Industrial Gas turbine control
Torsten Strand
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  - control
    - load or speed = fuel control
    - max power
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  - protection
    - risk for personal injuries (explosion, fire, flying objects)
    - engine failures
  - maintenance
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GT application Review (1), offshore & marine

- Fast Ferry, 60 knots
- Buquebus, 450 persons & 50 cars
- BP Ula
- FPSO
- Leadon Field
Application Review (2),
land based

Co-Generation

City of Chaska, MN, USA
Gendorf, Germany

Combined Cycle

City of Redding, CA, USA
Sandreuth, Germany

Simple Cycle
The industrial gas turbine is delivered as a complete package including all systems for its operation.
A gas turbine is an air breathing engine, operating with a surplus of air (only 30% of the Oxygen is used for combustion)
- the air is compressed and heated in the compressor
- fuel is added in the combustor, combustion at constant pressure
- the hot gas is expanded in
  - the compressor turbine, which drives the compressor
  - the power turbine, which drives the compressor or generator
- The gas temperatures in the combustor and the turbine inlet stages is higher than the melting point of the material in spite of the fact that it is of high temperature Ni-based alloy type
  - compressor air is used to cool the combustor walls and the hollow blades of the first two stages
SGT-600 is a twin shaft 24 MWe gas turbine used for electric power generation and compressor drive. The compressor has 10 stages, compressor turbine 2 stages and power turbine 2 stages.
SGT-800 Core engine

45 MW single shaft unit, running at 6000 rpm
15 stage compressor, pressure ratio 20
3 stage turbine, turbine inlet temp 1427 °C
The gas turbine in the T-S Diagram

\[ \eta_c = \frac{(t_{3s} - t_2)}{(t_3 - t_2)} \]

\[ \eta_{ct} = \frac{(t_{5m} - t_6)}{(t_{5m} - t_{6s})} \]

\[ \eta_{pt} = \frac{(t_{6m} - t_7)}{(t_{6m} - t_{7s})} \]
DLE combustor for 25 ppmv with EV burners since 1991
Dual Fuel EV-Burner

Features
- Mixing of the gas and air is achieved shortly after the gas injection holes
- Vortex breakdown stabilizes the flame in free space
- No mechanical flame holder is necessary

Benefits
- Homogenous mixture leads to very low emission levels
- Design is simple and reliable
AEV dual fuel burner, more details

Concentric tubes for fuel supply

Main gas

Main oil

Pilot oil

Pilot gas
All gas turbines are delivered as a package that includes

- a base skid on which the core engine and gear box are mounted
- on or in the skid are the systems mounted
  - lubrication oil tank, pumps and valves
  - fuel oil pumps and gas valves
  - measuring equipment
  - sound cover etc

With the turbine is delivered the control equipment for

- gas turbine control
- generator control
- electric power control if applicable
- the local control panel
SGT-800, 3-D view
Simple cycle

Exhaust with silencer
Air intake filter
Electrical and Control module
Ventilation Inlet

Fire extinguishing
Ventilation Outlet
Signal handling module
Gas fuel unit 2
Gas fuel unit 1
Propane tank (start liquid fuel)

Lube oil sys. Lube oil cooler
Generator
Generator air intake
Generator air outlet

25/04/2006
Auxiliary systems
Gas fuel system SGT-600

Gas fuel unit 2, located inside the GT enclosure

Quick shut-off valves

Enclosure wall

From gas fuel unit 1

Ventilation valves

Gas control valves

To atmosphere
Control system standard Configuration
SGT-800 Power Generation (Simple Cycle)

- **Hardcopy**
- **Event & alarm printer (option)**
- **TCP/IP**
- **Operate IT Process Portal**
- **Pocket Computer, SMS alarming, e-mail (Options)**

- **Generator Control panel**
  - Sequencing
  - Open loop
  - Optional Modbus or Ethernet OPC

- **GT control panel (On turbine skid)**
  - Dual Fieldbus AF100
  - Governor
  - Safety Ch. 1
  - Dual CPUs

- **Generator protection**
- **Synchron. equipment**

- **Fire extinguishing**
- **Lube oil VFD**
- **Start VFD**
- **MCC**
- **GCB**

- **AVR**
- **AC-servo drive**
- **Vibration Monitor**

- **OPTIONS IN RED**

*Enhanced instrumentation reliability, "2 out of 3" on instruments tripping during operation.*
The gas turbine is controlled in different ways depending on application but

