SPEEDTRONIC™ MARK V GAS TURBINE CONTROL SYSTEM

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INTRODUCTION

The SPEEDTRONIC™ Mark V Gas Turbine Control System is the latest derivative in the highly successful SPEEDTRONIC™ series. Preceding systems were based on automated turbine control, protection and sequencing techniques dating back to the late 1940s, and have grown and developed with the available technology. Implementation of electronic turbine control, protection and sequencing originated with the Mark I system in 1968. The Mark V system is a digital implementation of the turbine automation techniques learned and refined in more than 40 years of successful experience, over 80% of which has been through the use of electronic control technology.

The SPEEDTRONIC™ Mark V Gas Turbine Control System employs current state-of-the-art technology, including triple-redundant 16-bit microprocessor controllers, two-out-of-three voting redundancy on critical control and protection parameters and Software-Implemented Fault Tolerance (SIFT). Critical control and protection sensors are triple redundant and voted by all three control processors. System output signals are voted at the contact level for critical solenoids, at the logic level for the remaining contact outputs and at three coil servo valves for analog control signals, thus maximizing both protective and running reliability. An independent protective module provides triple redundant hardwired detection and shutdown on overspeed along with detecting flame. This module also synchronizes the turbine generator to the power system. Synchronization is backed up by a check function in the three control processors.

The Mark V Control System is designed to fulfill all gas turbine control requirements. These include control of liquid, gas or both fuels in accordance with the requirements of the speed, load control under part-load conditions, temperature control under maximum capability conditions or during startup conditions. In addition, inlet guide vanes and water or steam injection are controlled to meet emissions and operating requirements. If emissions control uses Dry Low NO_X techniques, fuel staging and combustion mode are controlled by the Mark V system, which also monitors the process. Sequencing of the auxiliaries to allow fully automated startup, shutdown and cooldown are also handled by the Mark V Control System. Turbine protection against adverse operating situations and annunciation of abnormal conditions are incorporated into the basic system.

The operator interface consists of a color graphic monitor and keyboard to provide feedback regarding current operating conditions. Input commands from the operator are entered using a cursor positioning device. An arm/execute sequence is used to prevent inadvertent turbine operation. Communication between the operator interface and the turbine control is through the Common Data Processor, or <C>, to the three control processors called <R>, <S> and <T>. The operator interface also handles communication functions with remote and external devices. An optional arrangement, using a redundant operator interface, is available for those applications where integrity of the external data link is considered essential to continued plant operations. SIFT technology protects against module failure and propagation of data errors. A panel mounted back-up operator display, directly connected to the control processors, allows continued gas turbine operation in the unlikely event of a failure of the primary operator interface or the <C> module.

Built-in diagnostics for troubleshooting purposes are extensive and include "power-up," background and manually initiated diagnostic routines capable of identifying both control panel and sensor faults. These faults are identified down to the board level for the panel and to the circuit level for the sensor or actuator components. The ability for on-line replacement of boards is built into the panel design and is available for those turbine sensors where physical access and system isolation are feasible. Set points, tuning parameters and control constants are adjustable during operation using a security password system to prevent unauthorized access. Minor modifications to sequencing and the addition of relatively simple algorithms can be accomplished when the turbine is not operating. They are also protected by a security password.

A printer is included in the control system and is connected via the operator interface. The printer is capable of copying any alpha-numeric display shown on the monitor. One of these displays is an operator configurable demand display that can be automatically printed at a selectable interval. It provides an easy means to obtain periodic and shift logs. The printer automatically logs time-tagged alarms, as well as the clearance of alarms. In addition, the printer will print the historical trip log that is frozen in memory in the unlikely event of a protective trip. The log assists in identifying the cause of a trip for trouble shooting purposes.

The statistical measures of reliability and availability for SPEEDTRONIC™ Mark V systems have quickly established the effectiveness of the new control because it builds on the highly successful SPEEDTRONIC™ Mark IV system. Improvements in the new design have been made in microprocessors, I/O capacity, SIFT technology, diagnostics, standardization and operator information, along with continued application flexibility and careful design for maintainability. SPEEDTRONIC™ Mark V control is achieving greater reliability, faster mean-time-to repair and improved control system availability than the SPEEDTRONIC™ Mark IV applications.

As of May 1994, almost 264 Mark V systems had entered commercial service and system operation has exceeded 1.4 million hours. The established Mark V level of system reliability, including sensors and actuators, exceeds 99.9 percent, and the fleet mean-time-between-forced-outages (MTBFO) stands at 28,000 hours. As of May 1994, there were 424 gas turbine Mark V systems and 106 steam turbine Mark V systems shipped or on order.

CONTROL SYSTEM HISTORY

The gas turbine was introduced as an industrial and utility prime mover in the late 1940s with initial applications in gas pipeline pumping and utility peaking. The early control systems were based on hydro-mechanical steam turbine governing practice, supplemented by a pneumatic temperature control, preset startup fuel limiting and manual sequencing. Independent devices provided protection against overspeed, overtemperature, fire, loss of flame, loss of lube oil and high vibration.

Through the early years of the industry, gas turbine control designs benefited from the rapid growth in the field of control technology. The hydro-mechanical design culminated in the "fuel regulator" and automatic relay sequencing for automatic startup, shutdown and cooldown where appropriate for unattended installations. The automatic relay sequencing, in combination with rudimentary annunciator monitoring, also allowed interfacing with SCADA (Supervisory Control and Data Acquisition) systems for true continuous remote control operation.

This was the basis for introduction of the first electronic gas turbine control in 1968. This system, ultimately known as the SPEEDTRONIC™ Mark I Control, replaced the fuel regulator, pneumatic temperature control and electro-mechanical starting fuel control with an electronic equivalent. The automatic relay sequencing was retained and the independent protective functions were upgraded with electronic equivalents where appropriate. Because of its electrically dependent nature, emphasis was placed on integrity of the power supply system, leading to a DC-based system with AC- and shaft-powered back-ups. These early electronic systems provided an order of magnitude increase in running reliability and maintainability.

Once the changeover to electronics was achieved, the rapid advances in electronic system technology resulted in similar advances in gas turbine control technology (Table 1). Note that more than 40 years of gas turbine control experience has involved more than 5,400 units, while the 26 years of electronic control experience has been centered on more than 4,400 turbine installations. Throughout this time period, the control philosophy shown in Table 2 has developed and matured to match the capabilities of the existing technology. This philosophy emphasizes safety of operation, reliability, flexibility, maintainability and ease of use, in that order.

CONTROL SYSTEM FUNCTIONS

The SPEEDTRONIC™ Gas Turbine Control System performs many functions including fuel, air and emissions control; sequencing of turbine fuel and auxiliaries for startup, shutdown and cooldown; synchronization and voltage matching of the generator and system; monitoring of all turbine, control and auxiliary functions; and protection against unsafe and adverse operating conditions. All of these functions are performed in an integrated manner that is tailored to achieve the previously described philosophy in

Table 1
ADVANCES IN ELECTRONIC CONTROL CONCEPTS

System Type	Mark I	Mark II	Mark II ITS	Mark IV	Mark V
Introduced	1966	1973	1976	1982	1991
Total Shipped	850	1825	356	1080	530
Sequencing	Relays	Discrete Solid State Components		TMR Micro-processor	TMR Micro-processor
Control	Discrete Solid State	Inte-grated Circuits	I.C.s & Micro-processor	TMR Micro-processor	TMR Micro-processor
Protection	Relays	Relays & Solid State	I.C.s & Micro-processor	TMR Micro-processor	Independent TMR Micro-processor
Display	Analog Meters & Relay Annunciator	Analog and Digital Meters; Solid State Annunciator		CRT & LED Aux. Display	VGA Color Graphics
Input	Pushbuttons and Bat Handle Switches			Membrane Switches	Keyboard and/or CPD
Fault Tolerance	Manually Rejectable Failed Exhaust Thermocouples		Automatically Rejected Failed T.C.s	Hardware-based	SIFT

the stated priority.

The speed and load control function acts to control the fuel flow under part-load conditions to satisfy the needs of the governor. Temperature control limits fuel flow to a maximum consistent with achieving rated firing temperatures and controls air flow via the inlet guide vanes to optimize part-load heat rates on heat recovery applications. The operating limits of the fuel control are shown in Figure 1. A block diagram of the fuel, air and emissions control systems is shown in Figure 2. The input to the system is the operator command for speed (when separated from the grid) or load (when connected). The outputs are the commands to the gas and liquid fuel control systems, the inlet guide vane positioning system and the emissions control system. A more detailed discussion of the control functionality required by the gas turbine may be found in Reference 1.

