Considerations in the Design, Construction and Interconnection of Cogeneration Facilities

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Abstract:

- With the gradual retirement of coal fired generation in Alberta, gas fired generation and renewables are growing. In 2016 and for the first time in Alberta, installed capacity of gas fired generation exceeded coal fire ones. A significant part of the existing and planned gas fire generation in Alberta is configured and proposed as cogeneration with high efficiency. The February 2017 IEEE/SAS, PES/IAS Joint Chapter will discuss topics and considerations associated with cogeneration such as selection of configurations, critical aspects of design, construction commissioning and operation of cogenerating facilities connections to the Alberta Interconnected System and experience and lesson learned.
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- That presentation will be done by multiple presenters and will be organized as follows:
  - Introduction and definitions and overall review
  - Process aspects of cogeneration
  - Electrical engineering considerations for cogeneration
  - Interconnection to the Alberta Interconnected Electrical System (AIES)
  - Experience with existing cogeneration facilities
  - Wrap up and conclusions

References (Books)

- Cogeneration--combined heat and power (CHP): thermodynamics and economics, (Horlock)
- Handbook for Cogeneration and Combined Cycle Power Plant, (Boyce)
- Small-Scale Cogeneration Handbook, (Kolanowski)
- Conversion of Coal-Fired Power Plants to Cogeneration and Combined-Cycle Bartnik & Buryn)
- IET Digital Library: Cogeneration and District Energy Systems, (Rosen& Koohi-Fayegh)
- Cogeneration Design Guide /90392 (Paperback – ASHRAE)
- Cogeneration Design Guide (Orlando)
- Cogeneration & Small Power Production Manual, (Spiewak & Weiss)

INTRODUCTION

Definitions:

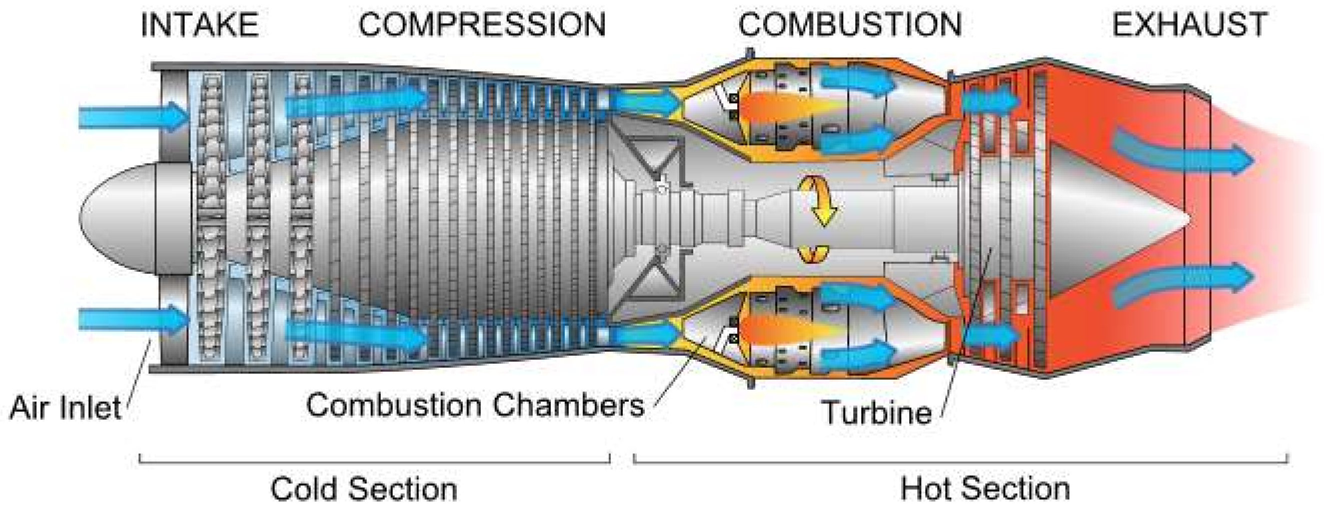
- Cogeneration: is the process of jointly generating two useful forms of energy (most common: electricity and heat)., especially the utilization of the steam left over from electricity generation to produce heat.
- Combine Cycle Generation: A high efficiency cycle, which include both gas turbine generator, heat recovery steam generator and electrical stream generator.
- Combined cycle cogenerations: a combination of combined cycle generation and cogeneration as described above.

Definitions (for future reference):

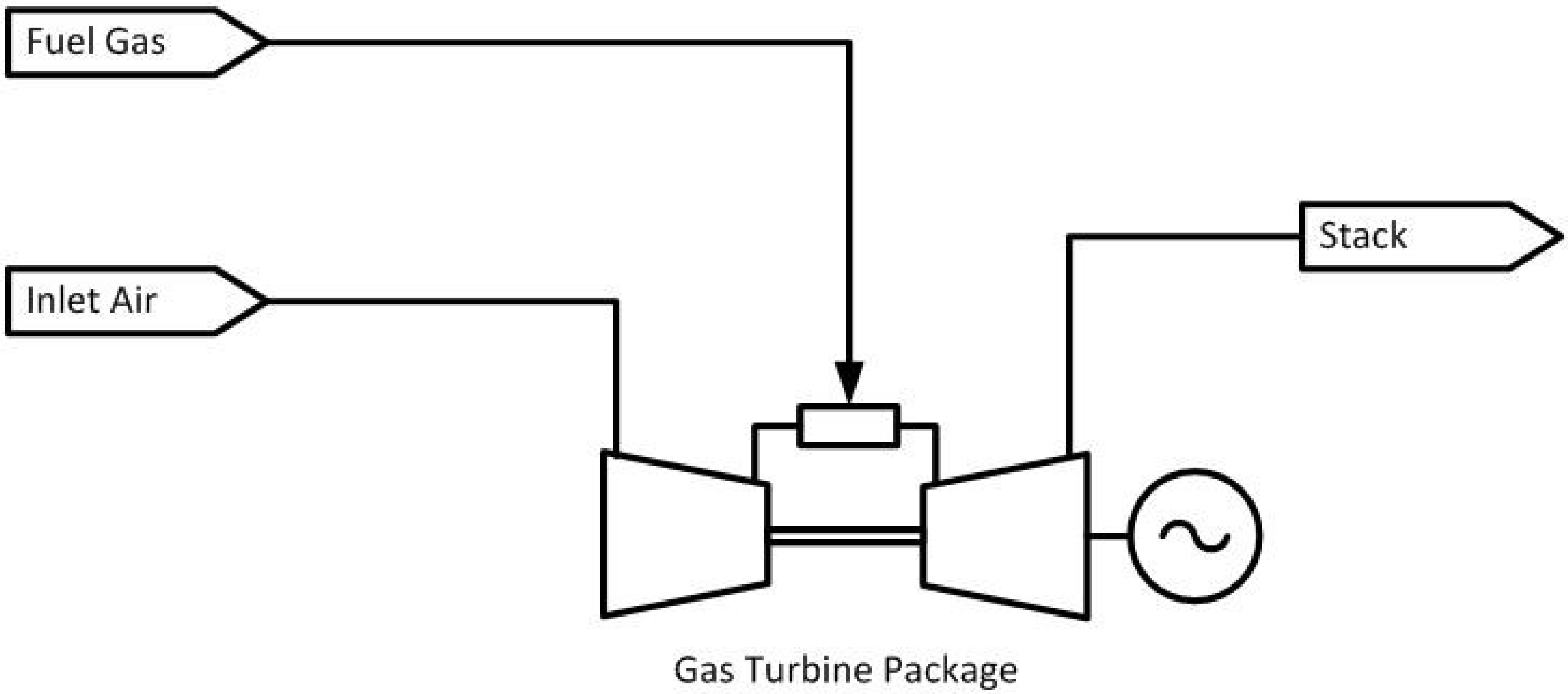
- Trigeneration or combined cooling, heat and power (CCHP) refers to the simultaneous generation of electricity and useful heating and cooling from the combustion of a fuel or a solar heat collector cycle generation.
- Topping cycle plants primarily produce electricity from a steam turbine. The exhausted steam is then condensed and the low temperature heat released from this condensation is utilized for district heating, water desalination or other purposes
- Bottoming cycle plants produce high temperature heat for industrial processes, then a waste heat recovery boiler feeds an electrical plant.

The "process" aspect of cogeneration

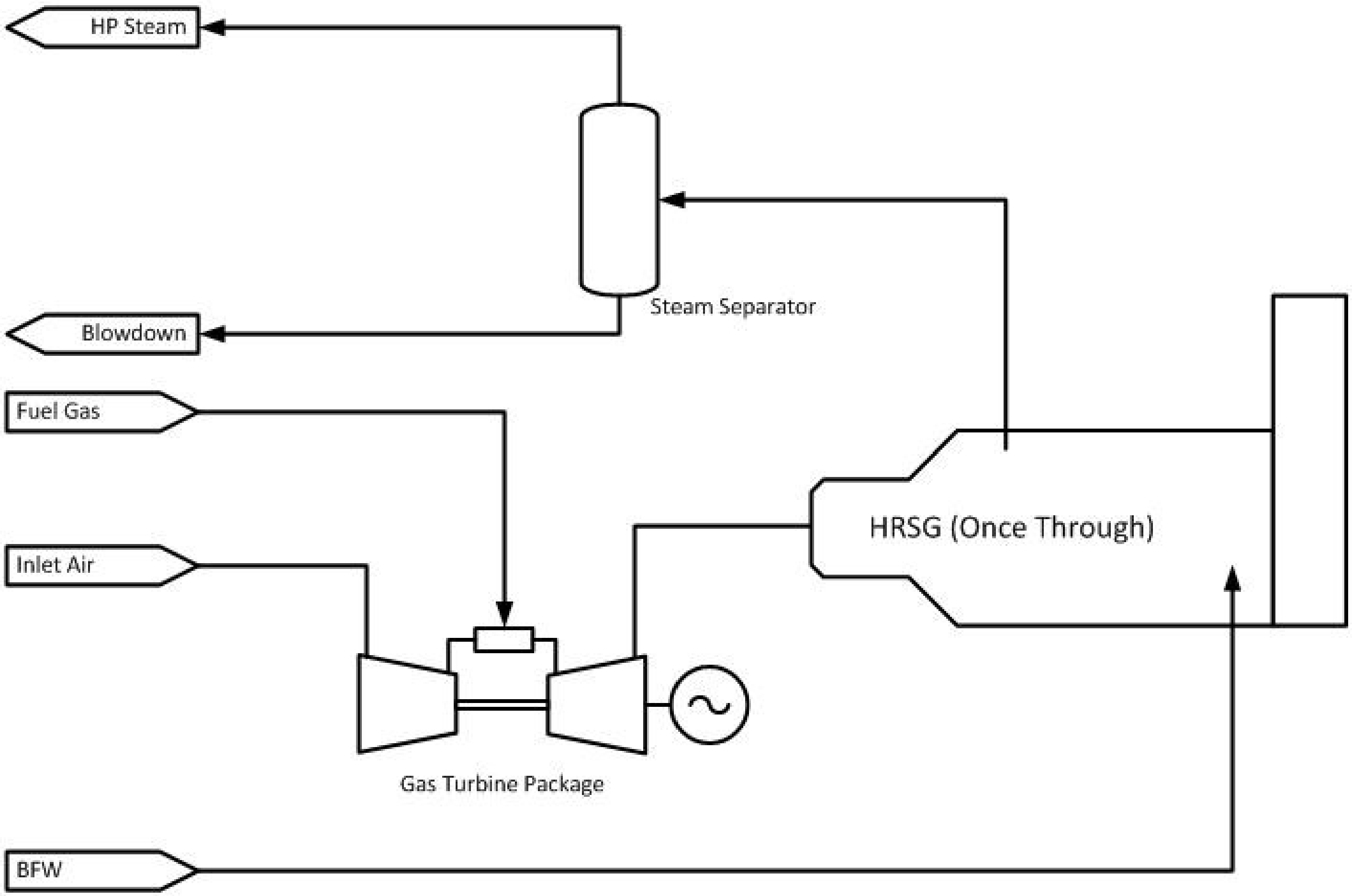
Gas Turbine Power Generation



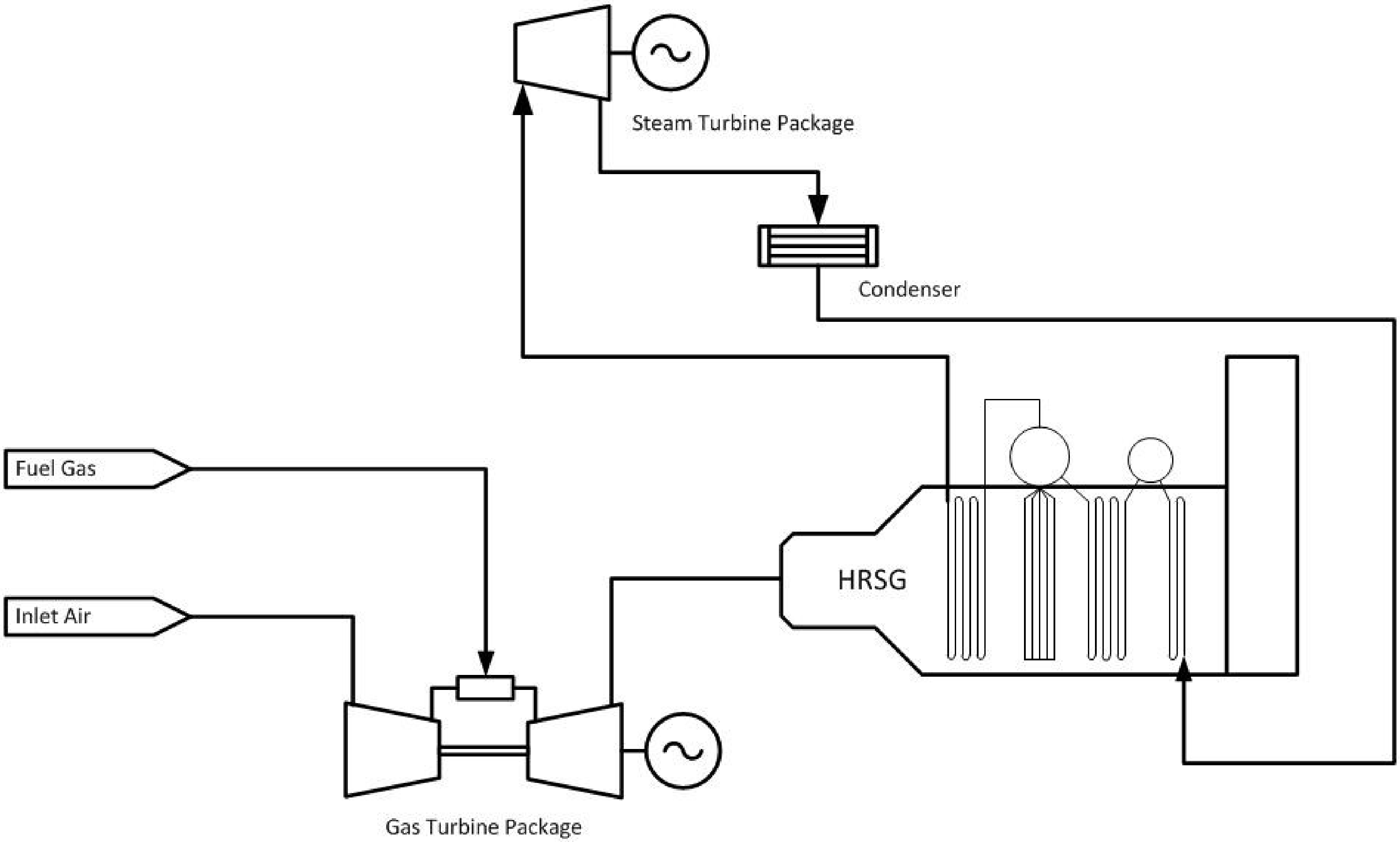
Simple Cycle



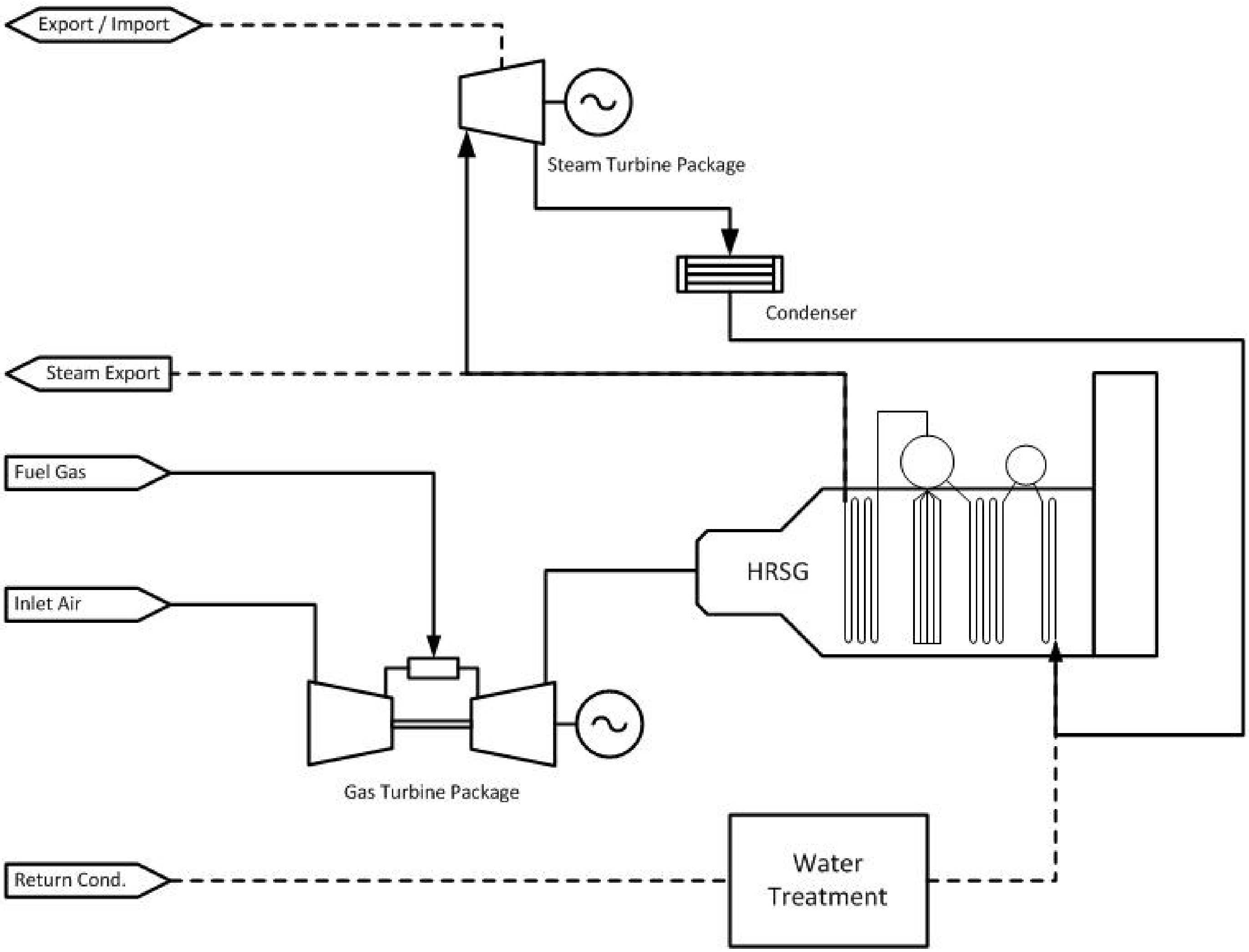
Cogeneration (SAGD Example)



Combined Cycle



Combined Cycle Cogeneration



Configuration Efficiencies

- LM6000PH Gas Turbine
- One Pressure Level (30 bar, 450°C)
- No Supplemental Firing