- in simple cycle arrangement for power generation there are two modes
  - constant power at a given electric frequency
  - full power
- in cogeneration coupled to a process industry the steam demand from the waste heat recovery boiler is governing the gas turbine heat input
- in combined cycle operation the total power or heat demand is governing the gas turbine heat input
Generally the basic control is simple

- more fuel gives more power, but in the gas turbine the air flow has to be matched to the fuel flow in order to provide
  - long life of hot parts
  - low emissions
- for the twin shaft unit the air flow increases with load, since the gas generator rotor accelerates
- for the single shaft unit the air flow is increased by opening of the inlet guide vanes of the compressor in a controlled way
In order to provide long life of the gas turbine parts there are limitations for the operation on:
- turbine inlet temperature, to protect the turbine front end
- turbine exit temperature, to protect the exit end of the turbine and the exhaust casing and waste heat recovery boiler
- rotor speed to protect compressor and turbine discs from rupture
- power to protect the shafts, gear box and generator

Full power is reached when the lowest of these limits is reached. The limits are somewhat dependent on ambient conditions and fuel type.

The temperature limits can be overruled by the customer in order to make some 10% more power, peak power, but at shorter lifetime of the engine hot section.
Turbine inlet temperature limit

- Most often the limitation is the maximum turbine gas inlet temperature, TIT, which can be one of:
  - combustor exit temperature
  - rotor inlet temperature
  - turbine mixed inlet temperature

- TIT is a characteristic temperature that is related to a certain life time of the hot parts in the turbine.

- For an industrial turbine the design life time of the hot parts is usually around 40000 equivalent hours.

- The customer can choose to operate at a shorter hot section life at times when electric price is high, peak power or flat rating.
The life time of a component is usually determined by:
- high temperature creep due to high stress and high temperature or
- low cycle fatigue LCF caused by the start and stop cycles.

The life time consumption is most often calculated as Equivalent hours. Each part has its own Eq.hour formula depending on design and operation conditions. For the older gas turbines creep was the critical factor, but in modern gas turbines LCF is dominating.

For simplicity in the control system every company has their own formula for equivalent hours based on the most critical part, which usually is the first turbine blade. The simple one is a mixture of creep hours and LCF cycles:

\[
\text{Eq.hrs} = \text{operating hrs} \times \text{fuel factor} + \text{starts} \times \text{start factor}
\]

- cf = 1.0 for natural gas
- cf = 1.4 for diesel oil
- cstart = 15 ÷ 50
The turbine inlet temperature can not be measured, since it is too hot and too risky.

The control system language is not apt for complicated computations, so simplicity is preferred.

How is the turbine inlet temperature calculated from measured values:

- \( t_2, p_2 \)
- \( t_3, p_3 \)
- \( t_7, p_7 \)

\[
\begin{align*}
t_{5m} &= \frac{t_7}{(1-\eta^*(1-(p_7/p_5)^{(\kappa-1)/\kappa})} \cong t_7 + k_1 \frac{p_5}{p_7} + k_2 \\
t_5 &= \frac{(t_{5m}c_{p5m} - x \cdot t_3c_{p3})}{(1-x)c_{p5}} \cong \frac{(t_{5m} - x \cdot t_3)}{(1-x)} \\
x &= \frac{m_{cool}}{m_2}
\end{align*}
\]
The gas turbine in the T-S Diagram

- The gas turbine in the T-S Diagram

**Equations:**

- Combustor cooling: \( \eta_{ct} = \frac{t_{5m} - t_6}{t_{5m} - t_{6s}} \)
- Turbine cooling: \( \eta_{pt} = \frac{t_{6m} - t_7}{t_{6m} - t_{7s}} \)
- Combustor efficiency: \( \eta_c = \frac{t_{3s} - t_2}{t_3 - t_2} \)

**Points:**

- \( T_{flame} \)
- \( t_5 \)
- \( p_5, t_{5m} \)
- \( p_3, t_3 \)
- \( p_6, t_6 \)
- \( p_7, t_7 \)
T5/T7 factor vs pressure ratio

T5/T7 factor vs pressure ratio graph showing the relationship between T5/T7 factor and turbine pressure ratio. The graph includes a calculation curve and an approximation curve.
The gas turbine in the T-S Diagram

\[ T_{\text{flame}} \]

