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Part-Load Gas Turbine Engine Analysis

Outline

- Intent and Motivation
- Thermodynamic Modeling
  - Core Equations
  - Model Types
- Engine Control Theory
- Numerical Methods
- Logic Branching
- Conclusion

Intent and Motivation

Current Manufacturer Models

- Manufacturer curves closely guarded
- Manufacturer curves are not well explained (proprietary)
  - Curve discontinuities
  - Engine control and throttling
  - Hardware limitations
    - Maximum Temperatures
    - Minimum Flow Rates

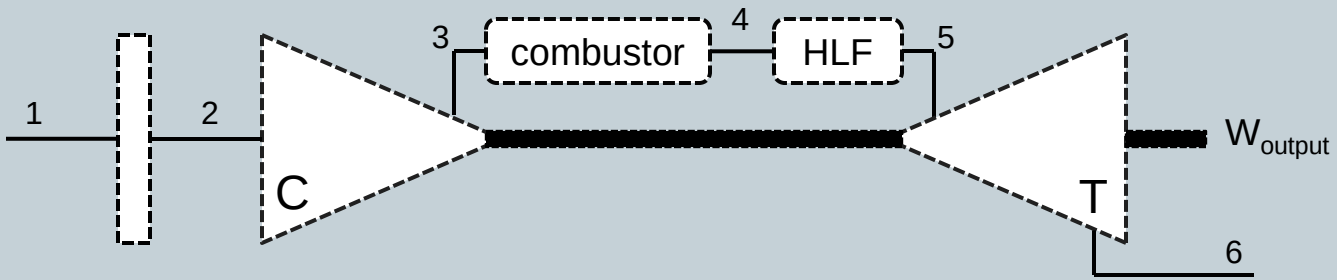
Thermodynamic Modeling

Assumptions

- Thermodynamic Equations Only
  - No complex fluid dynamics models
  - Simplified gas turbine engine thermodynamic models (EBE)
- Losses:
  - Combustor pressure drop (~4%)
  - Polytropic turbine efficiency (assumed, 90%)
  - Polytropic compressor efficiency
  - No bleed air (except variable VFR)
  - No turbine cooling air
- LHV_{fuel} based model

Gas Turbine Cycle Design

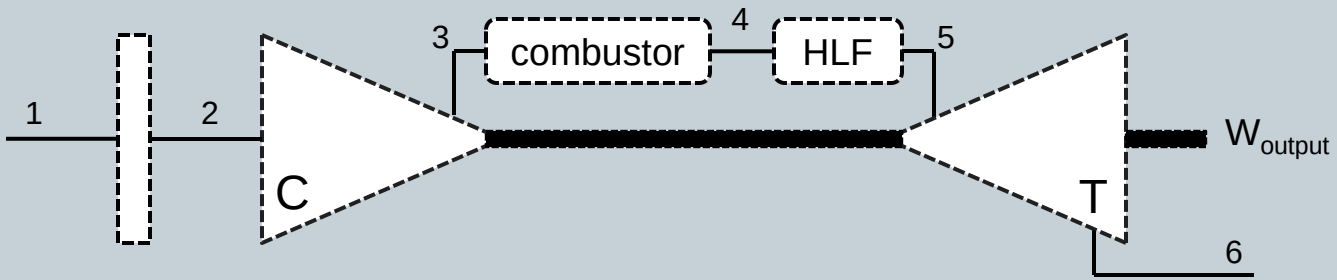
- Simple Cycle



State	Description	State	Description
1	Ambient, Pre-IGV	4	Post-Combustor, Pre-Heat Loss
2	Post-IGV, Pre-Compressor	5	Post-Heat Loss/Gain, Pre-Turbine
3	Post-Compressor, Pre-Combustor	6	Post-Turbine (ambient pressure)

Gas Turbine Cycle Design

- Combined Cycle



  - Differs only in HRSG pressure and engine control techniques
  - GTE Analysis only!

State	Description	State	Description
1	Ambient, Pre-IGV	4	Post-Combustor, Pre-Heat Loss
2	Post-IGV, Pre-Compressor	5	Post-Heat Loss/Gain, Pre-Turbine
3	Post-Compressor, Pre-Combustor	6	Post-Turbine (HRSG back pressure)

Equations

- Heavily Reliant on:
  - Conservation of Energy

$$m_{total}(CP_5T_5 - CP_6T_6) = W_{output} + m_{total}(CP_3T_3 - CP_2T_2)$$

  - Turbine and Compressor Efficiency Equations

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{\left(\frac{\gamma-1}{\gamma}\right)\left(\frac{1}{\eta_c}\right)} \qquad \frac{T_6}{T_5} = \left(\frac{P_6}{P_5}\right)^{\frac{\gamma-1}{\gamma}\eta_t}$$

  - Choked Flow at Turbine Inlet

$$m_{total}\frac{\sqrt{T5}}{P5} = constant$$

  - Predefined Variable Volumetric Flow Rate (VVFR) over Compressor

$$m_{air}\frac{T_2}{P_2} = f_{vfr} \cdot constant$$

Equations

- Core equations used in model are all similar
  - The differences come from the input parameters.
  - Off-design case numerical solver:
    - 11 equations / 11 unknowns
  - Full-Load case numerical solver:
    - 1 equation / 1 unknown (specific heats)
  - Part-Load case numerical solver:
    - 11 equations / 11unknowns
  - Solution method for each type of system is unique!