The fuel command signal is passed to the gas and liquid fuel systems via the fuel signal divider in accordance with the operator's fuel selection. Startup can be on either fuel and transfers

Table 2
GAS TURBINE CONTROL PHILOSOPHY

- Single control failure alarms when running or during startup
- Protection backs up control, thus independent
- Two independent means of shutdown will be available
- Double failure may cause shutdown, but will always result in safe shutdown
- Generator-drive turbines will tolerate full-load rejection without overspeeding
- Critical sensors are redundant
- Control is redundant
- Alarm any control system problems
- Standardize hardware and software to enhance reliability while maintaining flexibility

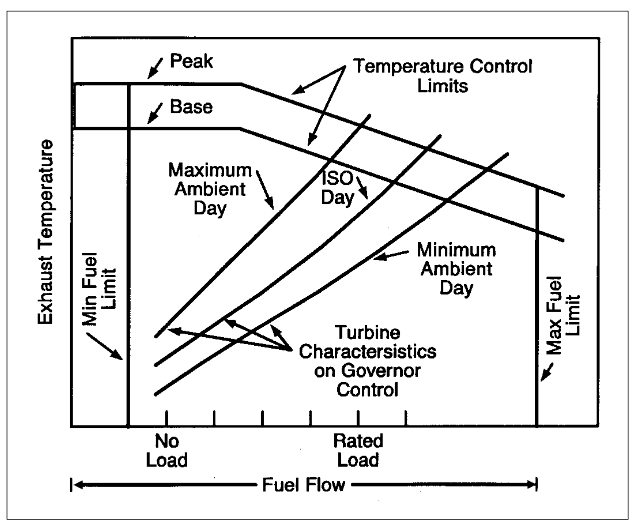

Figure 1. Gas turbine generator controls and limits

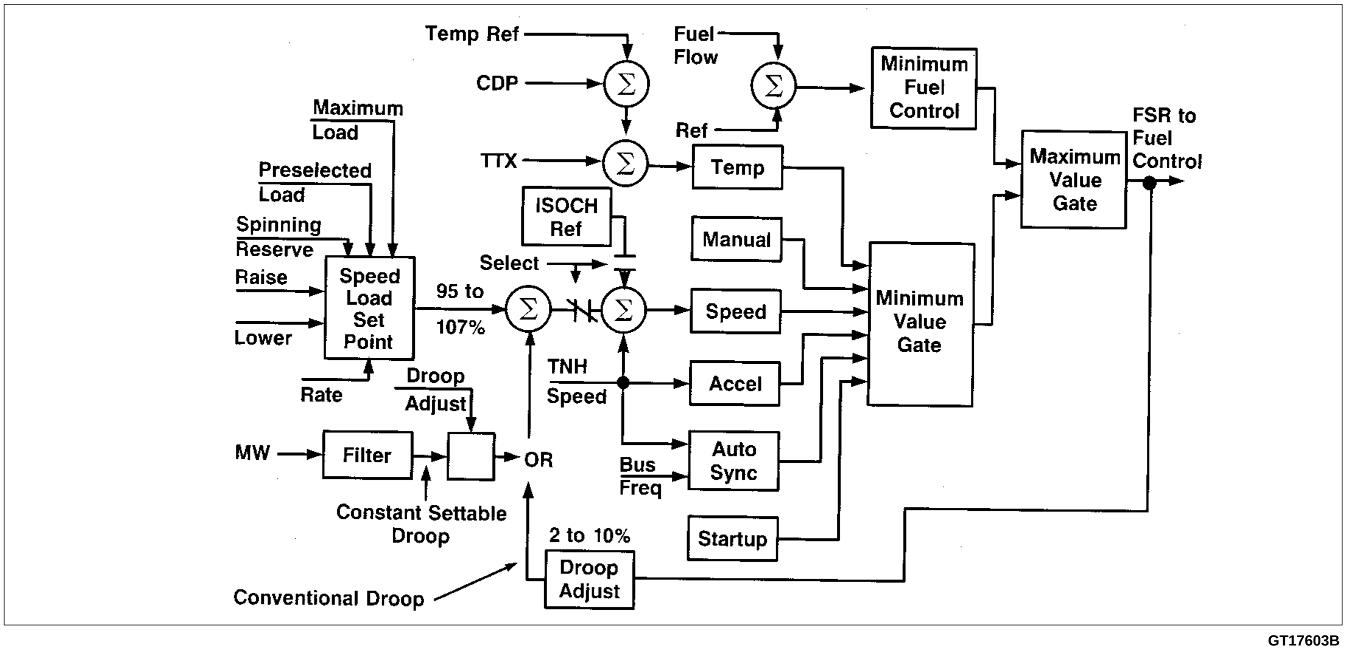

Figure 2. Gas turbine fuel control

under load are accomplished by transitioning from one system to the other after an appropriate fill time to minimize load excursions. System characteristics during a transfer from gas to liquid fuel are illustrated in Figure 3. Purging of the idle fuel system is automatic and continuously monitored to ensure proper operation. Transfer can be automatically initiated on loss of supply of the running fuel, which will be alarmed, and will proceed to completion without operator intervention. Return to the original fuel is manually initiated.

The gas fuel control system is shown schematically in Figure 4. It is a two-stage system, incorporating a pressure control proportional to speed and a flow control proportional to fuel command. Two stages provide a stable turndown ratio in excess of 100:1, which is more than adequate for control under starting and warm-up conditions, as well as maximum flow for peak output at minimum ambient temperature. The stop/speed ratio valve also acts as an independent stop valve. It is equipped with an interposed, hydraulically-actuated trip relay that can trip the valve closed independent of control signals to the servo valve. Both the stop ratio and control valves are hydraulically actuated, single-acting valves that will fail to the closed position on loss of either signal or hydraulic pressure. Fuel distribution to the gas fuel nozzles in the multiple combustors is accomplished by a ring manifold in conjunction with careful control of fuel nozzle flow areas.

The liquid fuel control system is shown schematically in Figure 5. Since the fuel pump is a positive displacement pump, the system achieves flow control by recirculating excess fuel

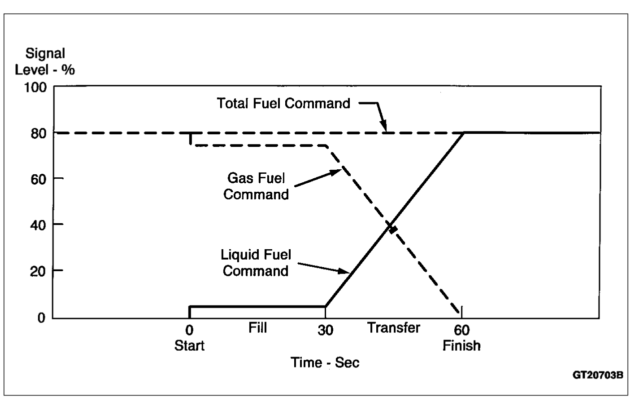

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Figure 3. Dual fuel transfer characteristics gas to liquid

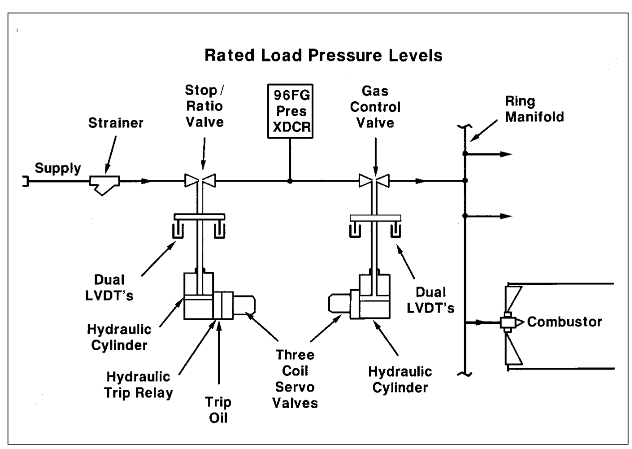

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Figure 4. Gas fuel control system

