# Course:
# ELEC ENG 3110 Electric Power Systems
# ELEC ENG 7074 Power Systems PG
# (Semester 2, 2021)

## Power and Frequency Control (Part 1)

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# Power and Frequency Control

- **Background**
  - **Overview of power and frequency control provided in lecture 1**

  - **Frequency related to balance between supply and demand**
    - **If demand exceeds supply frequency decreases**
    - **If supply exceeds demand frequency increases**

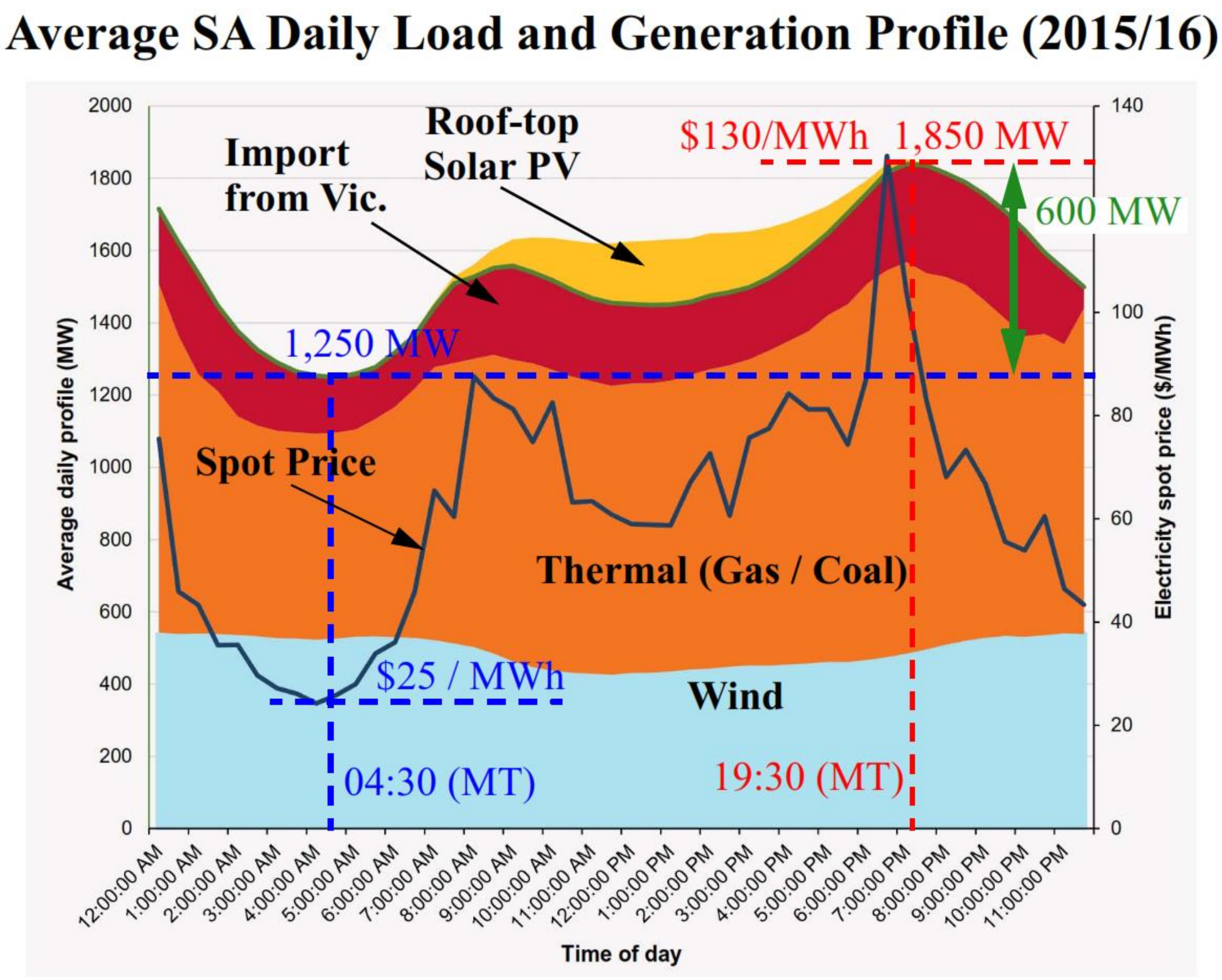
  - **Demand changes continuously so supply must be adjusted to maintain demand-supply balance and thus frequency**

  - **Frequency must be regulated within tight tolerances required for satisfactory system operation**
    - **Hieracrhical, time segregated controls**
      - **Security constrained dispatch**
      - **Automatic generation control (AGC)**
      - **Turbine speed governors (synchronous machines)**
      - **Frequency controllers (asynchronous sources – growing application)**

  - **Frequency / power control largely decoupled from voltage / reactive power control**

