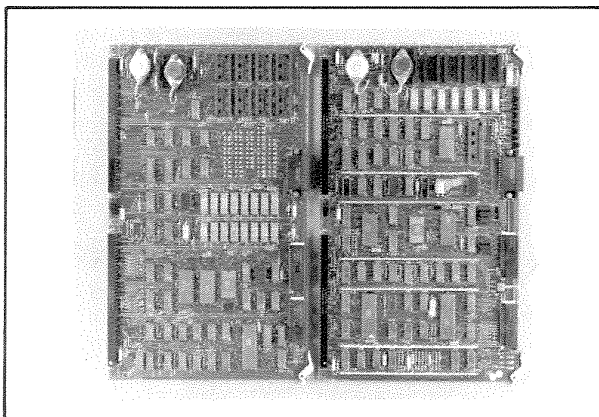


Figure 23



Figure 24

Control Center (MECC) test. When a control system is shipped, the cards have accumulated a total of about 2500 equivalent hours of operating time.

Sensors

The sensors for the turbine control system have been designed and selected to provide the necessary high performance with high reliability. A brief description of these sensors follows:

Magnetic Speed Pickups

These sensors are comprised of a permanent magnet core and pole piece, surrounded by a coil and metal housing. As the shaft teeth pass under the pickup, the magnetic flux increases and decreases. This induces an AC voltage in the coil. Magnetic pickups are used on each shaft of the turbine and the liquid fuel flow divider (also on the output shaft of certain starting devices). The signals are processed in the control for zero speed detection, speed indication and control, and electronic overspeed protection.

Position Sensors

The Linear Variable Differential Transformer (LVDT), used for position sensing, is illustrated schematically in Fig. 25. Coil A is connected to a constant voltage oscillator running at approximately 3K Hz. The magnetic core is connected with a non-magnetic stainless steel rod to the position that is being sensed. Coils B and C intercept equal amounts of flux if the core is centered. If the core moves toward coil B, more voltage is produced in B while coil C voltage decreases. By connecting the coils in opposition and adding some primary voltage, the transducer outputs an AC

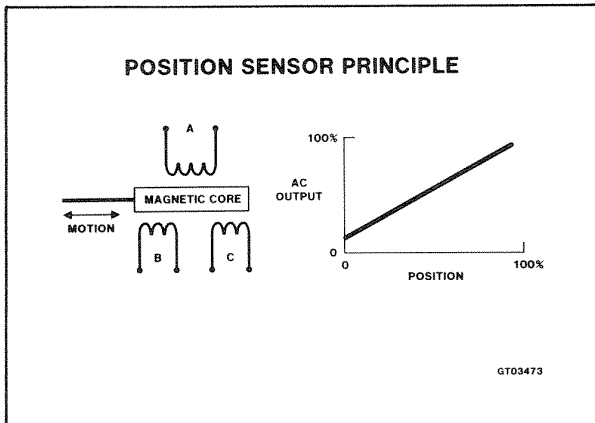


Figure 25

voltage that increases linearly with position. The offset shown in the plot (Fig. 25) is deliberately added for failure detection (most failures cause the output voltage to drop). Redundant sensors are used in critical applications by selecting the highest voltage, again taking advantage of the preferred failure mode. High accuracy, large clearances, sealed construction and fast response make these sensors extremely reliable.

Thermocouples

The exhaust thermocouples in use on current models utilize long, semi-flexible, stainless-steel construction (Fig. 26). The body of the thermocouple is 3/16" in diameter, which gives substantial strength while retaining sufficient flexibility. The tip is swaged to 1/16" (1.6 mm) diameter

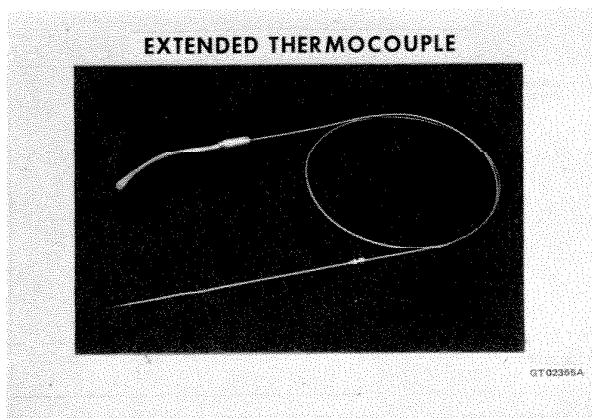


Figure 26

for fast response, and maintains the ungrounded (insulated tip) construction. The insulation is high-purity, anhydrous magnesium oxide. Chromel-alumel is used for the thermocouples.

