TSTE26 Powergrid and technology for renewable production

Lecture 8
Frequency control
and transient stability

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Outline

- Automatic Voltage Regulation
- Frequency control
- Angle & frequency
- Inertia of rotor
- Power transfer capability
- Dynamic stability
  - Faults

Electric Power Systems, A first course by Ned Mohan
- Chapter 11 Transient & Dynamic stability of power systems
- Chapter 12.3 Automatic generation control

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Simple Basic Principles

- Voltage Control – Reactive Power
  - Too low voltage add reactive power
    - Generator control (over-exited higher field current)
    - Capacitor shunts Static VAR compensators
  - Too high voltage reduce reactive power
    - Generator control (under-excited, lower field current)
    - Inductor shunts Static VAR compensators

- Frequency Control – Active Power Balance
  - If frequency drops add power generation (hydro power)
  - If frequency increases reduce power generation or stop consumption

Voltage Regulation

Voltage stabililty is important in a grid:
- Too high voltage results in magnetic saturation of transformers and motors. Electronics can break.
- Too low voltage results in slowing down asynchronous machines, diming lights etc. Synchronous machines lose peak power. Power transfer capacity in power lines reduced.

Voltage stability achieved by:
- control of magnetisation excitation of synchronous machines
- connection of inductors/capacitances (static var controllers SVC, STATCOM, etc)
- power electronics (e.g. HVDC, wind power inverters)
- syncronous compensators (synchronous machines not connected to any load or turbine).
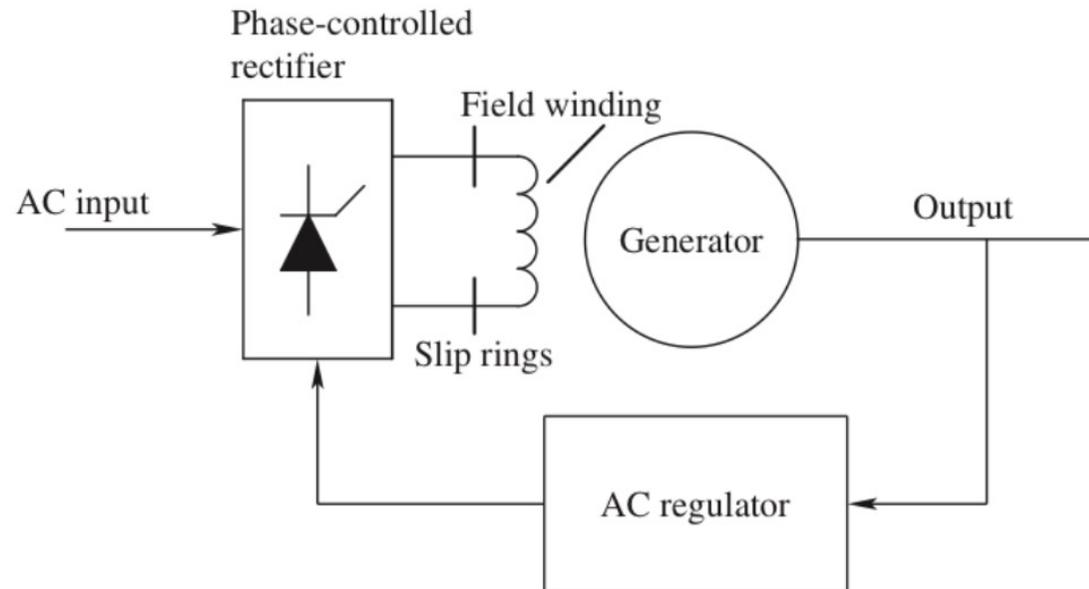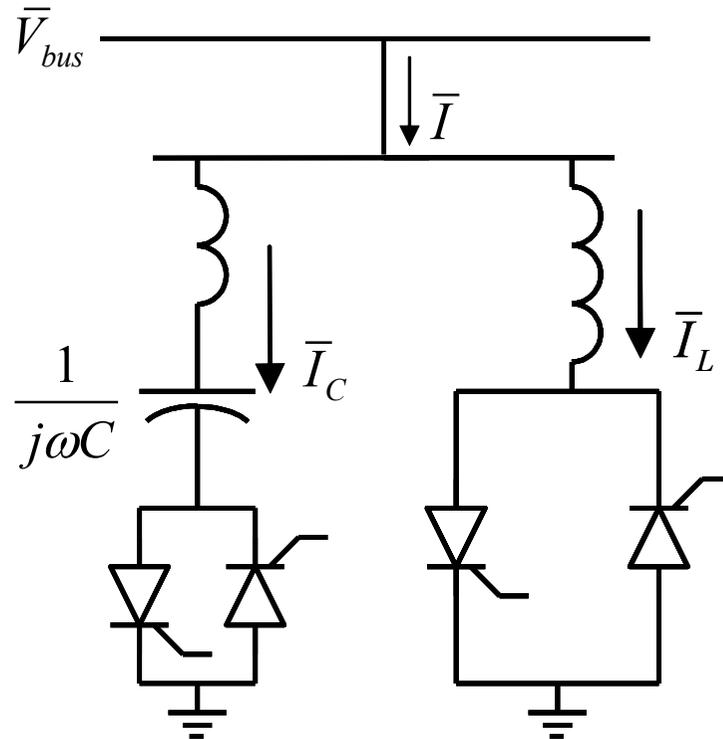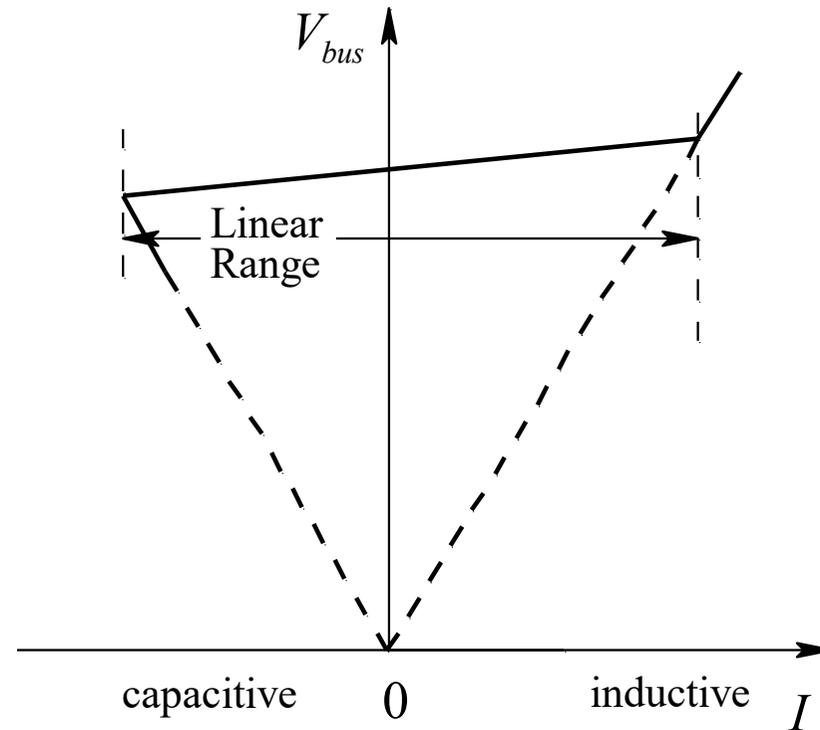
Automatic Voltage Regulation

FIGURE 12.1 Field exciter for automatic voltage regulation (AVR).

