Operation of a two-shaft gas turbine-driven synchronous generator

Technical, economic and ecological advantages possible.

By **Nabil Abu-Khader**, Ph.D.

INTRODUCTION

Synchronous AC generators are connected to a local electrical bus via a generator breaker. An electrical current will be delivered into that circuit only when that breaker is closed, in which case the generator is said to be on-line. The frequency of the generated waveform is directly proportional to the generator's rotational speed. The current and power delivered to the connected electrical bus depends on the interaction of the developed voltage with the connected resistive and reactive loads. If the generator is driven by a GT, the power delivered to it is primarily a function of the fuel flow to that turbine.

Compressor Controls Corporation (CCC) has developed various application software solutions called "control applications" (or just "controllers") to drive, protect, and sequence the entire GT unit. In this article, we will demonstrate how a two-shaft GT drives a synchronous generator using GT and GEN controllers.

GT CLOSED-LOOP TO NPT SYNCHRONOUS SPEED

After passing all start permissives, a two-shaft GT enters the startup sequence where it passes through two phases:

- **Open-loop control:** During the initial phase of a turbine startup, the fuel demand is calculated using open-loop control techniques. This phase typically consists of ignition, flameproof, FCV warmup and FCV ramp sub-phases.
- **Closed-loop control:** After the open-loop control phase, the turbine applies closed-loop control to ramp up NHP and then NPT to the synchronous (sync) speed. This phase depends on the startup goal and typically consists of NHP warmup, NHP acceleration, NHP loading, NPT warmup, NPT control, and NPT loading sub-phases. Sync speed should be between NPT minimum and maximum governor speeds.

The startup sequence "quickly" ramps the local SP through NHP and NPT pre-configured critical zones. This minimizes the turbine's operating time at these critical speeds.

For a two-shaft GT driving a synchronous generator, normally NPT loop is selected as the main control loop PV. This loop will be controlled when no limiting conditions exist. That loop then calculates a PID bidirectional response to deviations of its PV from a speed SP. The remaining loops operate as limiting control loops to protect the turbine against excessive speeds (like NPT), pressures (like CDP), and temperatures (like EGT), in addition to other protection functions like flameout and axial compressor surge.

If only one limiting loop is active, its PID response is selected. If multiple limits are exceeded, the GT controller selects the high limiting loop with the lowest or most-negative proportional plus derivative response and adds the lowest or most-negative differential integral from any active loop.

ISOCHRONOUS VS. DROOP CONTROL

The generated frequency of an AC generator is typically governed by the below relationship (Eq.1):

$$f = \frac{N \cdot P}{120}$$

Where:
f : is the frequency generated in [Hz]
N : is the generators' speed in [rpm]
P : is the number of magnetic poles

When only one generator is connected to a bus, a fixed frequency can be maintained only by manipulating the fuel flow to maintain a constant speed. This is called ***isochronous (speed) control***. These units offer 0% droop, i.e., constant speed from no load to full load.

When several generators are interconnected, electromagnetic forces equalize their frequencies. The rotational speed of each is called its sync speed, which is always a fixed multiple of the

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bus frequency. The desired frequency is maintained by controlling the speed of one unit. All others are regulated using ***droop (power or regulation) control***:

- A rise in the frequency and generator speeds reduces each controller's droop, causing it to reduce its turbine's power output.
- A drop in the frequency and generator speeds increases each controller's droop, causing it to raise its turbine's power output.

The droop control loop uses the difference between the NPT speed (sync speed) and the speed SP to determine the required power output of the generator. The GT controller manipulates its FCV to maintain that required power output.

A single generator and local bus are usually connected to a public utility grid via a utility breaker. Thus, isochronous control should be applied when the generator breaker is closed but the utility breaker is not (on-line, off-grid), but droop control is more appropriate when both breakers are closed (on-line, on-grid).

Droop percentage (or droop control gain), % *Kd* describes the relationship of the generator's speed change from no load to full load. It is typically calculated as per Eq.2:

$$\% \, Kd = \frac{\text{speed at no load} - \text{speed at full load}}{\text{speed at full load}} \, .100$$

Figure 1 shows a 4% droop example. A 4% frequency deviation causes 100% change in load, which also means that a 1% frequency deviation causes 25% change

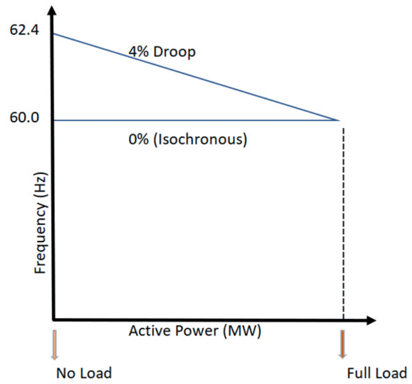


FIGURE 1: Isochronous vs. 4% droop control.

in load and so on. The speed at no load corresponds to a frequency of 62.4 Hz, while the speed at full load corresponds to a frequency of 60.0 Hz.

