Digital Control Retrofit of an Industrial Gas Turbine

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ABSTRACT

As worldwide power requirements increase, power generation facilities must begin to think more closely about the reliability of existing units. In order to enhance plant capability, many power producers are considering control upgrades to aging equipment as an alternative to adding new machinery.

This paper details an advanced digital control system coupled with a progressive valving scheme and a unique man-machine interface that features the following:

1. Increased unit reliability due to the replacement of the pneumatic control system with a state-of-the-art, digital controller and an electro-hydraulic fuel valve,
2. Cooler, more predictable start-ups achieved by removing the relay sequencer and substituting an advanced software-driven sequencer,
3. An intuitive, color graphics operator control station that offers trending, archiving, and rapid configuration.

The scope of this paper will describe this system as it applies to a Westinghouse 191G gas turbine. This unit is located at a peaking facility in Astoria, New York. The control retrofit was successfully completed in June 1991.

INTRODUCTION

The advent of digital, industrial control technology has brought an increasing interest in improving power generation availability. Availability can be defined as the probability that a system will be operable for a given period of time. One economical method of increasing plant availability is the retrofit of original control schemes with more reliable, state-of-the-art control systems. To achieve increased reliability, the decision was made to retrofit the turbine controls on a Westinghouse 191G gas turbine at a peaking facility in Astoria, New York. A digital control system was selected which would replace the original fuel control, sequencer and fuel oil valves as well as provide a user-friendly operator interface. The original sequencing relays, pneumatic speed and temperature controllers, and pneumatic fuel valves were replaced with the following:

- A Woodward NetCon 5000 control system
- A color-graphics, operator control station with trending and data logging
- Two magnetic pick-ups for speed detection
- A hydraulic power unit to supply hydraulic pressure for the fuel valve
- A fuel valve actuator and liquid fuel valve

The advantages realized in the new system included easily-configurable software, the ability to monitor, log, and trend turbine parameters and events, and a significantly reduced number of pneumatic devices and relays. This resulted in a turbine which was more reliable, and a control system which lent itself more easily to troubleshooting. Other advantages related to the application software were cooler, more reliable, and therefore fewer starts. This translated into a longer projected turbine life.
The original control system integrated five modes of control. These controllers were a speed controller, an acceleration limiter, a starting combustor outlet temperature controller, an exhaust temperature controller, and a loading rate limiter. Five distinct pneumatic signals were generated in the system, one for each control channel. The signals were combined through a series of low pressure selectors, allowing the controller with the lowest pneumatic output signal to control the throttle valve. The integrity of this system relied heavily on a clean, dry pneumatic system, which was difficult and time-consuming to maintain.

For the retrofit, all five of the control loop functions were incorporated into a digital control system. This system was comprised of two chassis for the CPU and I/O module housing, one power supply and inverter, one computer-based operator interface, one operator control panel, a digital speed-matching auto-synchronizer and a real power sensor. The control chassis included:

- a CPU containing the system microprocessor and software; this module is responsible for executing the software and performing the hardware addressing
- a serial communication module for data exchange with external devices such as the computer-controlled operator interface or printers
- two J-type, isolated thermocouple modules, eight channels each, for monitoring bearing and exhaust gas temperatures; cold-junction compensation is performed on the module
- two K-type, isolated thermocouple modules, eight channels each, for monitoring combustor outlet temperatures; operation is identical to the J-type module
- three discrete input modules, twenty-eight channels each, for monitoring contact closures including pressure switches, hand switches, and various relay contacts
- two discrete output modules, twenty-eight channels each, to drive solenoid valves, indicating lamps, or to activate motors and pumps; devices requiring high current draws were routed through interposing relays
- an eight-channel, 4-20 milliamp current output card for meter readouts
- an eight-channel, 4-20 milliamp current input module for inputs from pressure, load, and flow transducers
- a magnetic pickup sensing module for turbine speed monitoring
- a current driver module to provide a signal output to the fuel valve actuator

The software for the control is designed to be user-friendly allowing the user to configure turbine control loops or sequencing using blocks of code called menu-oriented-editor or MOE blocks. This facilitates troubleshooting, as each block output may be accessed from a vacuum-fluorescent display located directly on the front panel of the digital control. The program is configured and compiled on a PC and downloaded directly to the CPU or may be stored on UVFOMS which are then mounted in sockets on the CPU. This simplifies the process of logic changes as well as minimizing the time required.