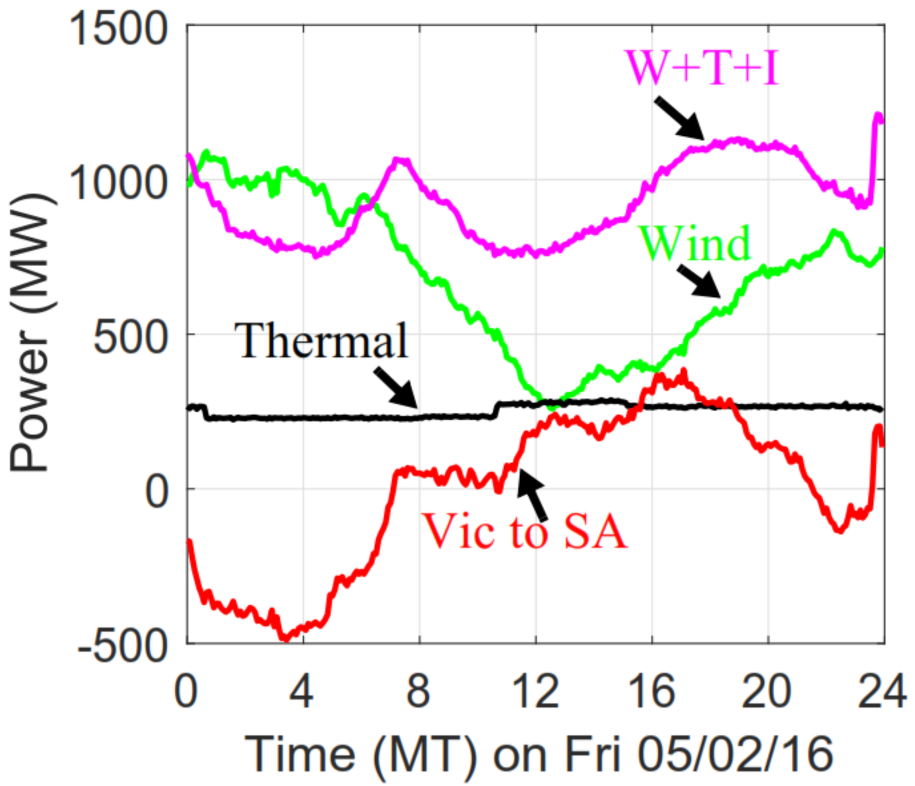
# Daily demand profile (Review Lecture 1)

- Real power demanded by system loads varies continuously.
- Demand profile changes in shape and magnitude daily, weekday to weekend, seasonally.
- Highly weather dependent
- Increasing levels of intermittent generation results in overall increase in net variability
- Decreasing levels of controllable generation must respond to variability in the demand-supply balance.
- Focus now is on automatic frequency controls

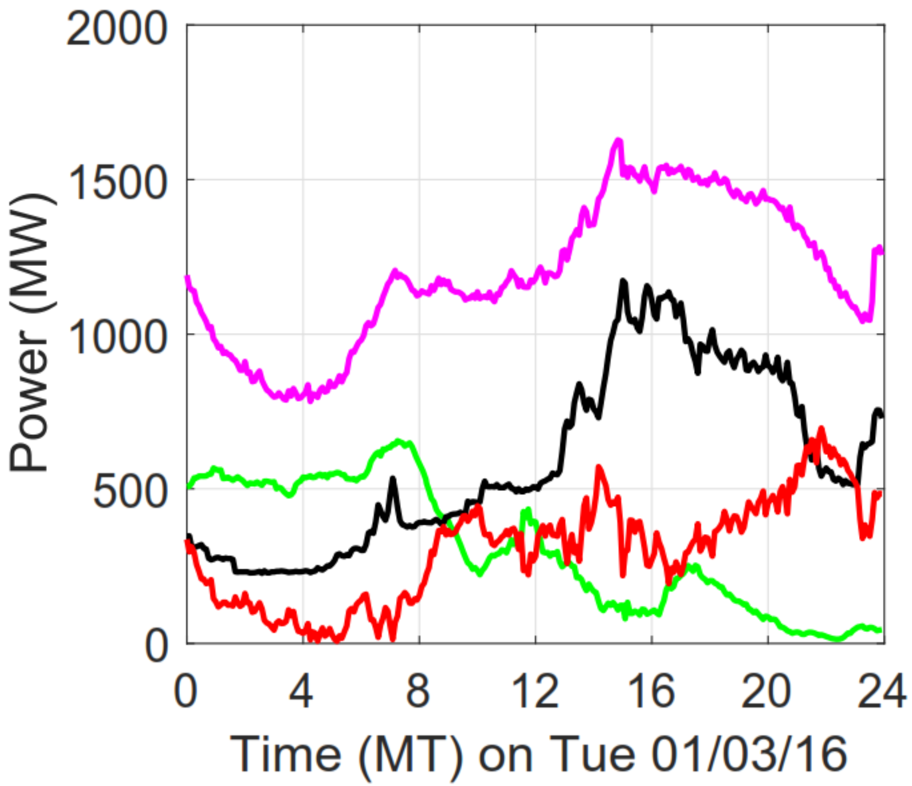



AEMO, "South Australian Electricity Report: South Australian Advisory Function", August 2016

# Illustration of Intermittency and Variability of SA Wind Generation

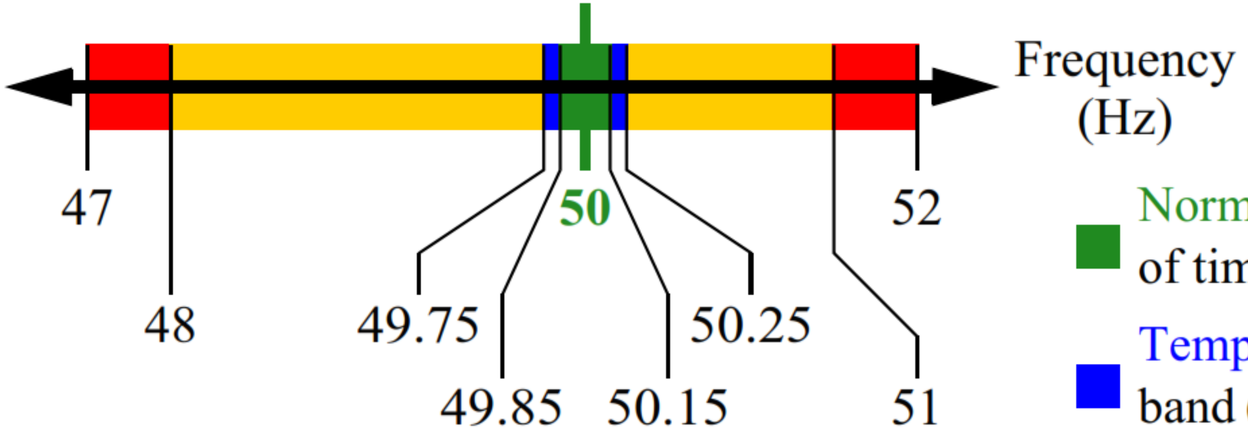



- Light load, SA thermal generation minimum
- High wind (1000 MW) overnight, SA exports excess wind to Vic.
- Wind falls by 750 MW to 250 MW by midday and then increases again. Slack taken up by interconnectors.