The excitation current of a synchronous machine can be automatically controlled to achieve a pre-defined voltage. The voltage can be measured at the generator or after e.g. a transformer.
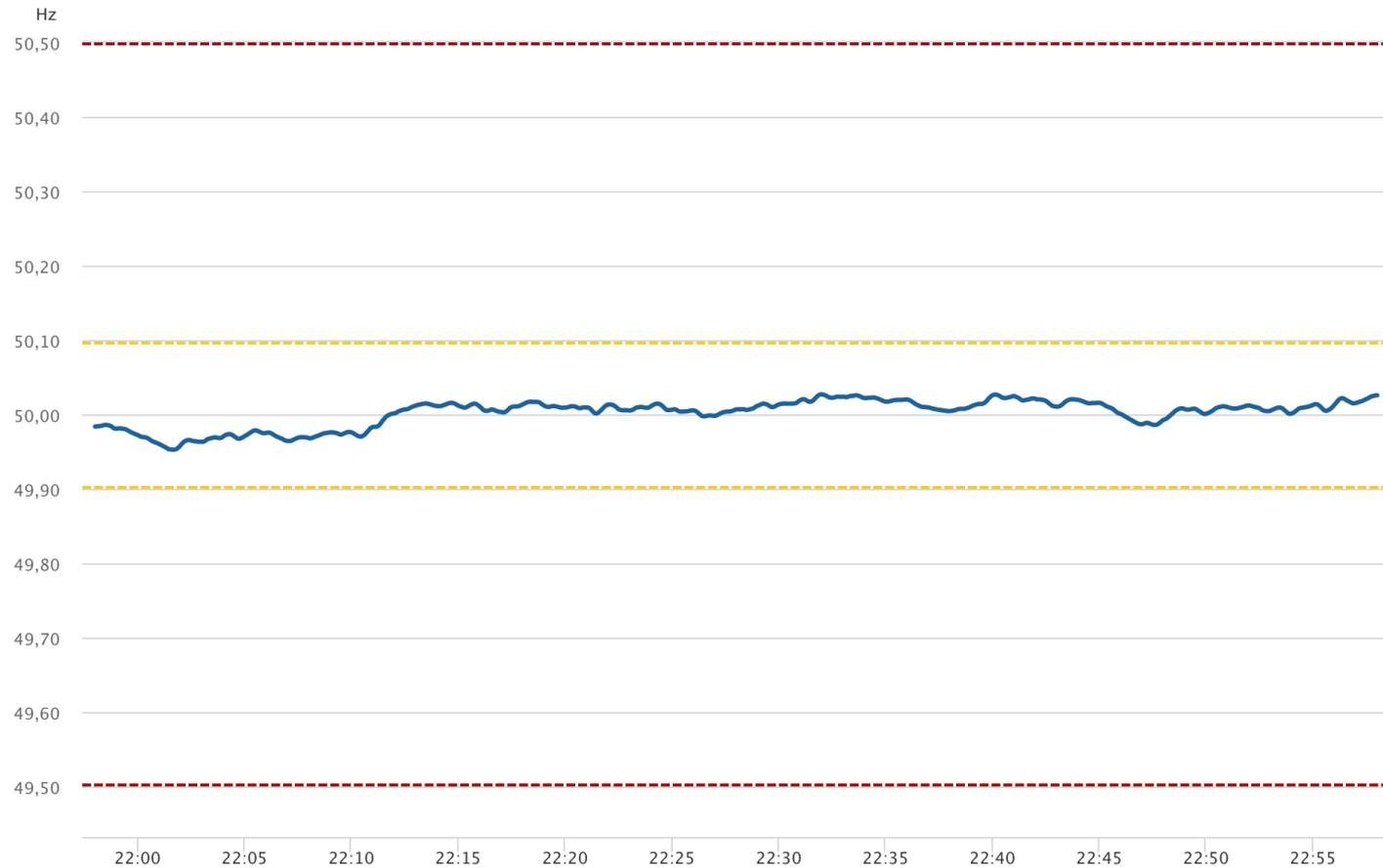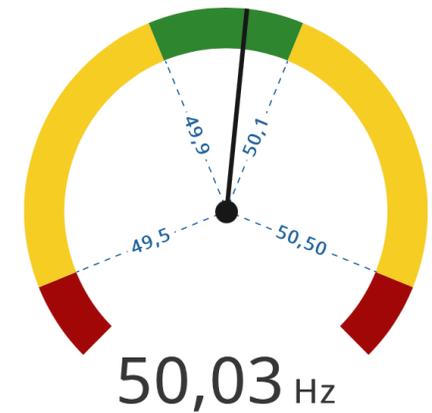
Voltage Control by TSC and TCR Combination

(a) (b)

Frequency
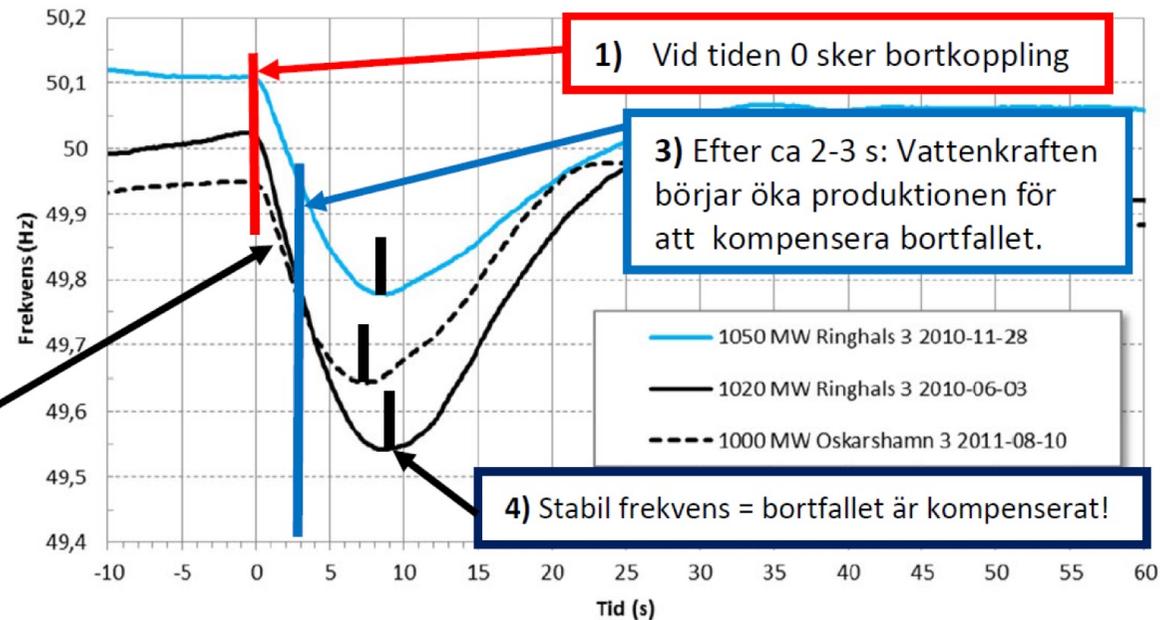
Varies between 49.9Hz and 50.1Hz under normal operation in Sweden.

Frequence stability - Rotating mass

Rotating inertia in (primarily) directly connected synchronous machines contribute with inertia that stabilizes the grid.

2) Momentan kompensation kommer från energi från roterande komponenter. Då minskar deras rotations-hastighet och frekvensen i elnätet dalar

1) Vid tiden 0 sker bortkoppling

3) Efter ca 2-3 s: Vattenkraften börjar öka produktionen för att kompensera bortfallet.

1050 MW Ringhals 3 2010-11-28
1020 MW Ringhals 3 2010-06-03
1000 MW Oskarshamn 3 2011-08-10

4) Stabil frekvens = bortfallet är kompenserat!

"Input power"+change in rotating energy=consuption

Wind power can contribute by adjusting turbine speed when grid frequence diviate from reference value.

SVK frequency reserve

Översiktlig kravbild för reserver

Uppdaterad 11 oktober 2023

| Avhjälpande åtgärd	Frekvenshållningsreserver			Frekvensåterställningsreserver	
FFR	**FCR-D upp**	**FCR-D ned**	**FCR-N**	**aFRR**	**mFRR**
Snabb frekvensreserv (Fast Frequency Reserve)	Frekvenshållningsreserv -Störning uppreglering (Upward Frequency Containment Reserve - Disturbance)	Frekvenshållningsreserv -Störning nedreglering (Downward Frequency Containment Reserve - Disturbance)	Frekvenshållningsreserv -Normaldrift (Frequency Containment Reserve - Normal)	Automatisk Frekvens-återställningsreserv (Automatic Frequency Restoration Reserve)	Manuell Frekvens-återställningsreserv (Manual Frequency Restoration Reserve)
Uppreglering	Uppreglering	Nedreglering	Symmetrisk upp- och nedreglering	Upp- och/eller nedreglering	Upp- och/eller nedreglering
Minsta budstorlek 0,1 MW	**Minsta budstorlek** 0,1 MW	**Minsta budstorlek** 0,1 MW	**Minsta budstorlek** 0,1 MW	**Minsta budstorlek** 1 MW	**Minsta budstorlek** Kapacitetsmarknad: 1 MW** Energiaktiveringsmarknad: 5MW
Aktivering Automatiskt vid frekvensförändringar vid låg nivå av rotationsenergi	**Aktivering** Automatisk linjär aktivering inom frekvensintervallet 49,90-49,50 Hz	**Aktivering** Automatisk linjär aktivering inom frekvensintervallet 50,10-50,5 Hz	**Aktivering** Automatisk linjär aktivering inom frekvensintervallet 49,90-50,10 Hz	**Aktivering** Automatiskt vid frekvensavvikelse från 50,00 Hz	**Aktivering** Manuellt på begäran av Svenska kraftnät
Aktiveringstid Tre alternativ för 100 %: - 0,7 sek (vid 49,50 Hz) - 1,0 sek (vid 49,60 Hz) - 1,3 sek (vid 49,70 Hz)	**Aktiveringstid** Aktiveringstid för FCR-D upp redovisas i dokumentet med tekniska krav för frekvens-hållningsreserver (FCR) Se krav 2 på sida 18	**Aktiveringstid** Aktiveringstid för FCR-D ned redovisas i dokumentet med tekniska krav för frekvens-hållningsreserver (FCR) Se krav 2 på sida 18	**Aktiveringstid** Aktiveringstid för FCR-N redovisas i dokumentet med tekniska krav för frekvens-hållningsreserver (FCR) Se krav 1 på sida 14 samt krav 9 på sida 28	**Aktiveringstid** 100 % inom 5 minuter	**Aktiveringstid** 100 % inom 15 min
Volymkrav för Sverige Upp till ca 100 MW	**Volymkrav för Sverige** Upp till 558 MW	**Volymkrav för Sverige** Upp till 538 MW*	**Volymkrav för Sverige** 231 MW	**Volymkrav för Sverige** Upp till 111 MW	**Volymkrav för Sverige** Kapacitetsmarknad: Upp till 200 MW Energiaktiveringsmarknad: Inga volymkrav
Uthållighet - Uthållighet: 30 sek alternativt 5 sek - Repeterbarhet: Redo för aktivering inom 15 minuter	**Uthållighet** Uthållighet: Minst 20 min	**Uthållighet** Uthållighet: Minst 20 min	**Uthållighet** Uthållighet: 1 h	**Uthållighet** Uthållighet: 1 h	**Uthållighet** Uthållighet: 1 h

Possibility for both producers and consumers to be active.

