Dynamic Modelling and Simulation of Power Systems

WATERLOO
ENGINEERING
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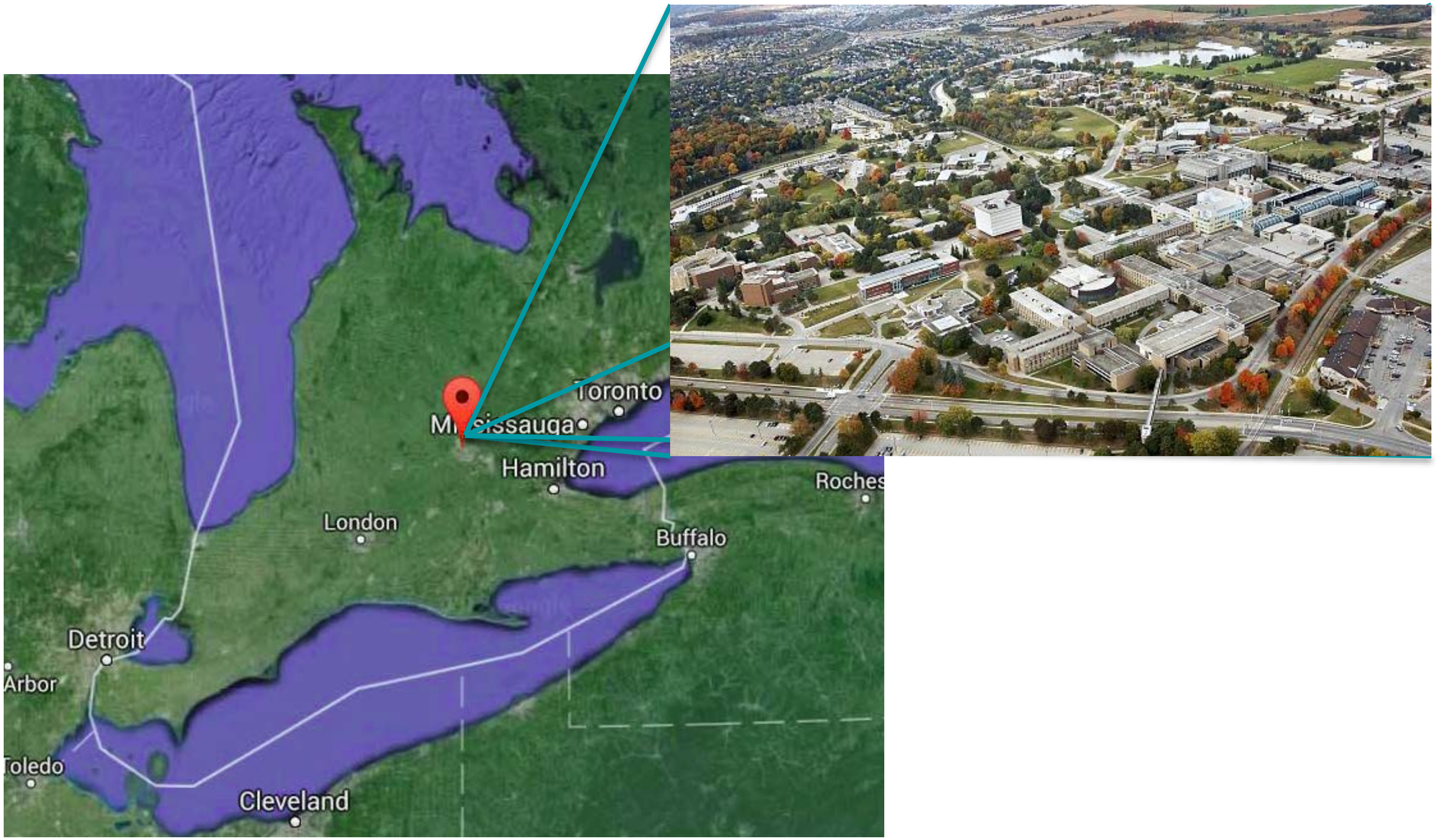
The University of Waterloo

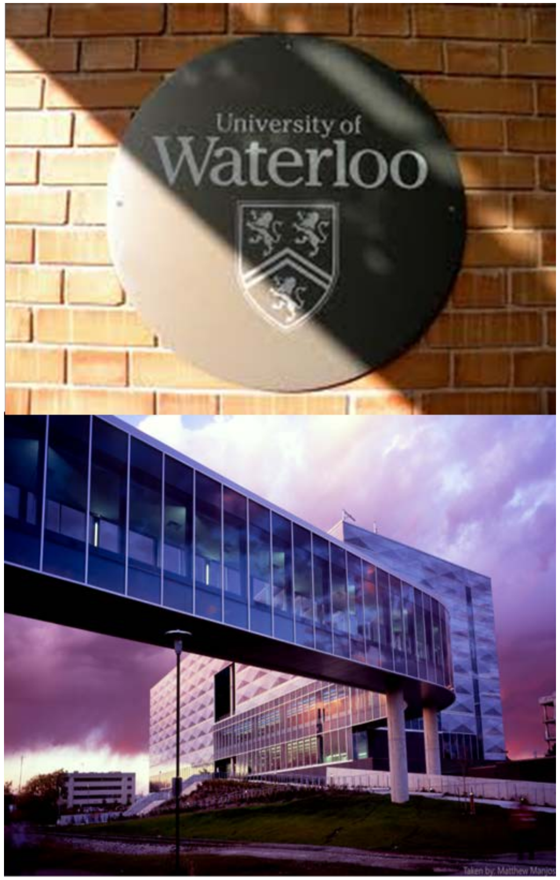


Waterloo Quick Facts

- 6 Faculties: Applied Health Sciences, Arts, Environmental Studies, Science, Math, Engineering.
- 29000 undergraduate students, 4800 graduate students (4500 international), 1100 faculty members, 2184 staff.
- Largest co-operative education program in the world:
  - 18,500/yr students enrolled
  - 5200 employers
  - Students earned $225M (2014)