Combustor cooling

Turbine cooling

\[ \eta_{ct} = \frac{(t_{5m} - t_6)}{(t_{5m} - t_{6s})} \]

\[ \eta_{pt} = \frac{(t_{6m} - t_7)}{(t_{6m} - t_{7s})} \]

\[ \eta_c = \frac{(t_{3s} - t_2)}{(t_3 - t_2)} \]

\[ \eta_p = \frac{(t_{5m} - t_6)}{(t_{5m} - t_{6s})} \]
Finally the formula can be reduced to

\[ t5 = \frac{(t7 + k1*p5/p7 + k2 - k3*x*t3)}{(1-x)} \]

- For simplicity the control system computes the maximum allowed \( t7 \) for the maximum \( t5 \)
  - \( t7\text{limit} = t5\text{limit}*(1-x) - k1*p3/p7 - k2 + k3*x*t3 \)

- the constants in the equation is derived from performance program calculations and adjusted after performance tests

- the average temperatures \( t3 \) and \( t7 \) is measured by a few operating probes, which are not measuring the true averages. During the performance tests a number of special probes are used to get the true averages. The operating values are then corrected for the differences found at the performance test.
• Generally the material temperature of a gas turbine blade should be lower than 850°C, but with oxidation protective coatings and thermal boundary coatings (ceramic layers) temperatures at around 950°C is used, but often with reduced life time as the result.

• the internally cooled blade has a metal temperature in between the gas temperature and the cooling air temperature. The cooling factor for the blade is determined in tests

\[ \varepsilon = \frac{t_m - t_{cool}}{t_{gas} - t_{cool}} \]

and the material temperature can be estimated during operation

\[ t_m = t_{cool} + \varepsilon \cdot (t_{gas} - t_{cool}) \]

• With stress levels that come from FEM calculations, the material temperature and the material data, the blade life consumption can be computed
SGT-600 Turbines

Gas temp 1215°C

Internally cooled blades for a material temp of 850°C

Gas temp 545°C

Uncooled blades

Gas temp 800°C
- The $t_7$ limit calculated from the $t_5$ limit is usually the critical one, but at high ambient temperatures the $t_7$ limit based on the maximum turbine exit temperature could be lower.

- This is usually a fixed temperature based on the material quality of the exhaust casing.

- The control system chooses the lowest of the two $t_7$ limits.
• On a twin shaft unit the gas generator rotor is running free. The speed is determined by the thermodynamic balance between compressor and turbine.
  • usually the gas generator rotor speed is going down in speed with increasing ambient temperature, but at very low ambient temperatures the speed may become too high, creating excessive stresses in the rims of the discs where the blades are attached

• on units always operating in hot climate, the split of power between compressor turbine and power turbine is changed to increase the speed (and air flow) of the gas generator rotor.

• How?
Maximum power

- Due to the higher density of the air at low ambient temperature, the air mass flow is increased. More fuel can be added and the power goes up.

- The generator capacity is usually the limit for power output, but there may be some limitation in shafts, gear teeth and couplings.

- Most of these parts are however designed for electrical shortening torque
Power Limitations from ambient temperature

-45 -30 -15 0 15 30 45

Ambient temperature °C

Power generation MW

Nominal Power

Max generator power

Max compressor speed

Max turbine inlet temperature at 40000 hrs life

Flat rating

Peak Power

Power output MW
IGV and bleed valves

![Graph showing IGV and bleed valve positions](image-url)
Combustion control

Basic strategy to keep within window in as wide operating range as possible

- Combustor control strategy -
Combustion system control and supervision

- The basic control is to govern the gas valves or oil pumps for correct flow, but...
  - a low emission system has a limited operating window, in which it is can be quite complicated to stay
  - many tricks are used to achieve acceptable part load performance

- Very often a pilot flame is used to stabilise the main flame when the flame temperature is getting too low (moving the CO line to the left), but with a NOx penalty

- Fuel staging is one common practise, thus concentrating the fuel to fewer burners with higher flame temperature as a result. Uneven turbine temperatures can be harmful to turbine life

- Reduction of burner air flow by
  - combustor bypass which reduces the flow to the burner but not to the turbine
  - compressor bleed, that reduces the flow to both burner and turbine
SGT-700 combustion control
Low NOx >50% load

NOx ~ 10 ppmv on gas
NOx ~ 20 ppmv on diesel oil
Combustion Control Strategies

- The control strategies vary with the machine type and burner design
  - in GT10B there is a pilot and a combustor bypass system
  - in GTX100 the air flow can be controlled by the compressor inlet guide vanes, but there is also a pilot

- Since the emissions are very much dependent on the flame temperature, it is used as the controlling parameter.