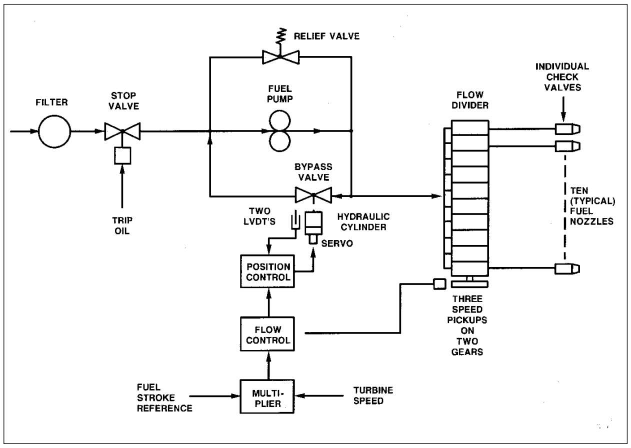

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Figure 5. Liquid fuel control system

from the discharge back to the pump suction. The required turndown ratio is achieved by multiplying the fuel command by a signal proportional to turbine speed. The resultant signal positions the pump recirculation, or bypass valve, as appropriate to make the actual fuel flow, as measured by the speed of the liquid fuel flow divider, equal the product of turbine speed and fuel command. This approach ensures a system in which both the liquid and gas fuel commands are essentially equal. Fuel distribution to the liquid fuel nozzles in the multiple combustors is achieved via the flow divider. This is a proven mechanical device that consists of carefully matched gear pumps for each combustor, all of which are mechanically connected to run at the same speed.

Control of nitrogen oxide emissions may be accomplished by the injection of water or steam into the combustors. The amount of water required is a function of the fuel flow, the fuel type, the ambient humidity and nitrogen oxide emissions levels required by the regulations in force at the turbine site. Steam flow requirements are generally about 40% higher than the equivalent water flow, but have a more beneficial effect on turbine performance. Accuracy of the flow measurement, control system and system monitoring meets or exceeds both EPA and all local code requirements. An independent, fast-acting shutoff valve is provided to ensure against loss of flame from over-watering on sudden load rejection.

Emissions control using Dry Low NO_X combustion techniques relies on multiple-combustion staging to optimize fuel/air ratios and achieve thorough premixing in various combinations, depending on desired operating temperature. The emissions fuel control system regulates the division of fuel among the multiple-combustion stages according to a schedule that is determined by a calculated value of the combustion reference temperature. The control system also monitors actual combustion system operation to ensure compliance with the required schedule. Special provisions are incorporated to accommodate off-normal situations such as load rejection.

The gas turbine, like any internal combustion engine, is not self-starting and requires an outside source of cranking power for startup. This is usually a diesel engine or electric motor combined with a torque converter, but could also be a steam turbine or gas expander if external steam or gas supplies are available. Startup via the generator, using variable frequency power supplies, is used on some of the larger gas turbines. Sufficient cranking power is provided to crank the unfired gas turbine at 25% to 30% speed, depending on the ambient temperature, even though ignition speed is 10% to 15%. This extra cranking power is used for gas path purging prior to ignition, for compressor water washing, and for accelerated cooldown.

A typical automatic starting sequence is shown in Figure 6. After automatic system checks have been successfully completed and lube oil pressure established, the cranking device is started and, for diesel engines, allowed to warm up. Simple-cycle gas turbines with conventional upward exhausts do not require purging prior to ignition and the ignition sequence can proceed as the rotor speed passes through firing speed. If ignition does not occur before the 60 second cross-firing timer times out, the controls will automatically enter a purge sequence, as described later, and then attempt to refire.

However, if there is heat recovery equipment, or if the exhaust ducting has pockets where combustibles can collect, gas path purging ensures a safe light-off. When the turbine reaches purge speed, this speed is held for the necessary purge period, usually sufficient to ensure three to five volume changes in the gas path. Purge times will vary from one minute to as long as 10 minutes in some heat recovery applications. When purging is completed, the turbine rotor is allowed to decelerate to ignition speed. This speed has been found to be optimum from the standpoint of both thermal fatigue duty on the hot gas path components, as well as offering reliable ignition and cross firing of the combustors.

The ignition sequence consists of turning on

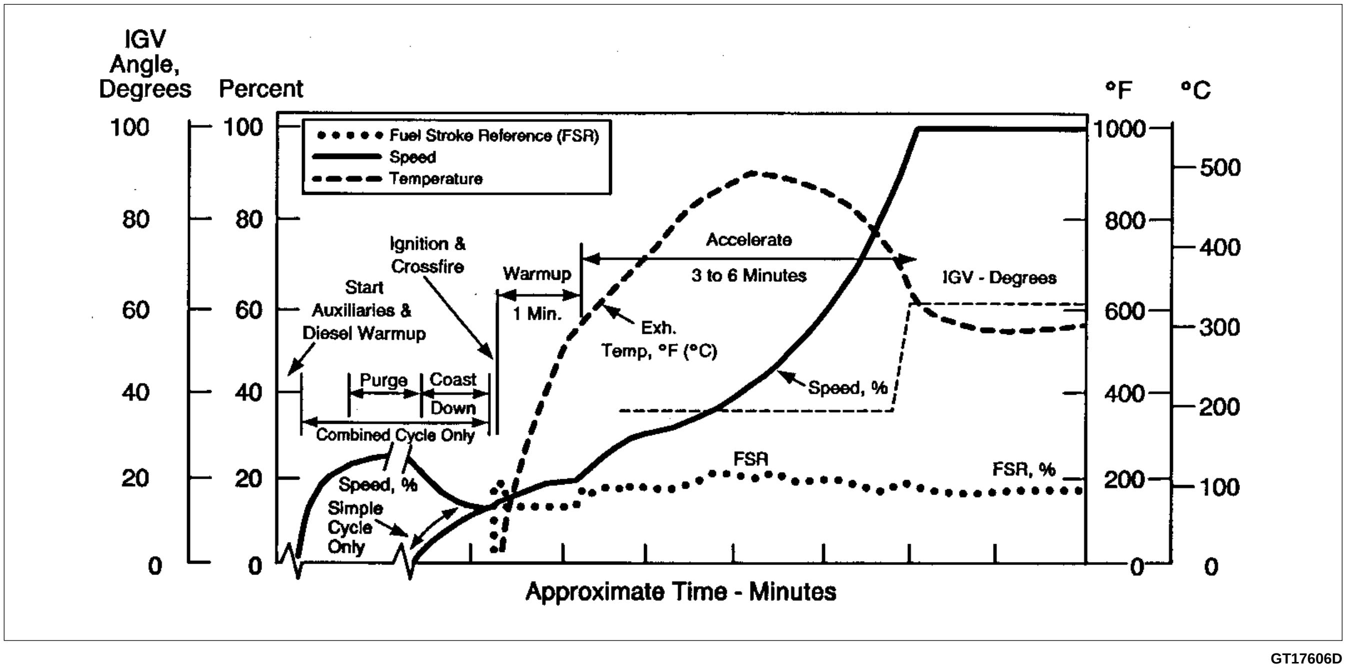

Figure 6. Typical gas turbine starting characteristics

ignition power to the spark plugs and then setting firing fuel flow. When flame is detected by the flame detectors, which are on the opposite side of the turbine from the spark plugs, ignition and cross-firing are complete. Fuel is reduced to the warm-up value for one minute and the starting device power is brought to maximum. If successful ignition and cross firing are not achieved within an appropriate period of time, the control system automatically reverts back to the purge sequence, and will attempt a second firing sequence without operator intervention. In the unlikely event of incomplete cross firing, it will be detected by the combustion monitor as a high exhaust temperature spread prior to loading the gas turbine.

After completion of the warm-up period, fuel flow is allowed to increase and the gas turbine begins to accelerate faster. At a speed of about 30% to 50%, the gas turbine enters a predetermined program of acceleration rates, slower initially, and faster just before reaching running speed. The purpose of this is to reduce the thermal-fatigue duty associated with startup.

At about 40% to 85% speed, turbine efficiency has increased sufficiently so that the gas turbine becomes self sustaining and external cranking power is no longer required. At about 80% to 90% speed, the compressor inlet guide vanes, which were closed during startup to prevent compressor surge, are opened to the full-speed, no-load position.

As the turbine approaches running speed, synchronizing is initiated. This is a two or three step process that consists of matching turbine generator speed, and sometimes voltage, to the bus, and then closing the breaker at the point where the two are in phase within predetermined limits.