The droop SP, SP_D can be calculated using Eq.3:

$$SP_D = Ns + Ns \cdot \frac{Kd}{100} \cdot \frac{SP_J}{Jmax}$$

Where:
SP_J : is the desired power [power EU]
Jmax : is the maximum power [power EU]
Ns : is the nominal sync speed [rpm]

The difference between the speed SP and the nominal sync speed, J_D in [rpm] can be calculated as per Eq.4:

$$SP_D = Ns \cdot \frac{Kd}{100} \cdot \frac{J}{Jmax}$$

Where:
J : is the current delivered power [power EU].

The speed SP to the GT controller, SP_N in [rpm] can be calculated as per Eq.5:

$$SP_N = SP_D - J_D$$

The error, *e* in [rpm] that the GT controller uses to calculate its PID response can be calculated as per Eq.6:

$$e = SP_N - N$$

Where *N* is the current generator's actual speed [rpm].

Thus, SP_N will equal the generator's actual speed at steady state (the GT controller's error will then be zero).

INTEGRATED DROOP CONTROL CALCULATION EXAMPLE

Consider a two-shaft GT driving a two-pole synchronous generator with *Jmax* = 10.00 MW, *Kd* = 4%, and *Ns* = 3600 rpm. The generator is delivering 5.00 MW power output. Due to frequency disturbances, the delivered power dropped to 2.50 MW,

- To find the droop SP range:

Speed at full load = 3600 rpm ➞ *f* = 60 Hz.
Speed at no load = 3744 rpm ➞ *f* = 62.4 Hz.
$3600 \leq SP_D \leq 3744$ rpm.

- To find the droop SP that caused this drop of power:

$$SP_D = 3600 + 3600 \cdot \frac{4}{100} \cdot \frac{2.5}{10} = 3636 \text{ rpm}$$

(since SP_J = 2.50 MW)

Note that this speed corresponds to 60.6 Hz (1% change in frequency). Since speed SP (corresponding to 5.00 MW) remains constant, the difference between the speed SP and the new sync speed (3636 rpm) has decreased which decreases the generated power to 2.50 MW.

- To find difference between the speed SP and the nominal sync speed:

$$J_D = 3600 \cdot \frac{4}{100} \cdot \frac{5}{10} = 72 \text{ rpm}$$

(Since *J* = 5.00 MW)

- To find the speed SP to the GT controller:

$$SP_N = 3636 - 72 = 3546 \text{ rpm}$$

- To find the corresponding error that caused the FCV to close until the power dropped to 2.50 MW:

e = 3656 – 3600 = –36 rpm
(Generator's speed)

This error will then become zero at steady state.

GENERATOR OPERATION AND SYNCHRONIZATION

When the generator breaker is closed, the GEN controller signals the GT controller to select its main loop to be one of two modes (based on utility breaker position):

- If the utility breaker is open, typically isochronous control is applied (unless droop is selected). Isochronous control mode selects the NPT control/limiting loop, with the local SP corresponding to the unit's nominal sync speed and frequency.
- If the utility breaker is closed, the local bus is assumed to be connected to the utility grid and droop control is applied. Droop control mode selects the generator's PID loop, which regulates NPT using a

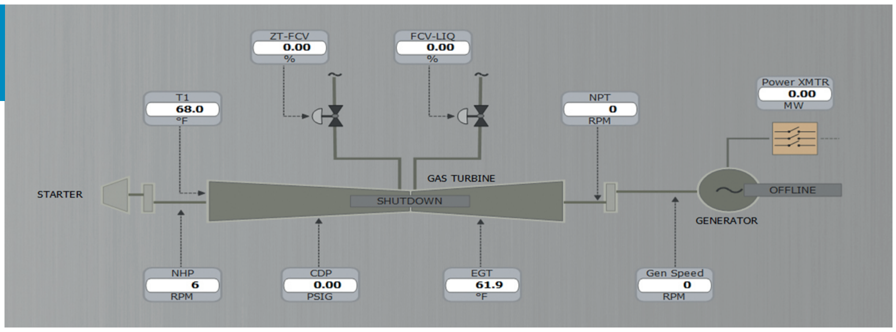


FIGURE 2: A two-shaft GT driving a synchronous generator.

separate set of PID coefficients and a local SP supplied by the GEN controller. In most cases, the generator is brought on-line under droop control. The droop SP is then initialized to the configured minimum power level.