Configuration	Output [kW]	Heat Rate [kJ / kWh]	Electrical Efficiency [%]	Class 43 Heat Rate [Btu / kWh]
Simple Cycle	47,800	8821	40.8	-
Cogeneration	47,600	8858	40.6	5110
Combined Cycle	61,600	6844	52.6	7594
CC Cogen (50% extracted at 15 bar)	56,500	7460	48.3	6353

Aeroderivative vs Frame Turbine

- GE LM6000PH vs GE Frame 7E.03
- One Pressure Level (30 bar, 450°C)
- No Supplemental Firing

Configuration	Heat Rate [kJ / kWh]	Electrical Efficiency [%]	GT Exhaust Temp [°C]
Simple Cycle			
LM6000	8821	40.8	479
7E.03	10624	33.9	550
Combined Cycle			
LM6000	6844	52.6	479
7E.03	7256	49.5	550

Impact of Ambient Conditions

GE LM6000PH Operating in Simple Cycle

Ambient Temperature (@101.3 kPa)	Power Output
-20ºC	54700 kW
15ºC	47800 kW
35°C	38500 kW

Ambient Pressure (@15°C)	Power Output
101.3 kPa (0 m)	47800 kW
93.8 kPa (645 m)	44100 kW
87.0 kPa (1265 m)	40600 kW

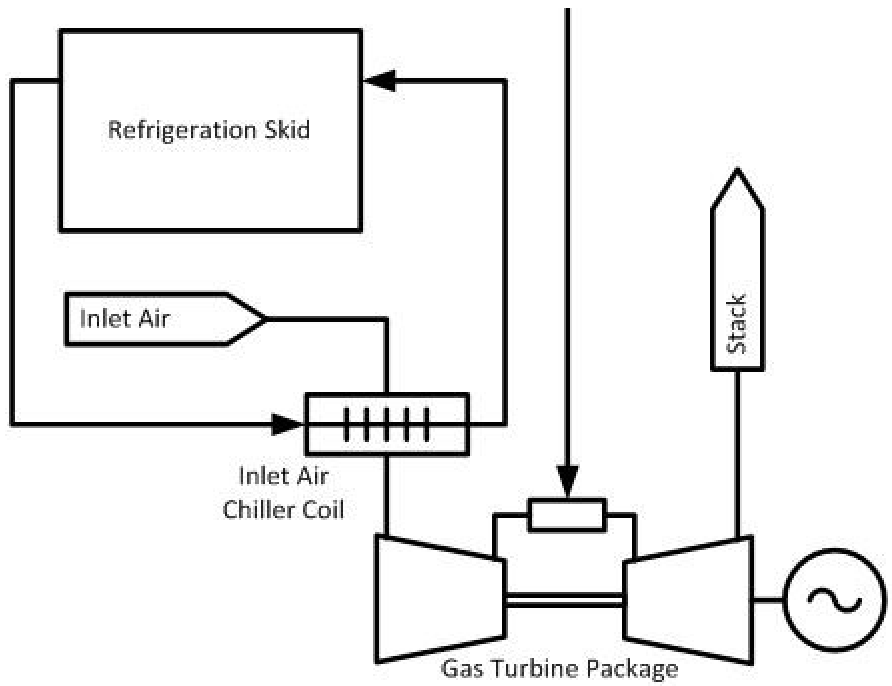
Impact of Ambient Conditions

What can be done to “overcome” power output changes due to ambient conditions?

Inlet Air Cooling

- Cooling water
- Evaporative
- Chiller
- Fogger

The denser the air,
The higher the power.



Other Ways to Increase Power

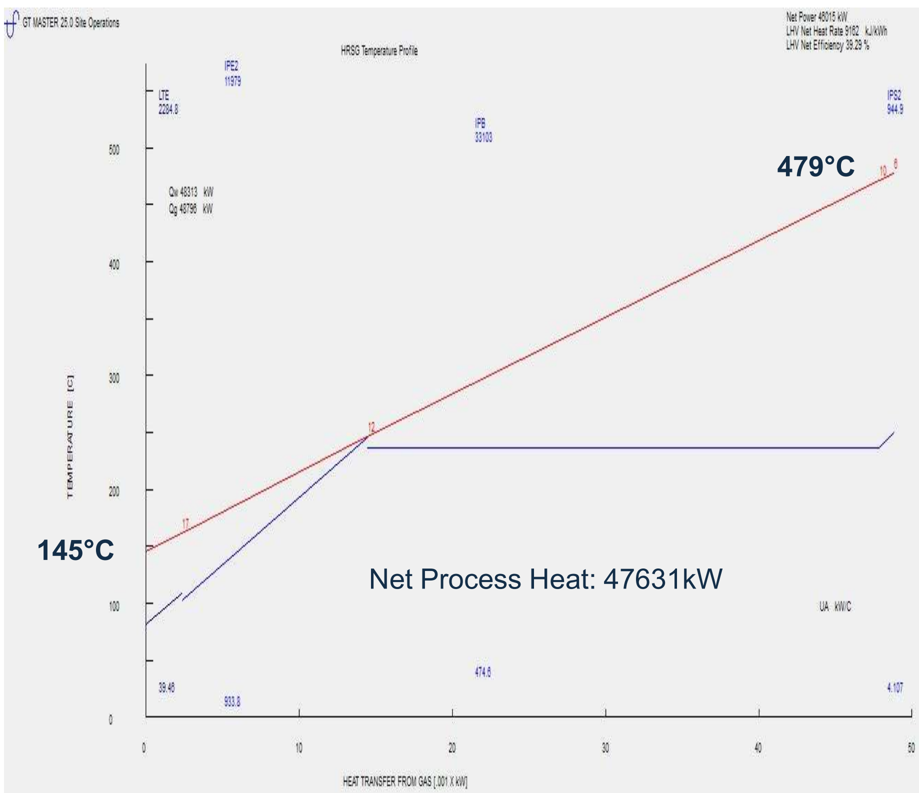
In a Combined Cycle configuration (i.e. with a Steam Turbine), more steam gives you more power.

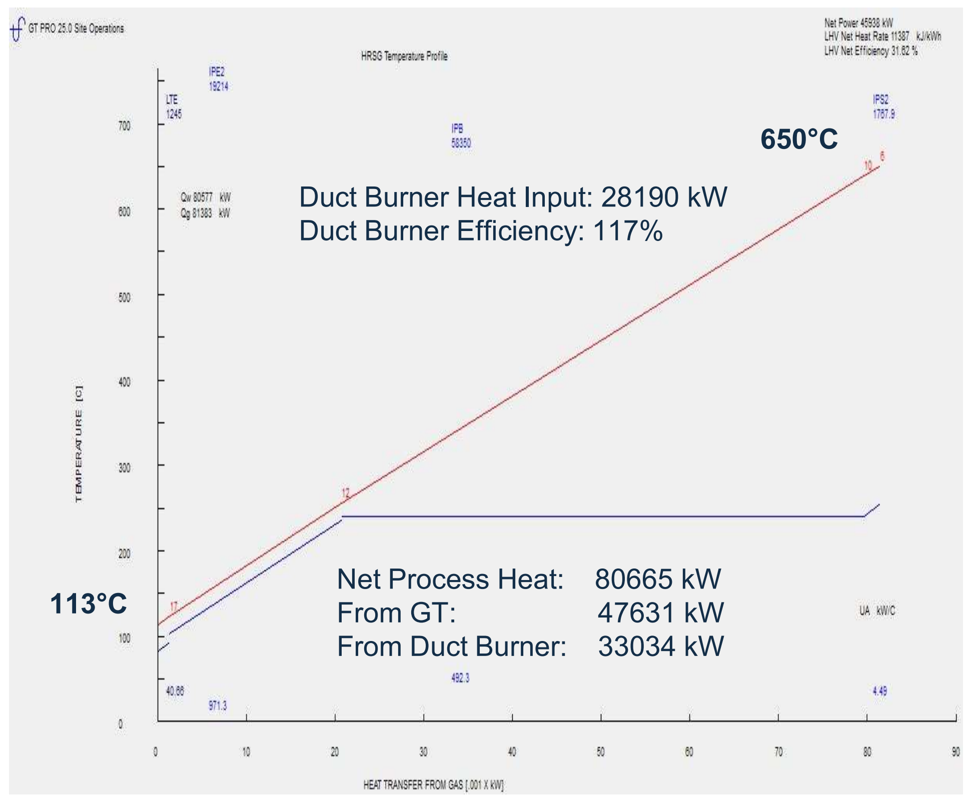
How to maximize steam in a Heat Recovery Steam Generator (HRSG)?

- *Surface Area*
  - HRSGs are massive heat exchangers but more surface area is more expensive.
- *Multiple Pressure Systems*
  - By increasing the number of steam pressure levels, more efficient heat recovery can be attained and thus produces more power.
- *Duct Firing*
  - Largest impact on steam generation and makes power generation more customizable.

The “Magic” of Duct Firing

- Duct Firing can make an HRSG more efficient

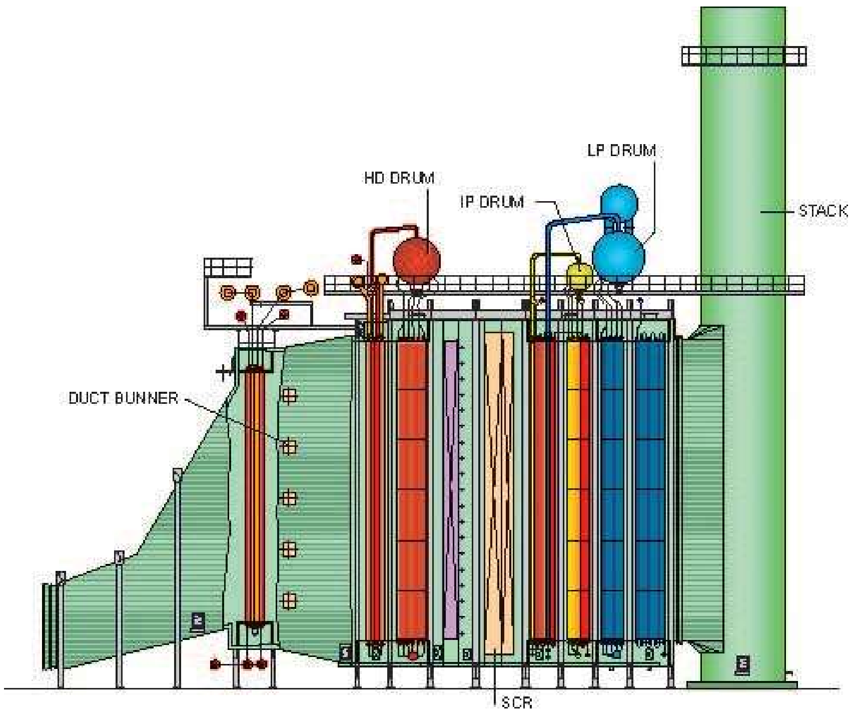


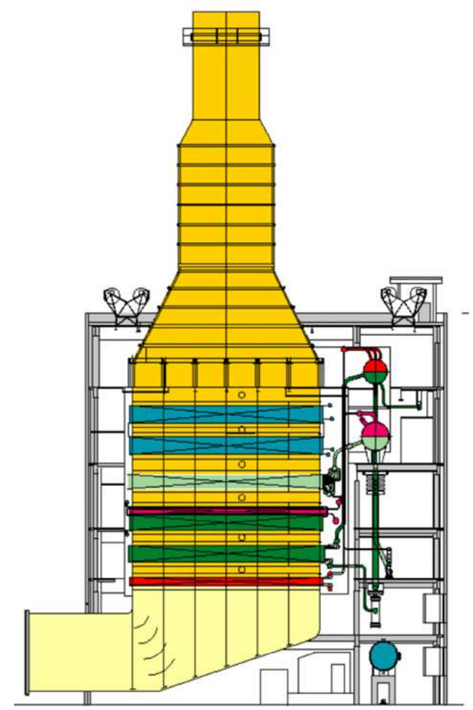


Equipment Options and Considerations

Heat Recovery Steam Generators – Drum Style

- Can be horizontal (North America) or vertical (Europe)

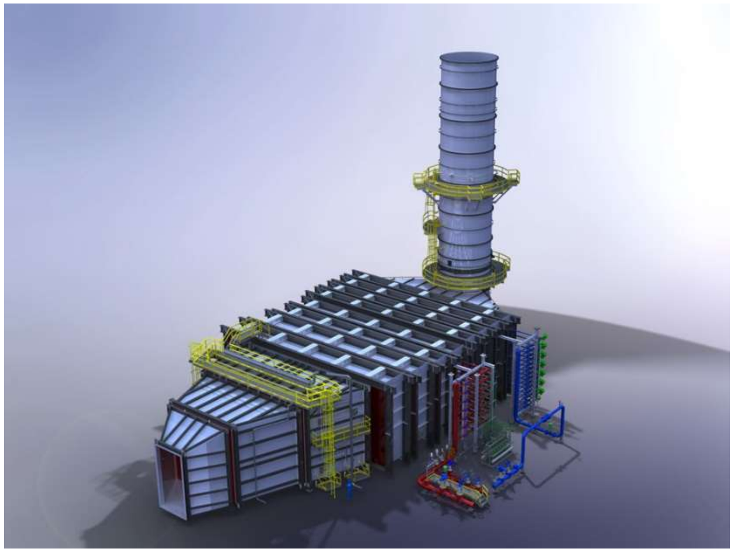


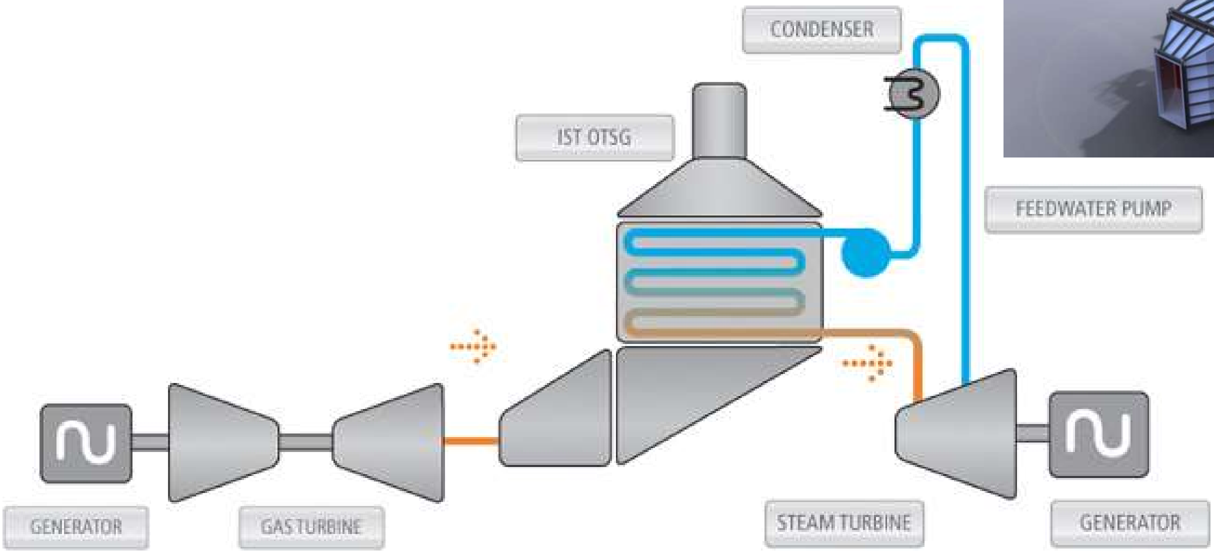


Equipment Options and Considerations

Once Through Steam Generators

- Used in Heavy Oil facilities
- Used in Combined Cycle applications



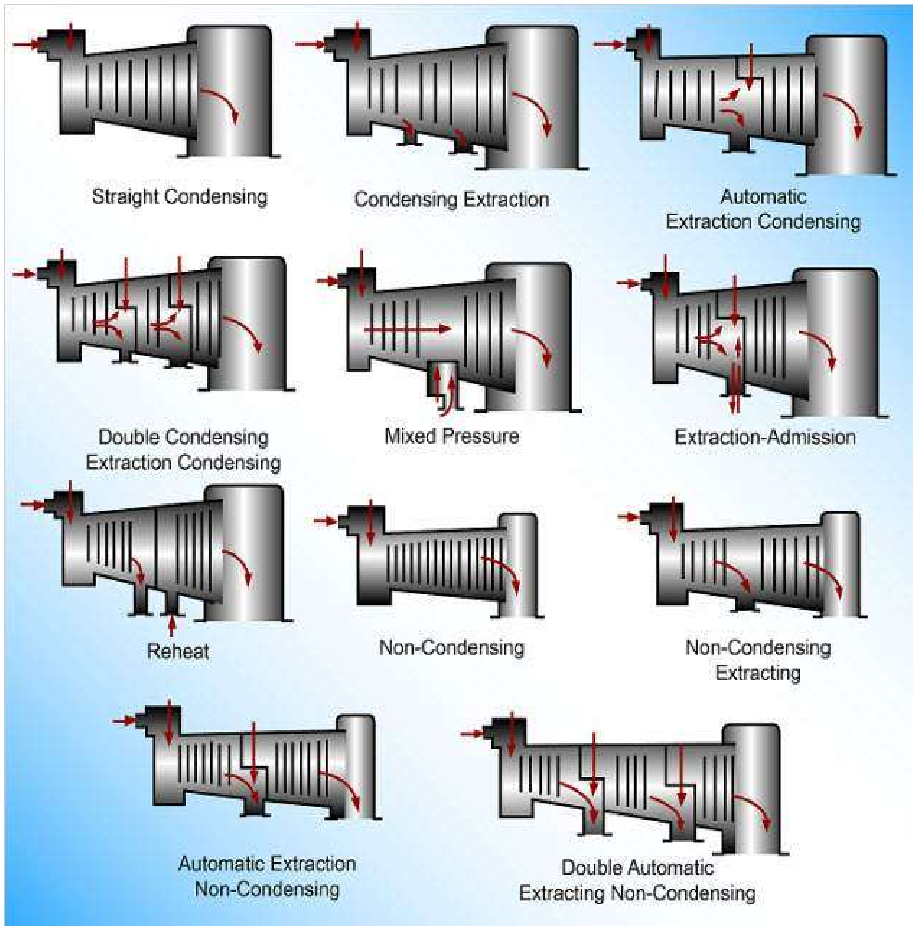


Equipment Options and Considerations

Steam Turbine

- Very flexible in cogeneration applications.
- The lower the exit pressure, the higher the power generation.