* Aktuell upphandlingsplan är lägre än volymkravet då FCR-D ned är en ny produkt sedan januari 2022. Upphandlingsplanen uppdateras kvartalsvis.
  Mer information finns på Svenska kraftnäts webbplats: www.svk.se/aktorsportalen/bidra-med-reserver/behov-av-reserver-nu-och-i-framtiden/

** Ett avropat bud på kapacitetsmarknaden innebär ett åtagande om att lämna bud på energiaktiveringsmarknaden.

För mer utförlig information om kraven, se Balansansvarsavtal och tillhörande regeldokument. De finns för nedladdning på Svenska kraftnäts webbplats: www.svk.se/aktorsportalen/balansansvarig/balansansvarsavtalet/

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The synchronous generator
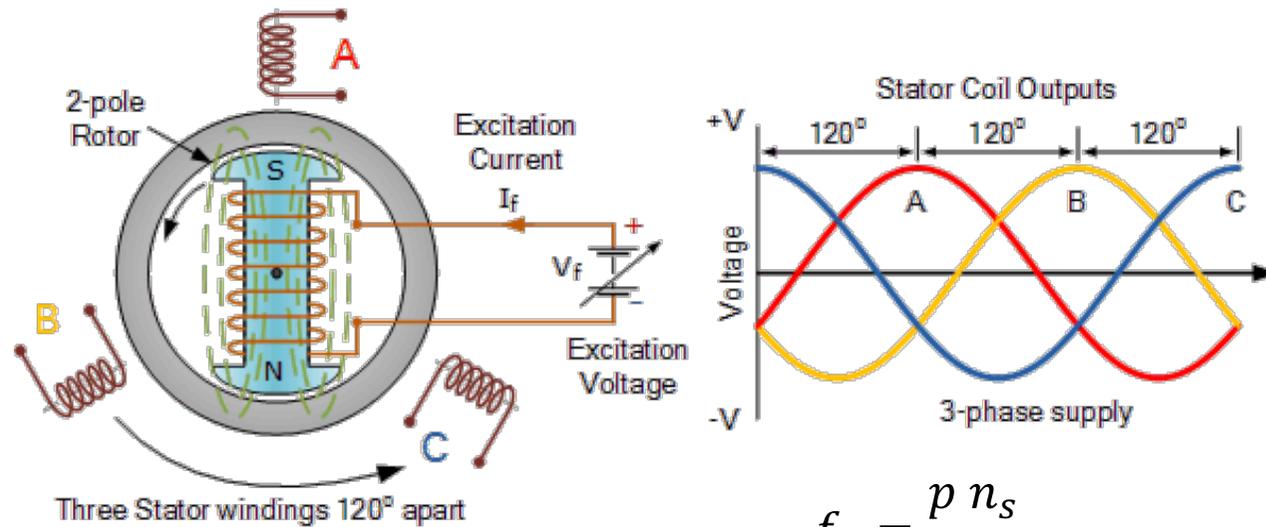
$$f_s = \frac{p}{2}\frac{n_s}{60}$$

Frequency [Hz]	50							
No of poles	2	4	6	8	12	24	36	48
Rotational speed [rpm]	3000	1500	1000	750	500	250	167	125

Rotational speed [rpm]	10							
No of poles	2	12	24	36	48	96	192	384
Frequency [Hz]	0.2	1.0	2.0	3	4	8	16	32

Rotational system, Inertia

$$J_m \frac{d^2\delta_m}{dt^2} = T_m - T_e$$
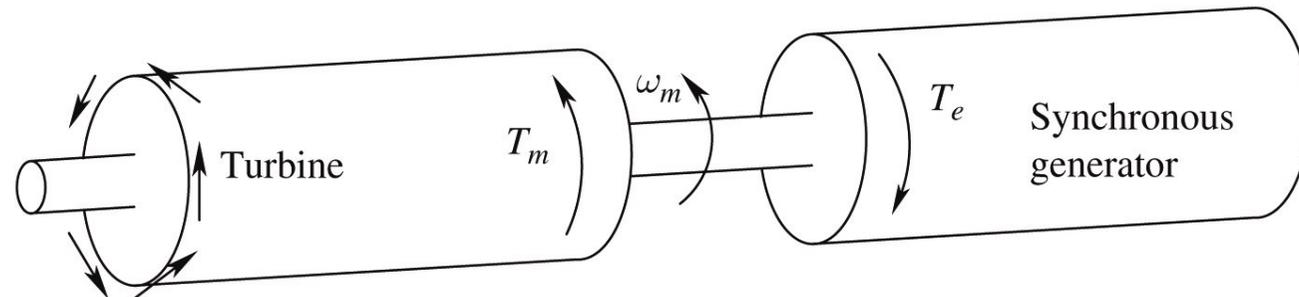
$$P_m = \omega_m T_m$$

- J_m: Total moment of inertia of rotor mass [kgm]
- T_m: Mechanical torque [Nm]
- T_e: Electric torque [Nm]

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Frequency – Power balance

- To maintain frequency stability
- Power generation must equal the consumption

Frequency control - Power balance

To maintain frequency stability, power generation must equal the consumption.
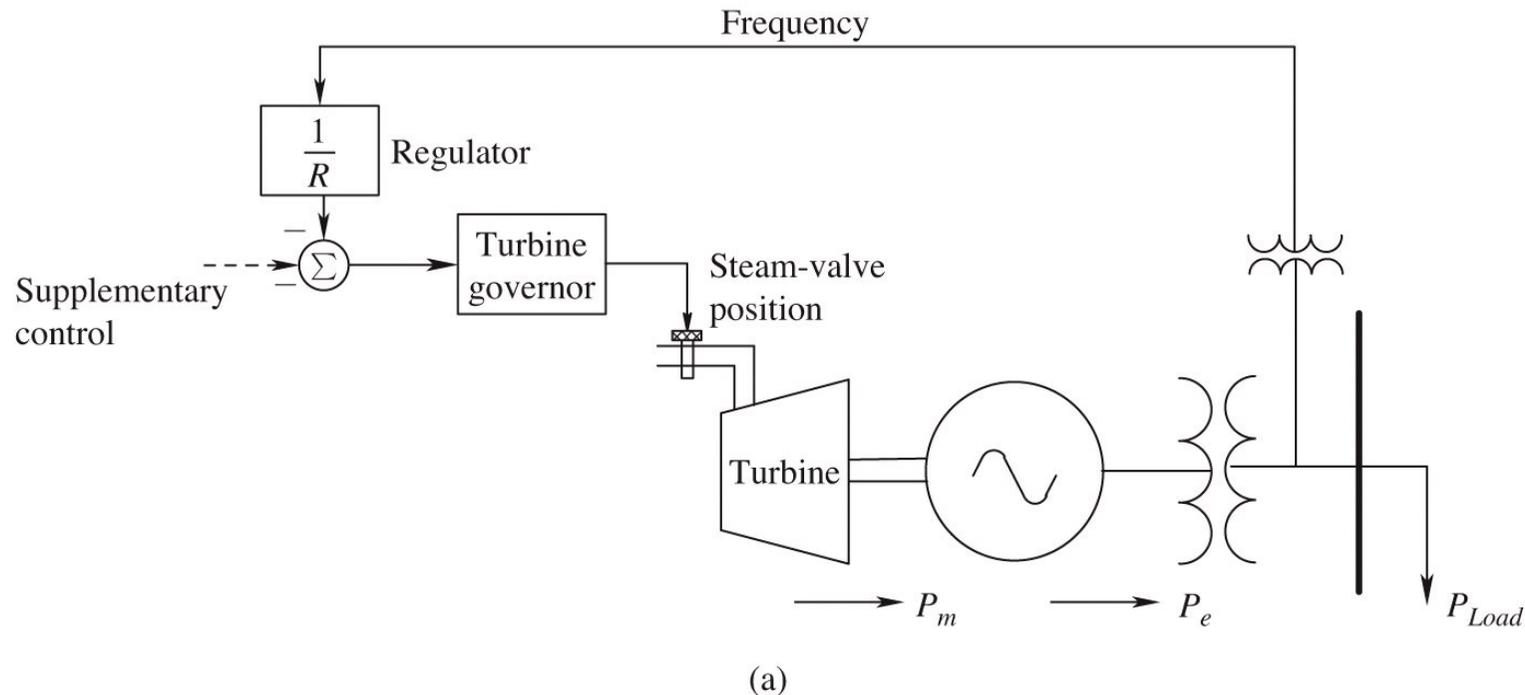
Figure 12.2a
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Controller measures frequency and controlles e.g. the vanes (amount of water) in a hydro power plant