The generator must be synchronized with the bus prior to bringing it on-line. An on-line generator always rotates "in-sync" with any other units on the same electrical bus or grid. Although the GT controller sequences can be used to accelerate the unit to its sync speed, an external system must be used to equalize the voltage, frequency, and phase angle prior to closing the generator's breaker.

In the event of a sudden or large load change, droop control will stabilize the grid frequency at an offset from its desired value while the lead generator's isochronous controller restores the desired frequency.

If the generator breaker is opened while the generator is on-line, the resulting mismatch between the generator's load and the turbine's power output can rapidly accelerate the unit beyond its maximum safe speed. In such situations, the GEN controller protects the unit by rapidly reducing the fuel flow to the turbine or by initiating an ESD, depending on the GEN controller's configuration settings.

If the utility breaker opens while the local bus is importing or exporting power to the grid from several generators, a companion logic controller should initiate step changes in their outputs and SPs as well as switch one of them to isochronous control to minimize the impact on the local bus.

SIMULATION DEMONSTRATION

Figure 2 shows the same two-shaft GT driving a two-pole synchronous generator example discussed above. A logic was custom designed to sequence the turbine startup before the generator's breaker can be closed. Initially, the turbine is shut-down and the generator is off-line.

Unit start: The GT1 controller must be "Reset" before the turbine can be started. Once "Reset" is asserted, and after passing all start permissives, the GT1 controller changes its state from "Shutdown" to "Ready to Run". The turbine can then be started by initiating "Start" command. As the turbine enters the startup sequence, the fuel control valve (ZT-FCV) ramps open. The turbine will then go through both the open- and closed-loop control phases until NPT reaches the bus sync speed of 4525 rpm as shown in Figure 3. This corresponds to a generator's sync speed of 3600 rpm (60 Hz) because of the gear box between the turbine and the generator.

This turbine can be started and run on either gaseous or liquid fuel. Only all-gas or all-liquid (100%) settings are possible for startup. Initially the selection is set to "Gas" via ZT-FCV. Once sync speed is reached, we can switch to "Liquid" via FCV-LIQ.

During closed-loop control, this unit's speed is maintained between minimum (4400 rpm) and maximum (6500 rpm) NPT governor speeds.

Bringing the generator on-line: When NPT gets within 5 rpm of the bus sync speed

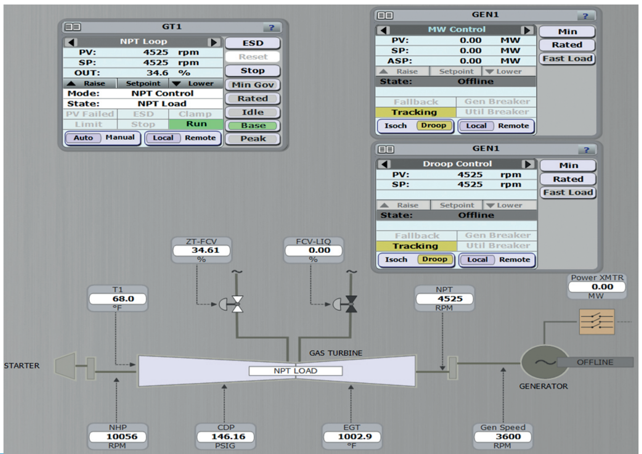


FIGURE 3: Unit is at bus sync speed of 4525 rpm NPT (3600 rpm generator's speed).