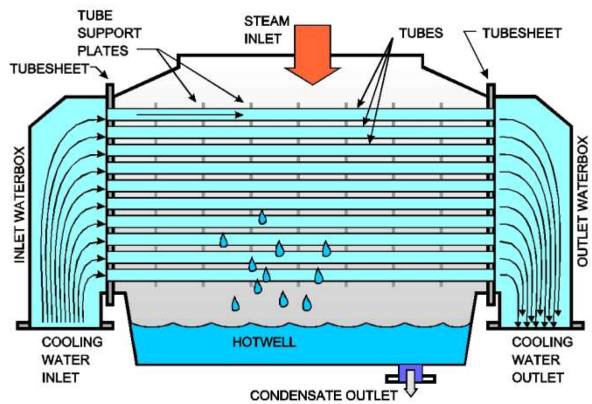
Condensing Pressure	Condensing Temperature
2.34 kPaa	20°C
4.24 kPaa	30°C
7.38 kPaa	40°C

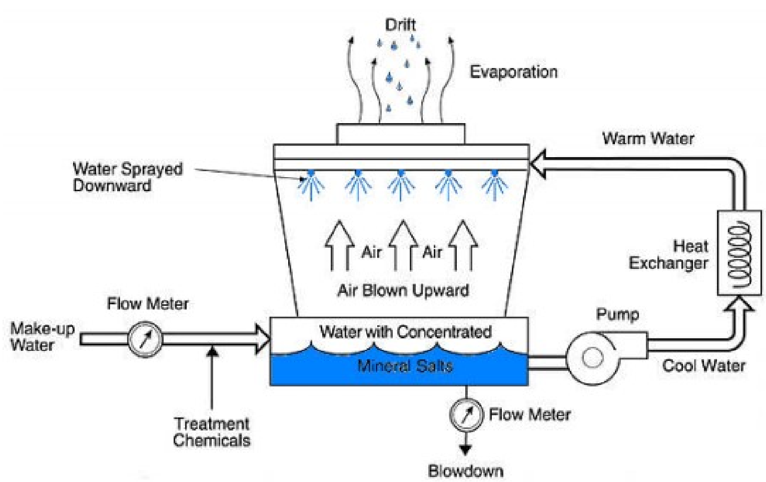


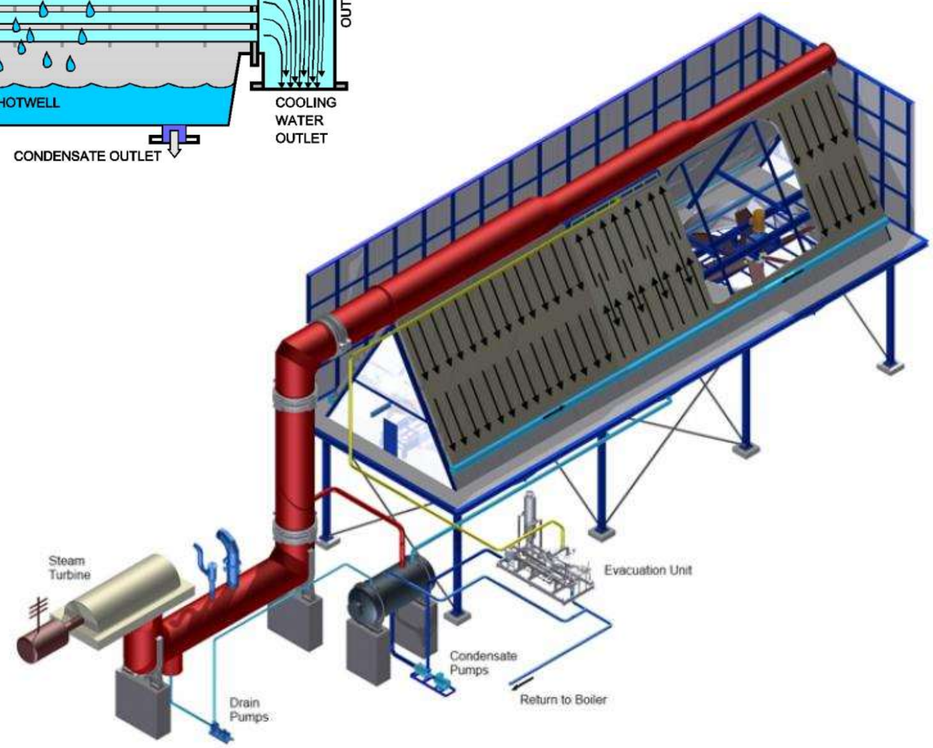
Equipment Options and Considerations

Condensers

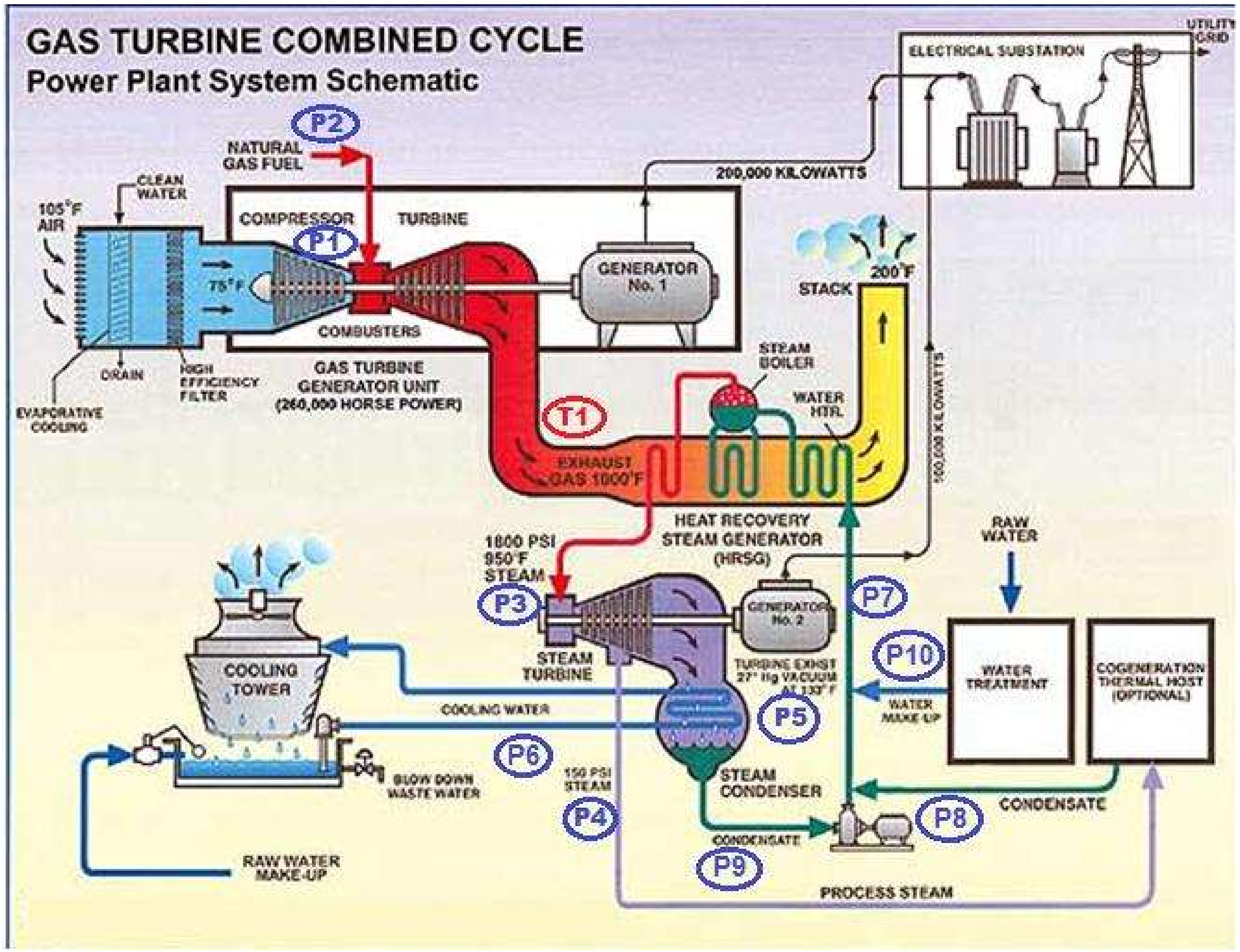
- Direct Cooled
- Cooling Tower
- Air Cooled







Efficient Power Generation

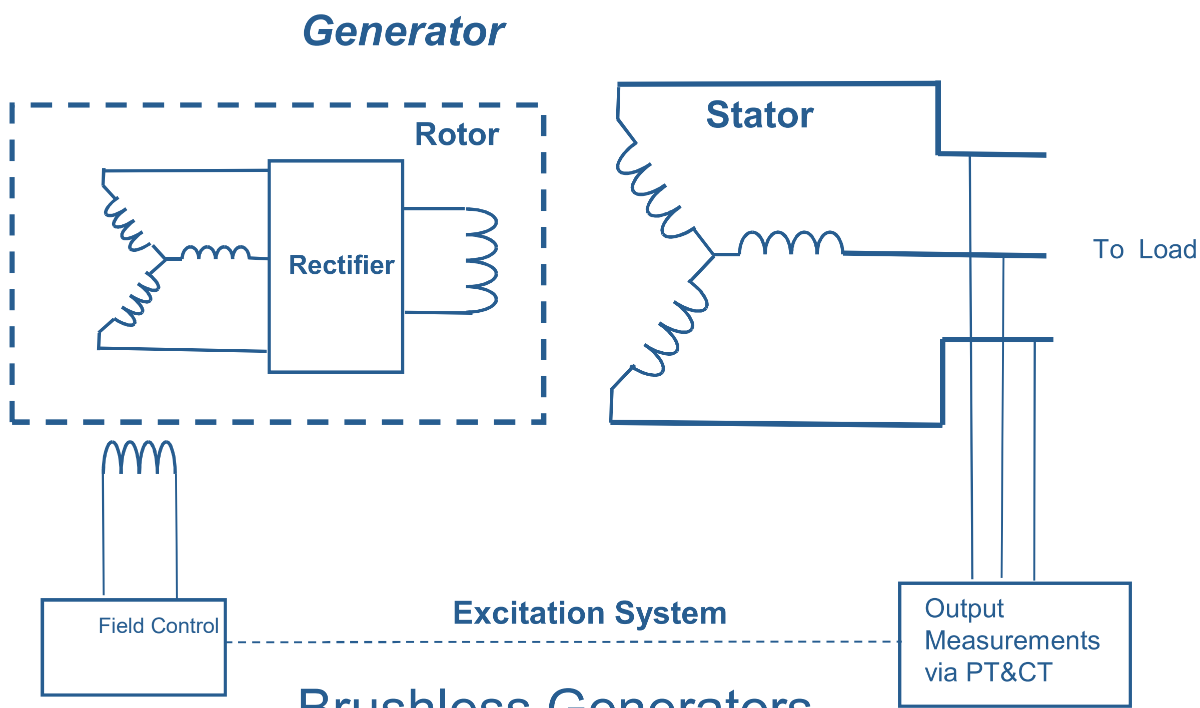


Electrical engineering considerations for cogeneration

Critical Aspects of Cogeneration Design

- Safety during construction, startup, operations and maintenance
- Reliability of steam and electricity outputs
- Economics
- Main system components:
  - Generator and excitation system
  - Connection to step up transformer: cable, cable bus or IPS
  - Step up transformer (GSU)
  - Switchgear/ bus / breakers
- Special design aspects beyond typical industrial/commercial facilities:
  - Short circuit levels: bus and breaker selection
  - Bus configuration and connection to existing facility and AIES
  - Protection and protection coordination
  - Successful islanding

Generator Types Used in Cogeneration



Brushless Generators
(Simplified Presentation)

Other Types are also used in cogeneration where size, economical considerations and/or jurisdictions requirements exist

Sizing Generators & Capability Curves

Generators key sizing aspects:

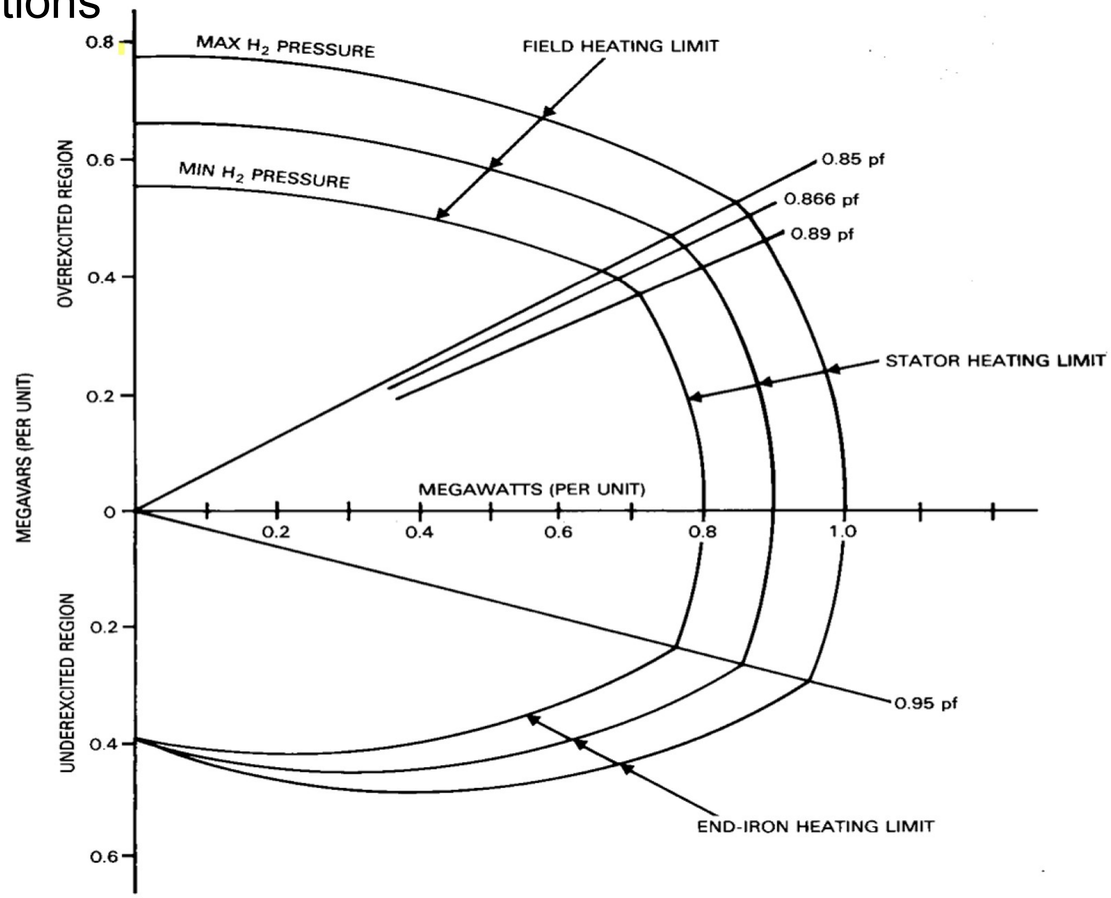
- Receive all turbine mechanical energy (shaft) & convert it to electrical energy (MW)
- Provide voltage support when connected to the outside World (MVARs from excitation system)
- Rating in MVA = $\sqrt{MW^2 + MVAR^2}$
- Cooling system to dissipate losses within generator

Key Electrical/Control Components of Generator/Turbine Block

- Generator
- Excitation System
- Auxiliaries (cooling, ventilation, noise control, termination etc)
- Protection, synchronization, and control of generator breaker
- Voltage control (Excitation control)
- Frequency control (Turbine governor control)
- Control and operation as part of the interconnected system

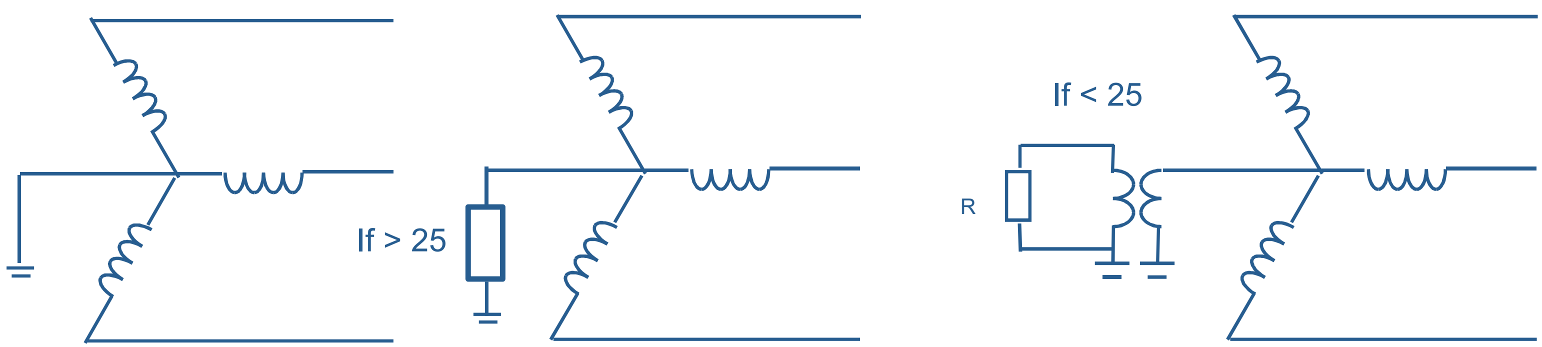
Key Components for Generator Control

- Synchronization & trip of Generator Breaker
- Voltage control (Excitation control)
- Frequency control (Turbine governor control)
- Operating ranges are represented by capability curves (See next two parts of the presentations



Generator Neutral Grounding

- In majority of Cogeneration configurations; neutrals were either solidly grounded (small generators), low resistance (medium- bus connected) or high resistance grounded (HRG)
- Recently, HRG is recommended wherever possible to reduce line-ground fault currents see IEEE Papers & standards



Solidly Neutral Grounded

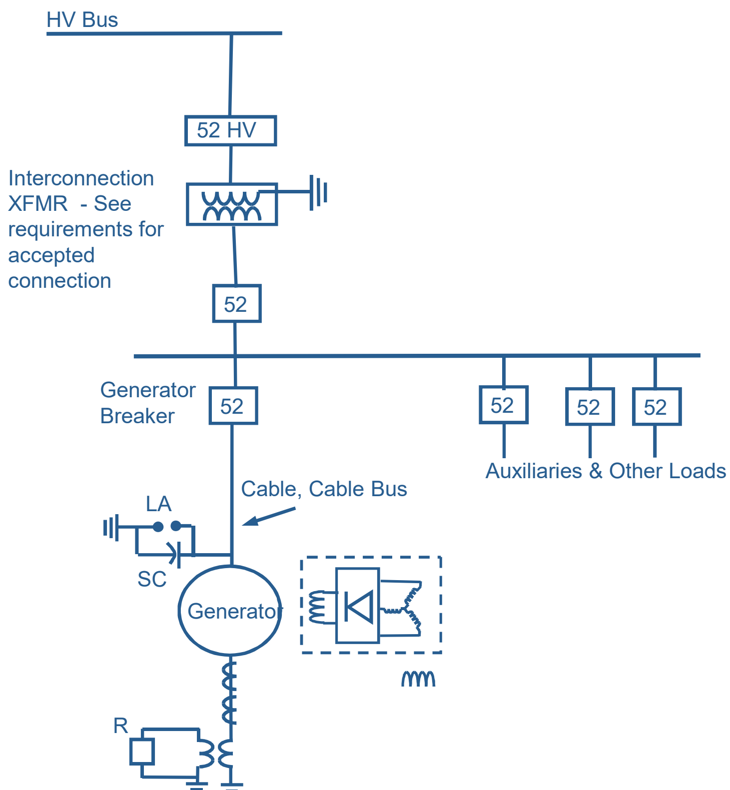
Low Resistance Neutral Grounded

High Resistance Neutral Grounded

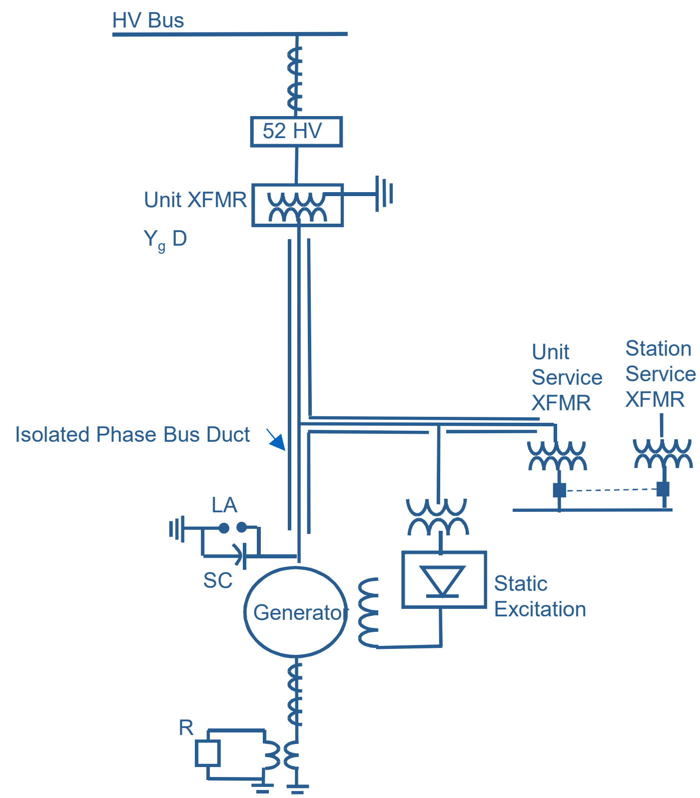
Generator Step up Transformer

- In many cogeneration applications, transformers connected to generator directly or through a generator breaker could be subjected to additional stresses.
- IEEE Standards C57.116-2014 "Guide for Transformers Directly Connected to Generators" address some practical concerns such as possible over fluxing and high short circuit levels
- Where cogeneration plant auxiliaries are set to have back feed from connecting utility during start up, transformers connection and phasing shall be checked for start up and normal operating conditions