- The flame temperature is a function of
  - the normalised Air/Fuel ratio \( \lambda = \frac{m_{\text{air}}}{m_{\text{fuel}}} / (\frac{m_{\text{air}}}{m_{\text{fuel}}} \text{st}) \)
  - the air temperature

- The flame temperature is basically calculated as \( t5 \) above, but there are other methods, more or less successful
  - \( \lambda \) can be calculated from the Oxygen left in the exhaust air
  - \( \lambda \) can be calculated from measured fuel and air flows
The pilot/total fuel flow ratio and the bypass are flow rate are then governed by the flame temperature.

Usually the turbine is started on 100% pilot, which is then reduced with increasing power to a few % at full load, but not fully closed. At a fast load reduction the pilot has to be quick to avoid flame out.

The pfr schedule is determined at tests and is dependent on combustion stability for the lower limit and emissions for the higher limit. The pilot is usually a diffusion flame that produces a lot of NOx.

Many units does not have a bypass system, but bleeds off air from the compressor. The combustion effect with higher flame temperature can be achieved, but at a loss of part load efficiency. The limit for the bleed is very often the turbine exit temperature.
Performance with bleed/bypass options

GT10B Performance with bypass alternatives

- Tflame with bypass or bleed
- Tflame without
- Efficiency
- Efficiency with anti-icing
- Efficiency with bleed 3

- W/wo Bypass
- 80% load

Graph showing performance metrics versus power kW and temperature (Tflame) with different options.
The combustion is checked by:
- flame detectors
- exhaust temperatures
- pulsation measurements

If the flame detectors do not see a flame, the fuel is directly shut off to prevent an explosion, since re-ignition can happen.

The t7 probes in the turbine diffuser can detect burners that are not working well by showing:
- too low temperature, indicating some blockage of fuel injectors
- too high temperature, which could be the result of fuel leakage or some disturbance on the air side

The control system checks the deviations and gives alarm and reduces load if certain limits are reached.
Sequencing

- The start up of a gas turbine is fully automatic, but ....
  - there are a lot of sequences to perform in a short time, starting and checking
    - lube oil system
    - ventilation of gas generator room to prevent explosion from fuel fumes
    - ventilation to turbine and exhaust duct by running the gas generator at ventilation speed to prevent explosion of remaining fuel
    - fuel system for leaks
    - measurement systems etc
    - compressor inlet guide vanes and bleeds
  - Finally the gas generator is brought up to ignition speed. After cross ignition the rotor is accelerated along ramps up to idle speed.
  - During the acceleration the compressor bleed valves are closing.
  - At idle the electrical breakers are closed at phasing speed and the loading starts
Mech drive start

- Turbine exhaust temp
- GG speed
- Prim fuel flow
- PT speed
- Compressor exhaust pressure
- IGV
Transients

- Fuel change over
  - automatic fuel change over is possible on dual fuel units
  - the change over from gas to oil if gas pressure gets too low is done in 10 to 30 seconds, depending on requirement
  - the transient operation requires a speed up of the control amplification and quite a lot of fine tuning

- the fuel change over from oil to gas is usually initiated manually when the gas system is back in operation

- Surge protection
  - if for some reason the compressor runs into the surge line, the unit will trip after the first surge cycle
During operation the performance deteriorates mainly due to fouling of the compressor. Dust from the air attaches to the blade surfaces and increases the flow losses.

Deterioration also comes from the wear of seals increasing leakages.

The control system checks the loss in performance and indicates when it is time to do a compressor wash
  - on line or off line

Most of the performance is regained at an off line wash, while the on line wash has less good effect but is used when it is not possible to stop.