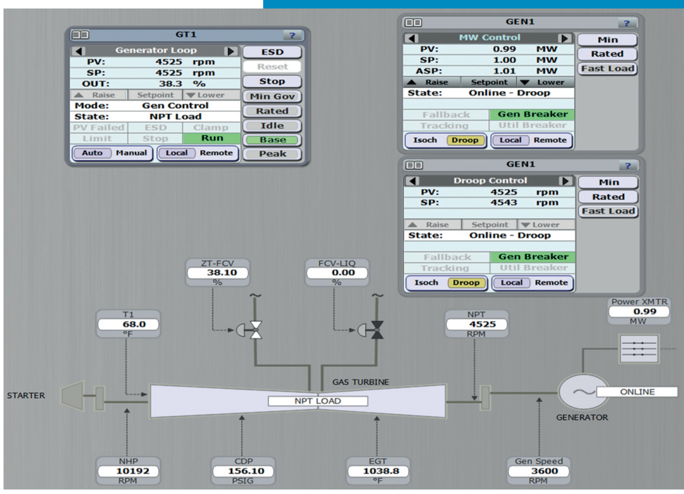
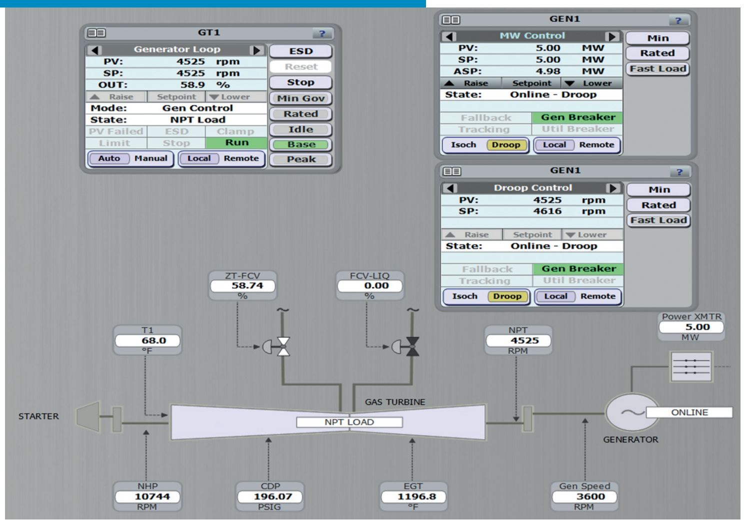


FIGURE 4: Delivering 1.00 MW power output.

FIGURE 5: Delivering 5.00 MW power output.



of 4525 rpm, the generator can be put on-line by closing the generator's breaker. As shown in Figure 4, when the breaker is closed, the GEN1 controller begins controlling the output power using the minimum power SP of 1.00 MW. This ramps the speed SP from 4525 rpm to 4543 rpm. Since the difference between the sync speed and the speed SP has increased, the GT1 controller increases its FCV output (from 35% to 38%) to deliver the required power.

Delivering more power output: Let us increase the power SP to 5.00 MW by asserting "Rated" on the GEN1 controller. As shown in Figure 5, the speed SP has increased from 4543 rpm to 4616 rpm (corresponding to the new power SP of 5.00 MW). Since the difference between the sync speed and the speed SP has increased, the GT1 controller further increases its FCV output (from 38% to 59%) to satisfy the new power output requirement. There is no change in frequency as it is fixed on the grid.

Increasing the bus sync speed (Droop control): The speed SP (which corresponds to the power SP of 5.00 MW requirement) does not change; here 4616 rpm NPT. As the bus sync speed is increased, the generated power decreases since the difference between the bus sync speed and speed SP has decreased. As discussed in the calculations example above, as the bus sync speed increases to 4570 rpm NPT (3636 rpm generator's speed, i.e., 60.6 Hz), >

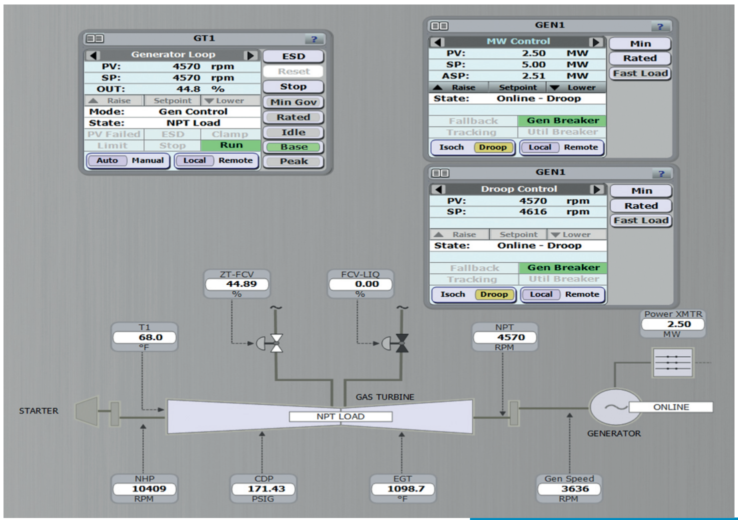


FIGURE 6: Result of bus sync speed increase. Power decreased to 2.50 MW (25% change in load) due to frequency increase by 1% (60.6 Hz).

the output power decreases to 2.50 MW (25.0% change in load since frequency increased by 1.0%). FCV ramps close from 59% to 45% to satisfy this power decrease requirement. The steady state condition is shown in Figure 6 where the error in the GT1 controller equals to zero.