Kaplan hydro power turbine

Guide vanes

Generator

Stator

Rotor

Turbin/
generatoraxel

Turbin

Led-
skena

Vatten-
flöde

Turbinblad

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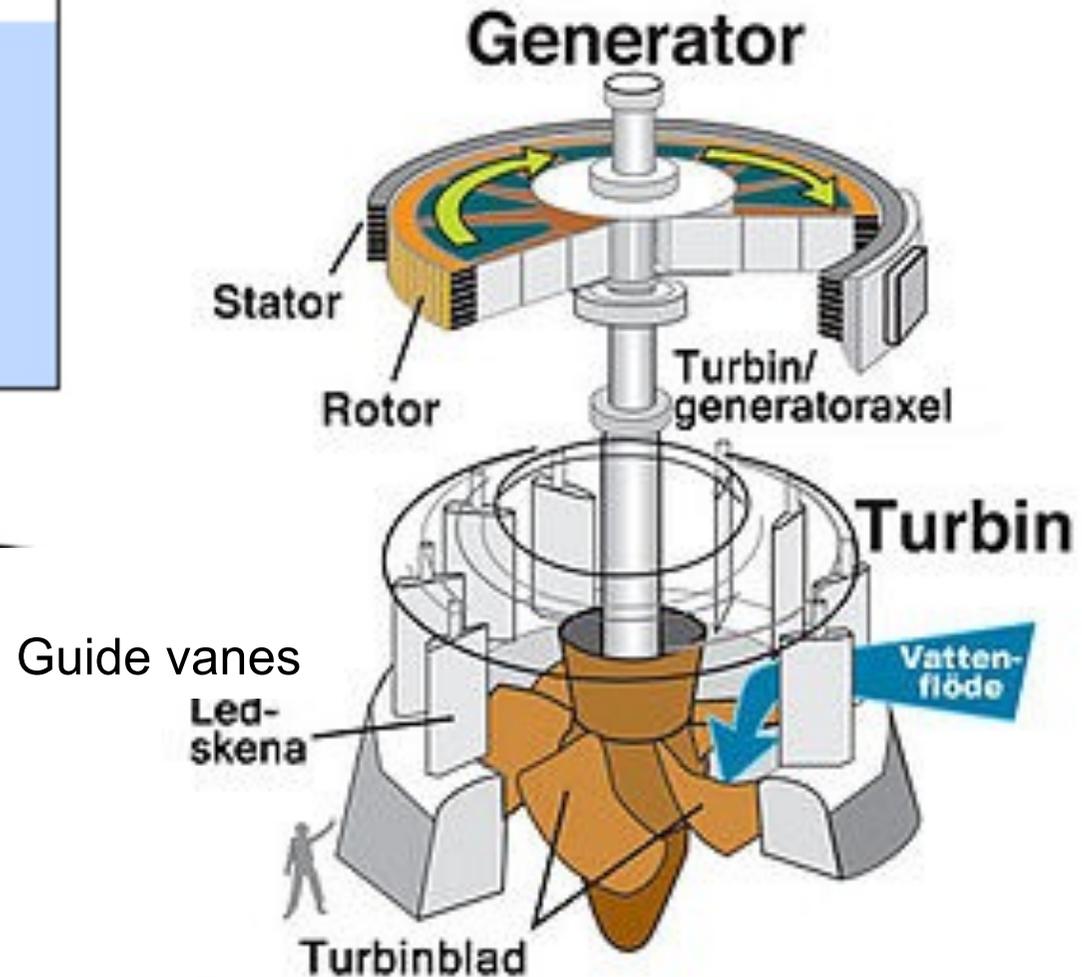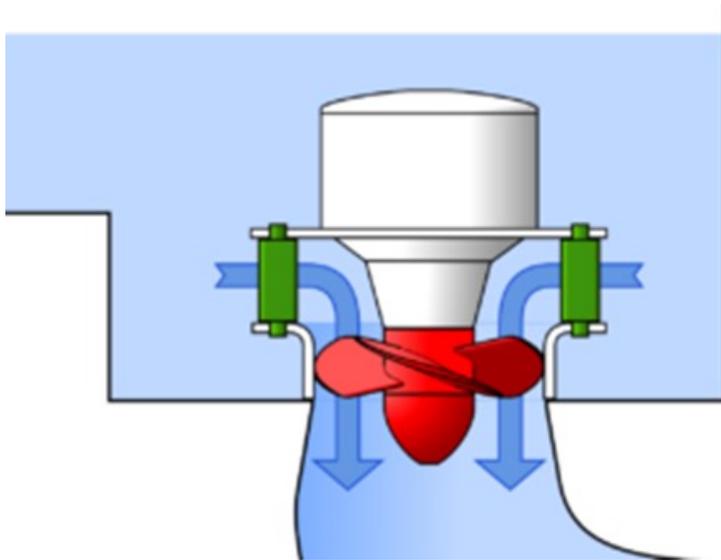
Frequency droop characteristic
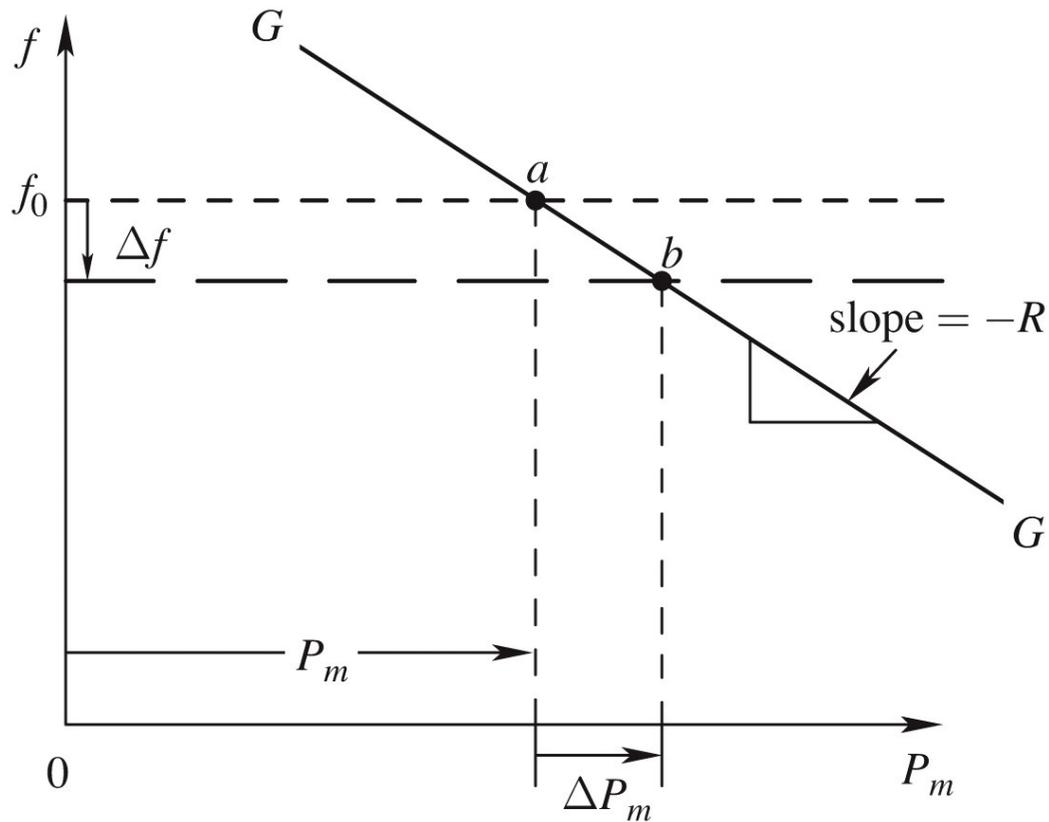
Example how the generator output is changed if the frquency deviates from 50Hz.

$$R = -\frac{\Delta f}{\Delta P} \left[\frac{Hz}{MW}\right]$$

R is called the speed regulation and has a positive value.

Does a large or small R give larger action?