Connection of Generator to Step up Transformer



Typical Medium Size (cogeneration) arrangement



Typical very large generator (utility) arrangement

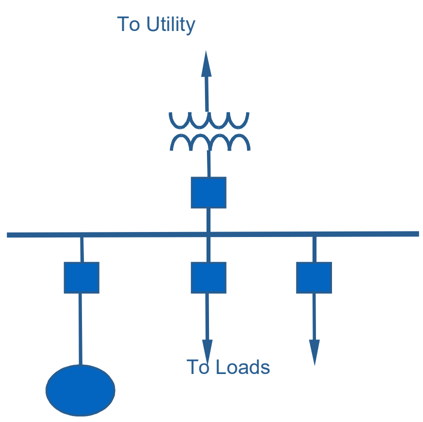
Please note that other connections are also available depending on site conditions and generator and turbine sizes and configurations

Short Circuit & Breaker Selection

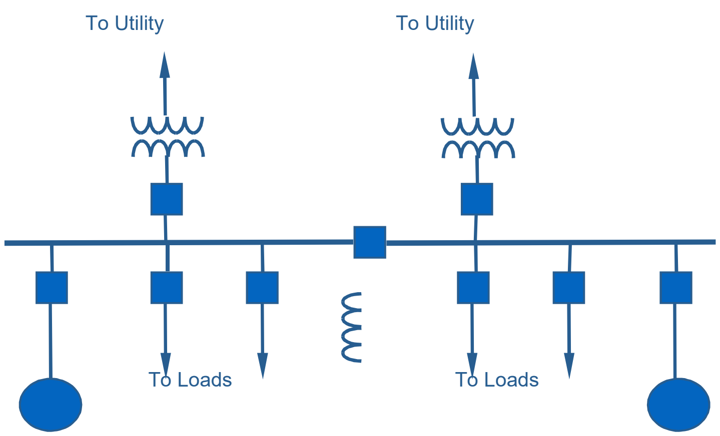
- For small synchronous machines:
  - Sub-transient direct axis reactance X''_d
    - Ranges from .09 – .17 pu (9-17%), time: 0 to 6 cycles
    - Determines maximum instantaneous current and current at time if fast circuit breaker opens on a fault (i.e: molded case circuit breakers for small sets)
  - Transient direct axis reactance X'_d
    - Ranges from .13 – .20 pu (13-20%), time 6 cycles to 5 sec
    - Determines current at short time delay of circuit breakers
  - Synchronous reactance X_d
    - Ranges from 1.7 – 3.3 pu (170-330%) time: after 5 sec
    - Determines steady state current without excitation support (PMG)
    - Zero sequence reactance X_0 . Ranges from 0.06 – 0.09
    - Negative sequence reactance X_2 Ranges from 0.10 – 0.22 pu (10-22%) A factor in single-phase short circuit current
    - Generator breaker sizing is an important topic with a few critical items to verify, check references including IEEE/IEC 62271-C37-013-2015

Bus Selection and Design

- Bus rating for short circuit and load current
- Arc flash requirements
- Reliability and economics in bus configurations

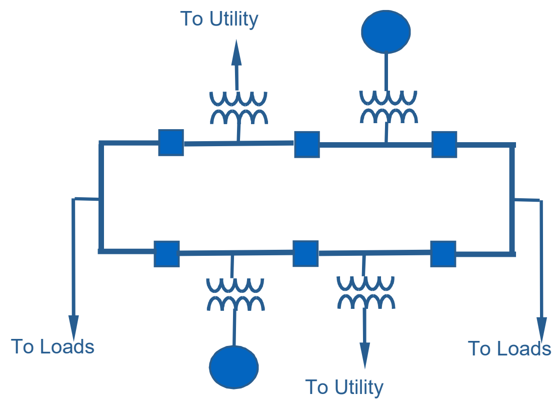


a) Single Bus- One Section

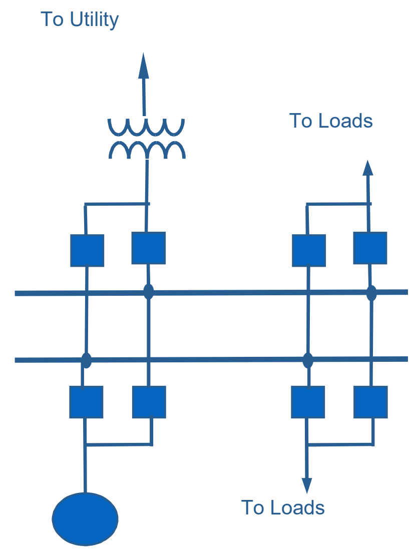


b) Single Bus- Two Section

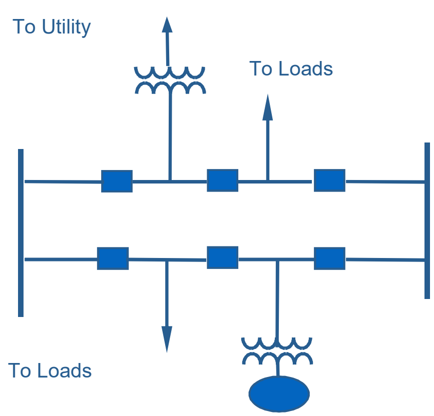
Other Bus Configurations



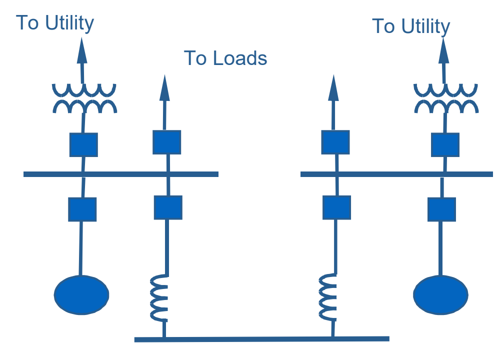
c) Ring Bus



d) Double Bus- One Section



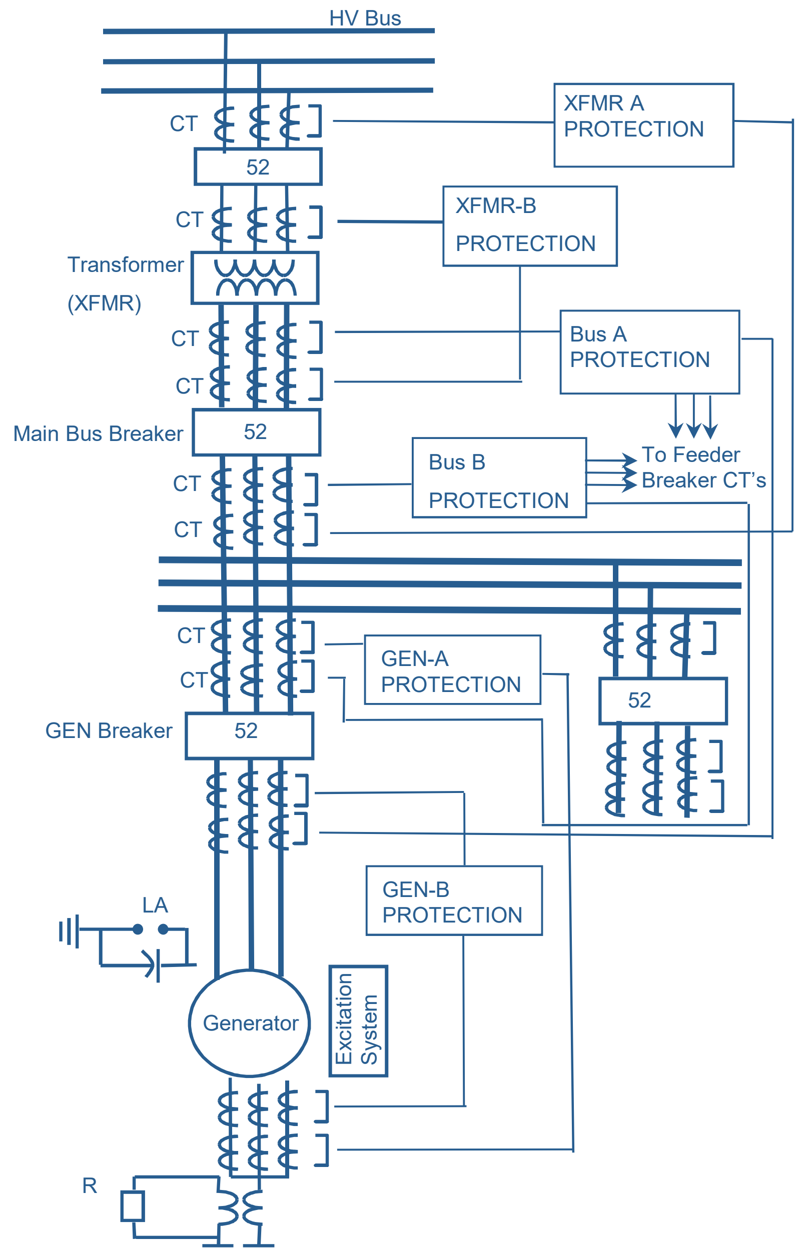
e) $1\ ^{1}/_{2}$ Breaker Scheme



f) Main and Synchronizing Bus

Protection Notes

- Figure is not intended for detailed design (PT's SA, other protection functions are not shown)
- CT's for protection zones are shown to demonstrate the importance of coherence in protection design
- Some redundancy in protection is required to ensure reliability
- Care shall be given to overlap between zone, in order to quickly locate faults, isolate them and resume operation
- High resistance grounding: why it is very important and what are the recommended schemes?

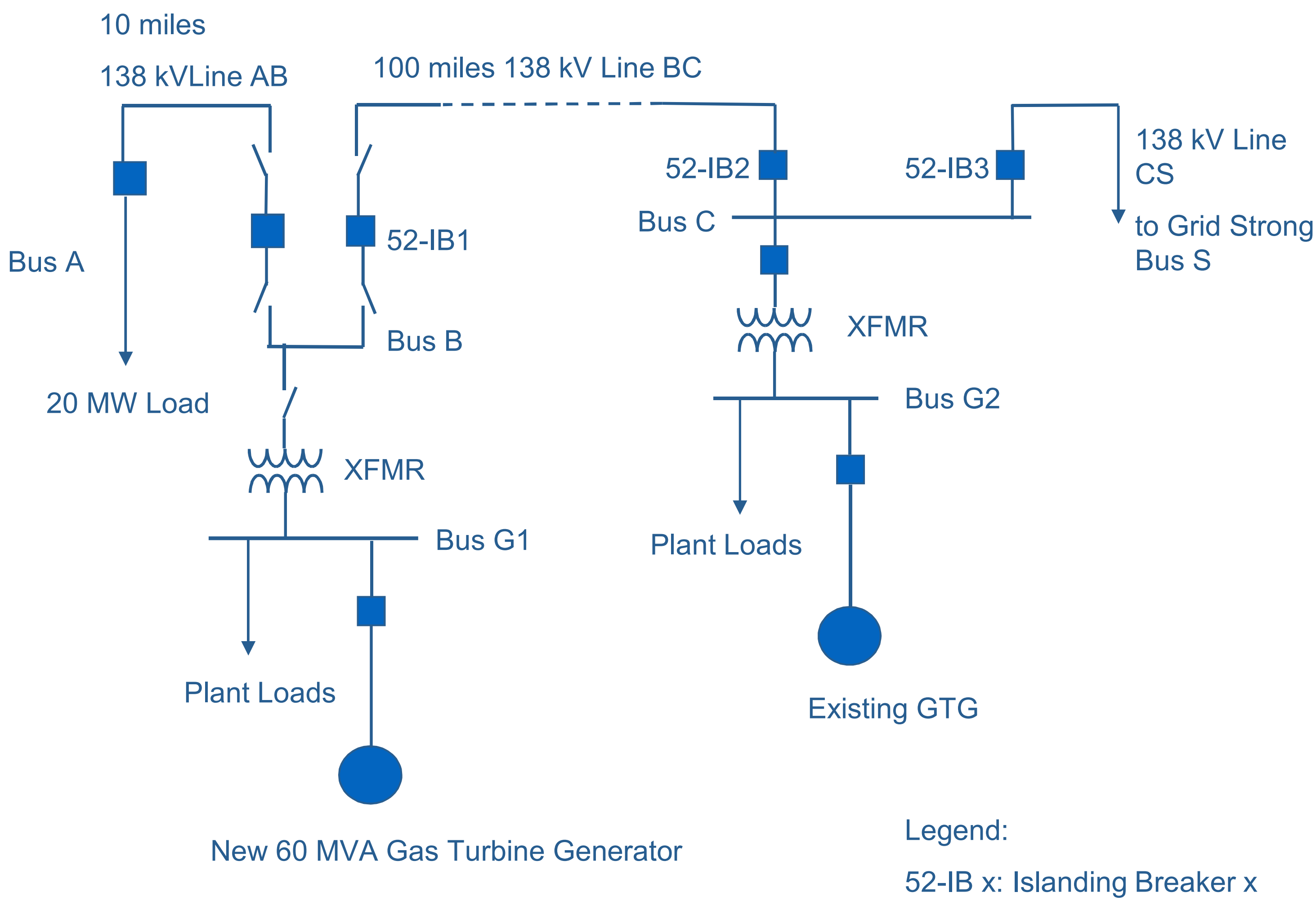


Protection Notes (Cont.)

- Bus protection and arc flash considerations
- Breaker fail protection: when and why?
- Reverse power protection: (acting when synchronizing with the grid)
- Over and under frequency
- Over voltage and Volt/Herts
- Transformer protection and including gas and other protection functions
- Back up protection
- Interconnection protection and distance protection applications

Islanding Considerations

- Islanding - plant powered solely by local generation and not connected to 3rd party
  - Intentional islanding (fault)
  - Un-intentional islanding (plant operator)
- Success requires 2 basic conditions
  - Stable system (voltage and/or frequency)
  - Balance of load and generation (MWs & MVARs)
- Design principles
  - Fault quickly isolated from all sources
    - Prevent equipment damage
    - System stability
  - Only those sources feeding fault should be isolated
  - Load shed may be required
    - Must be fast to prevent tripping generation/load
    - Process impacts must be carefully evaluated (hierarchy)
  - System must identify one slack generator to operate isochronouse
  - Design allows connection/synch back with 3rd party



Connection of Generator at an end of a long line with Possible Islanding

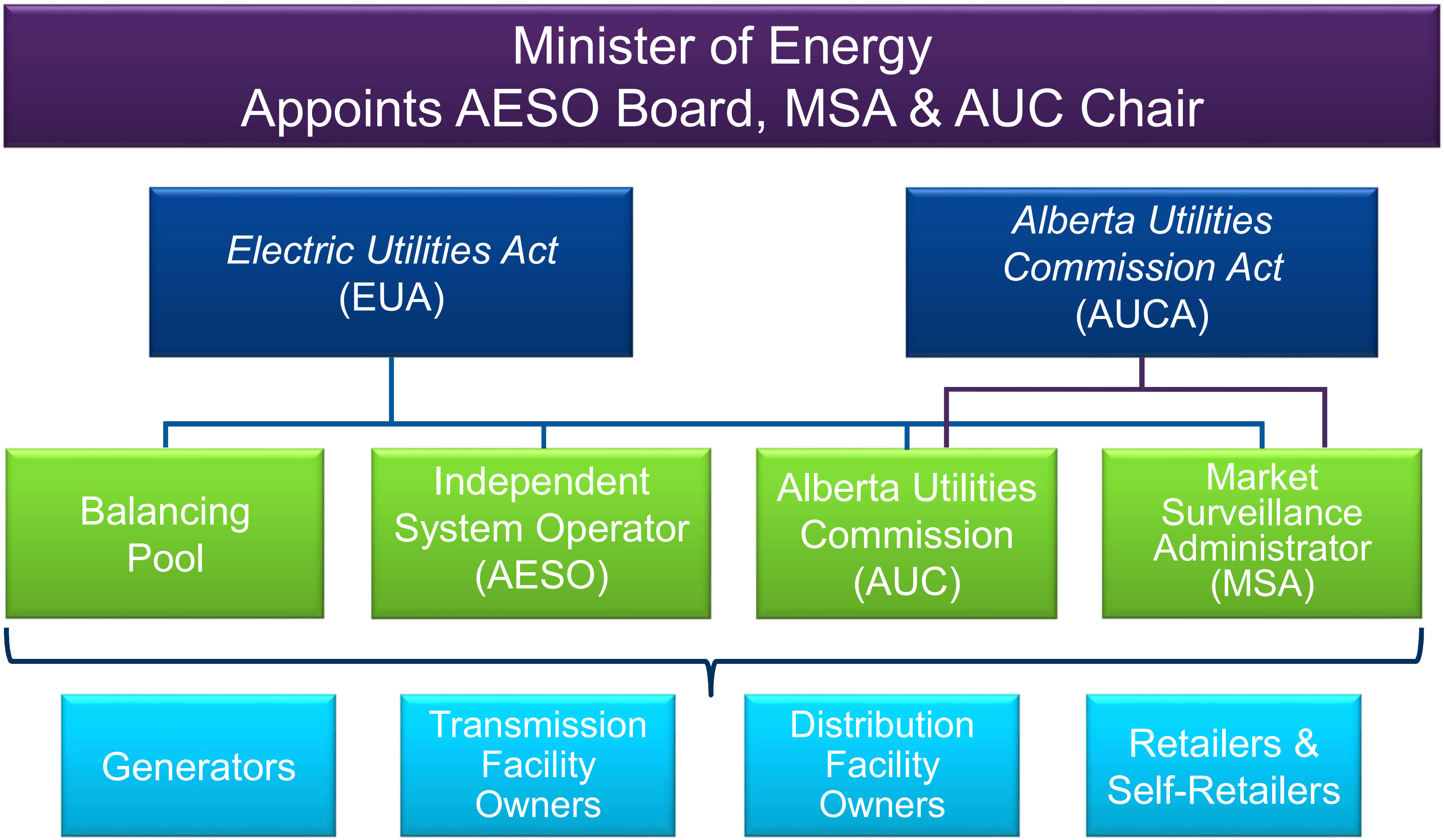
Interconnection to the Alberta Interconnected Electrical System (AIES)

Interconnecting Cogeneration Systems to the Transmission Network

Fred Ritter, Chief Engineer, AESO

** Information source: AESO*

Power industry structure in Alberta



* Information source: AESO

The AESO’s core functions

Transmission System Development

Plan and develop transmission system to provide reliability, facilitate competitive market and investment in new supply