Decreasing the bus sync speed (Droop control): As the bus sync speed is decreased, the generated power increases since the difference between the bus sync speed and speed SP has increased. Let us return to the settings with bus sync speed of 4525 rpm and "Rated" power SP of 5.00 MW. As shown in Figure 7, as the bus sync speed decreases to 4502 rpm NPT (3582 rpm generator's speed, i.e., 59.7 Hz), the output power increases to 6.25 MW (12.5% change in load since frequency dropped by 0.5%). FCV ramps open to 69% to satisfy this power increase requirement. The steady state condition is shown in Figure 7 where the error in the GT1 controller equals to zero.

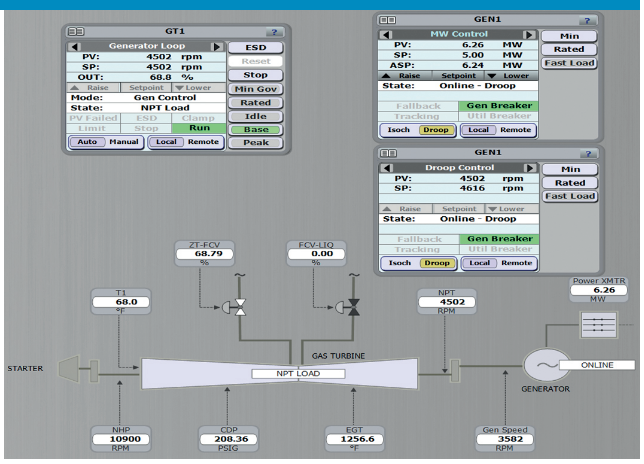
Isochronous control: Let us return to the settings with bus sync speed of 4525 rpm and "Rated" power SP of 5.00 MW. As shown in Figure 8, "Isoch" command was asserted. The GEN1 controllers will be in "Tracking" for bumpless transfer to droop control. During this mode, the fuel flow is varied to maintain the turbine and generator speed.

This mode is used to control the speed of a generator which is not connected to a grid, or the speed of one of the generators connected to a grid while all the others are regulated using droop control.

Open the generator's breaker under load: Let us return settings to "Droop" with 5.00 MW delivered power. If the generator's breaker is opened while the turbine is loaded, the NPT will briefly increase, then under-shoot the SP (4525 rpm) as the GT1 controller goes to the deceleration schedule as shown in Figure 9 (green trend). The GEN1 controller protected the unit by rapidly reducing the fuel flow to the GT1 controller; FCV opening dropped immediately from 59% to 35% (yellow trend).

On-line droop test: The on-line droop test feature, available within the GEN controller, simulates a disturbance ramp in the grid frequency to determine how quickly the power output of the controlled generator would respond to a real frequency variation; "Frequency-Up" or "Frequency-Down". Let us close the generator's breaker and return settings to "Droop" with 5.00 MW delivered power.

FIGURE 7: of bus sync speed decrease. Power increased to 6.25 MW (12.5% change in load) due to frequency drop by 0.5% (59.7 Hz).



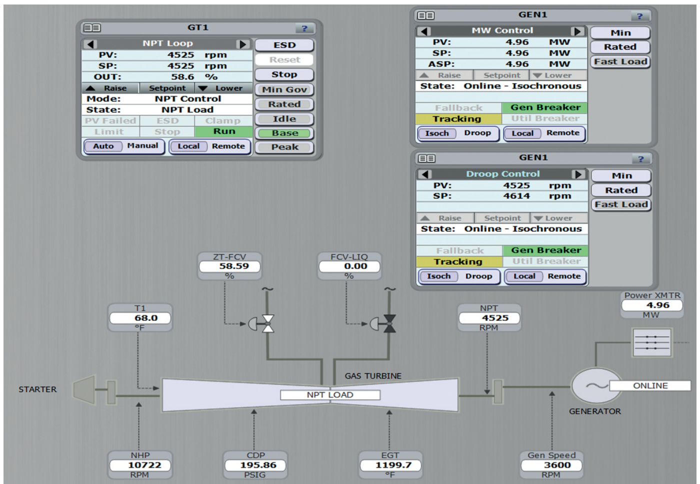


FIGURE 8: Isochronous control.