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System of machines
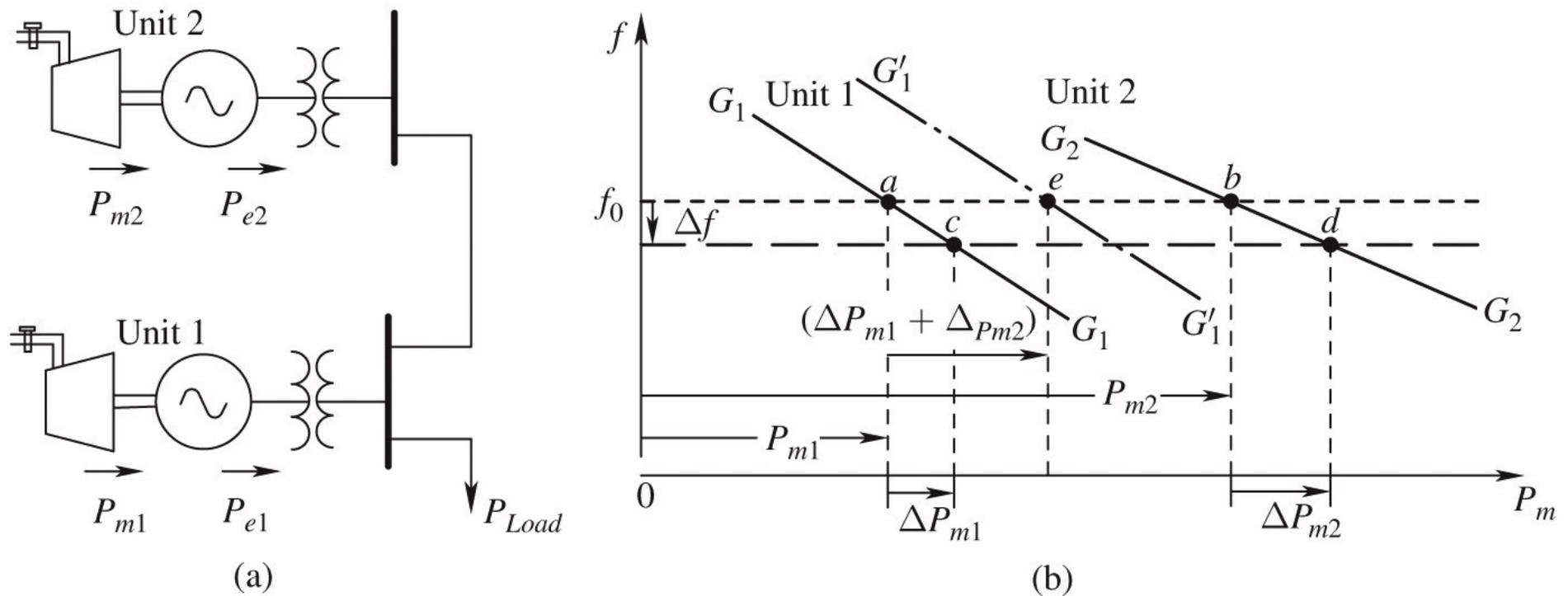
E.g. battery storage systems can also help.

All power plants can contribute

Relationship between change in load and frequency for two gereators in the system.

ΔP_{load} total system load change
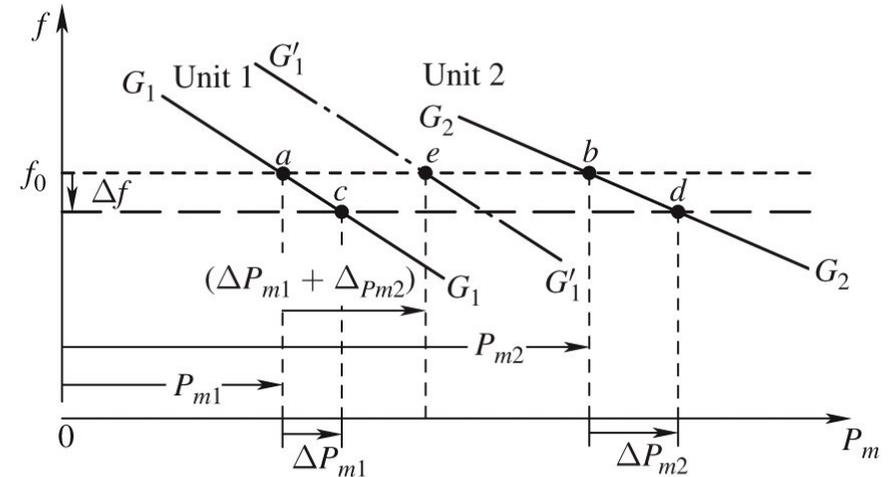
$$\Delta f(in~\%) = -R_1(in~\%) \cdot \Delta P_{m1}(in~pu) \Longrightarrow \Delta P_{m1} = -\frac{\Delta f}{R_1}$$

$$\Delta f = -R_2 \Delta P_{m2} \Longrightarrow \Delta P_{m2} = -\frac{\Delta f}{R_2}$$

$$\Delta P_{m1} + \Delta P_{m2} = \Delta P_{load}$$

$$-\frac{\Delta f}{R_1} - -\frac{\Delta f}{R_2} = \Delta P_{load}$$

$$\Delta f \left(\frac{1}{R_1} + \frac{1}{R_2} \right) = -P_{load}$$

$$\Delta f = -\frac{P_{load}}{\frac{1}{R_1} + \frac{1}{R_2}}$$

In general:

$$\Delta f = -\frac{1}{\sum \frac{1}{R_i}} \Delta P_{load}$$

The equivalent speed regulation:

$$R_{eq} = \frac{1}{\sum_i \frac{1}{R_i}}$$

What power production contributes?
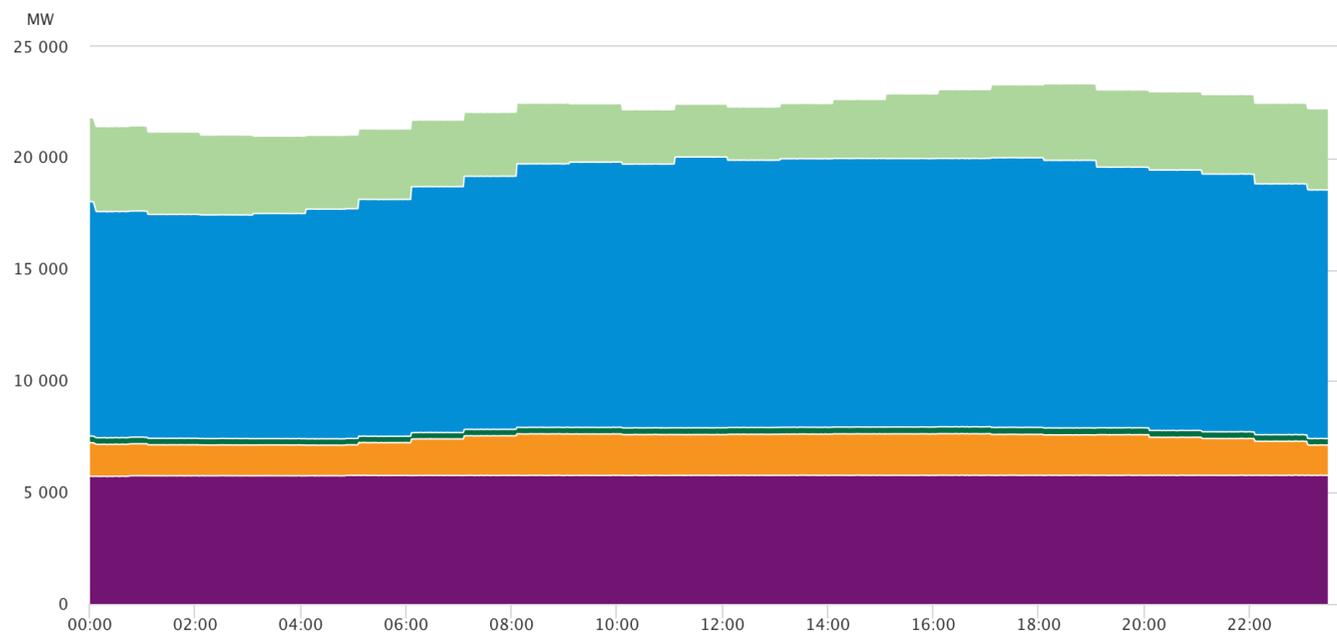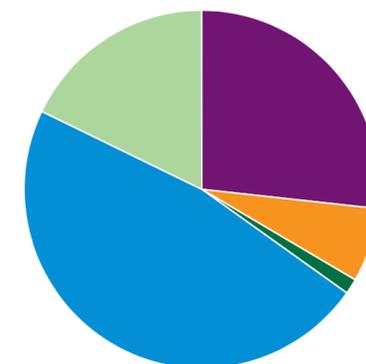
In Sweden almost only hydro contributes to frequency stability in short term.