The fuel control portion of the application program for the Westinghouse 191G consists of six control modes, five of which are speed control, acceleration control, combustor outlet temperature control, exhaust temperature control, and a start ramp. These five control modes are low signal selected, and the lowest signal is high signal selected with the sixth control channel, deceleration control, to establish a valve position. This protects the unit from surge conditions, and the possibility of a flame-out on a load rejection or other large transient. The output to the fuel valve is also limited in the amount it can increase during a step change and the rate of change thereafter, similar to the control theory of the load rate limiter in the previous control system.

The start ramp provides a linearly increasing reference for the fuel valve during start. When the ignitors are turned on, the start ramp moves instantly to its minimum flow position. Once flame is established in each combustor, the start ramp begins to ramp from this minimum position toward 100% open at the rate of 0.0913% per second. This corresponds to approximately 600 RPM per minute. Start ramp control is disabled once the turbine achieves the speed control point.

The combustor outlet temperature controller employs a PID loop and uses the average combustor outlet temperature and the combustor temperature reference as inputs. During the start-up phase, with compressor inlet temperatures above 80 degrees F, the combustor temperature reference is limited to 1150 degrees F (this value is discussed in the section on Retrofit Results). This limiting temperature falls linearly with decreasing compressor inlet temperature. This limit defines the maximum possible combustor outlet temperature that can be achieved during acceleration. Any excursion above this value will result in a reduction in the opening of the fuel valve. When the unit reaches synchronous speed, the combustor temperature reference is raised to 1550 degrees F.

The speed control loop also uses a PID controller with speed and speed reference
inputs. During a turbine start, the speed reference is nominally set to 4421 RPM. As the turbine speed approaches this point, fuel valve control is taken from the start ramp and transferred to the speed controller. The speed loop then ramps the turbine to its synchronous speed of 4912 RPM. The speed setpoint may then be adjusted by the operator for manual synchronization or, if automatic synchronization is enabled, the digital speed matching synchronizer will adjust speed and close the generator breaker. When the generator breaker closes, the speed control setpoint is biased by a load signal coming from the newly installed real power sensor, and is therefore in "load droop". This allows the operator to manually adjust the load on the turbine by changing the speed reference. If automatic loading is selected, the speed reference will ramp to its maximum setpoint, allowing the exhaust temperature controller to eventually limit the load on the unit. The ramp rate will be 2 MW/min if emergency loading is selected, and 1 MW/min for normal loading.

If the generator breaker opens at any time, the speed reference is instantly set to 4912 RPM (synchronous speed). If an automatic shutdown is selected by the operator, the speed reference will ramp to minimum load automatically and the control will open the generator and field breakers. The unit will then go into a fifteen minute cool-down period, and then shut down.

In the original system, turbine speed was determined by a gear-driven impeller which produced an oil pressure signal proportional to rotor RPM. This system was replaced by two magnetic pickups which provide a reliable speed signal for the speed control, as well as a digital turbine speed reading for operator use. This allows turbine speed measurement to be independent of oil viscosity, giving an exact reading for precise speed control.

The exhaust temperature controller is a PID loop with three distinct references; one for starting, one for base load control, and one for peak load control. The starting temperature reference is selected when the unit is accelerating while the base or peak reference is selected when the unit is on-line. Peak loading allows higher firing temperatures in the gas turbine for increased megawatt output. All three of these references are biased by compressor discharge pressure (CDP) as shown in Figure 1.

The acceleration controller acts as a fuel limiter for the entire turbine operating range. This overfueling limit is based on compressor discharge pressure and acts as a protective controller in the event of a sudden load pickup or other upward transient. The deceleration controller serves the opposite function, that is, in the occurrence of a full load rejection this curve prevents flame-out by setting the absolute minimum fuel limit for a given compressor discharge pressure. These protection curves are plotted in Figure 2, which also shows the nominal fuel valve position versus CDP curve. Note that the range of possible fuel valve positions between the two limiting curves is set such that variations in ambient conditions (chiefly compressor inlet temperature) do not cause interference with normal operation. Under normal operating conditions, acceleration and deceleration controllers are never encountered.
One obvious advantage of the retrofit was the replacement of the five pneumatic controllers, various pressure switches, solenoid valves, I/P’s, and totalizers. The function of these mechanical and pneumatic devices was then implemented in software. This eliminated the problem of deteriorating control due to age and wear while ensuring consistent starts and stable turbine control. Because the controllers and the fuel valves were pneumatic, their integrity depended on the quality of the air supplying them. Due to the long runs of pneumatic line involved, the compressor that originally supplied control air for the system ran almost continuously to supply sufficient air pressure for proper control.