Each thermocouple is provided with a thin-walled radiation shield which improves the accuracy of readings and provides mechanical support and protection.

The thermocouple cold-end terminations are made at junction boxes outside the turbine lagging to provide a low-temperature termination. The stranded runback wire to the turbine panel is teflon insulated chromel-alumel.

Pressure Transducers

These transducers are diaphragm-strain gauge devices. The small displacement of a stainless steel diaphragm (deflected by pressure) is sensed by four strain gauges; two sense compressive strain and two tensile strain. The gauges are connected in a bridge to provide an input signal to an instrumentation amplifier. The output of the amplifier is directly proportional to pressure. The pressure transducers also include protection against malfunctions caused by the surge effects such as from lightning. This built-in protection against electric transients has greatly improved sensor reliability, particularly in high lightning areas. Pressure sensors are used typically to measure compressor discharge pressure and fuel gas pressure.

Flame Detection

The ultraviolet flame sensor is comprised of a small cold-cathode gas discharge tube. High-quartz-bearing glass is used since it is transparent to ultraviolet light. The tube is filled with a mixture of gases typically containing hydrogen and a noble gas. The electrodes have a specially treated surface. When a specified voltage is applied to the tube, it will not fire unless ultraviolet light is present. When the tube fires, it discharges a capacitor to the point where the discharge stops. The capacitor is recharged, waiting for the ultraviolet light to trigger it. Thus, in the presence of ultraviolet, the tube fires repeatedly (i.e. a "relaxation oscillator"). The signal conditioning electronics sense the sharp pulses of current that indicate that the tube is firing. The use of a quartz glass results in a pressure barrier that retains the gas within, but allows the ultraviolet to pass through to the tube. The sensor is mounted on the combustor with an extended pipe incorporating a series gate valve, to allow testing and replacement of the sensor.

Vibration Transducers

The transducers are velocity sensitive such that the output voltage is proportional to the vibration velocity. Typically, a permanent magnet is seismically suspended on low compliance springs and is surrounded with a coil that is attached to the sensor frame, which is securely fastened to the turbine. With turbine vibration, the coil moves while the magnet remains still. The relative motion between coil and magnet induces a voltage which is processed by the electronics. Failure detection is accomplished by passing a small current through the coil which produces a DC output indicative of sensor resistance.

Synchronizer

The synchronizer employed on generator drive units automatically closes the generator breaker when phase and slip relationships are within proper limits. It is an important device since improper synchronization can result in significant generator, transformer or other damage.

A microprocessor-based synchronizer has been recently developed and field tested, and shown to result in superior performance, with higher potential reliability than the previously used electromagnetic synchronizing relays.

This synchronizer both matches turbine speed to the line frequency and commands the breaker to close. Input signals are taken from the generator and line potential transformers through an isolation module, which also includes the relay for delivering the "close" command to the breaker. After rejection of transients, the signals are converted to square waves and sent to the microcomputer card. This card, shown in Fig. 27, determines the phase, slip, and rate