System Operations

Direct reliable 24/7 operation of Alberta’s power grid

Transmission System Access

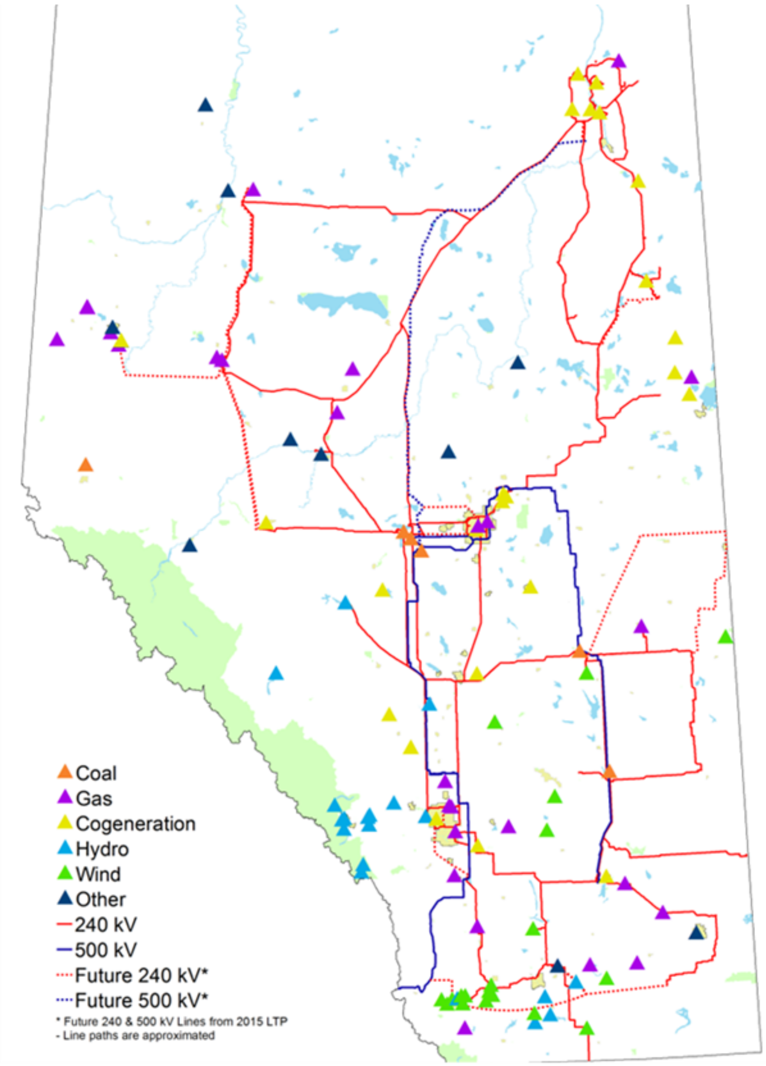
Provide access for both electricity generators and large industrial customers

Market Services

Develop and operate Alberta’s real-time wholesale energy market to facilitate fair, efficient, open competition

** Information source: AESO*

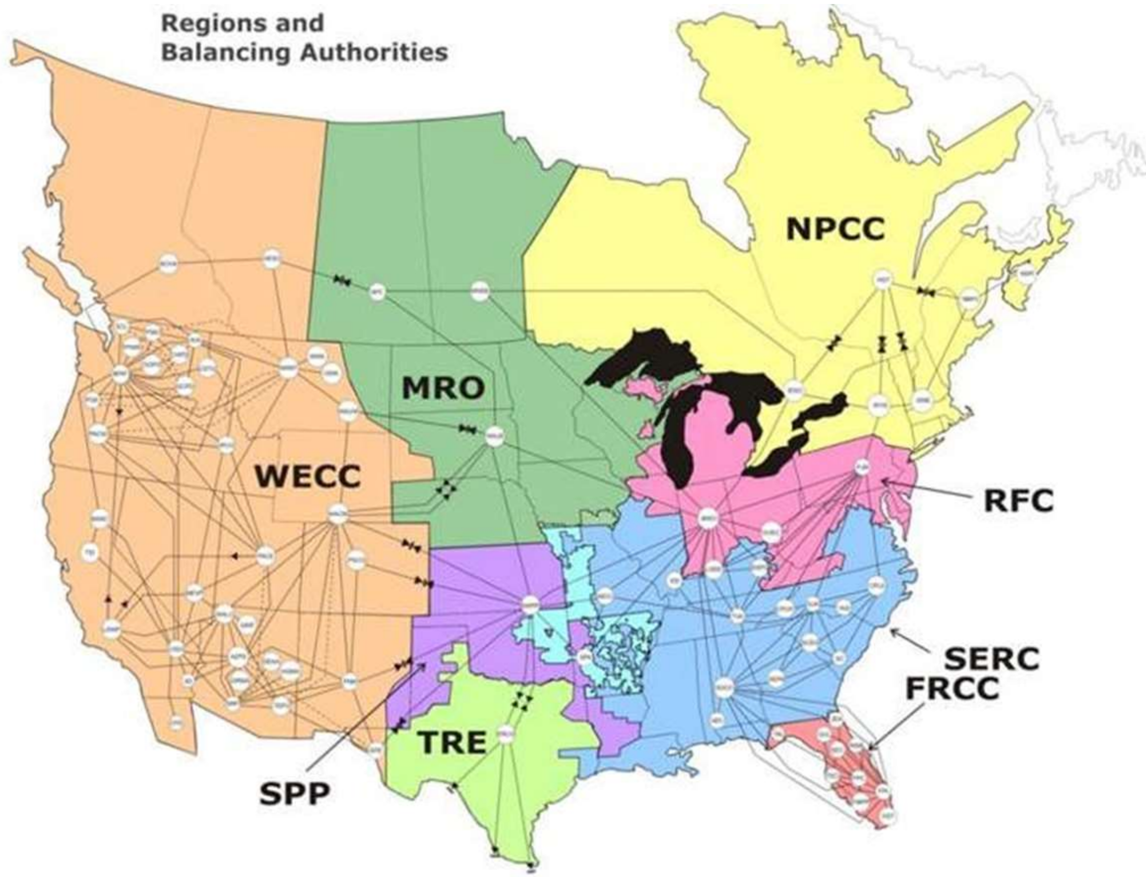
Snapshot: Alberta's power grid



- 26,000+ km of transmission
- ~235 generating units
- 16,423 MW installed generation
- 1,348 MW wind record Oct 2015
- 11,458 MW peak demand record Dec 2016
- Coal served 64% of Alberta demand for electricity in 2015
- Historical high load growth
- 200+ active connection requests

** Information source: AESO*

Connected to North America

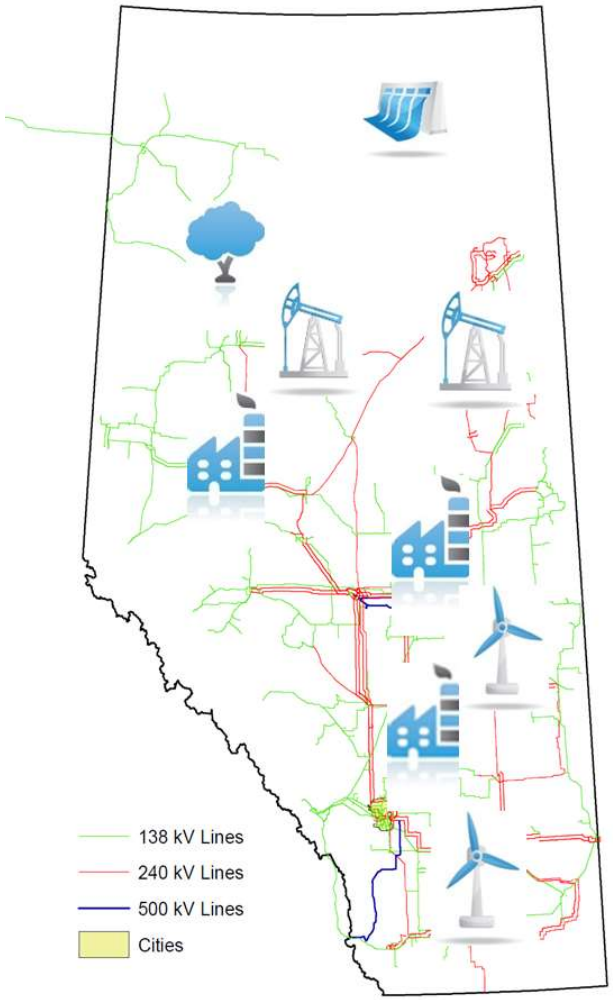


- Interconnections to neighbouring jurisdictions
  - British Columbia
  - Saskatchewan
  - Montana
- Interties provide import and export capabilities

* *Information source: AESO*

Evolving generation mix: transition from coal to renewables

Fuel		2017	2030
	Coal	6,299	0
	Cogen	4,729	5,548
	Gas	2,619	10,848
	Hydro	894	894
	Wind	1,445	5,663
	Other	437	469
	Total installed	16,423	23,422



** Information source: AESO*

Evolving generation mix: transition from coal to renewables

Existing	2030
AIL peak: 11,229 MW	AIL peak: 15,230 MW

Existing %	Type	MW	2030 %	Type	MW
39%	Coal-fired	6,289	0%	Coal-fired	0
28%	Cogeneration	4,502	24%	Cogeneration	5,548
11%	Combined-cycle	1,716	36%	Combined-cycle	8,541
6%	Simple-cycle	996	10%	Simple-cycle	2,307
5%	Hydroelectric	894	4%	Hydroelectric	894
9%	Wind	1,463	24%	Wind	5,663
3%	Other	428	2%	Other	469
	Total capacity	16,288 MW		Total capacity	23,422 MW

Existing capacity as of May 2016

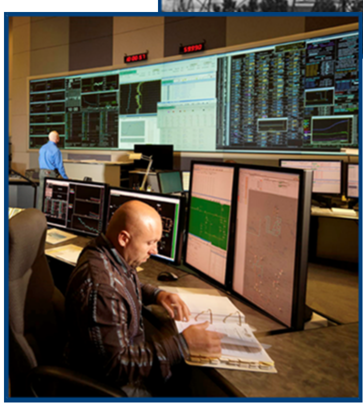
** Information source: AESO*

Alberta Reliability Standards

- Alberta Reliability Standards
  - NERC standards form the basis and cover wide range of topics
    - Resource and demand balancing, CIP, COM, emergency preparedness, design and maintenance, interchange scheduling, P&C, modelling and data, transmission operations and planning, voltage and reactive power
- Standards development process
  - AESO drafts, consults and files with AUC
- Compliance
  - AESO monitors compliance
  - WECC, by MSA agreement, monitors AESO
  - Non-compliance reported to MSA

** Information source: AESO*

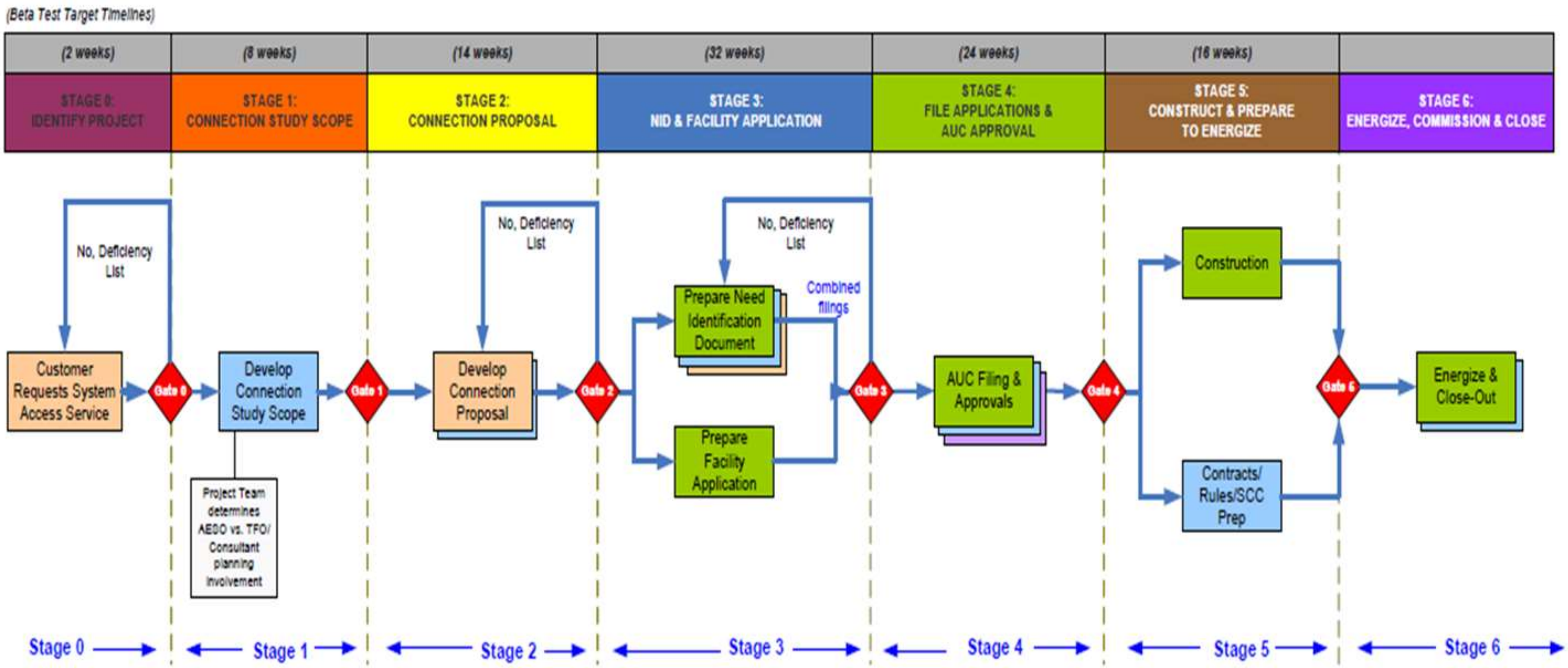
Interconnection to the AIES



- Application to the AESO
- Studies required to confirm transmission adequacy and system stability; need for good generator/load model
- Compliance with standards
- MSSC and transmission considerations
- AESO prepares FS; cogen typically dealt with as a ‘behind the fence’ type project
- Energization: ISO rule 505.3

* Information source: AESO

Connection process overview



See: www.aeso.ca/grid/connecting-to-the-grid/

* *Information source: AESO*

Transmission interconnection requirements

- ISO rules
  - Operational voice communication: 502.4
  - Protection: 502.3
  - Generator/load
  - Synchrophasor measurement: 502.9
  - Revenue metering
  - SCADA: 502.8
  - Transmission data

** Information source: AESO*

Technical requirements: applicability to generating units

- Requirements applied to generating units to connect to AIES are found in ISO Rules
  - Section 502.5: Generating Unit Technical Requirements
  - Section 502.6: Generating Unit Operating Requirements
- Generators are considered transmission system connected if either facility or generating unit (including step-up transformer) are connected at >25 kV
- Contact local DFO for requirements to connect to those systems

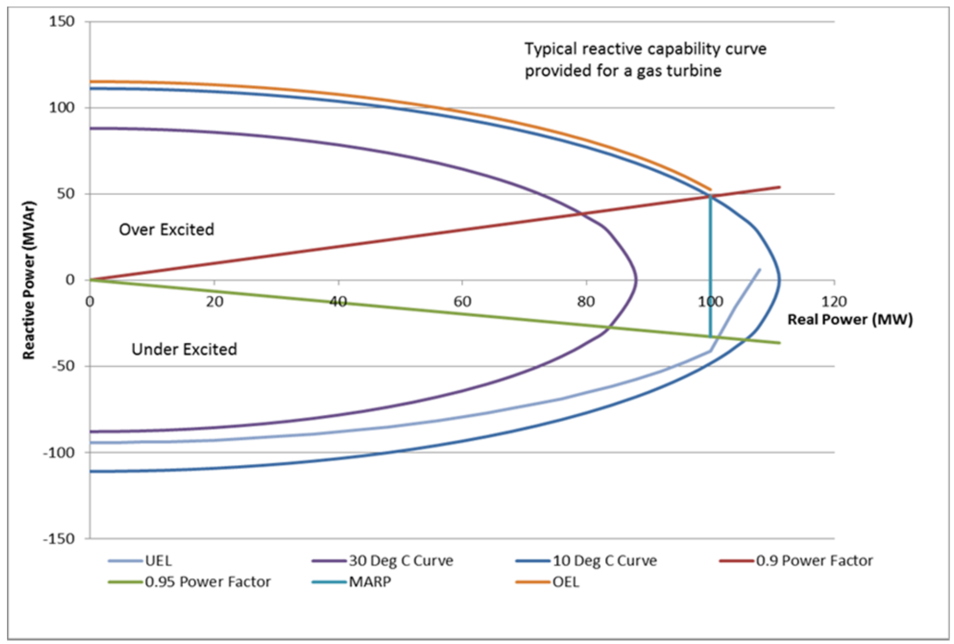
** Information source: AESO*

Key technical requirements: MARP and reactive power

- Maximum Authorized Real Power (MARP) is maximum output as measured at stator winding terminals under optimal conditions while meeting AESO requirements
  - Reactive power capability typically is limiting factor

- 0.9 power
  - factor
  - over-excited

- 0.95 power
  - factor
  - under-excited



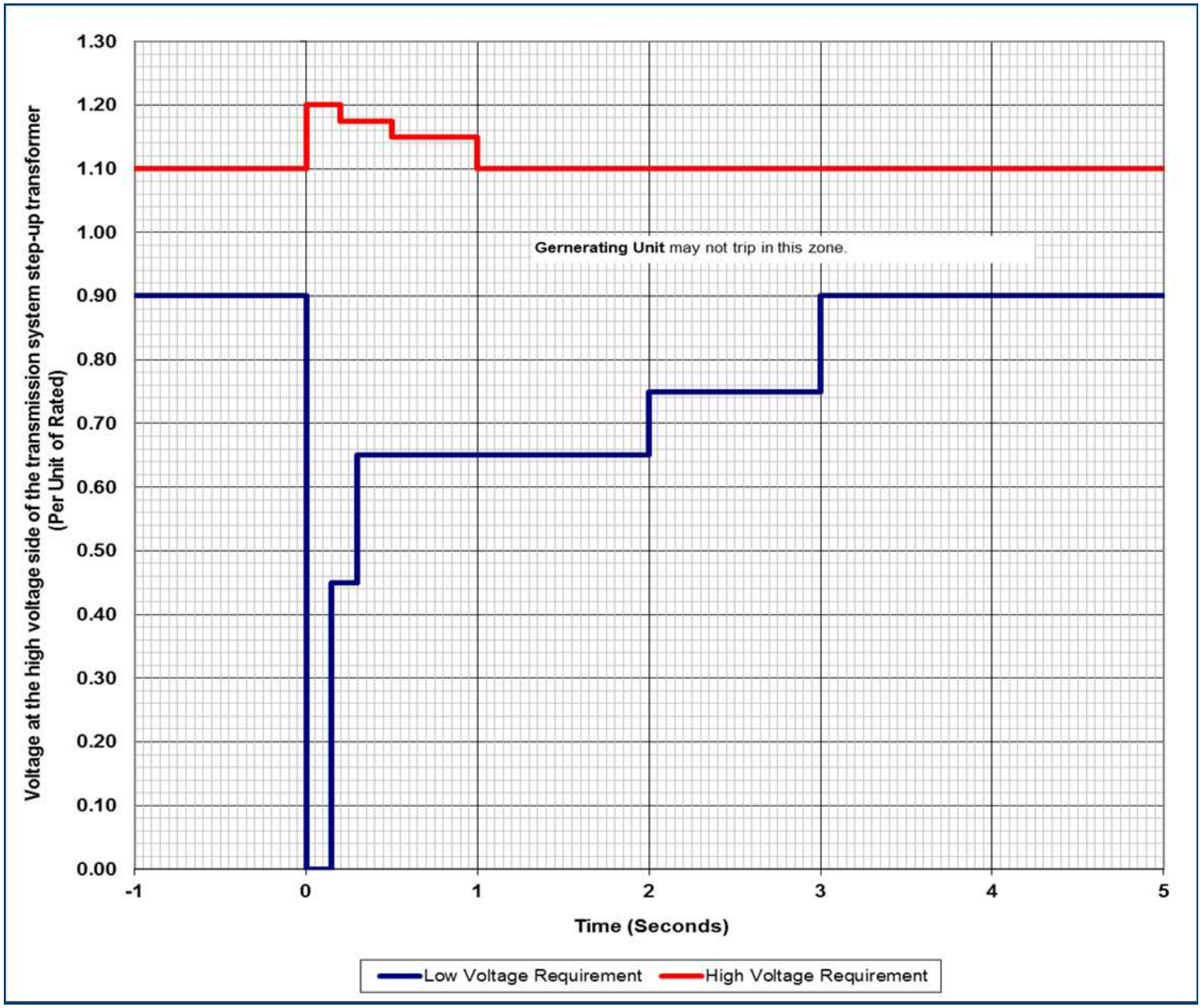
* Information source: AESO

Key technical requirements: voltage control

- All generating units connected to transmission system must have Automatic Voltage Regulator (AVR)
  - AVR must have capability to be set between 0.95 and 1.05 per unit at stator terminals
  - Must be capable of maintaining voltage at 0.5% of set point
- These modes of operation are not permitted:
  - Constant VAR control
  - Constant power factor control
- Point of control cannot be on high side of transmission system step-up transformer
- Allow for continuous operation between 0.90 and 1.10 per unit as measured on high side of transmission system step-up transformer