System of machines
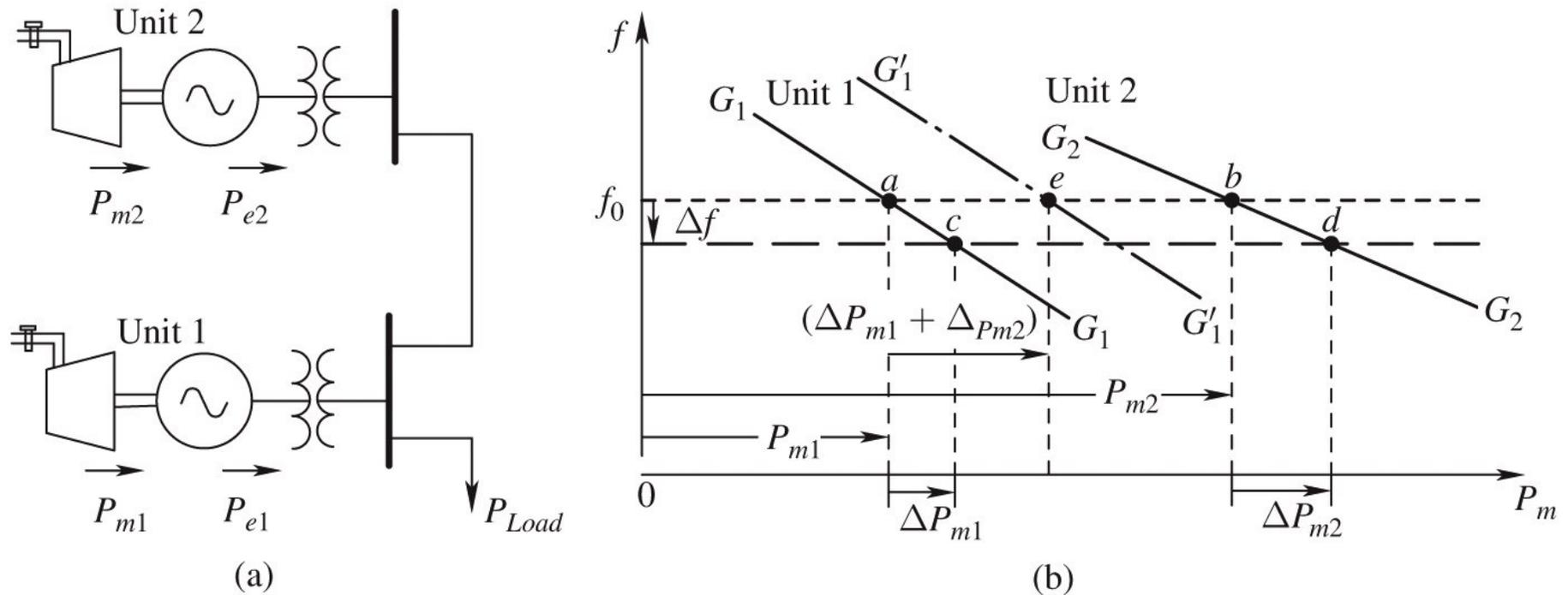
Figure 12.3

To avoid offsets in frequency due to shift in powers, some production units change their nominal power production. In this case this is illustrated by that production unit 1 increase the production at 50Hz from point a to point e. The TSO is responsible for this.

Example

Example 12.1

Consider two generators in parallel operating at 60 Hz and having widely different regulation, with $R_1 = 5\%$ and $R_2 = 16.7\%$. A load change of 0.1 pu occurs. Calculate the equivalent value of the regulation, the initial decrease in frequency, and how the change in load is shared by the two generators initially.

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = 3.85\%$$

$$\Delta f = -P_{load}R_{eq} = -0.1 \cdot 3.85\% = -0.385\% = -0.231 Hz$$

$$\Delta P_{m1} = -\frac{\Delta f}{R_1} = -\frac{-0.385}{5.0} = 0.077 pu$$

$$\Delta P_{m2} = -\frac{\Delta f}{R_2} = -\frac{-0.385}{16.7} = 0.023 pu$$

The frequecy after the load change is 59.77Hz.

Unit 1 with a smaller value of regulation picks up a greater share of the load.

Angle & Frequency

Stator voltage:

$$u_r(t) = \hat{U}\sin(\omega_s t + \delta) = \hat{U}\sin(\theta)$$

Grid frequency

$$\omega_s = 2\pi f_s$$

Voltage/rotor angle

Assume two poles: p=2

$$\theta \cdot \frac{p}{2} = \omega_s t + \delta(t)$$

Rotor speed

$$\omega_r = \frac{d\theta}{dt} = \omega_s + \frac{d\delta}{dt}$$

Rotor speed deviation

$$\omega_r - \omega_s = \frac{d\delta}{dt}$$

Rotor acceleration

$$\frac{d}{dt}(\omega_r - \omega_s) = \frac{d^2\delta}{dt^2}$$

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H-factor (inertia factor)

$$H = \frac{\text{Stored kinetic energy at synchronous speed } [MJ]}{\text{Generator rating } [MVA]}$$

$$H_{gen} = \frac{\frac{1}{2} J_m \omega_{syn,m}^2}{S_{rated,gen}}$$

The time in s for the rotor to double its speed if unloaded at rated mechanical power is 2H. Typical values for H are 1-2 seconds for hydro generators.

H-factor (inertia factor)

$$J_m \frac{d^2 \delta_m}{dt^2} = T_m - T_e$$

Figure 11A.2
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$$H_{gen} = \frac{\frac{1}{2} J_m \omega_{syn,m}^2}{S_{rated,gen}}$$

Substituting for J_m results in

$$\frac{2H}{\omega_s} \frac{d^2 \delta}{dt^2} = P_{m,pu} - P_{e,pu}$$

$$\frac{d}{dt}\left(\frac{\omega_r - \omega_s}{\omega_s}\right) = \frac{P_{m,pu} - P_{e,pu}}{2H}$$

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Power system including dynamics

Power station connected through two parallel lines

Circuit breakers
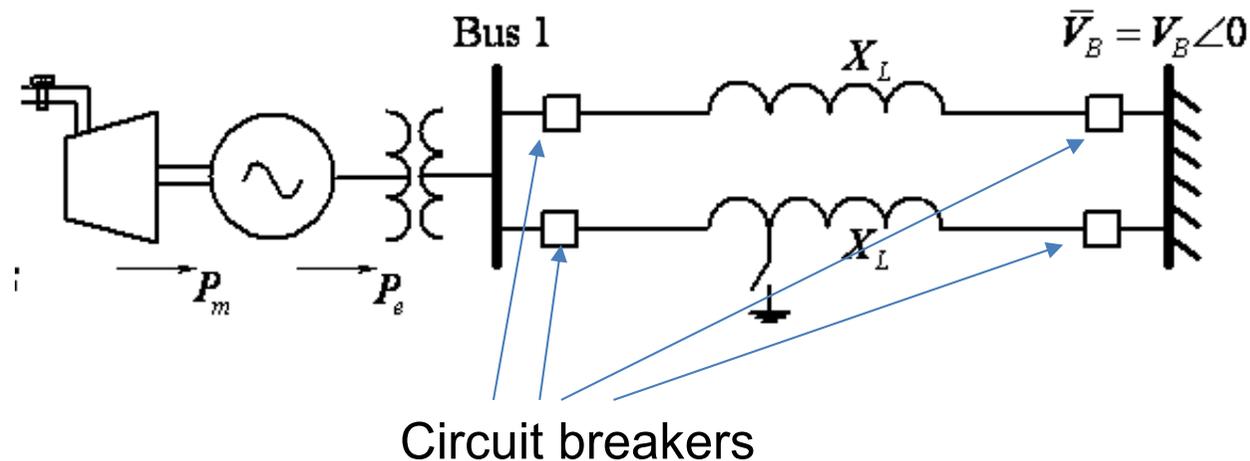
Normal operation
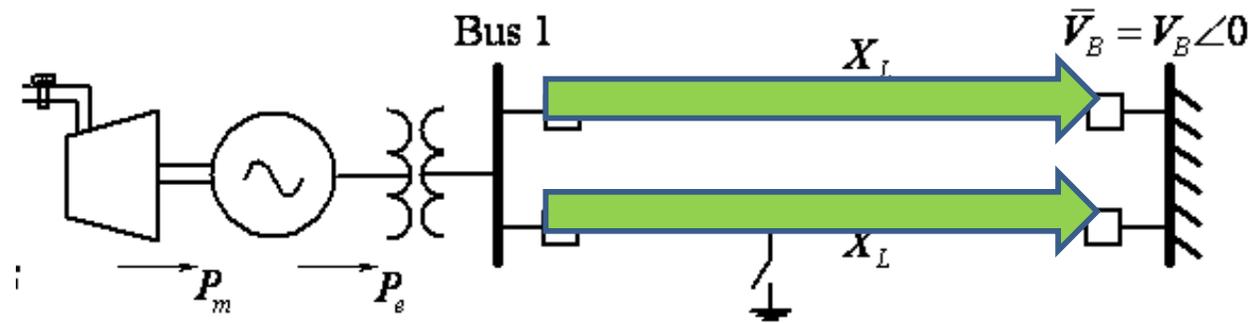
Fault on 2nd line
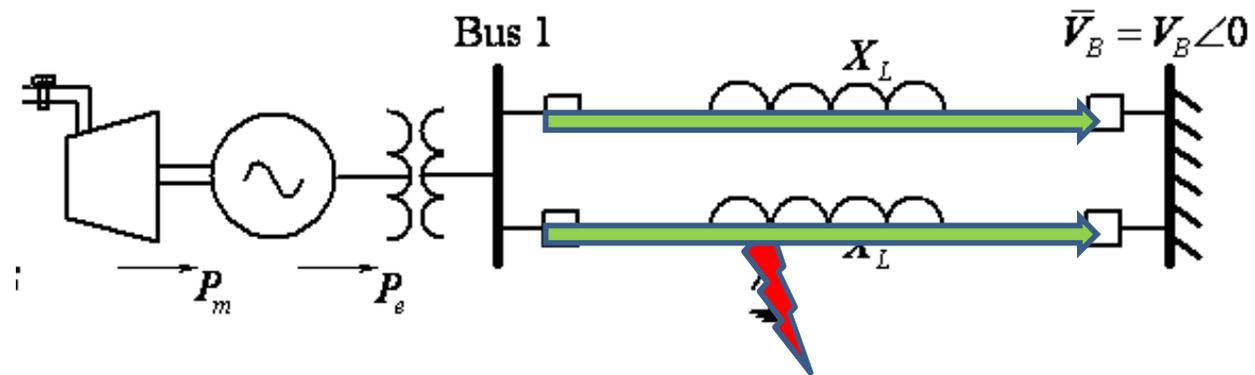
Faulty line disconnected
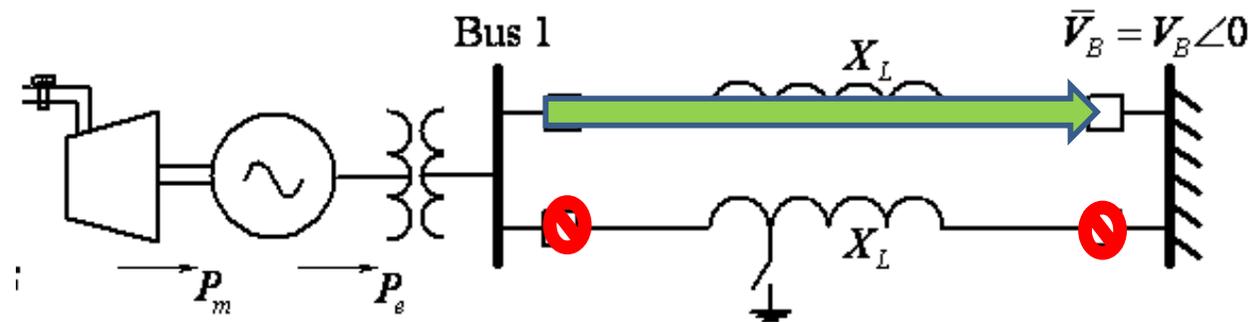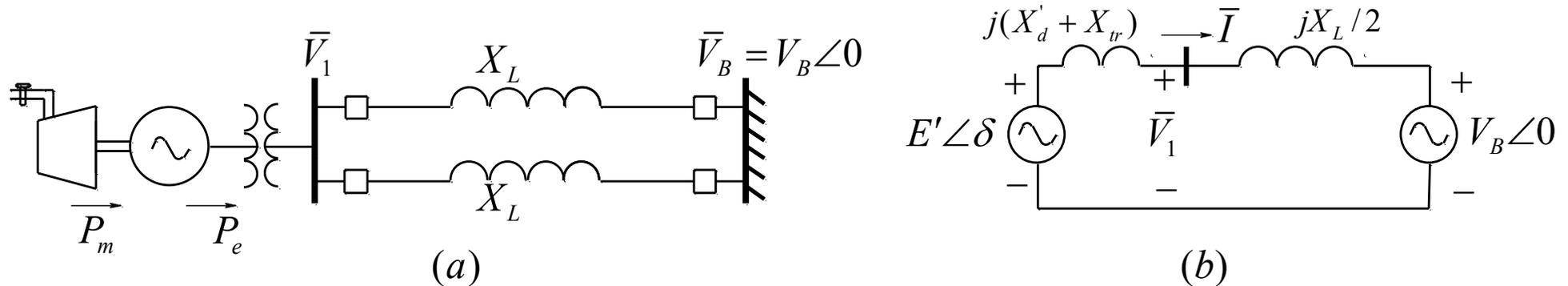
Power transfer capability