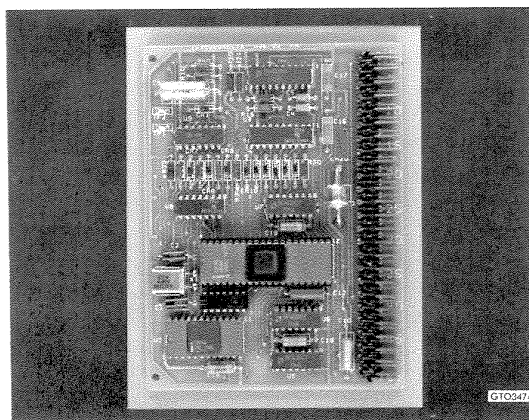


Figure 27

of change of slip. The turbine speed is automatically driven to a speed just above the line frequency then a breaker close command is given at the optimum moment to achieve a fast, but smooth, closure. The microsynchronizer is integrated into the turbine control panel, utilizes panel power supplies and directly controls the turbine governor. As can be seen in Fig. 27, it has very few parts, thus promising outstanding reliability. Because the device has only recently been put into production, the highly reliable (but lower accuracy) electromagnetic GXS relay has been maintained in a supervisory or checking role. One feature of the new system is its relative immunity to misadjustment; there simply are no adjustments. The breaker close-time is preset in the synchronizer by pin selection at the card socket.

Power system performance will be enhanced by the microprocessor synchronizer since it can quickly and accurately synchronize over a wider range of conditions that might be encountered during a system upset.

Servo Actuators

The analog output of the electronic control system operates mechanical devices on the turbine base by means of servo actuators. This equipment must provide large force capability with high response, stability and accuracy. Servo actuators are used to operate the fuel control valves (gas and liquid), the gas speed-ratio/stop valve, variable second-stage nozzle on two-shaft units and the inlet guide vanes on units where IGV modulation is employed.

The major components that make up a position servo, illustrated in Fig. 28 are the hydraulic actuator, the servo valve, and position transducer. The servo valve modulates the high-pressure supply oil to the actuator to provide a large force capability (from 1000 to 20,000 lbs.) in response

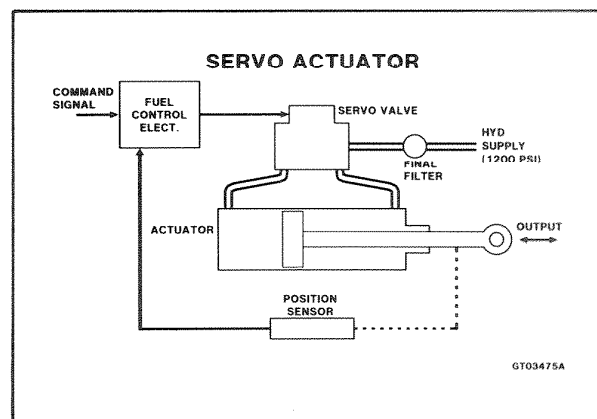


Figure 28

to a low-level input signal (typically less than 1 watt). The output position of the actuator is sensed with an AC type position transducer, as a linear-variable-differential-transformer (LVDT). The control electronics compares the actuator position with the command signal and generates the input signal to drive the servo valve. The LVDT position transducer is used because of its high reliability (no sliding electrical contacts) and its high resolution. The AC excitation (typically 3K Hz) is provided from an oscillator in the turbine control panel.

The servo valves have demonstrated high reliability, provided that hydraulic supply cleanliness is maintained. The supply includes a 0.5 micron main filter, and in addition, a final filter (40 micron) is used at each servo valve to contain contaminants that may bypass the main filter (e.g. during filter changeout). The two-stage servo valves also have a small integral filter for the first stage to further minimize contamination.

MAINTENANCE

The turbine control system has been designed to permit maintenance to be carried out with minimum disruption of the equipment. The page containing the electronic cards is on a roll out rack (see Fig. 22) to provide convenient access to the cards and the back plane wiring as necessary.

Maintenance aids include plug-in cards which electrically connect key signals in the panel to jacks on the maintenance cards for use with electrical monitoring equipment, thus avoiding test-lead connection on the relatively congested back-plane wiring. Another maintenance aid for calibration of the control system is the SPEEDTRONIC Calibrator. This test equipment plugs into the page in pre-assigned card slots, as shown in Fig. 29, and provides input