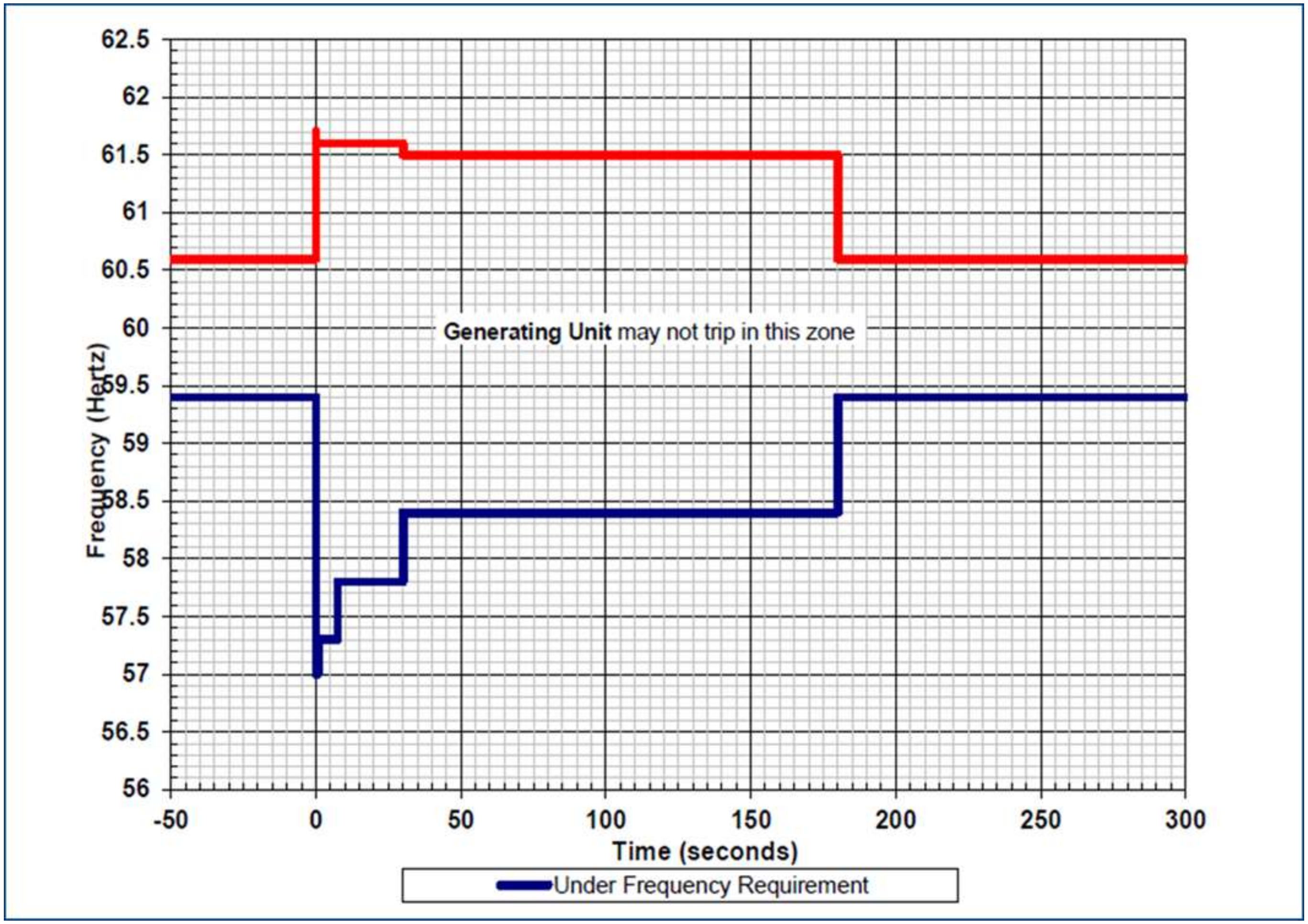
** Information source: AESO*

Voltage ride-through: 502.5: Appendix 2



** Information source: AESO*

Frequency ranges: 502.5: Appendix 3



** Information source: AESO*

Other technical requirements per 502.5 and 502.6

- Power system stabilizer
- Model validation (WECC) testing
- Transformer connection and sizing
- Frequency control (governor systems)
- Frequency ride-through
- Sequence-of-events recording
- Synchrophasor measurement

** Information source: AESO*

Ancillary services an opportunity

- Qualified generators may participate in ancillary services market
- Requirements in ISO Rules Division 205: Ancillary Services Market
  - Supplemental reserve
    - 5 MW minimum
    - Able to come on-line or increase output within 10 minutes of a directive
  - Spinning reserve
    - 10 MW minimum
    - Must be on-line and responsive to frequency
    - Able to increase output within 10 minutes of a directive
  - Regulating reserve
    - 15 MW minimum
    - Must be on-line and responsive to frequency
    - Able to follow AESO's AGC signal

** Information source: AESO*

Cogeneration snapshot: Jan. 11/17 at 2 p.m.

ASSET	MC	TNG	DCR
ATCO Scotford Upgrader (APS1)	195	105	25
Air Liquide Scotford #1 (ALS1)	96	81	6
AltaGas Harmattan (HMT1)	45	18	0
Base Plant (SCR1)	50	19	0
Bear Creek 1 (BCRK)	64	0	0
Bear Creek 2 (BCR2)	36	16	0
BuckLake (PW01)	5	5	0
CNRL Horizon (CNR5)*	203	197	0
Camrose (CRG1)*	10	9	0
Carseland Cogen (TC01)	95	76	0
Christina Lake (CL01)	101	96	0
Dow Hydrocarbon (DOWG)	326	156	40
Edson (TLM2)	13	10	0
Firebag (SCR6)	473	374	0
Foster Creek (EC04)	98	86	0
Joffre #1 (JOF1)	474	232	18
Kearl (IOR3)	84	10	0
Lindbergh (PEC1)*	16	16	0
MEG1 Christina Lake (MEG1)	202	181	0
MacKay River (MKRC)	197	199	0
Mahkeses (IOR1)	180	171	0
Muskeg River (MKR1)	202	182	12
Nabiye (IOR2)*	195	91	0
Nexen Inc #2 (NX02)	220	130	0
Poplar Creek (SCR5)	376	197	0
Primrose #1 (PR1)	100	88	0
Rainbow Lake #1 (RL1)	47	0	0
Redwater Cogen (TC02)	46	40	0
Shell Caroline (SHCG)*	19	0	0
Syncrude #1 (SCL1)*	510	432	0
U of C Generator (UOC1)*	12	14	0
University of Alberta (UOA1)*	39	15	15

** Information source: AESO*

AESO references

- **See:** www.aeso.ca
- **ISO rules**: www.aeso.ca/rules-standards-and-tariff/iso-rules/
- **Alberta Reliability Standards:** www.aeso.ca/rules-standards-and-tariff/alberta-reliability-standards/
- **AESO transmission tariff:** www.aeso.ca/rules-standards-and-tariff/tariff/
- **AESO connection process:** www.aeso.ca/grid/connecting-to-the-grid/connection-process/
- **Loss factors:** www.aeso.ca/grid/loss-factors/
- **Grid operations:** www.aeso.ca/grid/grid-operations/

** Information source: AESO*

Thank you

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** Information source: AESO*

Experience with existing cogeneration facilities

Topics

- Commissioning and Start-up
- Operation
- Islanding
- Maintenance Considerations

Commissioning and Start-Up
Typical Scope and Sequence

Electrical System
- Component tests
- Functional tests
- SCADA tests
- Energize GSU xfmr (backfeed)

Control System
- DCS loop checks
- Functional checks

Mechanical Equipment
- Engine commissioning
- HRSG & pipe chemical cleaning
- First fire of the turbine
- Steam blows of the steam piping

Systems
- Synchronization of the generators
- Power train on-line commissioning
- WECC tests
- Commercial operation

Commissioning and Start-Up
Common Start-Up Problems

Engines & turbines are usually well proven and start up ok.
Issues, if they exist, will likely be at interfaces.

Electrical systems require careful attention

- Excellent paper by Andrew R. Leoni and John P. Nelson on electrical commissioning errors (PCIC 2000):
  - *Some Lessons Learned from Commissioning Substation and Medium Voltage Switchgear Equipment*
- CT circuits (shorting screws, single-point grounding)
- Differential CT polarity
- Assuming factory wiring is correct
- Ground faults on DC circuits
- Problems often occur at interfaces

Commissioning and Start-Up
Common Start-Up Problems … continued

Allow extra time for heat recovery equipment, steam/water systems.

- Not as "packaged" as other mechanical equipment
- Lots of interfaces – again, problems seem to occur at interfaces

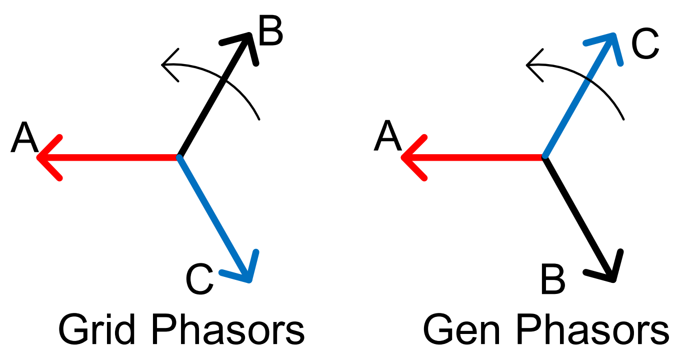
Commissioning and Start-Up
Proving Synchronism

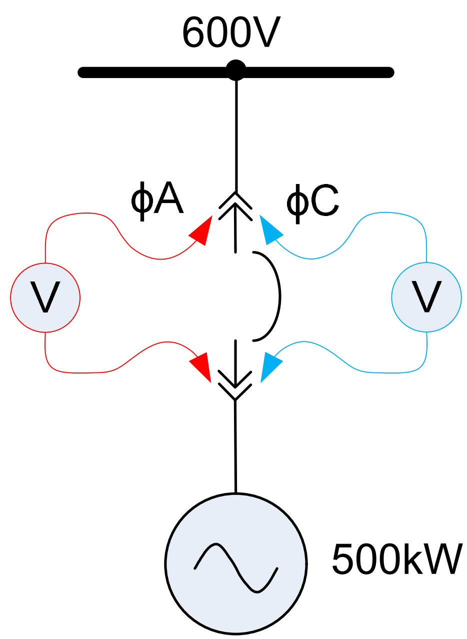
- Proof of synchronism is a critical commissioning activity.
- Failure to conclusively prove synchronism can have nasty consequences.

Small Gensets:

Direct voltage measurement across two phases is usually practical.

Use 2 voltmeters to detect this condition:



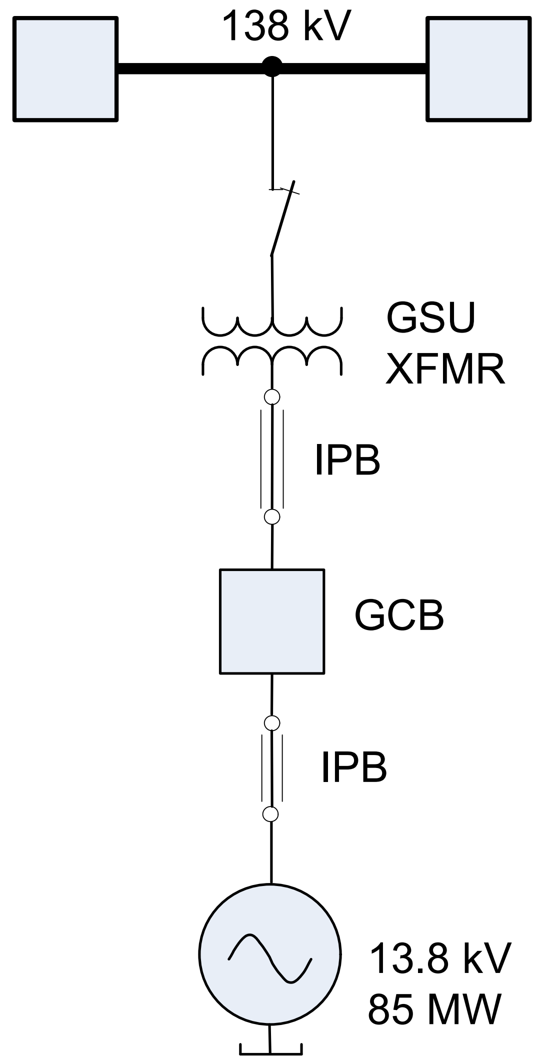


Commissioning and Start-Up
Proving Synchronism

Direct phase measurement is the ideal and foolproof way to prove synchronism. But it is not always practical.

- Physical restrictions can prevent access to primary conductors.
- Hazards due to high fault levels.
- Availability of adequately rated test equipment.

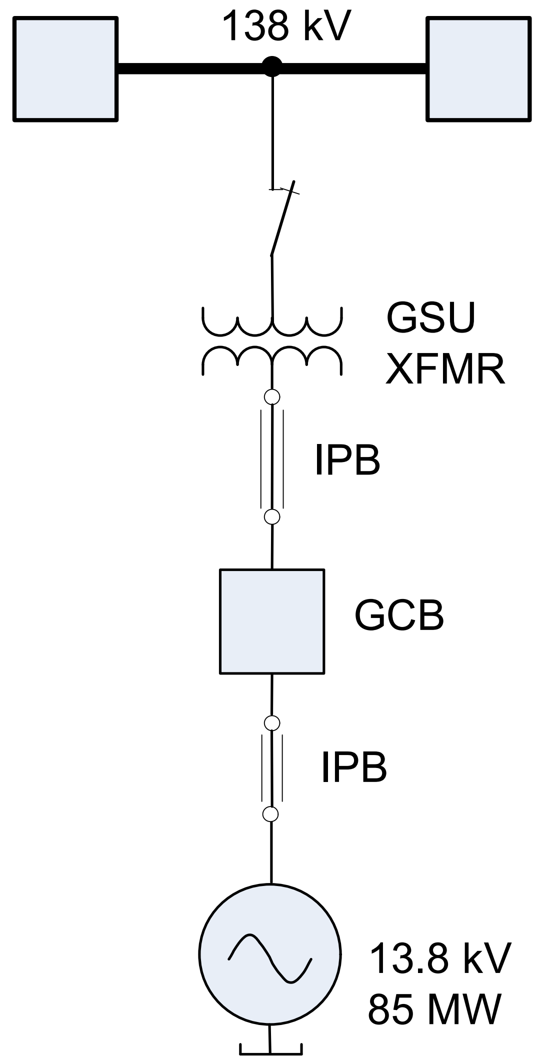
In such cases, consider using secondary circuits and phasor relationships. But be diligent.



Commissioning and Start-Up
Proving Synchronism

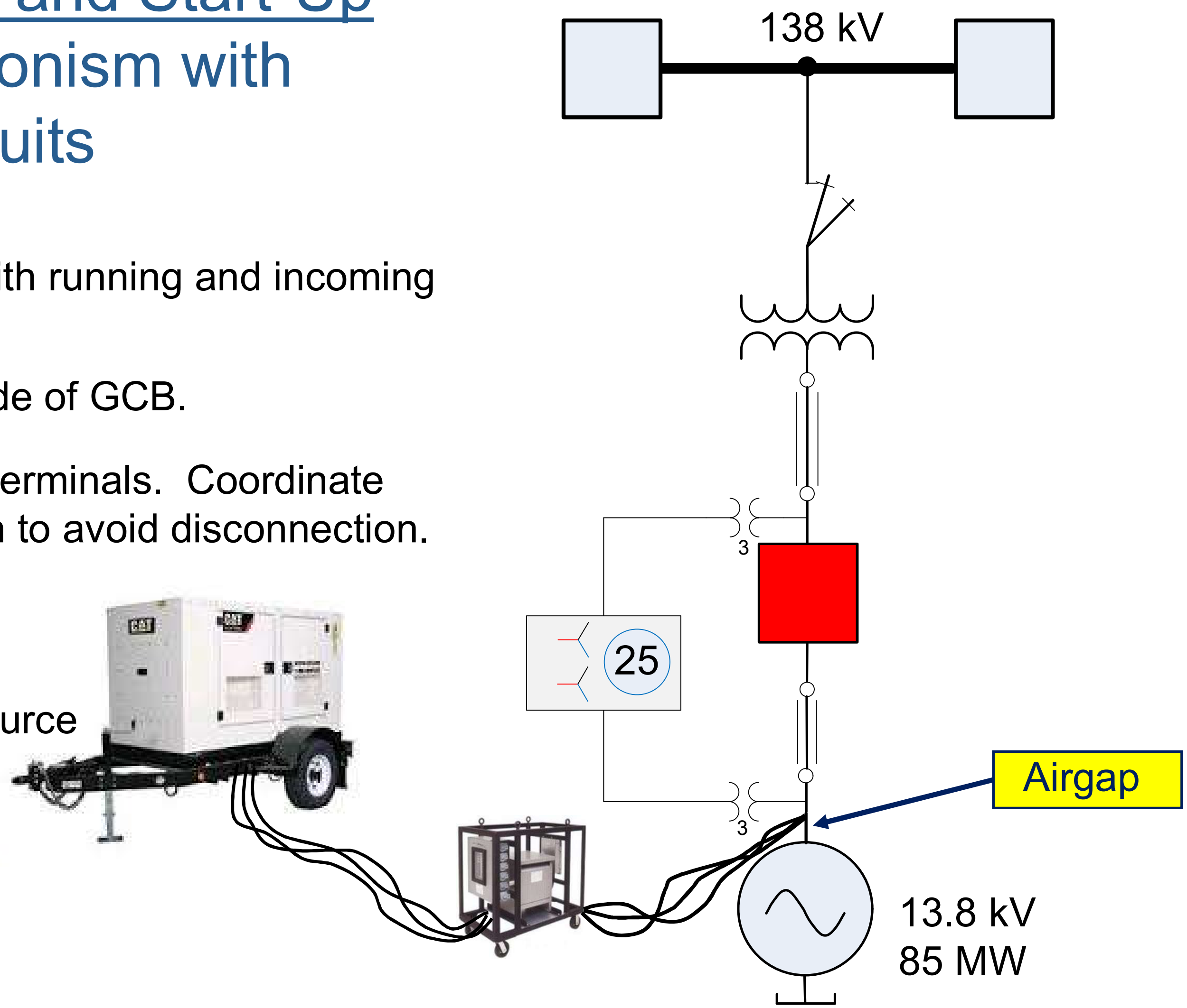
Proving synchronism with secondary circuits is elegant, but needs to be as close to foolproof as possible.

- Understand that two "secondary" wrongs can give false indication of a "primary" right.
- Forget the notion that double contingency failures or errors do not occur. They do.
- Use different test methods and overlapping proofs to validate system.