SEQUENCER

The original sequencer consisted of timers and relays, energized primarily by a variety of pressure switches, and wired in various parallel and series configurations to achieve the sequencing function for field devices. This sequencing configuration was comprised of 82 relays and 5 timers, all of which were removed or replaced along with their associated wiring.

With the new control system, all of the sequencing functions that were performed by relays are executed in software. This includes control of the lube oil system, fuel oil system, starting and stopping functions and annunciation of alarms and shutdowns.

With the original relay-based sequencer, a failure to start would cause all sequencing relays to return to their original state, not giving the operator much insight into the reason for the failed start. This could be due to a failure of the relay itself, or the failure of a pressure switch or other permissive for energizing or de-energizing the relay. The operator could then attempt to verify these permissives and the relay operation, or more likely, would simply start the unit again, and hope for the best. With the new control system, shutdowns and alarms are latched and annunciating until the operator acknowledges and resets them, and all start permissives are clearly annunciating so that they may be verified before a start attempt is made. This eliminates the need to start the unit for troubleshooting purposes and greatly reduces the time required to locate system problems.

FUEL VALVE

Perhaps the most significant contribution to the increase in turbine reliability was the replacement of the fuel valving. The original system consisted of a complex arrangement of pneumatically-controlled fuel valves (refer to Figure 3). Because the turbine was designed to run on fuel oil, the valving scheme is inherently complicated.

The fuel oil source to the system was a constant displacement pump that forwarded fuel oil from a sump area to the turbine system. This pump was protected by a relief valve which opened in the event of a sudden flow stoppage in the system, perhaps due to a downstream isolation valve closing immediately following an emergency shutdown.

This pump supplied fuel to the turbine through parallel branches consisting of a throttle valve and a throttle bypass valve. The throttle bypass was an on-off, pneumatic valve controlled by a timer. This valve was popped open at ignition with the intent to quickly fill the fuel line from the fuel valve to the nozzles. The bypass timer expired approximately 10 seconds after ignition was begun, closing this valve. The throttle valve itself had an initial lift that was mechanically set and flowed fuel oil during this acceleration. With the throttle bypass valve closed, this throttle valve was capable of flowing all of the fuel necessary to take the unit up to full load.

During this initial ramp to 50% rated speed, the throttle valve did not come off of its initial lift setting. The increase in fuel flow during this time was achieved by increasing the fuel pressure at the throttle valve inlet through use of the pump discharge pressure regulating valve.

The pump discharge pressure regulating valve was located at the output of the fuel oil pump. Its function was to steadily increase the pump output pressure being supplied to the throttle valve during acceleration. Thus, it functioned as a back-pressure regulating valve by steadily closing as the unit accelerated. The output of this valve returned fuel to the sump. It reached its maximum closure (and pump output pressure reached its peak) at 50% speed. From this point, the various control loops in the original system acted on the throttle valve directly to ramp the unit from 50% rated speed to full load.

Two positive shutoff valves were located downstream of the throttle valves. The overspeed trip valve was energized to open when a pressure switch detected that the mechanical overspeed trip system was armed. At this same time, the fuel oil isolation valve was opened. This scheme gave redundant protection to ensure that the flow of fuel was interrupted in the event of a shutdown. These
shutoff valves were retained in the final system and function in an identical manner.

Because the metering of the fuel through this system was rather uncertain, particularly during the initial light-off fuel scheduling, a manifold pressure limiting valve was employed. This on-off limiting valve was used in series with a relief valve to establish the proper fuel manifold pressure during the ignition phase. This valve was opened at ignition and closed by a speed switch at approximately 50% rated speed.

A complete description of the previous system follows: At light-off, both the overspeed trip valve and the fuel oil isolation valve were opened, providing a flow path to the fuel manifold. Fuel was delivered to the system at a constant flow by the fuel oil pump. Pump output pressure was controlled by the pump discharge regulating valve. This valve caused the pressure to increase at the inlet of the throttle valve during acceleration. To quickly fill the fuel lines between the pump and manifold, a throttle bypass valve was implemented. At the same time that fuel was flowing through the bypass valve, flow was also established through the main throttle valve. Ten seconds after the igniters were energized, the throttle bypass valve was closed. Flow through the throttle valve was increased over time as the pressure was brought up by the pump discharge pressure regulating valve. During this light-off period, the manifold pressure limiting valve established the proper manifold pressure. When the unit achieved approximately 50% rated speed (2456 turbine RPM), the manifold pressure limiting valve was closed and the pump discharge pressure regulating valve had integrated to its minimum opening. From this point, the unit was controlled solely by the regulation of the main throttle valve.