Turbine speed is matched to the line frequency with a small positive differential to prevent the generator breaker from tripping on reverse power at breaker closure. In the protective module, triple-redundant microprocessor-based synchronizing methods are used to predict zero-phase angle difference and compensate for breaker closing time to provide true zero angle closure. Acceptable synchronizing conditions are independently verified by the triple-redundant control processors as a check function.

At the completion of synchronizing, the turbine will be at a spinning reserve load. The final step in the starting sequence consists of automatic loading of the gas turbine generator, at either the normal or fast rate, to either a preselected intermediate load, base load or peak load. Typical starting times to base load are shown in Table 3. Although the time to full-speed no-load applies to all simple cycle gas turbines, the loading rates shown are for standard combustion and may vary for some Dry Low NO_X systems.

Normal shutdown is initiated by the operator and is reversible until the breaker is opened and the turbine operating speed falls below 95%. The shutdown sequence begins with automatic unloading of the unit. The main generator breaker is opened by the reverse power relay at

Table 3
SIMPLE CYCLE PACKAGE POWER PLANT STARTING TIMES

Model Series	Type of Start	Starting Device	Diesel Warmup Time (Minutes)	+	Turbine Starting Time (Minutes)	=	Time to Full Speed No Load (Minutes)	Total Time to Base Load (Minutes)
LM6000	Normal	Hydraulic	NA		7.0		7.0	12.0
MS5001P	Normal	Diesel	2		7.17		9.17	13.17
	Fast Load	Diesel	1/2		7.17		7.67	9.67
	Emergency	Big Diesel	1/2		4.0		4.5	5.0
MS6001B	Normal	Diesel	2		10.0		12.0	16.0
	Fast Load	Diesel	1/2		6.67		7.17	9.17
MS7001EA	Normal	Motor	NA		7.5		7.5	19.5
	Fast Load	Motor	NA		7.5		7.5	9.0
MS7001FA	Normal	Motor/LCI	NA		9.0		9.0	21.0
MS9001E	Normal	Motor	NA		8.17		8.17	20.17
	Fast Load	Motor	NA		8.17		8.17	9.67
MS9001FA	Normal	Motor/LCI	NA		9.0		9.0	21.0

LCI = Load Commutating Inverter (Static Starter)

about 5% negative power, which drives the gas turbine fuel flow to a minimum value sufficient to maintain flame, but not turbine speed. The gas turbine then decelerates to about 40% to 25% speed, where fuel is completely shut off. As before, the purpose of this "fired shutdown" sequence is to reduce the thermal fatigue duty imposed on the hot gas path parts.

After fuel is shut off, the gas turbine coasts down to a point where the rotor turning system can be effective. The rotor should be turned periodically to prevent bowing from uneven cooldown, which would cause vibration on subsequent startups. Turning of the rotor for cooldown or maintenance is accomplished by a ratcheting mechanism on the smaller gas turbines, or by operation of a conventional turning gear on some larger gas turbines. Normal cooldown periods vary from five hours on the smaller turbines to as much as 48 hours on some of the larger units. Cool down sequences may be interrupted at any point for a restart if desired.

Gas turbines are capable of faster loading in the event of a system emergency. However, thermal fatigue duty for these fast load starts is substantially higher. Therefore, selection of a fast load start is by operator action with the normal start being the default case.

Gas turbine generators that are equipped with diesel engine starting devices are optionally capable of starting in a blacked out condition without outside electrical power. Lubricating oil for starting is supplied by the DC emergency pump powered from the unit battery. This battery also provides power to the DC fuel forwarding pump for black starts on distillate. The turbine and generator control panels on all units are powered from the battery. An inverter supplies the AC power required for ignition and the local operator interface. Power for the cooling system fans is obtained from the main generator through the power potential transformer after the generator field is flashed from the battery at about 50% speed. The black start option uses a DC battery-powered turning device for rotor cooldown to ensure the integrity of the black start capability.

As mentioned, the protective function acts to trip the gas turbine independently from the fuel control in the event of overspeed, overtemperature, high rotor vibration, fire, loss of flame or loss of lube oil pressure. With the advent of microprocessors, additional protective features have been added with minimum impact on running reliability due to the redundancy of the microprocessors, sensors and signal processing. The added functions include combustion and thermocouple monitoring, high lube oil header temperature, low hydraulic supply pressure, multiple control computer faults and compressor surge for the aircraft-derivative gas turbines.

Because of their nature or criticality, some protective functions trip the stop valve through the hardwired, triple-redundant protective module. These functions are the hardwired overspeed detection system, which replaces the mechanical overspeed bolt on some units, the manual emergency trip buttons, and "customer process" trips. As previously mentioned, the protection model performs the synchronization function to close the breaker at the proper instant. It also receives signals from the flame detectors and determines if flame is on or off. A block diagram of the turbine protective system is shown in Figure 7. It shows how loss of lube oil, hydraulic supply, or manual hydraulic trip will

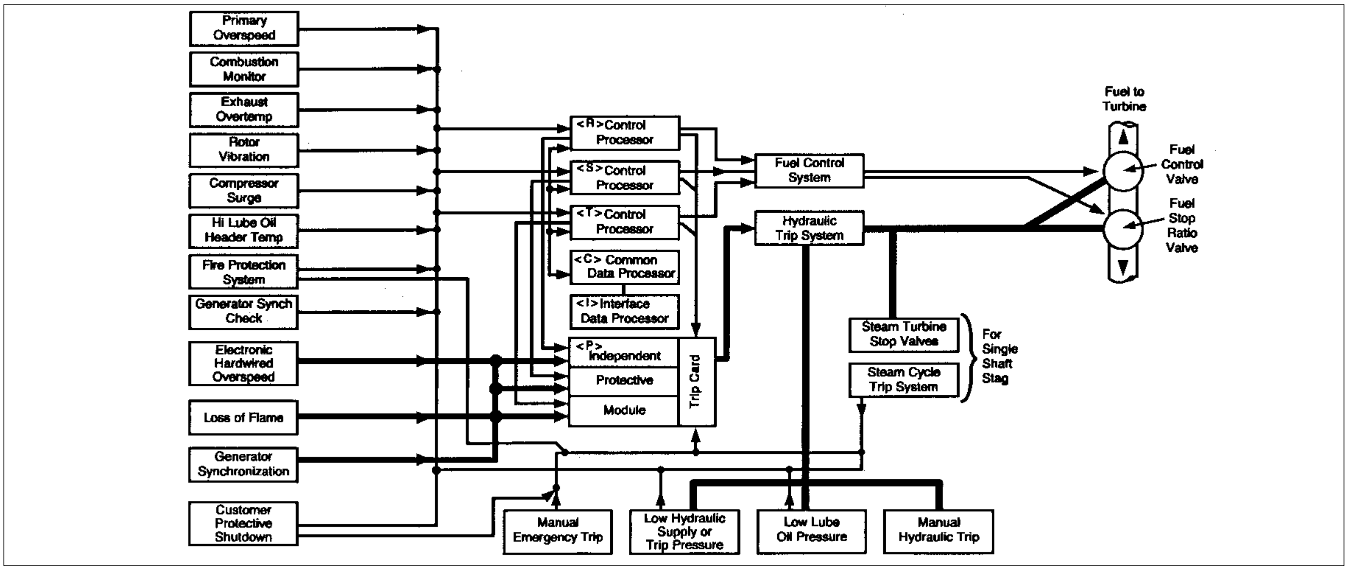

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Figure 7. Protective system block diagram; SPEEDTRONIC™ Mark V turbine control

result in direct hydraulic actuation of the stop valves.

Interfacing to other application-specific trip functions is provided through the three control processors, the hardwired protection module or the hydraulic trip system. These trip functions include turbine shutdown for generator protective purposes and combined-cycle coordination with heat recovery steam generators and single-shaft STAG™ steam turbines. The latter is hydraulically integrated as shown in Figure 7. Other protective coordination is provided as required to meet the needs of specific applications.