Fig. 11-1 Simple one-generator system connected to an infinite bus.

$$P_e = \frac{E'V_B}{X_{T1}} \sin \delta$$

Power versus rotor angle

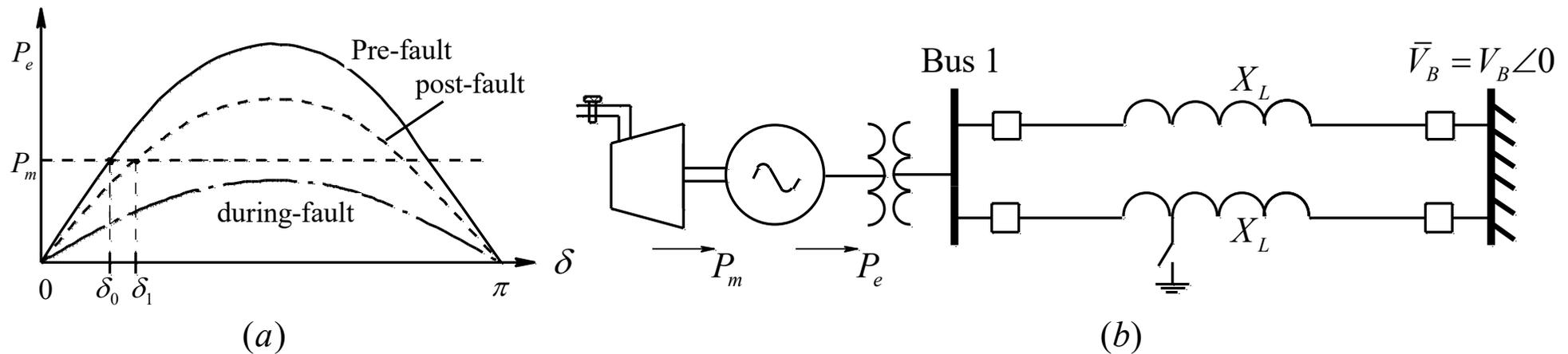$$P_e = \frac{E'V_B}{X_{T1}} \sin \delta$$

Fig. 11-2 Power-angle characteristics.

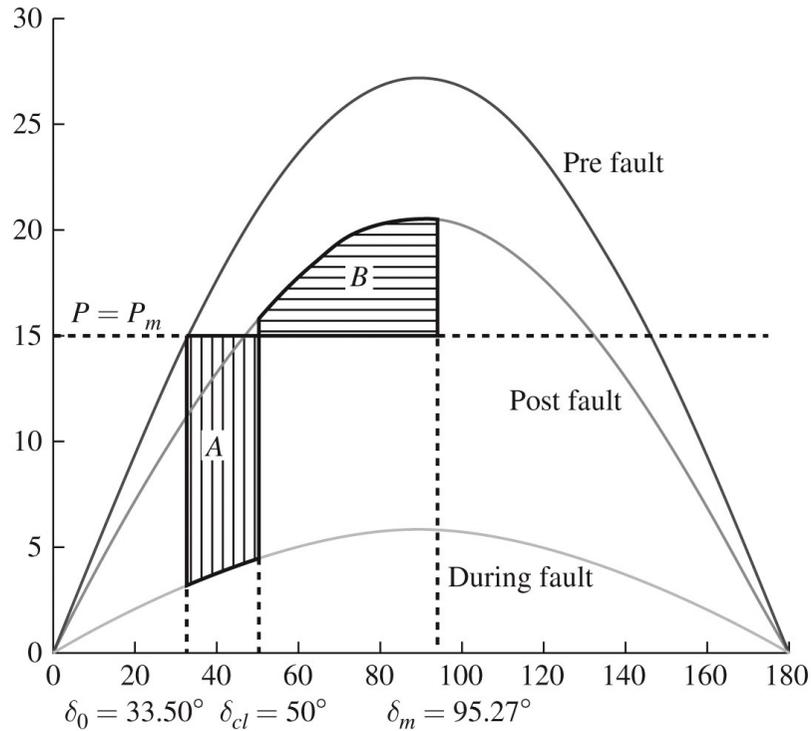# Equal area criterion

A: Rotor acceleration
B: Rotor retardation

Figure 11.7
© John Wiley & Sons, Inc. All rights reserved.

$$\frac{d}{dt}\left(\frac{\omega_r - \omega_s}{\omega_s}\right) = \frac{P_{m,pu} - P_{e,pu}}{2H}$$