Note that this scheme requires two control loops to drive two separate control valves—the fuel oil throttle valve and the pump discharge pressure regulating valve. Control of these two valves in conjunction with the throttle bypass valve and manifold pressure limiting valve achieved one purpose—the scheduled delivery of fuel at proper flow and pressure to the fuel nozzles of the gas turbine.

It was recognized by the customer that this fuel system was the main source of hot starts as well as failed start attempts. Perhaps the single most significant problem was accumulation of water in the pneumatic control lines. This water acted on the system in such a way that starts were not predictable even on a day-to-day basis. It was decided to introduce an electro-hydraulic fuel valve into the system in addition to control and sequencer replacement. This new scheme would eliminate the most troublesome equipment in the previous system.

Figure 4 displays the fuel valve arrangement after the retrofit. Note that the pneumatically-operated throttle valve, pump
discharge regulating valve, throttle bypass valve and manifold pressure limiting valve have been eliminated. In their place is a hydraulically-driven liquid fuel valve which is mated with an electrically-positioned torque motor servo-valve actuator. This actuator can deliver 55 foot-pounds of torque to the fuel valve assembly and its position is established electrically by the new fuel control system.

The new fuel valve incorporates an internal differential pressure regulator to maintain a constant pressure drop across the fuel metering port. The regulator works to control fuel flow much like the original system but it is incorporated within the single valve arrangement. A bypass outlet returns excess fuel to the sump. Because a constant pressure drop is always present across the metering port, flow is always proportional to the port opening and, thus, directly proportional to the position of the fuel valve. With this arrangement, a linear fuel valve position vs. fuel flow curve is established, greatly simplifying the fuel scheduling process. Because a unique flow is guaranteed for each position of the actuator/valve combination, the light-off flow level can be precisely and repeatedly set, eliminating the need for the throttle bypass valve and manifold pressure limiting valve. After light-off is achieved, the unit can be consistently accelerated by a time-based fuel valve ramp.

The system reliability is greatly increased through replacement of the pneumatic control devices with a single hydraulically-driven fuel valve. Cool start-ups are much more repeatable due to the consolidation of the throttle and pump discharge pressure regulating valves into one unit, requiring only a single control loop.

OPERATOR INTERFACE

The operator interface is based on a 32-bit computer and functions as an annunciator, operator control panel, data logging and trending package, and engineering station. It communicates with the turbine control using a serial data link utilizing Modbus protocol and operates as the master, relieving the turbine control system of the corresponding software responsibility. It can log, store, and trend analog pieces of data over a 30 day period. At any time within the 30 days, data may be permanently stored on a disk for future analysis. Analog inputs are stored in an archive for a maximum of 30 days. This analog data is presented in four different time-scale formats: 0-60 seconds, 0-60 minutes, 0-24 hours, and 0-30 days.

If desired, the operator may trend selected data with a resolution of one second, on a real time basis. The trend begins when it is started by the operator and ends when the operator stops it. The operator may then scroll through the trends and view data on a real time basis, providing exact data for parameters and the exact time corresponding to that data. All trends may be displayed or printed. At any time, new trending gauges may be created by selecting up to eight analog values to be displayed simultaneously on one graph.

The operator interface also automatically records an event log which stores, displays, and prints the date and time of all events, including alarms, trips, and operator commands. It will provide a first-out indication to alert the operator to the first trip occurrence in the event of a shutdown. At any time, event log data may be saved to a disk or printed. The event log retains the 300 most recent events.

The operator interface allows operator control functions such as start, stop, raise and lower. It also provides graphics which include the following:

- an overall turbine diagram displaying
- fuel supply
- fuel oil pump
- fuel oil pump relief valve
- overspeed trip valve
- oil isolation valve
- to manifold
- bypass to sump
- new control valve

FINAL VALVE SCHEMATIC

Figure 4
various parameters including speed, load, and average temperatures

- a diagram showing the outputs of each PID controller and the outputs of the LSS and HSS control bugs
- a page display of starting permissives and sequencing steps with each step being annunciated as it is completed
- graphs for monitoring each thermocouple as well as the temperature spread, with alarm and shutdown points referenced
- a check-off form similar to that previously used by the operators to take readings of various turbine parameters; this ensures accurate data and greatly reduces the time required to collect it.

All of the above features combine to create a system which is straightforward to use and facilitates troubleshooting. It alerts the operators to permissives that are not met, displays all pertinent system information and provides a quick path to turbine alarms and shutdows.