Programming

- Initial model prototyping done in Python and MATLAB
  - Interpreted language: slow!
  - Solution domain
    - 100% to 0% load calculated in steps
    - Switching occurred dynamically as the model was running
  - Languages have many built-in functions, which is convenient.
- Logic was reformulated when final code was written.
  - Successive looping changed to ***logic branching***
- Entirely standalone and written in C/C++

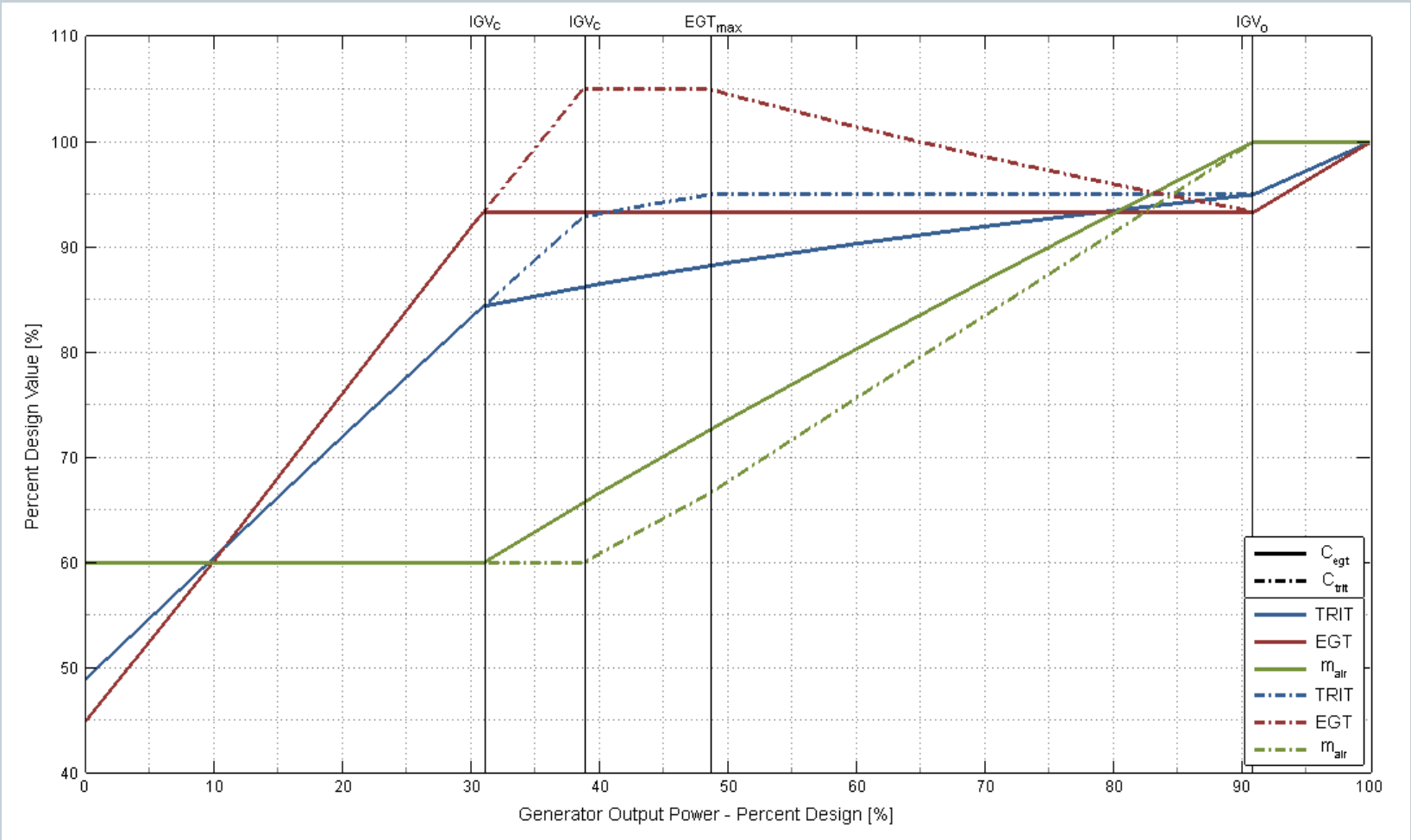
Logic Branching

Logic Branching

- Example: Assume we wish to know the part-load performance after the IGV have fully closed.
  - How do we know what the state values are if the engine has prior throttling and control mechanisms in place (like maximum EGT) that are influencing the system?
  - Too many unknowns, not enough knowledge of the system!
  - We use logic branching!

Results

Part-Load Case



Conclusions

Reiterate

- A part-load and off-design model was created
  - Tried to remove the shroud of mystery from the manufacturers “black box”
  - Gas turbine control mechanism
  - Off-design model
  - Part-load model

Questions?