Commissioning and Start-Up
Proving Synchronism with Secondary Circuits

- Multifunction relay with running and incoming phasor display.
- Wye PTs on each side of GCB.
- Airgap at generator terminals. Coordinate this with construction to avoid disconnection.
- Isolation above sync circuits.
- Temporary power source (3ph) connected to main conductors.
- Continuity through GCB.



Commissioning and Start-Up

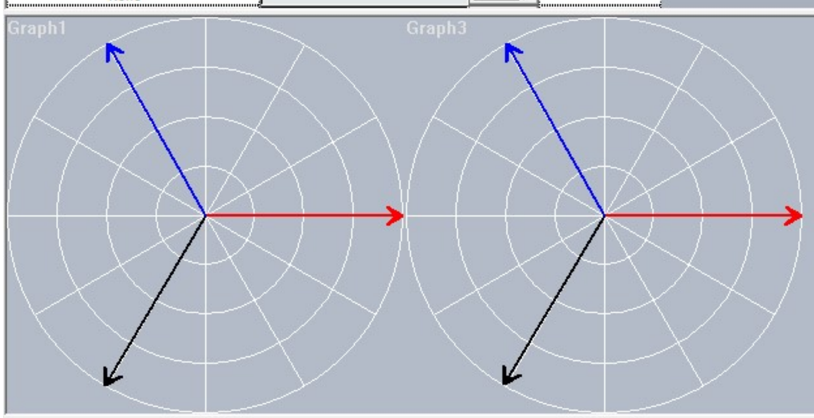
Proving Synchronism with Secondary Circuits

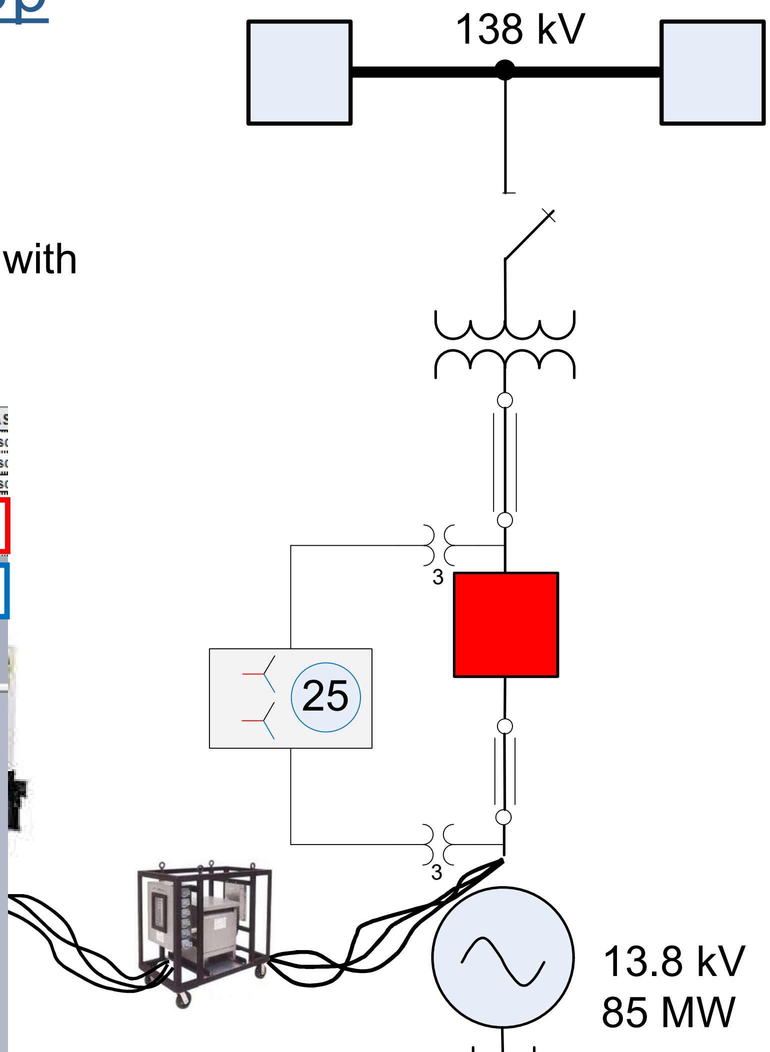
1. Record the two synchronizing phasors with three phase test voltage applied.

COMPONENT	MAGNITUDE / ANGLE	COLOR	ASSIGN TO	GRAPH	MAP PHAS
GEN (SRC 1)-Phasor Ia	0.000 A 0.0 deg		Phasor Set 1	1	Select Phas
GEN (SRC 1)-Phasor Ib	0.000 A 0.0 deg		Phasor Set 1	2	Select Phas
GEN (SRC 1)-Phasor Ic	0.000 A 0.0 deg		Phasor Set 1	3	Select Phas
GEN (SRC 1)-Phasor Vag	311.942 V 0.0 deg		Phasor Set 2		
GEN (SRC 1)-Phasor Vbg	311.739 V -120.8 deg		Phasor Set 2		
GEN (SRC 1)-Phasor Vcg	312.422 V -240.3 deg		Phasor Set 2		
GENBUS (SRC 2)-Phasor Vag	311.224 V -0.2 deg		Phasor Set 3		
GENBUS (SRC 2)-Phasor Vbg	310.028 V -120.8 deg		Phasor Set 3		
GENBUS (SRC 2)-Phasor Vcg	312.054 V -240.3 deg		Phasor Set 3		
None					
None					
None					

Gen Side

Grid Side

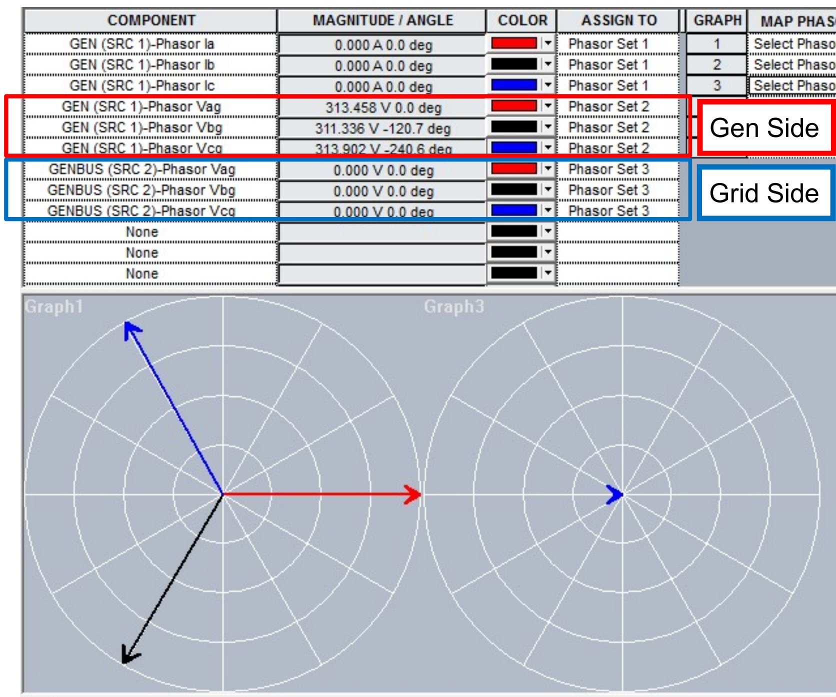




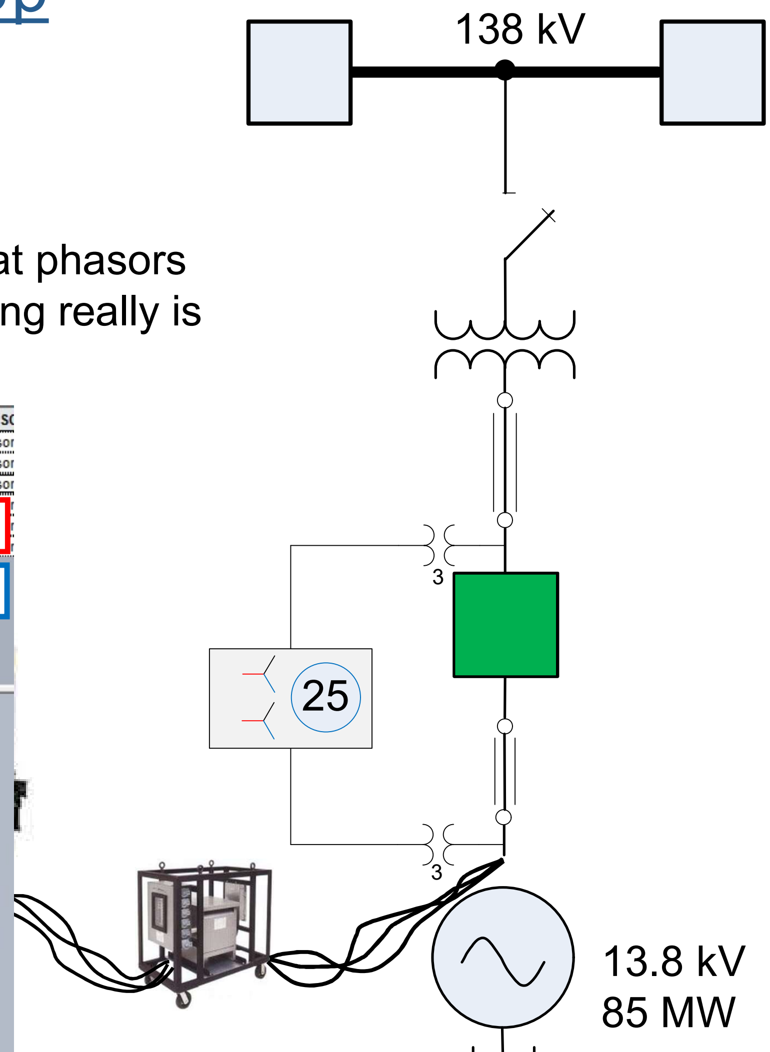
Commissioning and Start-Up

Proving Synchronism with Secondary Circuits

2. Open the generator breaker. Verify that phasors on one side collapse. Prove that sensing really is on opposite sides of the breaker.



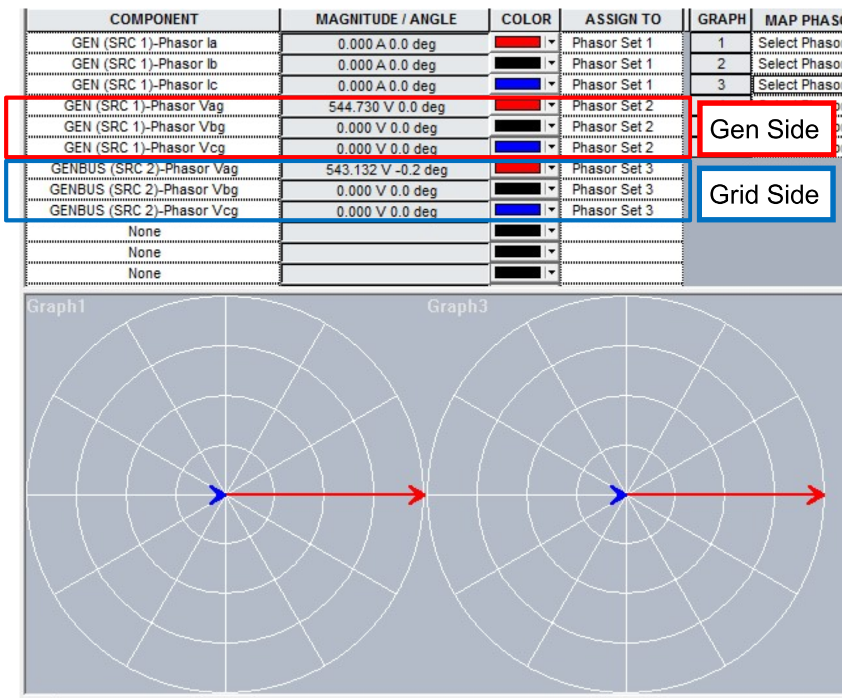
COMPONENT	MAGNITUDE / ANGLE	COLOR	ASSIGN TO	GRAPH	MAP PHASO
GEN (SRC 1)-Phasor Ia	0.000 A 0.0 deg		Phasor Set 1	1	Select Phasor
GEN (SRC 1)-Phasor Ib	0.000 A 0.0 deg		Phasor Set 1	2	Select Phasor
GEN (SRC 1)-Phasor Ic	0.000 A 0.0 deg		Phasor Set 1	3	Select Phasor
GEN (SRC 1)-Phasor Vag	313.458 V 0.0 deg		Phasor Set 2		
GEN (SRC 1)-Phasor Vbg	311.336 V -120.7 deg		Phasor Set 2		
GEN (SRC 1)-Phasor Vcg	313.902 V -240.6 deg		Phasor Set 2		
GENBUS (SRC 2)-Phasor Vag	0.000 V 0.0 deg		Phasor Set 3		
GENBUS (SRC 2)-Phasor Vbg	0.000 V 0.0 deg		Phasor Set 3		
GENBUS (SRC 2)-Phasor Vcg	0.000 V 0.0 deg		Phasor Set 3		
None					
None					
None					



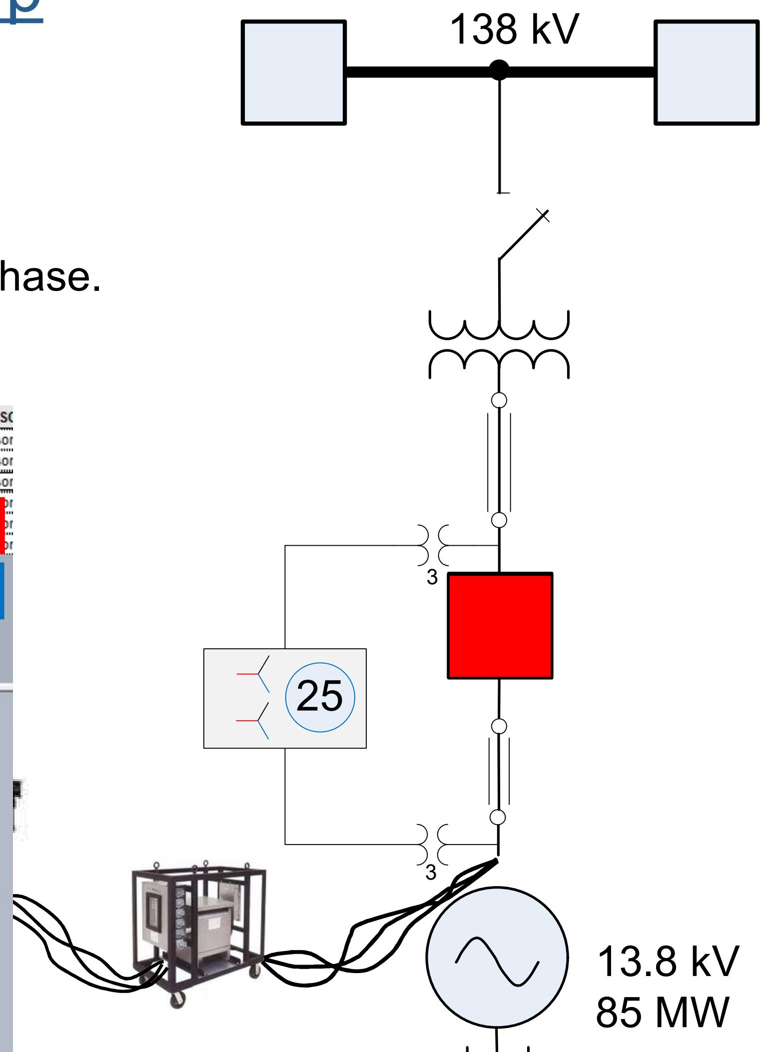
Commissioning and Start-Up

Proving Synchronism with Secondary Circuits

3. Close breaker and energize only one phase.



COMPONENT	MAGNITUDE / ANGLE	COLOR	ASSIGN TO	GRAPH	MAP PHASC
GEN (SRC 1)-Phasor Ia	0.000 A 0.0 deg		Phasor Set 1	1	Select Phasor
GEN (SRC 1)-Phasor Ib	0.000 A 0.0 deg		Phasor Set 1	2	Select Phasor
GEN (SRC 1)-Phasor Ic	0.000 A 0.0 deg		Phasor Set 1	3	Select Phasor
GEN (SRC 1)-Phasor Vag	544.730 V 0.0 deg		Phasor Set 2		
GEN (SRC 1)-Phasor Vbg	0.000 V 0.0 deg		Phasor Set 2		
GEN (SRC 1)-Phasor Vcg	0.000 V 0.0 deg		Phasor Set 2		
GENBUS (SRC 2)-Phasor Vag	543.132 V -0.2 deg		Phasor Set 3		
GENBUS (SRC 2)-Phasor Vbg	0.000 V 0.0 deg		Phasor Set 3		
GENBUS (SRC 2)-Phasor Vcg	0.000 V 0.0 deg		Phasor Set 3		
None					
None					
None					



Commissioning and Start-Up
Proving Synchronism with Secondary Circuits

4. Remove test equipment.

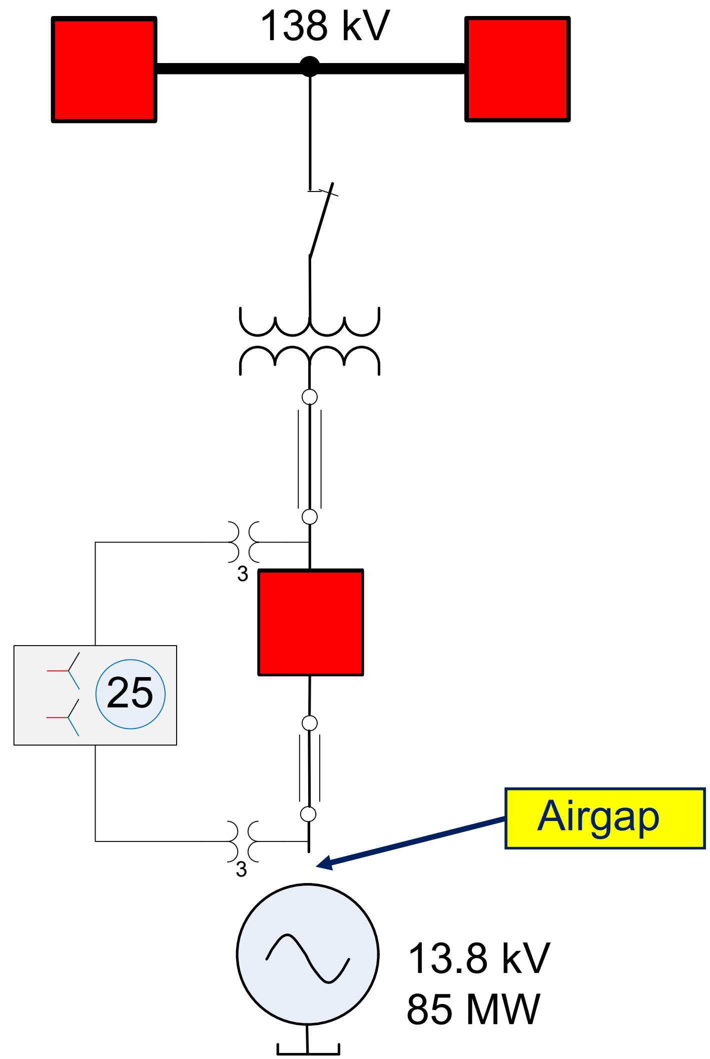
   Leave generator terminal air gap in place.

   Prepare for back-energization.

   Back-energize.

   Record phasors on each side of GCB. Safely store this information for future reference.

   Pay particular attention to phase rotation.