The deterioration due to wear is only reduced at overhauls, when blades and seals are exchanged.
Deterioration of $P_e$ and S.H.C up to 120,000 eq. hrs, nominal

- Deterioration is shown in comparison with “new and clean” engine. *No guarantee beyond original warranty period.*

**Natural gas fuel**
Average 1.4% H.R & 2.4% power

**Liquid fuel**
Average 1.8% H.R & 3.1% power

---

**Expected GT10B deterioration expanded to 120,000 h**
- *Gaseous fuel*
- *Liquid fuel*

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25/04/2006
Compressor washing system, SDB

- **Instrument air supply**
- **Reciprocating pump**
- **Washing unit**
- **Four washing nozzles**
- **Plenum**
- **Filling of fluid**
- **Drain delivery limits**
- **Rinsing detergent 80 liters (water+washing fluid)**
- **Watertank 80 liters**

Standard P&ID GT10B2: 992891
Remote supervision

- The control system can be accessed
  - at the local control room close to the turbine, which is used only by the service crews
  - the plant control room, in which the gas turbine control is a PC
  - at the gas turbine suppliers remote operation station
  - Alarm signals can be sent to operators mobile phone
Operator's station

- **HP B2000 workstations**
  - Very high computing performance
  - High resolution graphical user interface

- **Real-Time Accelerator**

- **System software**
  - UNIX, OSF/Motif, SQL, X Windows System, TCP/IP

PC available as an option
Unit start/stop

SGT-600 Operator displays
SGT-600 Operator displays

Unit operation
SGT-600 Operator displays

Log page

| Log page

<table>
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<tr>
<th><strong>Bearsen</strong></th>
<th><strong>Temp</strong></th>
<th><strong>Vibration</strong></th>
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<td>1 GG Axial</td>
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<td>NGG 0 rpm</td>
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<tr>
<td>1</td>
<td>NGG 0 rpm</td>
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<td>2</td>
<td>NPT 0 rpm</td>
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<tr>
<td>3</td>
<td>IGV 0 %</td>
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<td>4</td>
<td>BV1</td>
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<tr>
<td>5</td>
<td>BV2 0 %</td>
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<td>6</td>
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<td>8</td>
<td>Exh Press UNPa</td>
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<tr>
<th><strong>Cool &amp; Seal Air, Air Intake</strong></th>
<th><strong>Lubrication Oil</strong></th>
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<td></td>
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</tbody>
</table>
Fuel page

SGT-600 Operator displays
Lubrication oil

SGT-600 Operator displays
Typical Alarm and event list

Operator displays
Valuable features

- Excellent operator's interface with colour graphics
- One display for every sub system
- Trend monitoring
- Self supervisory
- System status displays
- Object displays for every signal in the system
- Alarm and event recording
- Hardcopy printer
- Function block programming with excellent printouts
- Programming of main controller from operator's screen
- Online programmable
- Open to external systems
- Good track record of retrofit - protects investment
- Minimized on site cabling (safe area installation)
Control system options

- 1 or more X-terminal remote OS
- MB300

Option

- Advant Station 520 OS
- Alarm & Event Matrix Printer
- Hardcopy Printer
- Opto modem and cable

Option

- Advant AC400
- Modbus
- Hardwired

Option

- Advant Fieldbus 100

Option

- AC 100
  - Safety System ch 1
  - Remote I/O

Option

- AC 100
  - Safety System ch 2
  - Turbine controller

Option

- AC 100
  - Voltage controller
  (power gen only)

Option

- AC 110

GT skid mounted equipment
Control system simulations

- The logics are basically figured out by us, the engine designers, but the logics are programmed by others.

- There will be errors both in the logics and the programming.

- Simulations to check it can be done in simple or sophisticated ways.

- In the simple way an Excel program can be used:
  - The gas turbine performance is calculated at small time steps:
    - 0.5 sec at fast transients (valve openings)
    - 1 sec at normal start sequences (acceleration and trip)
    - 10 sec at normal loading
  - Usually the rotor mass can be neglected (not at load rejection).
The compressor has
- variable guide vanes before stage 1&2
- bleed at stage 2 and 5

The operating line is determined by
- the compressor turbine flow areas
- turbine IGV+ cooling ducts
- bleed valves

Normalised inlet mass flow $m_n = m*p_2/p_n*\text{rot}(T_n/T_2)$
The compressor stage flow

The compressor blade path is like diffusers

In retarding flows the boundary layers grow and tend to separate.

Low stage load = many stages
Surge protection

GT10B Surge protection

Pressure ratio vs. Norm speed rpm

- p3/p2 operating line
- p3/p3 surge line