- Light-medium load, moderate wind (500 MW) overnight, falls to very low level later in the day.
- SA thermal generation and interconnectors responsive to variation in load and wind generation.

# Frequency Control Requirements (Review Lecture 1)




- Normal operating frequency band (No contingency, 99% of time in any 30 day period)
- Temporary excursion from normal operating frequency band (No contingency, return to normal band within 5 min)
- Operational frequency band after credible contingency (Graded stabilization and recovery times depending on the type of contingency. Stabilization to 49.5 to 50.5 Hz band in up to 2 min; Recovery to within normal band in up to 10 min.)
- Extreme frequency band following multiple contingencies. (Under-frequency load-shedding, protection operation; Stabilization within 2 min., recovery within 10 min.)

- Abridged version of AEMC Frequency Operating Standard[1]
- Tight frequency tolerance needed for satisfactory operation of the power system and the loads connected to it.

(1) Reliability Panel, AEMC, "Application of Frequency Operating Standards during periods of supply scarcity", Final Report, 15 April 2009.

# Synchronous machine rotor -- equations of motion (1)

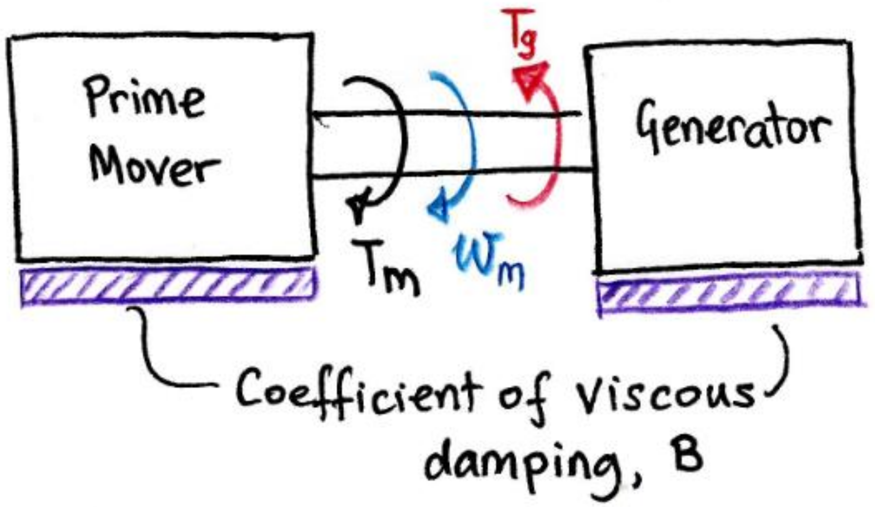
- Rotors of synchronous machines are at the heart of system frequency response

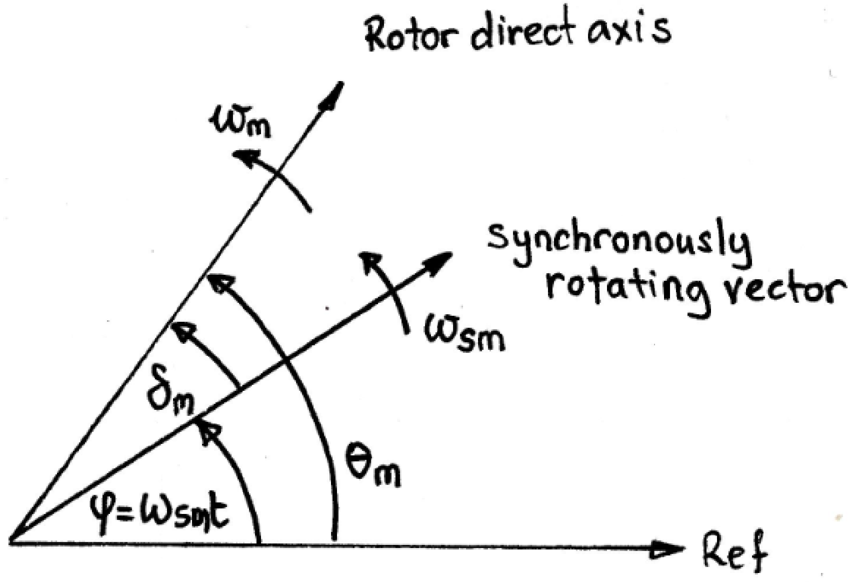
- The rotor of a synchronous generator is subjected to two opposing torques:

  - The driving mechanical torque developed by the turbine which acts in the direction of rotation; and

  - The electromagnetic torque developed due to the interaction of the magnetic fields created by the currents carried by the field and armature windings. This torque opposes the direction of rotation.

  - Rotor motion is measured relative to synchronously rotating reference frame



# Synchronous machine rotor -- equations of motion (2)

Acceleration equation – Newton's second law of motion applied to rotational system (SI units)

Acceleration (rad/s²)

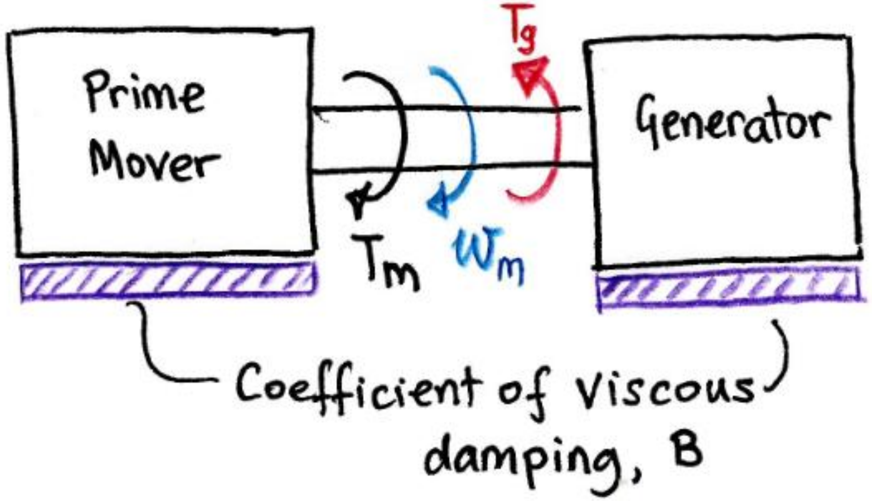
Electromagnetic Torque (N.m)