SPEEDTRONIC™ MARK V CONTROL CONFIGURATION

The SPEEDTRONIC™ Mark V control system makes increased use of modern microprocessors and has an enhanced system configuration. It uses SIFT technology for the control, a new triple-redundant protective module and a significant increase in hardware diagnostics. Standardized modular construction enhances quality, speed of installation, reliability and ease of on-line maintenance. The operator interface has been improved with color graphic displays and standardized links to remote operator sta-

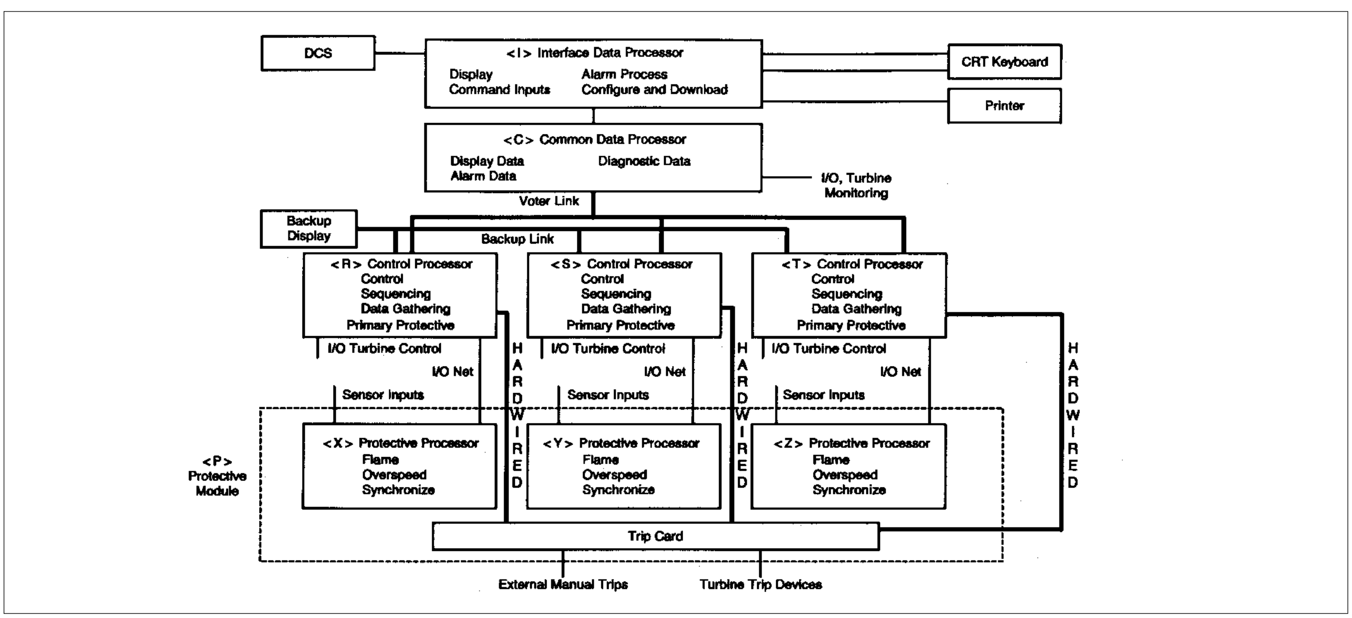

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Figure 8. Standard control configuration

tions and distributed control systems (DCS).

Figure 8 shows the standard SPEEDTRONIC™ Mark V control system configuration. The top block in the diagram is the Interface Data Processor called <I>. It includes a monitor, keyboard, and printer. Its main functions are driving operator displays, managing the alarm process and handling operator commands. <I> also does system configuration and download, off-line diagnostics for maintenance, and implements interfaces to remote operator stations and plant distributed control systems.

The Common Data Processor, or <C>, collects data for display, maintains the alarm buffers, generates and keeps diagnostic data, and implements the common I/O for non-critical signals and control actions. Turbine supervisory sensors such as wheelspace thermocouples come directly to <C>. The <I> processor communicates with <C> using a peer-to-peer communication link which permits one or more <I> processors. <C> gathers data from the control processors by participating on the voting link.

At the core of SPEEDTRONIC™ Mark V control are the three identical control processors called <R> <S> and <T>. All critical control algorithms, turbine sequencing and primary protective functions are handled by these processors. They also gather data and generate most of the alarms.

The three control processors accept input from various arrangements of redundant turbine and generator sensors. Table 4 lists typical redundant sensor arrangements. By extending the fault tolerance to include sensors, as with the Mark IV system, the overall control system availability is significantly increased. Some sensors are brought in to all three control processors, but many, like exhaust thermocouples, are divided among the control processors. The individual exhaust temperature measurements are exchanged on the voter link so that each control processor knows all exhaust thermocouple values. Voted sensor values are computed by each of the control processors. These voted values are used in control and sequencing algorithms that produce the required control actions.

One key output goes to the servo valves used in position loops as shown in Figure 9. These position loops are closed digitally. Redundant LVDTs (Linear Variable Differential Transformers, a position sensor) produce a signal proportional to actuator position. Each control processor measures both LVDT signals and chooses the higher of the two signals. This value is chosen because the LVDT is designed to have a strong failure preference for low voltage output. The signal is compared with the position

Table 4
CRITICAL REDUNDANT SENSORS

Parameter	Type	Function	Usage	Number
Speed	Mag. Pickup	CTL & PROT	Dedicated	3 to 6
Exhaust temperature	T.C.	CTL & PROT	Dedicated	13 to 27
Generator output	Transducer	Control	Dedicated	3
Liquid fuel flow	Mag. pickup	Control	Dedicated	3
Gas fuel flow	Transducer	Control	Dedicated	3
Water flow	Mag. pickup	Control	Dedicated	3
Actuator stroke	LVDT	Control	Shared	2/Actuator
Steam flow	Transducer	Control	Shared	1
Vibration	Seismic probe	Protection	Shared	8 to 11
Flame	Scanner	Protection	Shared	4 to 8
Fire	Switch	Protection	Shared	17 to 21
Control oil pressure	Switch	Protection	Shared	3
L.O. pressure	Switch	Protection	Shared	3
L.O. temperature	Switch	Protection	Shared	3
Exh. frame blwr.	Switch	Protection	Shared	2
Filter delta p.	Switch	Protection	Shared	3

Notes:

1. Dedicated sensors: one-third are connected to each processor
2. Shared sensors are shared by processors
3. Thee number of exhaust thermocouples is related to the number of combustors
4. Vibration and fire detectors are related to the physical arrangement
5. Generator output are redundant only for “constant settable droop” systems
6. Dry Low NO_X has four flame detectors in each of two zones

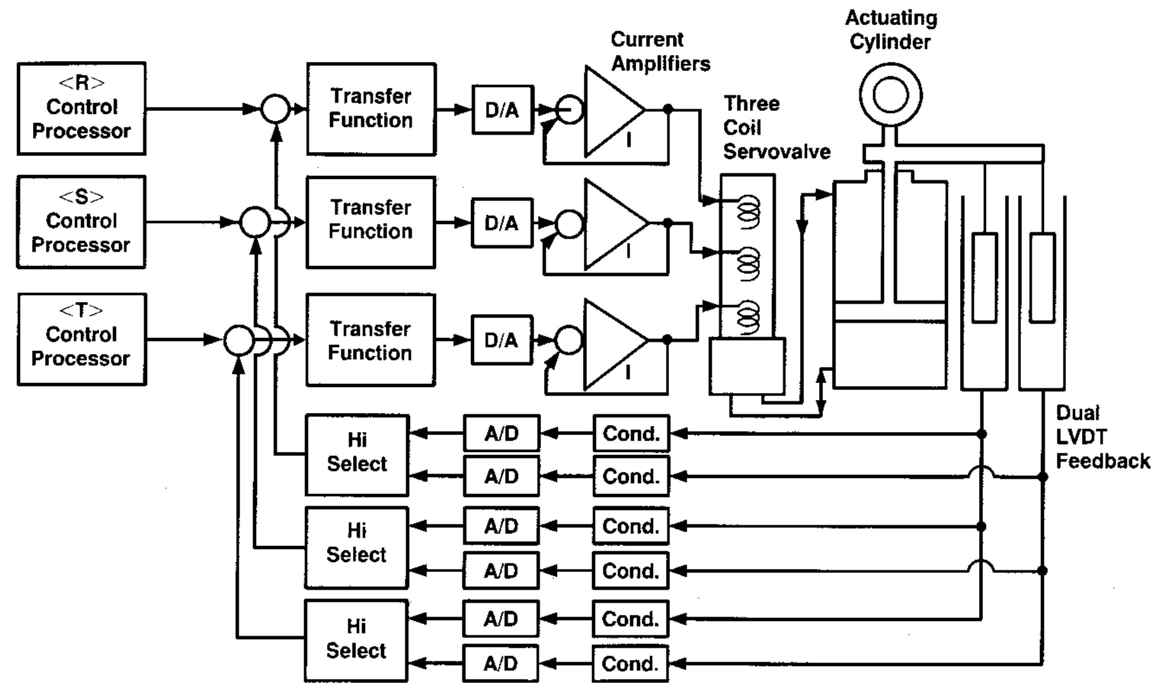

Figure 9. Digital servo position loops

command and the error signal passed through a transfer function and a D/A converter to a current amplifier. The current amplifier from each control processor drives one of the three coils. The servo valve acts on the sum of the ampere turns. If one of the three channels fails, the maximum current that one failed amplifier can deliver is overridden by the combined signals from the remaining two good amplifiers. The result is that the turbine continues running under control.