RETROFIT RESULTS

The final commissioning of this unit was completed in June of 1991. Discussions with the owner indicate that system availability under the previous control system was somewhere around 60%. The failed starts were chiefly attributable to inconsistent fuel scheduling during the start-up phase leading to 1) a failure to achieve ignition or 2) an overfuel condition leading to a trip on high combustor outlet temperature. These conditions are opposite problems (underfueling and overfueling) and demonstrate the unrepeatability of the original system.

A remarkable improvement in control can be

![Combustor Thermocouple Temperature Average (°F)](image-url)

*Figure 5*
observed in the start-up combustor outlet temperature curves. An actual graph obtained from the original control system has been replotted in Figure 5. This graph shows the combustor outlet temperature plotted versus time for an actual pair of start attempts. The first attempt was aborted due to an extreme combustor outlet temperature (in excess of 1500 degrees F). The operator immediately initiated a second attempt which resulted in a successful start. However, this graph indicates that the peak temperature achieved was 1480 degrees F. This is only 20 degrees F away from the trip point.

Figure 6 shows an actual start-up recorded with the digital control system. Note that the peak temperature allowed during the start-up phase was 1150 degrees F. This limit is exactly that imposed by the digital control. Any excursion above this temperature will result in a reduction in the fuel valve opening (with a corresponding reduction in fuel flow) in an effort to limit the start-up combustor outlet temperature. As the turbine continues to accelerate, more cooling air is brought in by the compressor, causing the combustor outlet temperature to fall back to about 850 degrees F where it again begins to climb (note that the significant rise in combustor outlet temperature approximately 15 minutes later is due to breaker closure and loading of the turbine to maximum load).

The reason that a temperature peak is observed after ignition is that less air is available to cool the hot gas path during turbine acceleration. This condition exists until about 50% rated speed, at which point the increase in air flow through the compressor is sufficient to overcome the heat generated in the combustor section. The
combustor outlet temperature begins to drop at this point. The important point to consider is that during this temperature-limiting period, control of the fuel valve is taken from the time-based start ramp and given over to a combustor outlet temperature-limiting PID control loop. It is critical during this phase that turbine acceleration be maintained while limiting the combustor outlet temperature.

An argument can be presented at this point that the combustor outlet limit can be brought even lower to further reduce hot gas path damage. This theory was tested on this unit during the start-up. During the initial testing of the turbine control system, a combustor outlet limiting temperature of 1000 degrees F was used. It was found that when control was taken over from the start ramp by the limiting PID, the fuel flow was cut back in order to maintain the 1000 degree F maximum limit. This reduction in fuel was significant enough to prevent the turbine from accelerating beyond this point. This combustor outlet limiting temperature was continuously moved up until it was determined that the turbine would consistently accelerate through this phase. The final value used was 1150 degrees F. This was determined to be the optimum point to guarantee acceleration while limiting the damage done to the hot gas path section. Thermal stress during start-up is kept to a minimum while ensuring unit extensively by the operators is the diagnostic capability of the operator interface computer. As has been mentioned, this interface collects sequence-of-event data, annunciates alarms and trips and automatically creates trend graphs for all analogs in the system. In addition, various graphics are employed to aid in diagnostic presentation. Perhaps the most useful of these is a bar graph page that indicates combustor outlet temperature for each pair of thermocouples in the combustor cans. This page is watched closely by the operators during ignition to determine ignitor status. The 191G has six combustor cans, with an ignitor in each can (there are no cross-flame tubes on this model). One of the most common failures in starting the 191G is an ignition failure (due to ignitors stuck in the retracted position or simply a bad ignitor). Thus, this graphics page will indicate clearly which combustor can failed to ignite. The operator is immediately pointed to the proper combustor upon which to check.

CONCLUSION

This project describes the very first digital control system to be placed on a Westinghouse 191G gas turbine. The original sequencing relays, pneumatic speed and temperature controllers, pneumatic fuel valves, and various pressure switches and solenoid valves were replaced. The following components were added:

- a Motorola 68030-based digital control system
- a color-graphics, operator control station with trend monitoring, logging, operator control, and advanced troubleshooting capabilities
- a significantly reduced number of pneumatic devices, relays, pressure switches, and solenoid valves
- a state-of-the-art actuator and liquid fuel valve combination

The advantages of the digital control system include:

- increased overall system configurability
- an intuitive, color-graphics, operator control station offering monitoring, logging, trending, operator control, and advanced troubleshooting capabilities
- a significantly reduced number of pneumatic devices, relays, pressure switches, and solenoid valves
- a hydraulic fuel valve providing linear flow characteristics, ensuring cooler and more reliable starts which translates into longer turbine life.

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