Commissioning and Start-Up
Proving Synchronism with Secondary Circuits

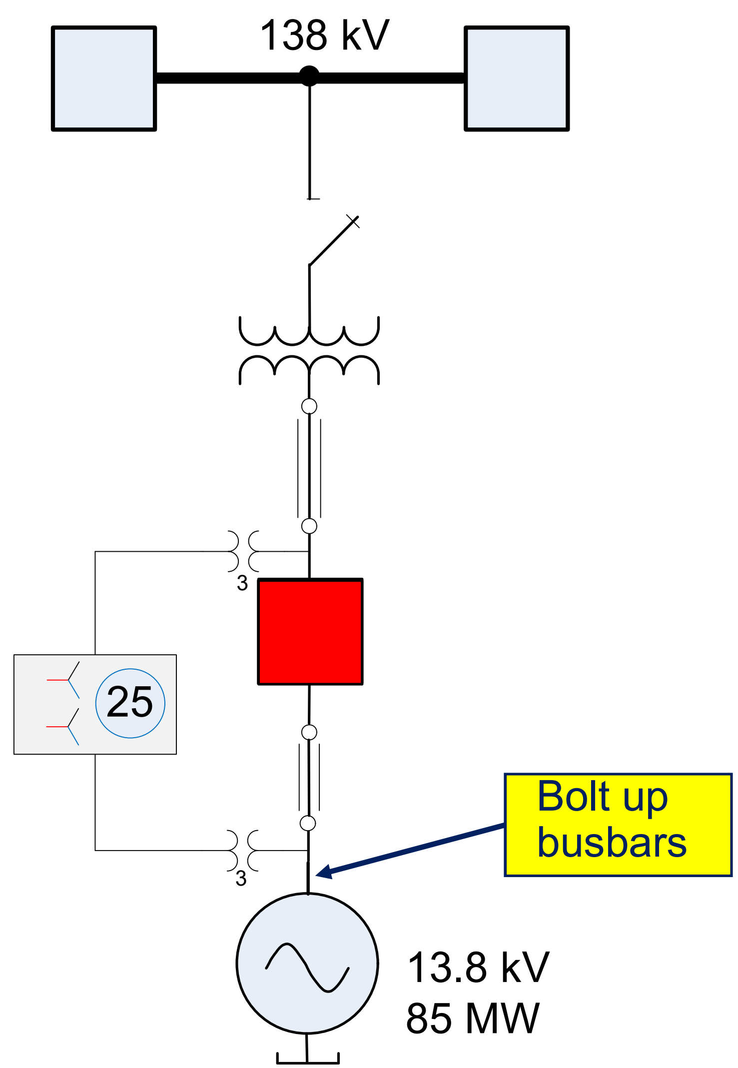
5. Close generator terminal air gap. Bolt up busbars, flexible braids. (Hint: ensure all material is available beforehand.)

   Open switch or breaker on HV side of GSU xfmr.

   Commission excitation system. Excite generator (and GSU xfmr).

   Record phasors on each side of GCB.

   Verify phase rotation is same as that recorded during backfeed.



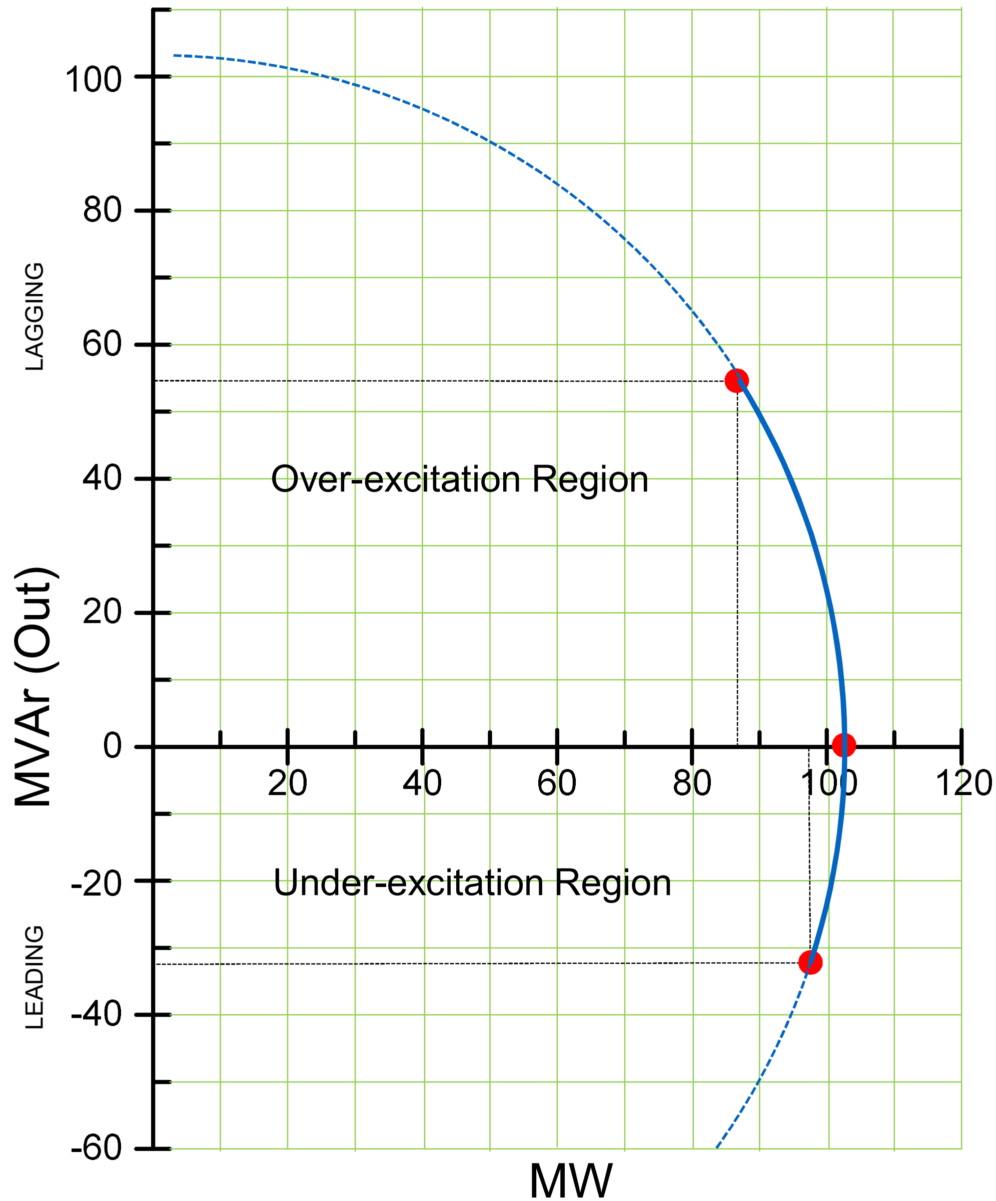
Operations
Capability Curve

Typical Generator Data:
87.55MW, 103.00 MVA
0.85 lag to 0.95 lead
40°C Cooling Air

At Unity pf:
103.0 MW
0.0 MVAr

At 0.85 Lagging pf:
87.6 MW
54.3 MVAr

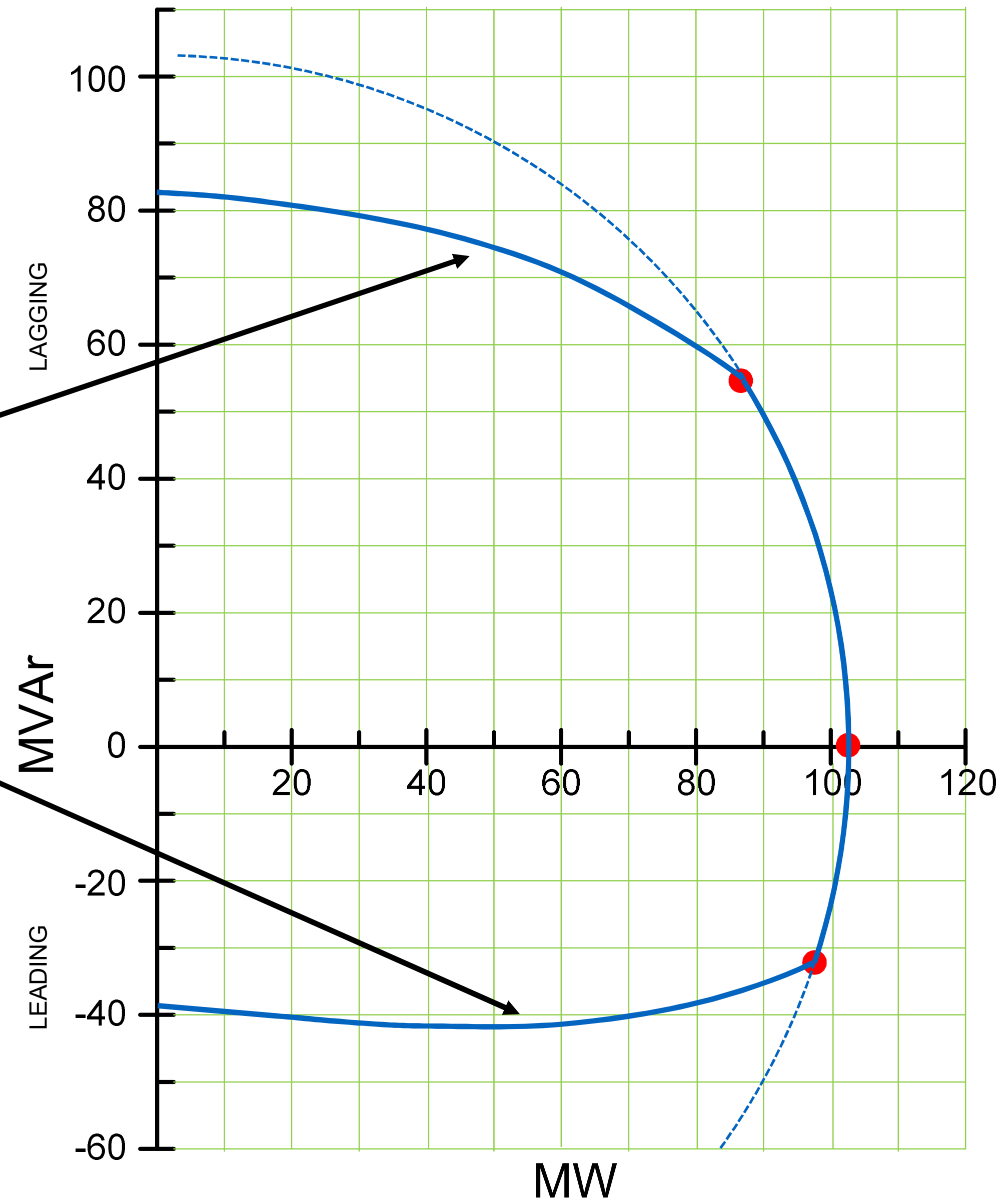
At 0.95 Leading pf:
97.8 MW
32.2 MVAr



Operations
Capability Curve

Current in over-excitation region is limited by rated field current

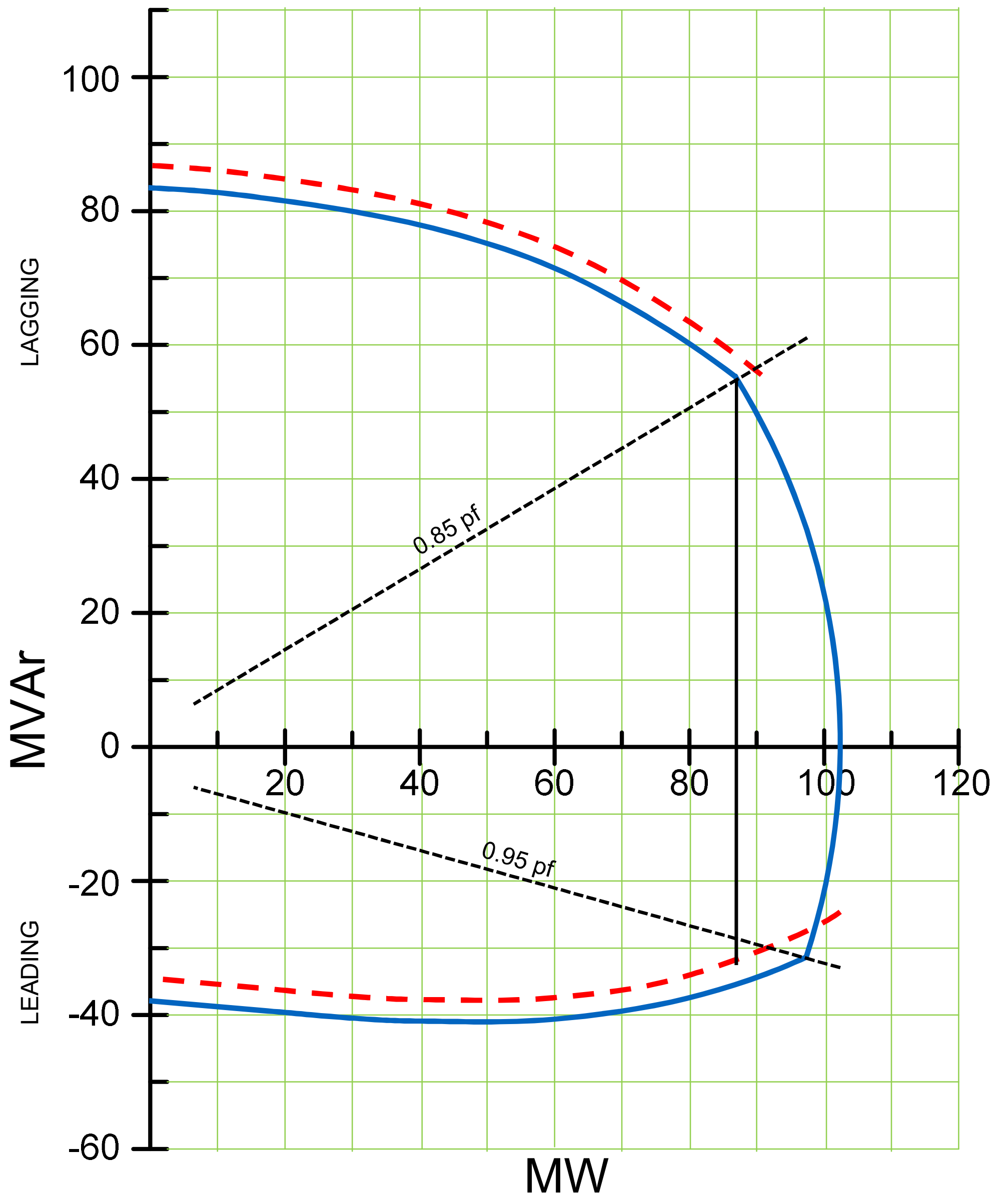
Current in under-excitation region is limited by core end heating



Operations
Capability Curve

Export reactive power (lagging / over excitation) is limited by rated field current

Import reactive power (leading / under excitation) is limited by core end heating

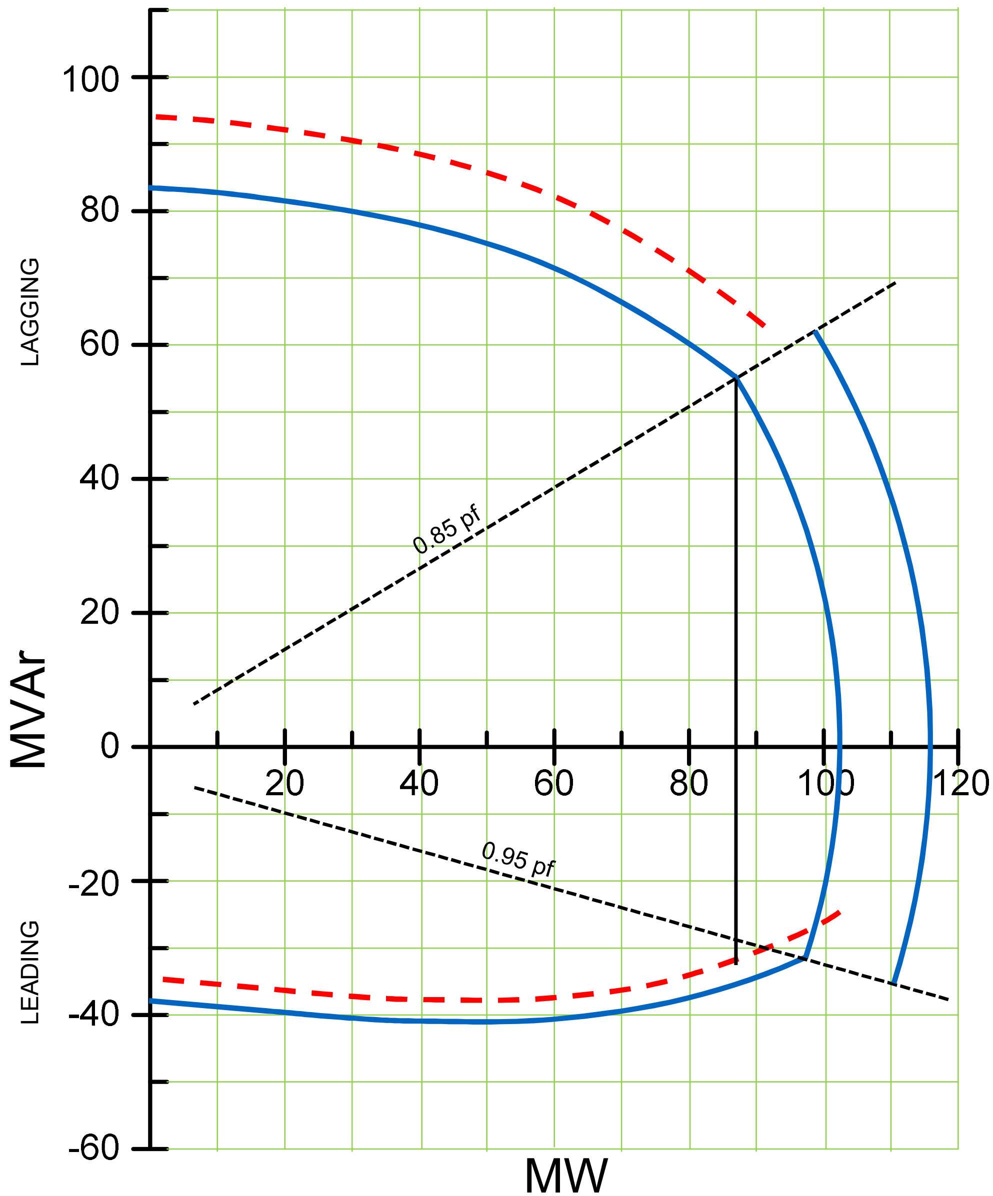


Operations

Capability Curve

Export reactive power (lagging / over excitation) is limited by rated field current

Import reactive power (leading / under excitation) is limited by core end heating



Operations
Generator Voltage Control

Show a few examples:

1. Unity power factor at generator
2. Unity power factor at grid intertie
3. Unity power factor at generator tie-point.

Message: Need to decide optimal operating mode. Ensure panel operators know operating objectives.

Commissioning and Start-Up
Proving Synchronism

Proof of synchronism is a critical commissioning activity.

Failure to conclusively prove synchronism can have nasty consequences.

Small Gensets:

- Direct voltage measurement across two phases is usually practical.

Large generators:

- Voltage magnitude, physical restrictions, extreme arc flash levels can make direct voltage measurements impractical.
- Probably need to consider less direct methods to prove synchronism.

Islanding

Typically most beneficial for co-generation facilities: Keep the process running (or minimize interruption). Less so for simple cycle or combined cycle facilities.

Implementation is often non-trivial. Cost versus benefit should be considered during DBM stage. Purchase the equipment and design the facility accordingly.

Islanding considerations:

Import versus export @ PoC
Detection of island condition
Turbine transient response
Flame robustness
Exciter response

Signal exchange with turbine
Transition to isochronous oper.
Interoperation of multiple units
Turbine load ramp rate
Ability to re-synchronize

Summary & conclusions
Questions & discussion