The SIFT system ensures that the output fuel command signals to the digital servo stay in step. As a result, almost all single failures will not cause an appreciable bump in the controlled turbine parameter. Diagnostics of LVDT excitation voltage, LVDT outputs that disagree, and current not equalling the commanded value make it easy to find a system problem, so that on-line repair can be initiated quickly.

An independent protective module <P> is internally triple redundant. It accepts speed sensors, flame detectors and potential transformer inputs to perform emergency electronic overspeed, flame detection and synchronizing functions. Hardware voting for <P> solenoid outputs is accomplished on a trip card associated with the module. The trip card merges trip contact signals from the emergency overspeed, the main control processors, manual trip push buttons and other hardwired customer trips.

Overspeed and synchronization functions are independently performed in both the triple-redundant control and triple-redundant protective hardware, which reduces the probability of machine overspeed or out of phase synchronizing to the lowest achievable values.

SPEEDTRONIC™ Mark V control provides interfaces to DCS systems for plant control from the <I> processor. The two interfaces available are Modbus Slave Station and a standard ethernet link, which complies with the IEEE-802.3 specification for the physical and medium access control (MAC) layers. A GE protocol is available for use over the ethernet link. A hardwired interface is also available.

Table 5 lists signals and commands available on the interfacing links. The table includes an option for hard-wired contacts and 4-20 ma signals intended to interface with older systems such as SCADA remote dispatch terminal units. The wires are connected to the I/O module

Table 5
INTERFACING OPTIONS

Hardwired
- Connects to common “C” processor I/O
- Commands to turbine control
  – Turbine start/stop
  – Turbine fast load
  – Governor set point raise/lower
  – Base/Peak load selection
  – Gas/Distillate fuel selection
  – Generator voltage (VARS) raise/lower
  – Generator synchronizing inhibit/release
- Feedback from turbine control
  – Watts, VARS and volts (analog for meters)
  – Breaker status
  – Starting sequence status
  – Flame indication
  – On temperature control indication
- Alarm management
  – RS232C data transmission only, from <1>

Modbus link
- Turbine control is Modbus slave station
- Transmission on request by master, 300 to 19,200 baud
- Connects to interface processor (I)
- RS232C link layer
- Commands available
  – All allowable remote commands are available
  – Alarm management
- Feedback from turbine control
  – Most turbine data available in the I data base

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Figure 10. Mark V operator interface

associated with <C>.

The “stage link” that interconnects the <C> processor with the <I> processor is an extendible Arcnet link that allows daisy chaining multiple gas turbines with multiple <I> processors. Thus a single gas turbine can be controlled from multiple <I> processors, or a single <I> processor can control multiple gas and steam turbines. For multi-unit configurations, the <I> processor can be equipped with plant load control capability that will allow plant level management of all units for both real and reactive power. The <I> processor, or Operator Interface, is shown in Figure 10.

In process plants where maintaining the link to the DCS is essential to keeping the plant online, two <I> processors are used to obtain redundant links to the DCS system. For critical installations, a redundant <C> processor option, referred to as the <D> processor, is available that ensures that no single hardware failure can interrupt communications between the gas turbine and the DCS system.

A specially configured PC is available to act as a “historian,” or <H> processor, for the gas turbine installation. All data available in the Mark V data base can be captured and stored by the historian. Analog data is stored when the values change beyond a settable deadband, and events and alarms are captured when they occur. In addition, data can be requested periodically or on demand in user definable lists. The historian is sized so that about a month’s worth of data for a typical four unit plant can be stored on line, and provisions are included for both archiving and restoring older data. Display options include a full range of trending, cross-plotting and histogram screens.

Compliance with recognized standards is an important aspect of SPEEDTRONIC™ Mark V controls. It is designed to comply with several standards including:

- ETL — Approval has been obtained for labeling of the Mark V control panel, with ETL labeling of complete control cabs
- CSA/UL — Approval has been obtained for the complete SPEEDTRONIC™ Mark V control panel
- UBC — Seismic Code Section 2312 Zone 4
- ANSI — B133.4 Gas Turbine Control and Protection System
- ANSI — C37.90A Surge Withstand

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Figure 11. Mark V turbine control panel

HARDWARE CONFIGURATION

The SPEEDTRONIC™ Mark V gas turbine control system is specifically designed for GE gas and steam turbines, and uses a considerable number of CMOS and VLSI chips selected to minimize power dissipation and maximize functionality. The new design dissipates less power than previous generations for equivalent panels. Ambient air at the panel inlet vents should be between 32 F and 72 F (0 C and 40 C) with a humidity between 5 and 95%, non-condensing. The standard panel is a NEMA 1A panel that is 90 inches high, 54 inches wide, 20 inches deep, and weighs approximately 1,200 pounds. Figure 11 shows the panel with doors closed.

For gas turbines, the standard panel runs on 125 volt DC unit battery power, with AC auxiliary input at 120 volt, 50/60 Hz, used for the ignition transformer and the <I> processor. The typical standard panel will require 900 watts of DC and 300 watts of auxiliary AC power. Alternatively, the auxiliary power can be 240 volt AC 50 Hz, or it can be supplied from an optional black start inverter from the battery.

The power distribution module conditions the power and distributes it to the individual

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Figure 12. Panel internal arrangement

power supplies for the redundant processors through replaceable fuses. Each control module supplies its own regulated DC busses via AC/DC converters. These can accept an extremely wide range of incoming DC, which makes the control tolerant of significant battery voltage dips, such as those caused by starting a diesel cranking motor. All power sources and regulated busses are monitored. Individual power supplies can be replaced while the turbine is running.

The Interface Data Processor, particularly a remote <I>, can be powered by house power. This will normally be the case when the central control room has an Uninterruptible Power Supply (UPS) system. AC for the local <I> processor will normally be supplied via a cable from the SPEEDTRONIC™ Mark V panel or alternatively from house power.

The panel is constructed in a modular fashion and is quite standardized. A picture of the panel interior is shown in Figure 12, and the modules are identified by location in Figure 13. Each of these modules is also standardized, and a typical processor module is shown in Figure 14. They feature card racks that tilt out so cards can be individually accessed. Cards are connected by front-mounted ribbon cables which can be easily disconnected for service purposes. Tilting the card rack back in place and closing the front cover locks the cards in place.

Considerable thought has been given to the routing of incoming wires to minimize noise and crosstalk. The wiring has been made more accessible for ease of installation. Each wire is easily identified and the resulting installation is neat.

The panels are made in a highly standardized manufacturing process. Quality control is an integral part of the manufacturing; only thoroughly tested panels leave the factory. By having

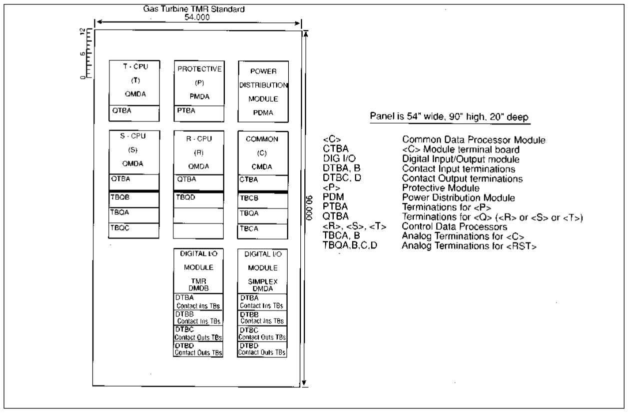

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Figure 13. Module map of panel interior

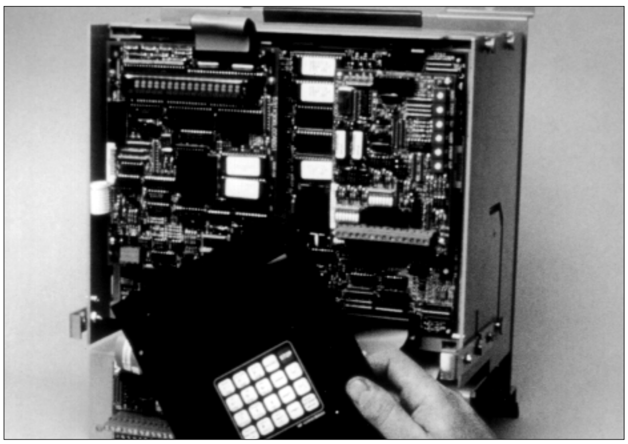

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Figure14. Typical processor module

a highly controlled process, the resulting modules and panels are very consistent and repeatable.