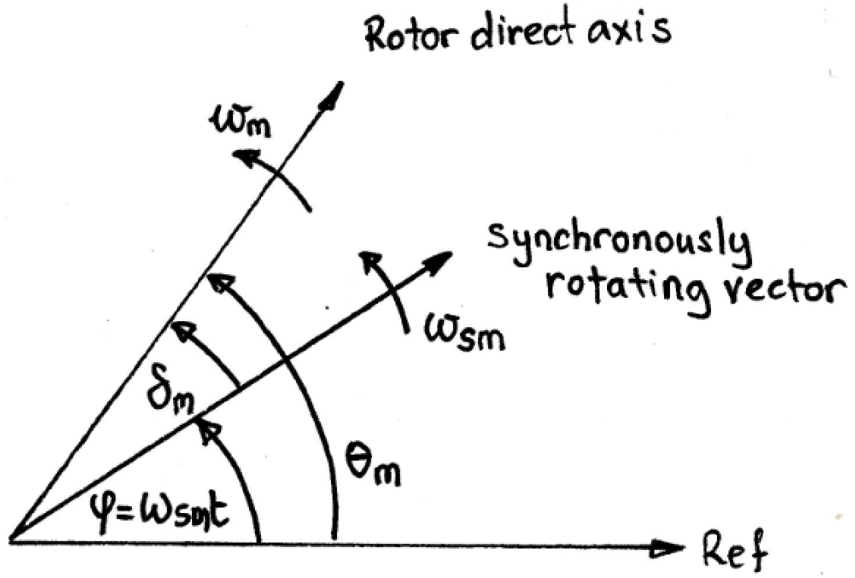
$$J\frac{d\omega_m}{dt} = T_m - T_g - B(\omega_m - \omega_{sm})$$

Mechanical Torque (N.m)

Total moment of inertia of the rotating system (kg·m²)

Damping Torque (Friction effects)



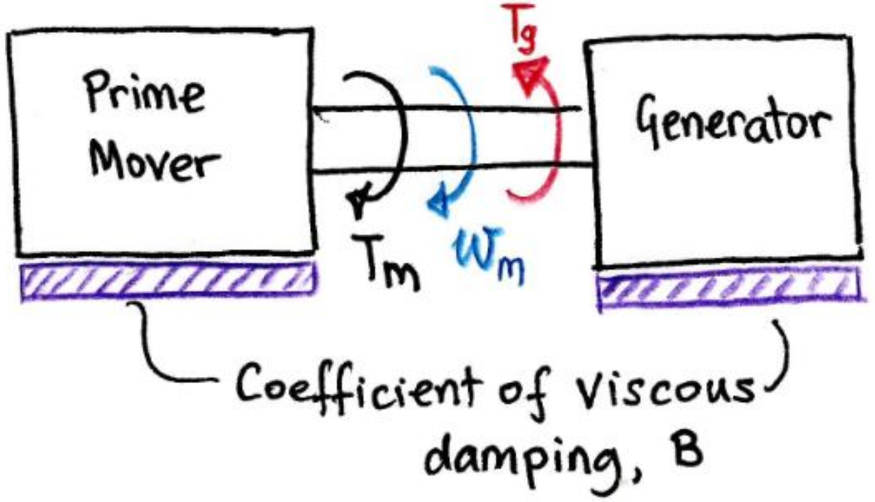
# Synchronous machine rotor -- equations of motion (3)

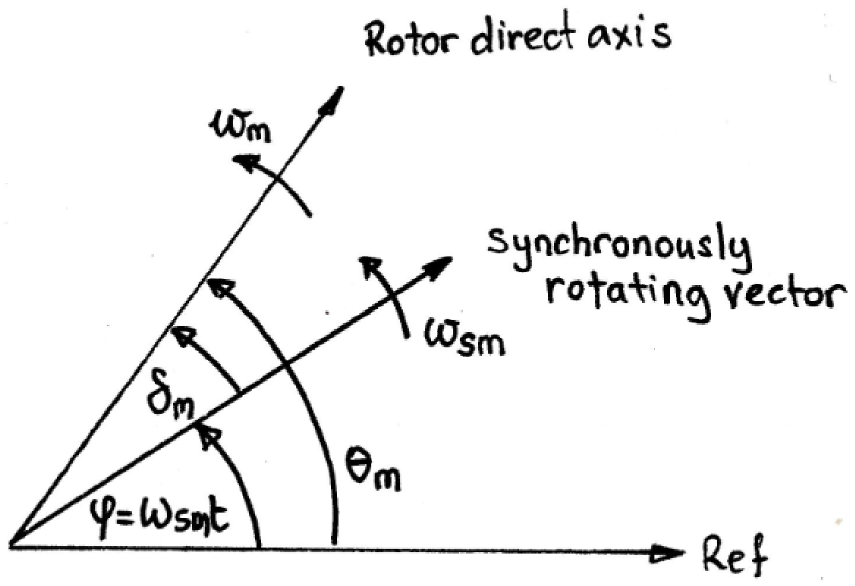
## Rotor-speed equation

$$\theta_m = \omega_{sm} . t + \delta$$

$$\omega_m = \frac{d\theta_m}{dt} = \omega_{sm} + \frac{d\delta_m}{dt}$$

$$\Rightarrow \frac{d\delta_m}{dt} = (\omega_m - \omega_{sm})$$



# Synchronous machine rotor -- equations of motion (4)

Convert equations of motion in SI units to per-unit

Let the system frequency be $f_0$ Hz

so synchronous frequency is

$\boxed{\omega_s = 2\pi f_0}$ (elec. rad/s)