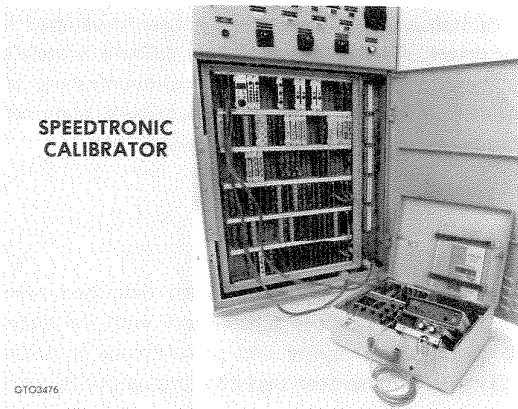


Figure 29

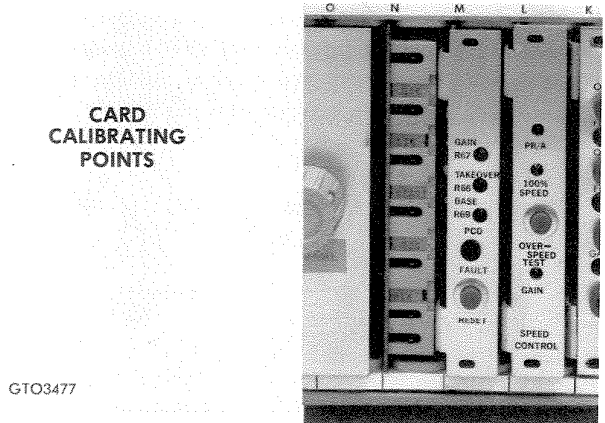


Figure 30

signals to the panel to simulate operation (speed signals, temperature signals, etc.) and test points to monitor the cards being calibrated.

Calibration of the panel is carried out at the cards by adjusting specific points at the card front while being monitored at the calibrator. Figure 30 illustrates the adjustment points on the temperature control card; R66, R67 and R69 are the "screw driver" adjustments. The calibration of the panel is carried out by following a step-by-step adjustment procedure documented in the Control Specification in the Instruction Book which is provided for each turbine. Calibration should be checked annually, although generally little readjustment is needed because of the low drift of the solid-state electronics. The calibration procedure also includes adjustment of devices such as pressure transducers, position sensors, etc., as outlined in the Control Specification.

Maintenance requirements for the hydromechanical control system and components is minimal. The overspeed hold should be tested and the main hydraulic filter changed out at prescribed intervals (typically annually). Experience to date has shown that regular maintenance greatly enhances the reliability and performance of the equipment.

INTERFACING LARGER SYSTEMS

When the gas turbine is used as a building block for larger systems, additional controls are necessary. STAG*

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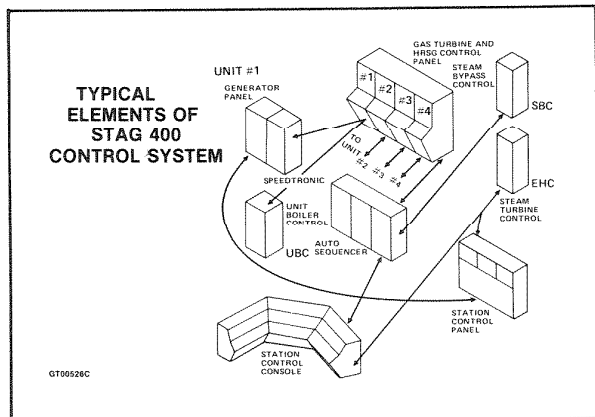


Figure 31

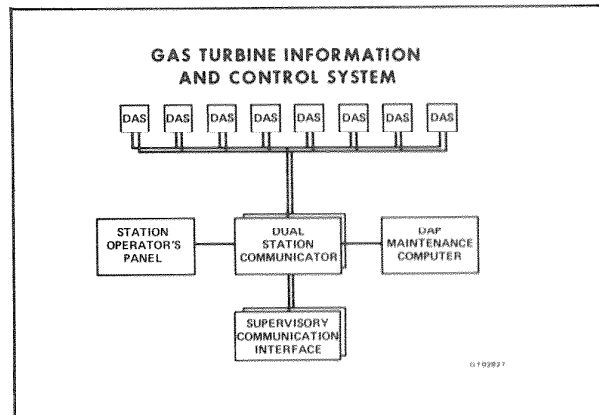


Figure 33

combined-cycle controls, Fig. 31, integrate the gas turbine controls, heat recovery steam generator, and steam turbine controls. These controls bring to the operator the capability to comprehend the total plant status, and to operate manually or automatically.