SOFTWARE CONFIGURATION

Improved methods of implementing the triple-modular redundant system center on SIFT technology and result in a more robust control. SIFT involves exchanging information on the voter link directly between <R>, <S>, <T> and <C> controllers. Each control processor measures all of its input sensors so that each sensor signal is represented by a number in the controller. The sensor numbers to be voted are gathered in a table of values. The values of all state outputs, such as integrators, for example, the load setpoint, are added to the table. Each control processor sends its table out on the voter link and receives tables from the other processors. Consider the <R> controller: it outputs its table to and receives the tables from the <S> and <T> controllers. Now all three controller tables will be in the <R> processor, which selects the median value for each sensor and integrator output, and uses these voted outputs in all subsequent calculations. <S> and <T> follow the same procedure.

The basic SIFT concept brings one sensor of each kind into each of <R>, <S> and <T>. If a sensor fails, the controller with the failed transducer initially has a bad value. But it exchanges data with the other processors and when the voting takes place, the bad value is rejected. Therefore, a SIFT-based system can tolerate one failed transducer of each kind. In previous systems, one failed transducer was likely to cause one processor to vote to trip. A failure of a different kind of transducer on another controller could cause a turbine trip. This does not happen with SIFT because the input data is exchanged and voted.

<C> is also connected to the voter link. It eavesdrops while all three sets of variables are transmitted by the control processors and calculates the voted values for itself. If there are any significant disagreements, <C> reports them to <I> for operator attention and maintenance action. If one of the transducers has failed, its output will not be correct and there will be a disagreement with the two correct values. <C> will then diagnose that the transducer or parts immediately associated with it have failed and will post an alarm to <I>.

Voting is also performed on the outputs of all integrators and other state variables. By exchanging these variables, fewer bumps in output are caused when a failure or a repair takes place. For instance, if a turbine is set to run on isochronous speed control with an isolated load, an integrator compares the frequency of the generator with the nominal frequency reference (50 Hz or 60 Hz). Any error is integrated to produce the fuel command signal. If one computer calculates an erroneously high fuel command, nothing happens because the processors will exchange the fuel command and vote and all will use the correct value of fuel command. When the processor is repaired and put back in service, its fuel command will initially be set to zero. But as soon as the first data is exchanged on the voter link, the repaired control processor will output the voted value that will be from one of the running processors so no bump in fuel flow will occur. No special hardware or software is needed to keep integrated outputs in step.

Since only one turbine is connected to each panel, the triple-redundant control information must be recombined. This recombination is done in software or, for more critical signals, in dedicated voting hardware. For critical outputs, such as the fuel command, the recombination of the signals is done by the servo valve on the turbine itself as previously explained.

For example, up to four critical 4 ma to 20 ma outputs are voted in a dedicated electronic circuit. The circuit selects the median signal for output. It takes control power for the electronics and the actual output current from all three sections such that any two control sections will sustain the correct output. Non-critical outputs are software voted and output by the I/O associated with <C>.

Logic outputs are voted by dedicated hardware relay driver circuits that require two or three "on" signals to pick up the output relay. Control power for the circuit and output relay is taken from all three control sections.

Protective functions are accomplished by the control processors and, for overspeed, independently by the Protective Module <P> as well. Primary speed pickups are wired to the control processors and used for both speed control and primary overspeed protection. The trip commands, generated by the primary overspeed protective function in the control processors, each activate a relay driver. The driver signals are sent to the trip card in the protective model where independent relays are actuated. Contacts from each of these three primary protective trip relays are voted to cause the trip solenoid to drop out. Separate overspeed pickups are brought to the independent protective module. Their relay contacts are wired in a voting arrangement to the other side of the trip solenoid and independently cause the trip solenoid to drop out on detection of overspeed.

The <I> processor is equipped with a hard disk which keeps the records that define the site software configuration. It comes from GE with the site-specific software properly configured. For most upgrades, the basic software configuration on the disk is replaced with new software from the GE factory. The software is quite flexible and most required alterations can be made on site by qualified personnel. Security codes limit access to the programs used to change constants and sequencing, do logic forcing, manual control and so forth. These codes are under the control of the owner so that if there is a need to change access codes, new ones can be established on site. Basic changes in configuration, such as an upgrade to turbine capability, requires that the new software be compiled in <I> and downloaded to the processor modules. The information for <C> is stored in EEPROM there. The information for the control processors is passed through <C> and stored in EEPROM in <R>, <S> and <T>. Once the download is complete, the <I> processor can fail and the turbine will continue to run properly, accepting commands from the local backup display while <I> is being repaired.

Changes in control constants can be accomplished on-line in working memory. For example, a new set of tuning constants can be tried. If they are found to be satisfactory, they can be uploaded for storage in <I> where they will be retained for use in any subsequent software download. <I> also keeps a complete list of variables that can be displayed and printed.

The most critical algorithms for protection, control and sequencing have evolved over many years of GE gas turbine experience. These basic algorithms are in EPROM. They are tuned and adapted with constants that are field adjustable. By protecting these critical algorithms from inadvertent change, the performance and safety of the complete fleet of GE gas turbines is made more secure.

OPERATION AND MAINTENANCE

The operator interface is comprised of a VGA color graphics monitor, keyboard and printer. The functions available on the operator interface are shown in Table 6.

Displays for normal operation center around the unit control display. It shows the status of major selections and presents key turbine parameters in a table that includes the variable name, value and engineering units. A list of the oldest three unacknowledged alarms appears on this screen. The operator interface also supports an operator-entered list of variables, called a user defined display, where the operator can type in any turbine-generator variable and it will be added to the variable list. Commands that change the state of the turbine require an arm activate sequence to avoid accidental operation. The exception is setpoint incrementing commands, which are processed immediately and do not require an arm-activate sequence.

Alarm management screens list all the alarms in the chronological order of their time tags. The most recent alarm is added to the top of the display list. The line shows whether the alarm has been acknowledged or not, and whether the alarm is still active. When the alarm condition clears, the alarm can be reset. If reset is selected and the alarm has not cleared, the alarm does not clear and the original time tag is retained.

The alarm log prints alarms in their arrival sequence, showing the time tags which are sent from the control modules with each alarm. Software is provided to allow printing of other information, such as copying of text screens, or making a listing of the full text of all alarms or turbine variables. When the printer has been requested to make such an output, it will form feed, print the complete list and form feed again. Any alarms that happened during the time of printing were stored and are now printed. An optional alternative is to add a second printer, dedicating one to the alarm log.

Administrative displays help with various tasks such as setting processor real time clocks and the date. These displays will include the selection of engineering units and allow changing between English and metric units.

There are a number of diagnostic displays that provide information on the turbine and on the condition of the control system. A partial list of the diagnostics available is presented in Table 7. The trip diagnostic screen traps the actual signal condition that caused a turbine trip. This display gives detailed information about the actual logic signal path that caused any trip. It is accomplished by freezing information about the logic path when the trip occurs. This is particularly useful in identifying the original source of trouble if a spurious signal manages to cause one of the control processors to call for a trip and does not leave a normal diagnostic trail. In SPEEDTRONIC™ Mark V controls, all trips are annunciated and information about the actual logic path that caused the trip is captured. In addition to this information, contact inputs are resolved to one millisecond, which makes this sequence of events information more valuable.