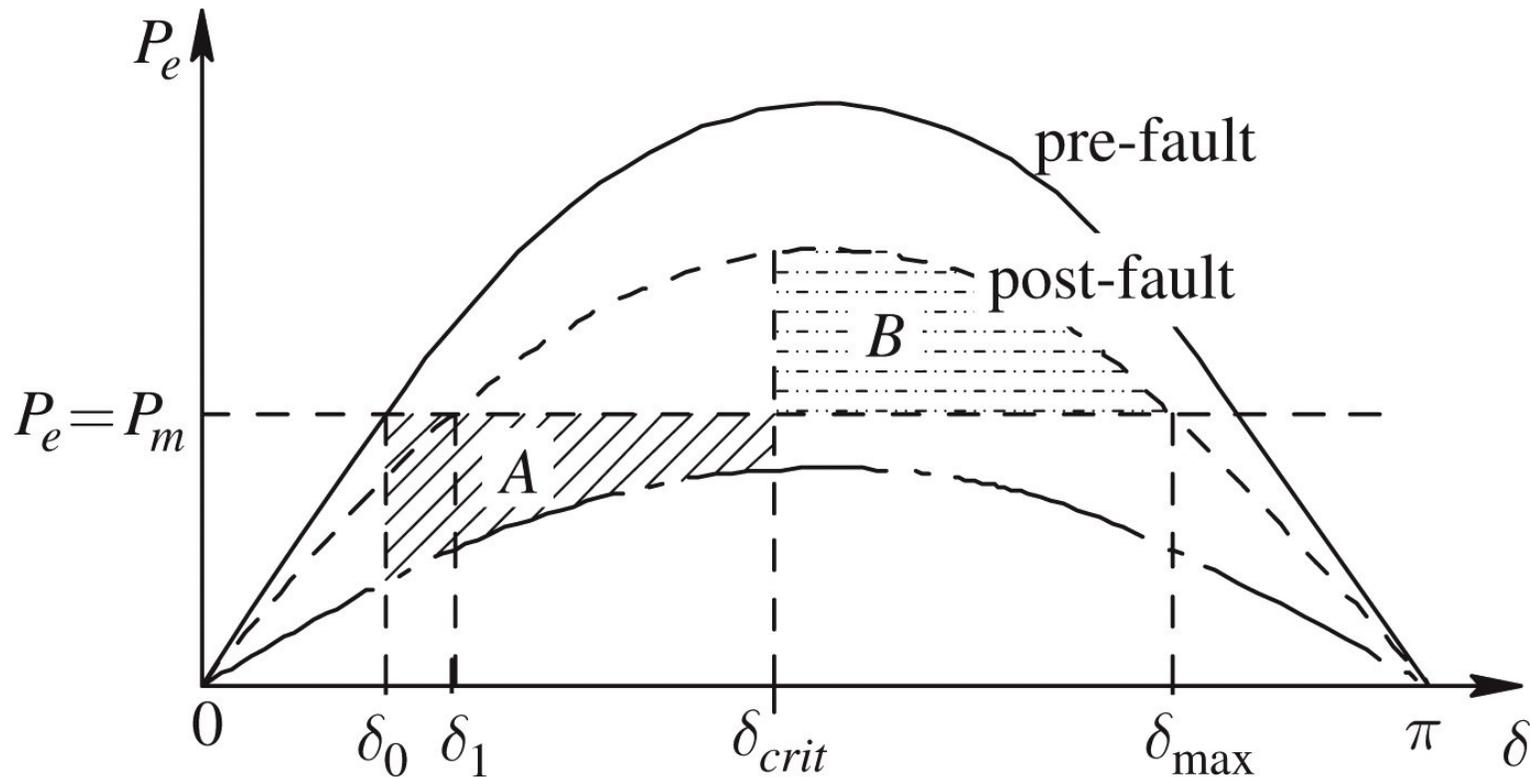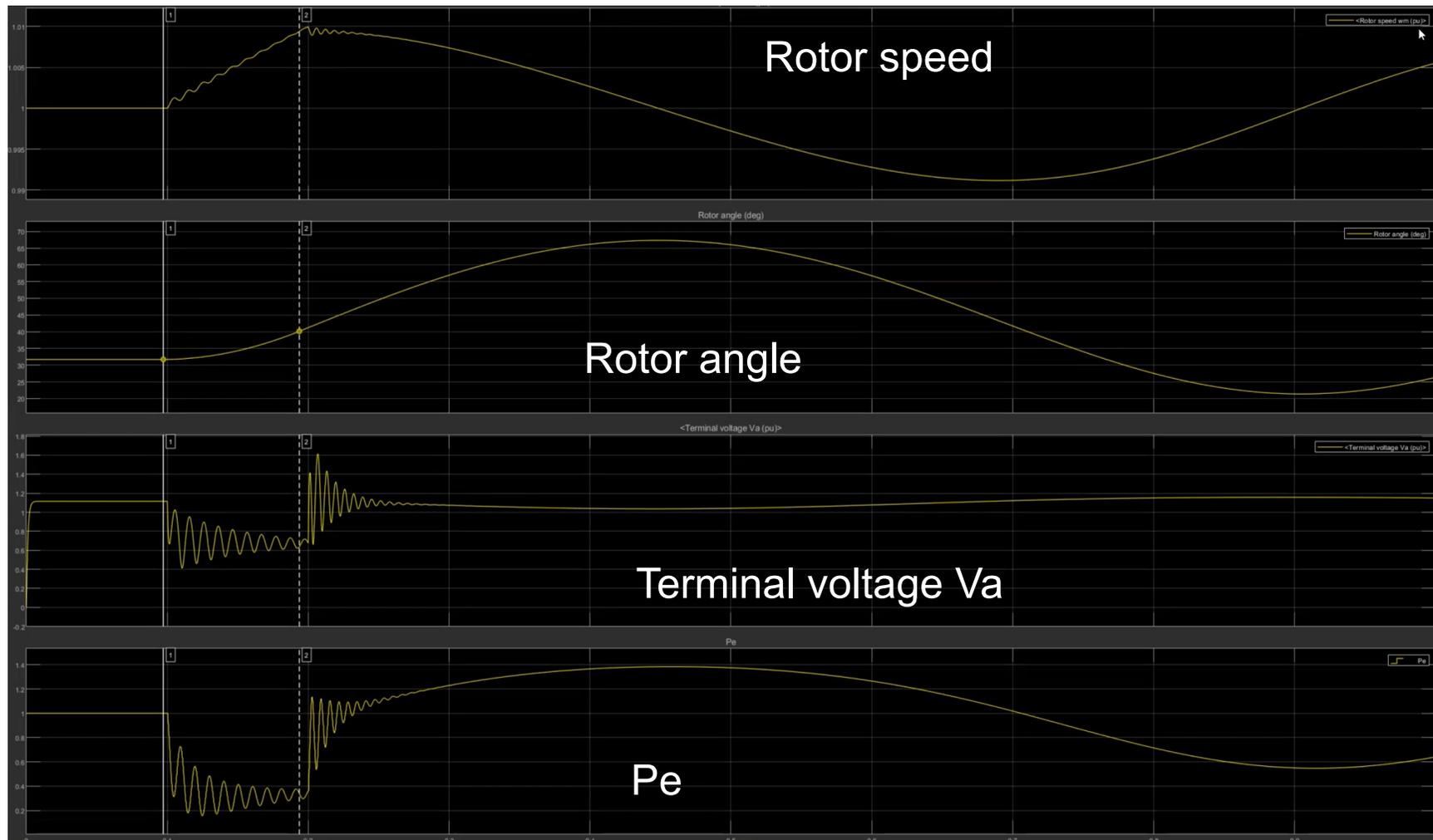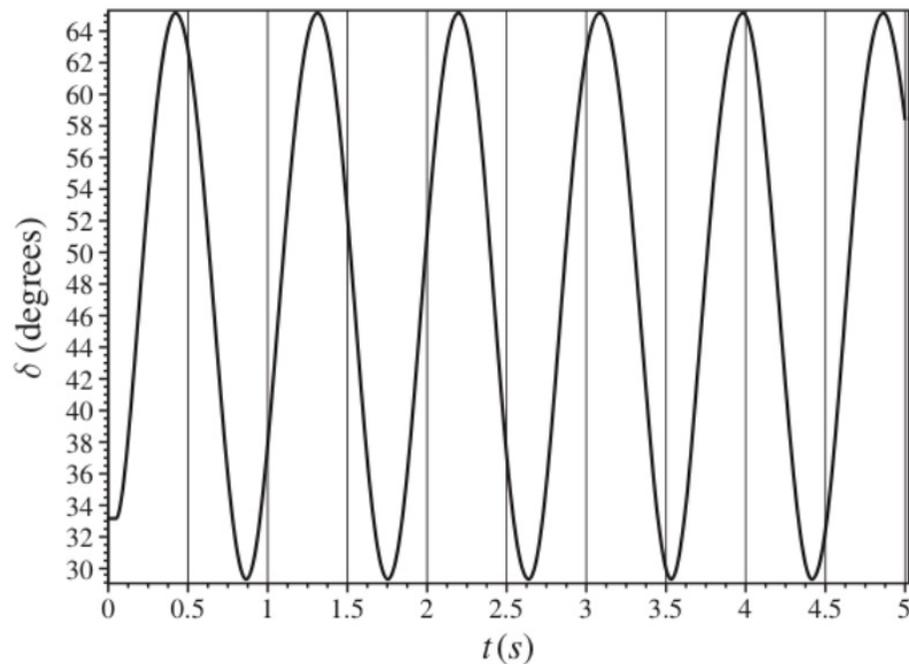LINKÖPING
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Critical fault clearing

Figure 11.6
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Example two powerlines

Rotor speed

Rotor angle

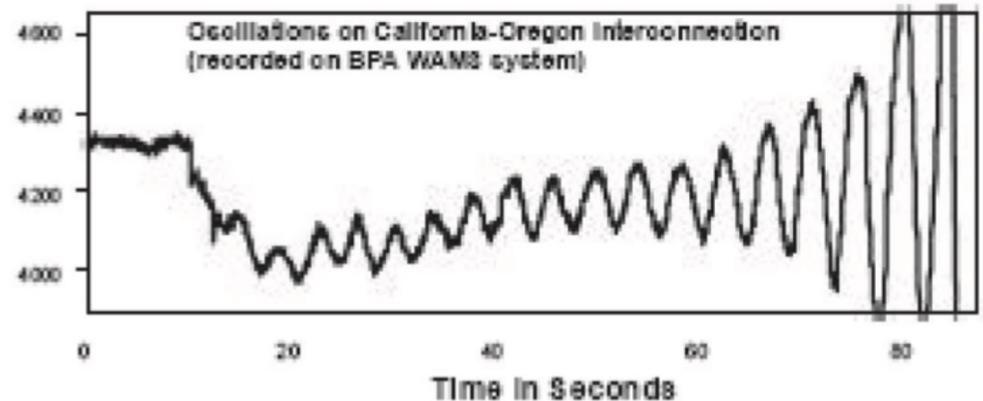Terminal voltage Va

Pe

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Oscillations

If there is no damping in the system, the rotor oscillations will continue.

Example of growing oscillations that resulted in a black out for millions of consumers in USA/Canada August 10, 1996.

Summary

- Grid frequency is determined by the balance between power production and power consumption
- Power output of generator stations are varied based on frequency feedback – Droop.
- Power change of a generator is relatively slow. In the order of seconds
- Transient frequency stability must be ensured by margins in load flow and by fast protections.

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