Let $p_f$ be the number of field pole pairs, then $\boxed{\omega_{sm} = \omega_s / p_f}$ mech. rad/s

Per-unit rotor-speed:

- Base speed is synchronous speed
- Note equality of per-unit mechanical and electrical rotor-speed

$$\omega_m^{(p)} = \frac{\omega_m}{\omega_{ms}} \times \frac{p_f}{p_f} = \frac{\omega}{\omega_s} = \omega^{(p)}$$

Per-unit mechanical speed

= per-unit electrical speed.

$$\delta = \delta_m \times p_f$$

# Synchronous machine rotor -- equations of motion (5)

Convert equations of motion in SI units to per-unit

Define the per-unit inertia constant $\boxed{H}$

$$\boxed{H} = \frac{\text{Rotor kinetic energy at synchronous speed (MW.s)}}{\text{MVA base} \times \text{Time base}}$$

$$= \frac{\frac{1}{2} J \omega_{sm}^2}{S_b \times t_b} = \boxed{\frac{\frac{1}{2} J \omega_{sm}^2}{S_b}}$$

$t_b = 1\,s$

$$\boxed{J = 2H\left(\frac{S_b}{\omega_{sm}^2}\right)}$$

$$2H\left(\frac{S_b}{\omega_{sm}^2}\right)\frac{d\omega_m}{dt} = T_m - T_g - B(\omega_m - \omega_{sm})$$

$$2H\frac{d\left(\frac{\omega_m}{\omega_{sm}}\right)}{dt} = \frac{T_m - T_g - B(\omega_m - \omega_{sm})}{S_b/\omega_{sm}}$$

per-unit rotor-speed

base torque

# Synchronous machine rotor -- equations of motion (6)

$$2H\frac{d\omega_m^{(p)}}{dt} = T_m^{(p)} - T_g^{(p)} - \frac{B.\omega_{sm}}{(S_b/\omega_{sm})}\left[\frac{\omega_m}{\omega_{sm}} - \frac{\omega_{sm}}{\omega_{sm}}\right]$$

$$2\boxed{H}\frac{d\omega_m^{(p)}}{dt} = T_m^{(p)} - T_g^{(p)} - D(\omega_m^{(p)} - 1)$$

per unit inertia constant

per unit damping constant.

Replace $\omega_m^{(p)}$ by $\omega^{(p)}$ and note that $\Delta\omega_m^{(p)} = \Delta\omega^{(p)} = (\omega - 1)$.

Thus $\dfrac{d\omega_m^{(p)}}{dt} = \dfrac{d\,\Delta\omega^{(p)}}{dt}$

$$\boxed{2H\frac{d\Delta\omega}{dt} = T_m - T_g - D\Delta\omega}$$

# Synchronous machine rotor equations of motion (7)

Per-unitization of speed-equation

$$\frac{d\delta_m}{dt} = \omega_{sm}\left(\frac{\omega_m}{\omega_{sm}} - \frac{\omega_{sm}}{\omega_{sm}}\right)$$

$$= \omega_{sm}\left(\omega_m^{(P)} - 1\right)$$

$$\frac{d(P_f \times \delta_m)}{dt} = \omega_{sm}\left(\frac{\omega_m}{\omega_{sm}} - \frac{\omega_{sm}}{\omega_{sm}}\right) \times P_f$$

$$\frac{d\delta}{dt} = \omega_s\left(\omega_m^{(P)} - 1\right) \quad (\text{elec. rad/s})$$

$$\boxed{\frac{d\delta}{dt} = \omega_s\left(\omega^{(P)} - 1\right) \quad (\text{elec. rad/s})}$$

**Summary:**
**Per-unit rotor-equations of motion**
**(Torque Formulation)**

All quantities in per-unit on $S_b$, $\omega_b = \omega_s$ , $T_b = S_b / \omega_b$

Acceleration equation

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}\left(T_m - T_g - D\Delta\omega\right)$$

Speed equation

$$\frac{d\delta}{dt} = \omega_s \Delta\omega$$

# Synchronous machine -- rotor equations of motion (8)

Convenient to express acceleration equation in terms of mechanical and electrical power rather than torque.

- It is shown at right that the per-unit perturbation in accelerating power and accelerating torque are identical
- The linearized rotor equations of motion in torque and power form are shown next …

Relationship between torque and power → $\underline{P = \omega T}$

Under steady state conditions $\frac{d\Delta\omega}{dt} = 0$ (i.e. speed is constant and equal to $\omega_0 = 1$ pu). Suppose that the steady state values of torque and power are $T_0$ and $P_0$ respectively then it follows that $P_0 = \omega_0 . T_0 = T_0$

Now, consider small perturbations in torque, power and speed about the initial steady state values

$$P = P_0 + \Delta P, \quad T = T_0 + \Delta T$$

$$\omega = \omega_0 + \Delta\omega = 1 + \Delta\omega$$

$$(P_0 + \Delta P) = (1 + \Delta\omega)(T_0 + \Delta T)$$

$$\doteq T_0 + \Delta T + \Delta\omega T_0 + \underset{\text{neglect}}{\text{h.o.t.}}$$

$$\doteq P_0 + \Delta T + \Delta\omega T_0$$

$$\therefore \Delta P = \Delta T + \Delta\omega T_0$$

Now,

$$(\Delta P_m - \Delta P_e) = (\Delta T_m - \Delta T_g) + \Delta\omega \underbrace{(T_{m_0} - T_{g_0})}_{= 0 \text{ in steady-state}}$$

$$\therefore \underline{\Delta P_m - \Delta P_e = \Delta T_m - \Delta T_g}$$

# Synchronous machine – Linearized rotor equations of motion

Following from the previous slide the per-unit linearized accelerating torque and accelerating power are equivalent resulting the following torque & power perturbation forms of the linearized equations of motion.