Multi-unit gas turbine installations are often constructed with a central control room. Cable remote master panels, one for each turbine, represents the standard approach for operating the gas turbines from the central control room. Figure 32 shows a typical cable remote panel.

Supervisory remote, the dispatch control of the machines from a distant city, is most often accomplished by installing remote control in each gas turbine cab and hard

wiring back to one central location where the telemetry equipment is located.

A new system, developed by the Gas Turbine Division simplifies these functions, and in addition has the capability of adding a minicomputer for maintenance purposes. Figure 33 shows the equipment involved. A microcomputer is built into each turbine control compartment that communicates serially with a pair of similar computers in the central control room. All the turbines share the communications cables. Two identical boards and two central control room computers are used for redundancy. The computers called station communicators, are inside the station operator's panel. This panel controls and displays the condition and operating status of up to eight gas turbines.

The station communicator computers interface with the telemetry equipment, avoiding the necessity for expensive cabling, signal conditioning and multiplexing equipment.

The maintenance minicomputer has been developed for generator drives. It gathers a significant amount of data on turbine operation from the station communicators and produces various logs, diagnostics, parts history, and operation summaries useful in performing maintenance.

SUMMARY

The SPEEDTRONIC control system described herein was designed to provide the turbine user with the highest practical degree of reliability and performance in turbine control. The system has been updated throughout its design life, to provide more complex monitoring and control func-

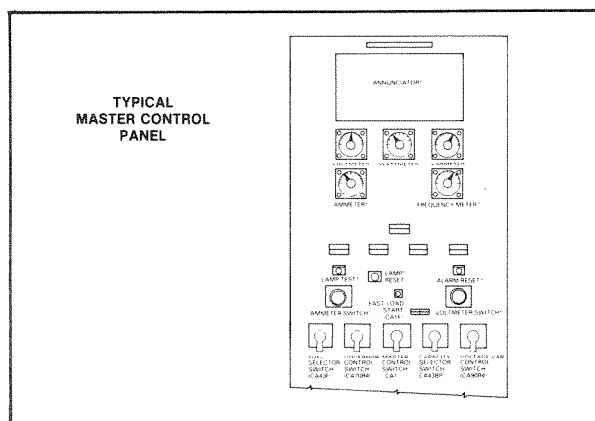


Figure 32

tional requirements, which have been possible only through the application of the latest technologies, such as integrated circuits and microcomputers. New control concepts, that are now in early design stages will provide even further reli-

ability improvements with additionally more complex requirements. The performance of the many SPEEDTRONIC control systems in use today indicate that the designs are more than fulfilling our expectations.

1981 GAS TURBINE REFERENCE LIBRARY

GER-2182	Advanced Materials and Coatings	GER-3110	Progress in Heavy Fuels
GER-2229	Gas Turbine and Heat Recovery Cycle Flexibility	GER-3112	Gas Turbine Availability/Reliability Reporting Systems
GER-2483	General Electric Heavy-duty Gas Turbine Design Philosophy	GER-3113	Why Gas Turbines?
GER-2484	Liquid Fuel Treatment Systems	GER-3114	Electric Utility Gas Turbine Applications
GER-2486	Emissions Performance of Industrial Gas Turbines	GER-3115	STAG Combined-Cycle Power Systems - Present and Future
GER-2490	Gas Turbine Inlet Air Treatment	GER-3116	The MS7001E Heavy-duty Gas Turbine
GER-2496	LM2500 Industrial Gas Turbine Package	GER-3117	Impact of Federal Energy and Environmental Regulations on Electric Utility Gas Turbines
GER-2498	Heavy-duty Gas Turbine Maintenance Practices for High Reliability	GER-3118	Combined-cycle Repowering - Mechanics and Economics
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GER-3108	Gas Turbine Regenerators	GER-3133	Data-Tronic Remote Control and Condition Monitoring System
GER-3109	The "All-Electric" Approach to Offshore Oil Production Facilities	GER-3134	Mark IV SPEEDTRONIC Control

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