The previously mentioned comparison of voting values is another powerful diagnostic tool. Normally these values will agree and significant disagreement means that something is wrong. Diagnostic alarms are generated whenever there is such a disagreement. Examination of these

Table 7
MONITORING AND DIAGNOSTICS

- Power
  - – Incoming power sources
  - – Power distribution
  - – All control voltages
  - – Battery ground, non-interfering with other ground detectors
- Sensors and actuators
  - – Contact inputs circuits can force and interrogate
  - – Open thermocouple
  - – Open and short on seismic vibration transducers
  - – LVDT excitation voltage
  - – Servovalve current feedback loopback test
  - – 4/20 MA control outputs — loopback testing
  - – Relay driver; voting current monitor
  - – RTD open and short
- Protective
  - – Flame detector; UV light level count output
  - – Synchronizer — phase angle at closure
  - – Trip contact status monitor
- Voted data

tion in the ultraviolet flame detection system.

In another example, the contact input circuits can be forced to either state and then be interrogated to ensure that the circuit functions correctly without disturbing their normal operation. The extent of this kind of diagnostics has been greatly increased in SPEEDTRONIC™ Mark V control over previous generations. This level of monitoring and diagnostics makes maintenance easier and faster so that the control system stays in better repair. A properly maintained panel is highly fault-tolerant and makes systems starting and running reliability approach 100%.

Once the diagnostic routines have located a failed part, it may be replaced while the turbine continues to run. The most critical function of the diagnostics is to identify the proper control section where the problem exists. Wrong identification could lead to powering down a good section and result in a vote to trip. If the failed section is also voting to trip, the turbine will trip. A great deal of effort has been put into identifying the correct section. To affect the repair, the correct section is powered down. The module is opened and tilted out, the offending card located, cables disconnected, card replaced and cables reconnected. The rack is closed and power is reapplied to the module. The module will then join in with the others to control the turbine and the fault tolerance is restored.

Should the fault be in the <I> or <C> processor, it is likely that the operator display will stop or go blank and commands can no longer be sent by the operator to the turbine from <I>. This upsets the operator much more than it disturbs the control processors or turbine. A back-up display is provided to handle this situation. It happens very infrequently, and repair of the normal operator interface will usually be accomplished in less than three hours. Optional redundant <I> processors make the use of the back-up display even more unlikely. The gas turbine control is completely automatic and needs little human intervention for starting, running, stopping or tripping once a sequence is initiated.

The back-up display provides for a minimum set of control commands: start, stop, raise load and lower load. It reports all process alarms by number. Since the alarm text can be altered on site in <I>, a provision is included to print the alarms with their internal alarm numbers. This list is used to look up the alarm name from the alarm number. The same is true for data points; however, a preselected list of key data points are programmed into the back-up panel that display the short symbol name, value and engineering units. The control ships from the factory with this limited list of key parameters established for the back-up display.

CONTROL SYSTEM EXPERIENCE

The SPEEDTRONIC™ Mark V Turbine Control System was initially put into service in May 1992 on one of three industrial generator drive MS9001B gas turbines. The system was subsequently put into utility service on two peaking gas turbines to obtain experience in daily starting service in order to develop a starting reliability assessment in addition to the continuous duty running reliability assessment. General product line shipments of the Mark V System on new unit production commenced early in 1993, with new installations starting up throughout the second half of that year.

Today, virtually all turbine shipments include Mark V Turbine Controls. This includes 424 new gas turbines and 106 new steam turbines either shipped or on order. In addition, almost 80 existing units have been committed to retrofitted SPEEDTRONIC™ Mark V Turbine Control Systems, however, the bulk of these are designed as Simplex rather than the triple-redundant systems associated with new units. This is due to the floor space available in retrofit applications. Reliability of the in service fleet, subsequent to commissioning and after accumulating more than 1.4 million powered operational hours on 264 units, has been as expected. Indicated MTBFO (mean time between force outages) is in excess of 28,000 hours for the system, which includes control panel, sensors, actuators and all intervening wiring and connectors. This performance is shown relative to the rest of the electronic control history in Figure 15.

Why is the Mark V system so much better than its predecessors? First, there are fewer components to fail and fewer types of components in the control panel. (This also means that there are fewer spares to stock.) Two-out-of-three redundancy on critical functions and components ensures that failures, which are less likely to begin with, are also less likely to cause a turbine trip. Extensive built-in diagnostics and the ability to replace almost any component while running further minimize exposure time, while running with a failed component when the potential to trip resulting from a double failure, is highest. Finally, the high degree of standardized, yet still flexible, software and hardware allowed a much greater degree of automated manufacturing and testing, substantially lowering the potential for human error, and increasing the repeatability of the process.

The Mark V system is a further improvement over the Mark IV system. Although the two-out-of-three voting philosophy is retained, its implementation is improved and made more robust through use of SIFT techniques. Components and types of components have been further reduced in number. Standardization of hardware and software has been carried several steps further, but flexibility has also been increased. Greater degrees of automated manufacturing and testing have been complimented by greater use of computer-aided engineering to standardize the generation and testing of software and system configuration. Thus, it is fully expected the Mark V system will further advance the continuing growth of gas turbine control system starting and running reliability.

SUMMARY

The SPEEDTRONIC™ Mark V Gas Turbine Control System is based on a long history of successful gas turbine control experience, with a substantial portion using electronic and microprocessor techniques. Further advancements in the goals of starting and running reliability and system availability will be achieved by logical evolution of the unique architectural features developed and initially put into service with the Mark IV system. Flexibility of application and ease of operation will also grow to meet the needs of generator and mechanical drive systems, in process and utility operating environments, and in both peaking and base load service.

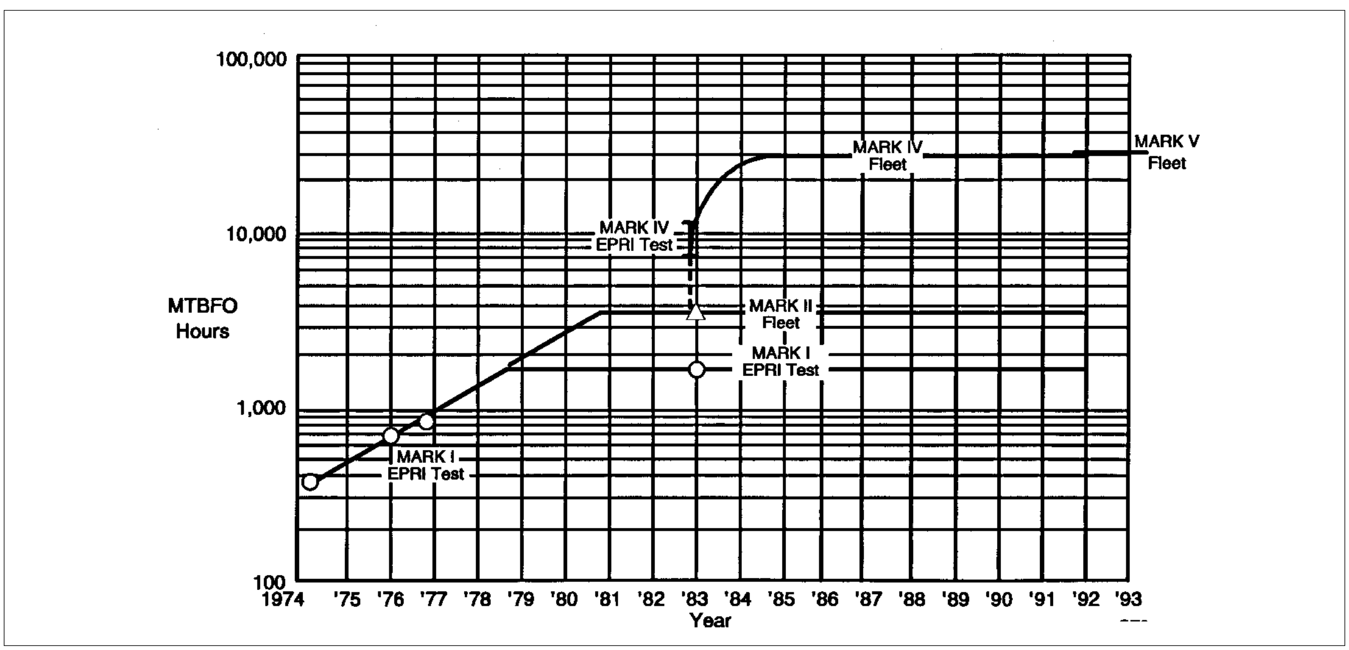

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Figure 15. Control system reliability

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