$$\frac{d\Delta\omega}{dt} = \underbrace{\frac{1}{2H}\left(\Delta T_m - \Delta T_g - D\Delta\omega\right)}_{\text{Torque Form}} = \underbrace{\frac{1}{2H}\left(\Delta P_m - \Delta P_e - D\Delta\omega\right)}_{\text{Power form}}$$

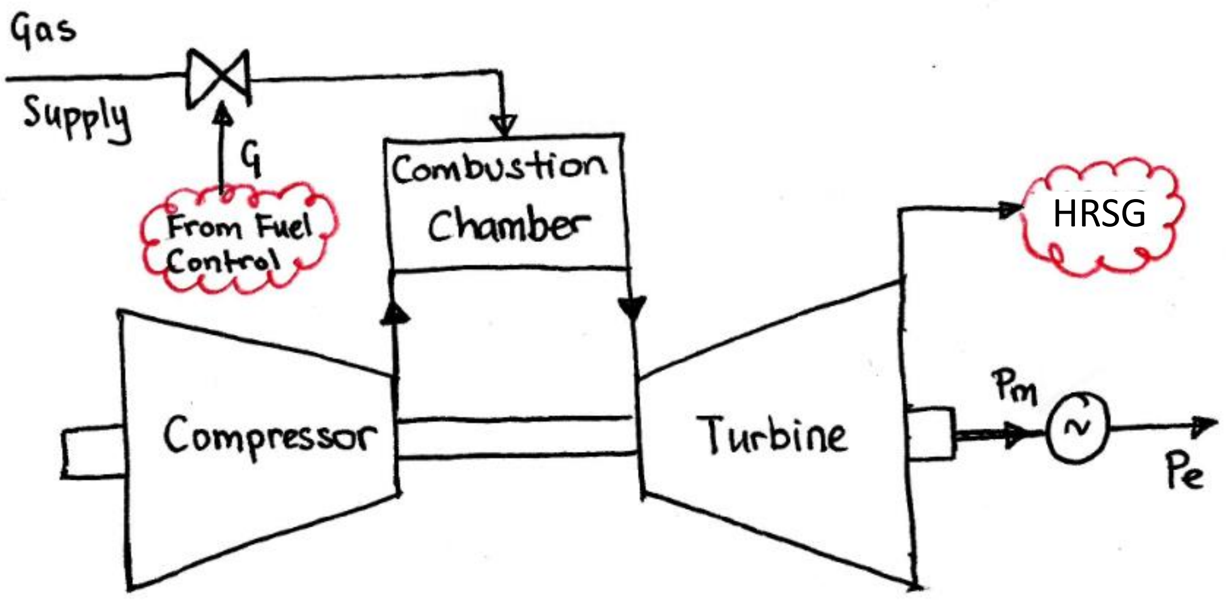
$$\frac{d\delta}{dt} = \omega_s \cdot \Delta\omega \quad , \quad \omega_s = 2\pi f_o$$

# Prime Movers (1)

- Provide high-level overview of just two examples of prime-movers
  - Steam turbines
  - Gas turbines (open / combined cycle)
  - Relevant to SA
  - Note that solar thermal plants employ steam turbines

# Prime Movers – Gas Turbines (1)

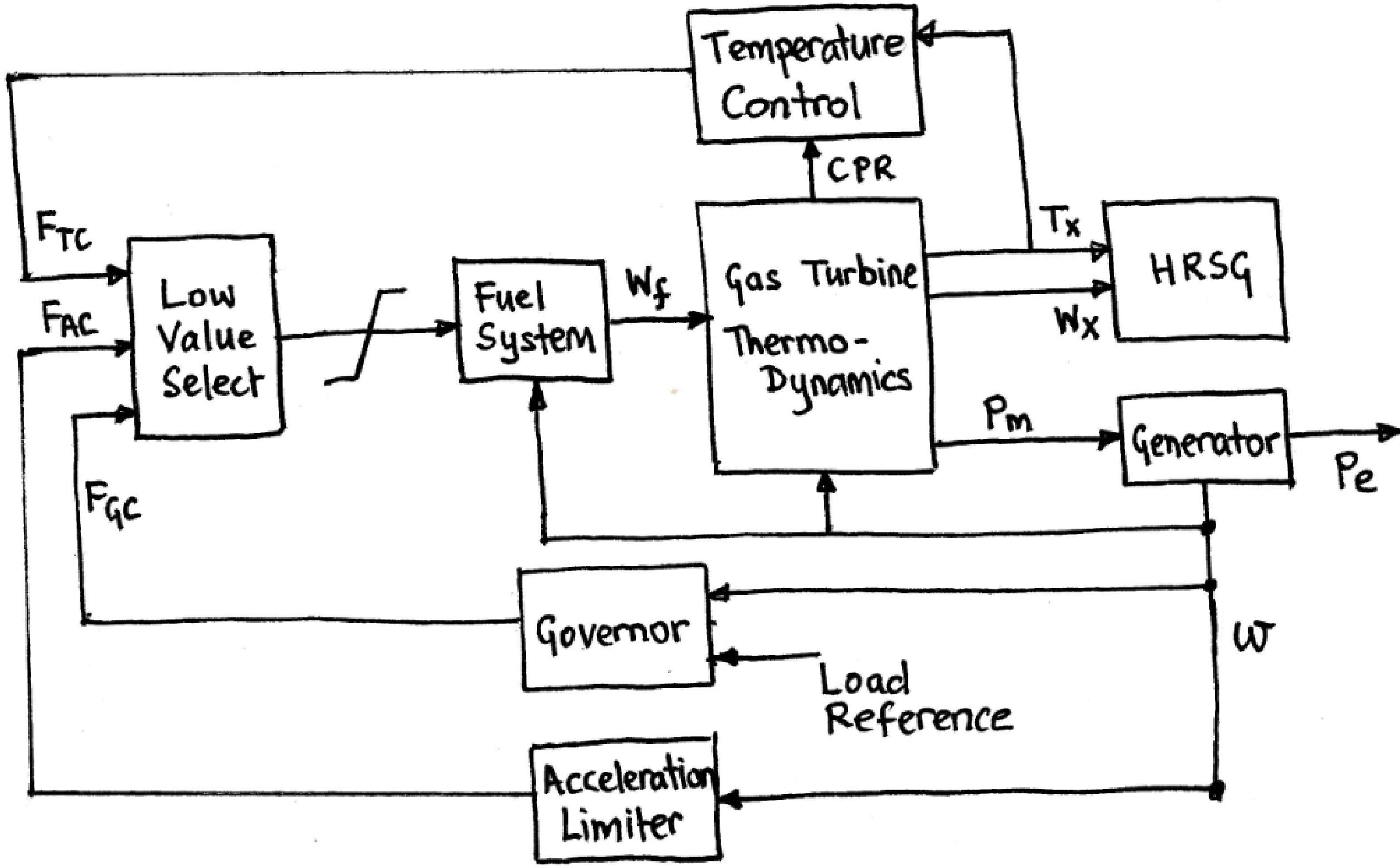
- Compressor
  - Pressurizes air drawn from atmosphere and feeds it to combustion chamber at very high speed
- Combustion System
  - Ring of fuel injectors
  - Controlled stream of fuel mixture burned at high temperatures (> 1100 deg. C)
- Turbine
  - Intricate array of alternating stationary and rotating aerofoil-section blades.
  - High temperature / high pressure gas stream expands through turbine.
  - Interaction of gas flow and turbine blades develop mechanical power to drive
    - Compressor
    - Electrical generator
- High temperatures => high efficiency
- Special materials to withstand temperatures