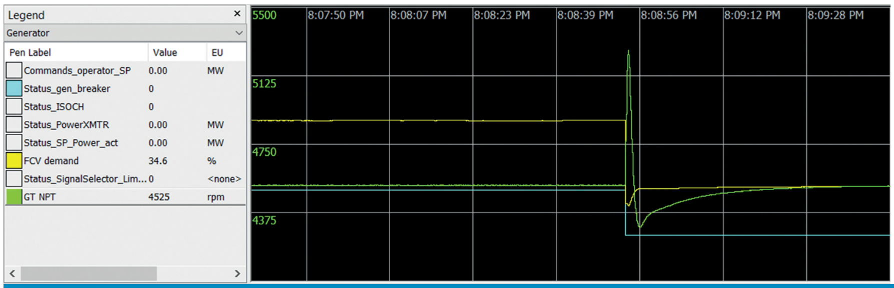


FIGURE 9: NPT and FCV reaction for the generator's breaker opening.

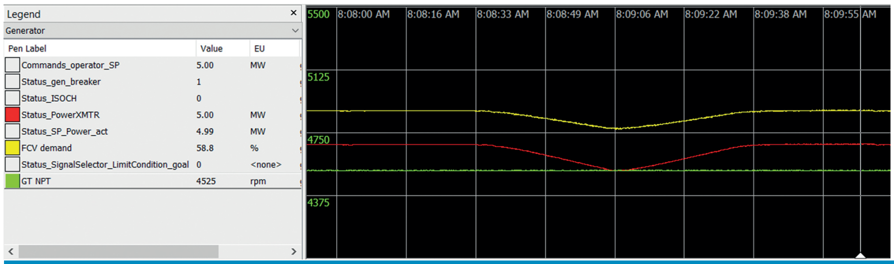


FIGURE 10: On-line droop test. The result of a simulated "Frequency Up" test command.

As shown in Figure 10, a "Frequency-Up" test command forces the unit's power output to decrease (red trend) since FCV started to close (yellow trend). After passing this test, the unit's power output returns to its original value before the test was initiated; here 5.00 MW, and FCV ramps up to its original position. During the test, the NPT (and accordingly the generator's speed) remains constant (green trend).

This test briefly varies the actual power output of the generator. While this should not be a problem when testing relatively small units, the test parameters for large generators must be carefully selected to avoid disrupting the grid.

Generator idling and shutdown:

- If the generator was running under droop control:
  - The unit can be idled by first asserting the GT1 controller's "Idle" command. This will cause the GEN1 controller to ramp the load SP down until the generator's breaker opens, thus taking the unit off-line. The GT1 controller's idle sequence then slows the turbine to its NHP idle speed.
  - If the GT1 controller's "Stop" command is asserted, it will wait for the generator's breaker to open before initiating its stop sequence. The stop sequence shuts the turbine down gradually. Typically, the selected SP (either the cooldown or the minimum governor speed) is then held constant until the cooldown timer expires, thus allowing the turbine to cool down, then closes the FCV completely as was shown in Figure 2.
- If the generator was running under isochronous control, the GT1 controller's "Idle" and "Stop" commands are disabled to prevent the grid's lead generator from being accidentally taken off-line.

NOMENCLATURE

AC : Alternating Current
GT : Gas Turbine
GEN : Generator
NHP : High-Pressure rotor Speed
CDP : Compressor Discharge Pressure
EGT or T4 : Exhaust Gas Temperature
NPT : Power Turbine Speed
T1 : Ambient/Inlet Temperature
PID : Proportional-Integral-Derivative
SP : Set Point
PV : Process Variable
FCV : Fuel Control Valve
OP : Operating Point
ESD : Emergency Shut Down

SUMMARY

In order to achieve integrated control of a GT-driven synchronous generator unit, various CCC controllers were developed. Because the speed of a synchronous generator is essentially fixed by the grid frequency, any imbalance between that speed and its SP will cause the GT controller to change the fuel flow; Thus, the power output of the generator can be regulated by manipulating the turbine's speed SP. A well-tuned synchronous generator control system should absorb upsets in the grid frequency and apply various limit loops to fully protect the unit while delivering the required power.