- Combined-cycle GTs provided with HRSG (Heat recovery steam generator)
  - Heat from GT exhaust gases recovered to produce steam to drive a steam generator.

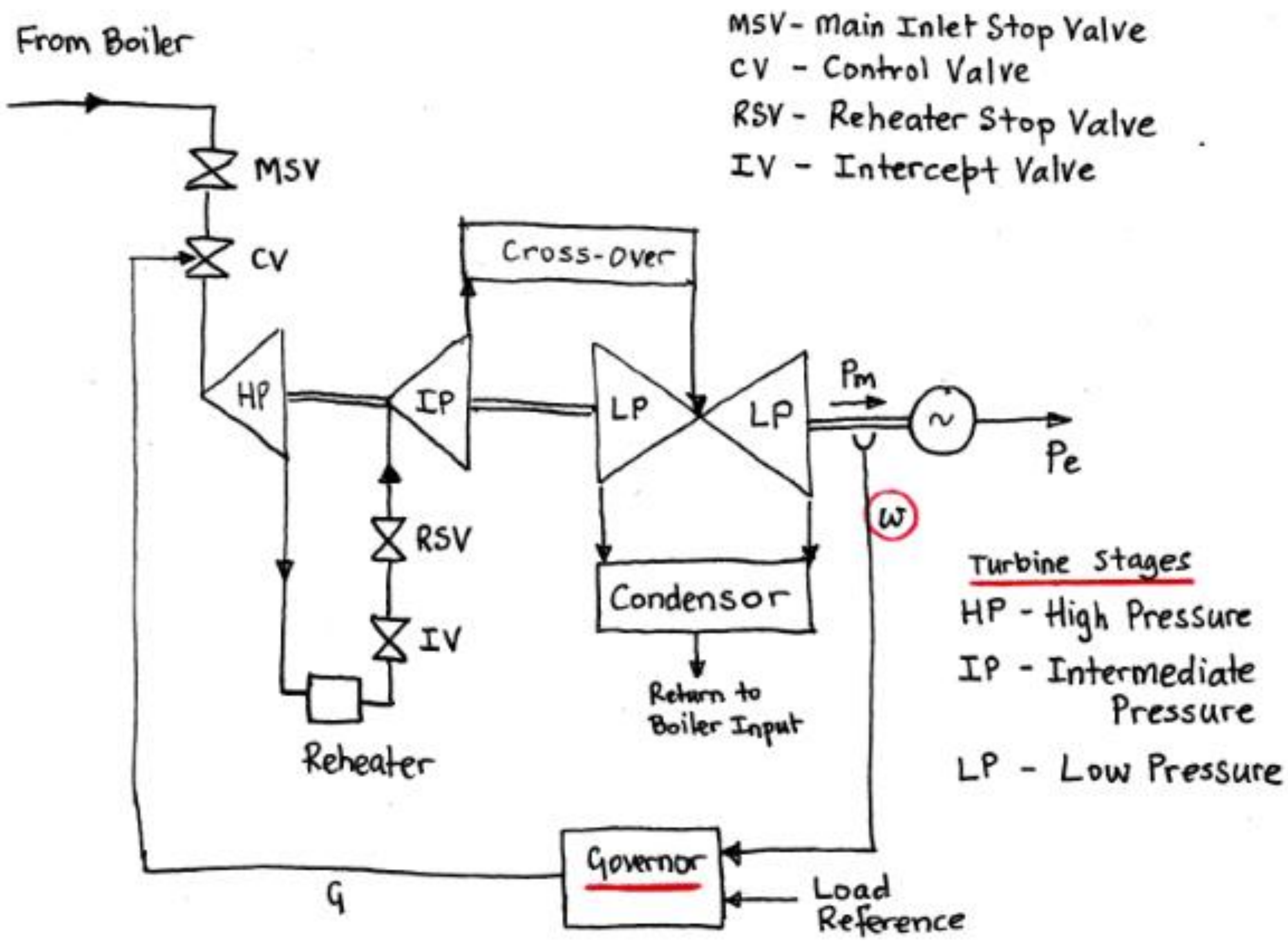
# Prime Movers – Gas Turbines (2)

- Simplified block diagram of main control elements in a gas turbine
  - Control of fuel flow is determined by one of three primary controls:
    - Temperature
    - Acceleration
    - Governor
  - The controller with the least fuel requirement has priority



# Prime Movers – Steam Turbines (1)

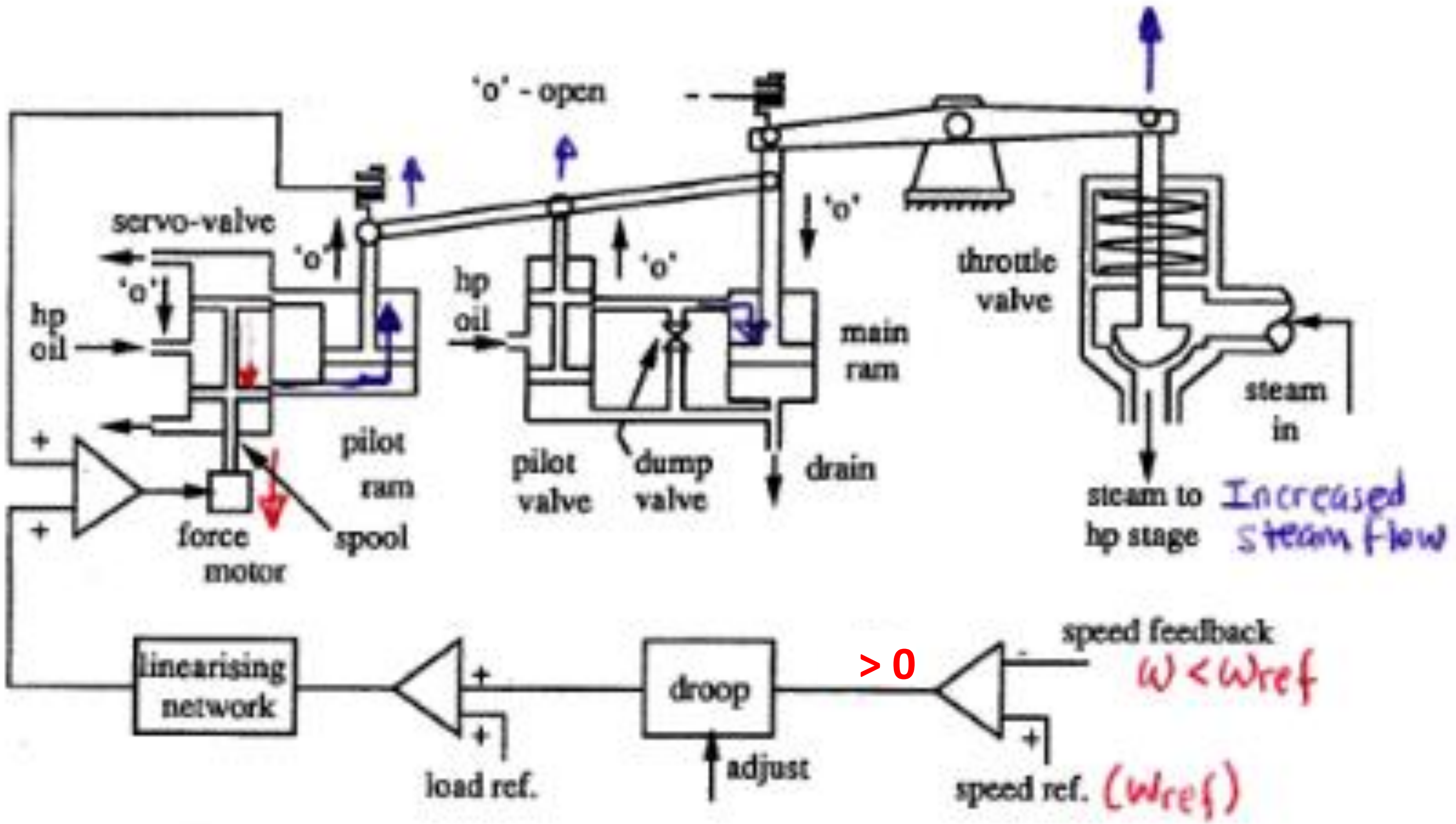
- High temperature (~ 560 deg. C) / high pressure (~ 150 bar) steam produced by boiler fed through steam chest.
  - MSV for emergency stop
  - CV controlled by governor to regulate steam flow and thus mechanical power
- Steam supplied to HP turbine stage.
  - Following expansion steam returned to boiler for reheating before being fed to IP
- Large volumes of steam in pipework leading to IP turbine so RSV provided to shut-off steam supply to IP in event of emergency.
  - Governor control of IV may be provided
- Exhaust steam from IP stage fed by cross-over pipe-work to one or more LP turbines.
  - Lower pressure => larger diameter pipework and turbine sections
  - Steam exhausted to condenser
- HP ~ 30% power, IP & LP ~ 70% of power




Due to large volumes of steam and extensive pipework in IP & LP sections significant delay (seconds) in response of Pm to change in G

# Example – Steam turbine governor

- Electro-hydraulic governor
- Suppose there is a fall in speed (w < wref)
- Electronic / digital processing transforms error to signal to cause the force motor to lower the spool
- HP oil admitted to lower side of the pilot ram chamber which raises the pilot piston.
- Lever action causes pilot valve to be raised
- HP oil admitted to the upper side of the main ram lowering the main piston.
- Opening of throttle valve increased in opposition to spring.
- Steam flow increased resulting in an increase in turbine power output that opposes the reduction in speed.
- Similar action occurs if there is an increase in the load reference (i.e. power output increased but not in response to speed change)




- Governor-throttle valve system time-constant typically 2-3 s for small disturbances.
- Emergency – Open dump valve to evacuate main ram and close control valve in 0.15 to 0.2 s