Waterloo Quick Facts

- $190 M annual research
- World's largest centre for education in math & computer sciences (Waterloo and Stanford = largest source of computer science talent recruitment in North America)
- World's largest concentration of quantum information research
- Canada's largest Engineering faculty
- WatCar – largest auto research centre in Canada (125 researchers)
- Waterloo Institute for Nanotechnology (70+ researchers)
- Water Institute (125 researchers)
- Waterloo Institute for Sustainable Energy (100+ researchers)
- Top research university six years in a row (Comprehensive category) Research Infosource



Waterloo Quick Facts

- Canada's largest engineering university
- Eight departments:
  - Chemical Engineering
  - Civil and Environmental Engineering
  - Electrical and Computer Engineering
  - Management Sciences
  - Mechanical and Mechatronics Engineering
  - Systems Design Engineering
  - School of Architecture
  - Conrad Business and Entrepreneurship
- 100% co-operative study

6554	Undergraduate Students
700	International Students
1829	Graduate Students
286	Faculty
202	Staff

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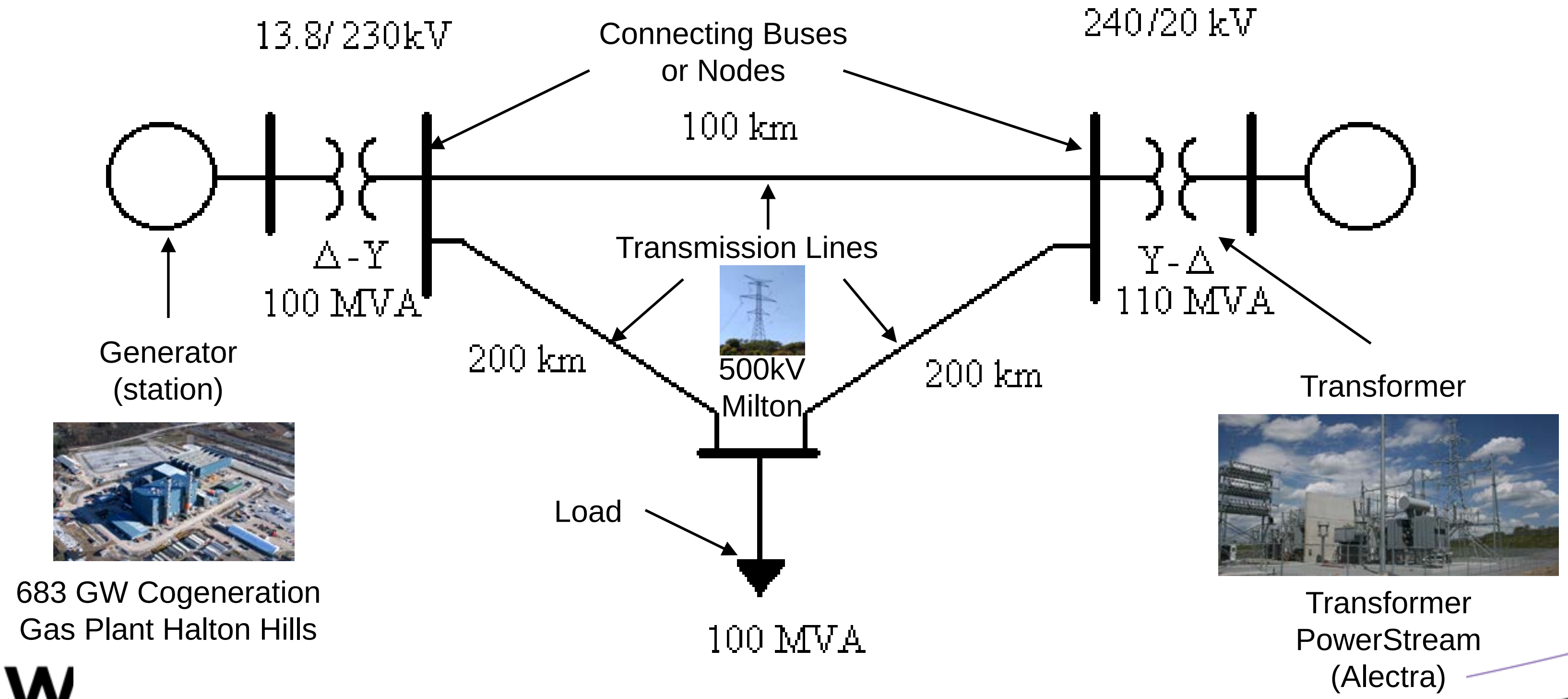
Overview

- Power systems:
  - Structure
  - Supply technologies
- Basic elements:
  - Generators
  - Transmission system:
    - Transformers
    - Transmission lines
  - Loads:
    - Inductions motors
    - Aggregate loads
  - Flexible AC Transmission Systems (FACTS)
  - Solar Photo-Voltaic Generation (SPVG)
  - Wind Generation (WG)
- Application example

Power System

- Operated by independent system operators (e.g. IESO):



13.8/ 230kV

Connecting Buses or Nodes

240/20 kV

100 km

Transmission Lines

Δ-Y 100 MVA

Y-Δ 110 MVA

Generator (station)

200 km

500kV Milton

200 km

Transformer

683 GW Cogeneration Gas Plant Halton Hills

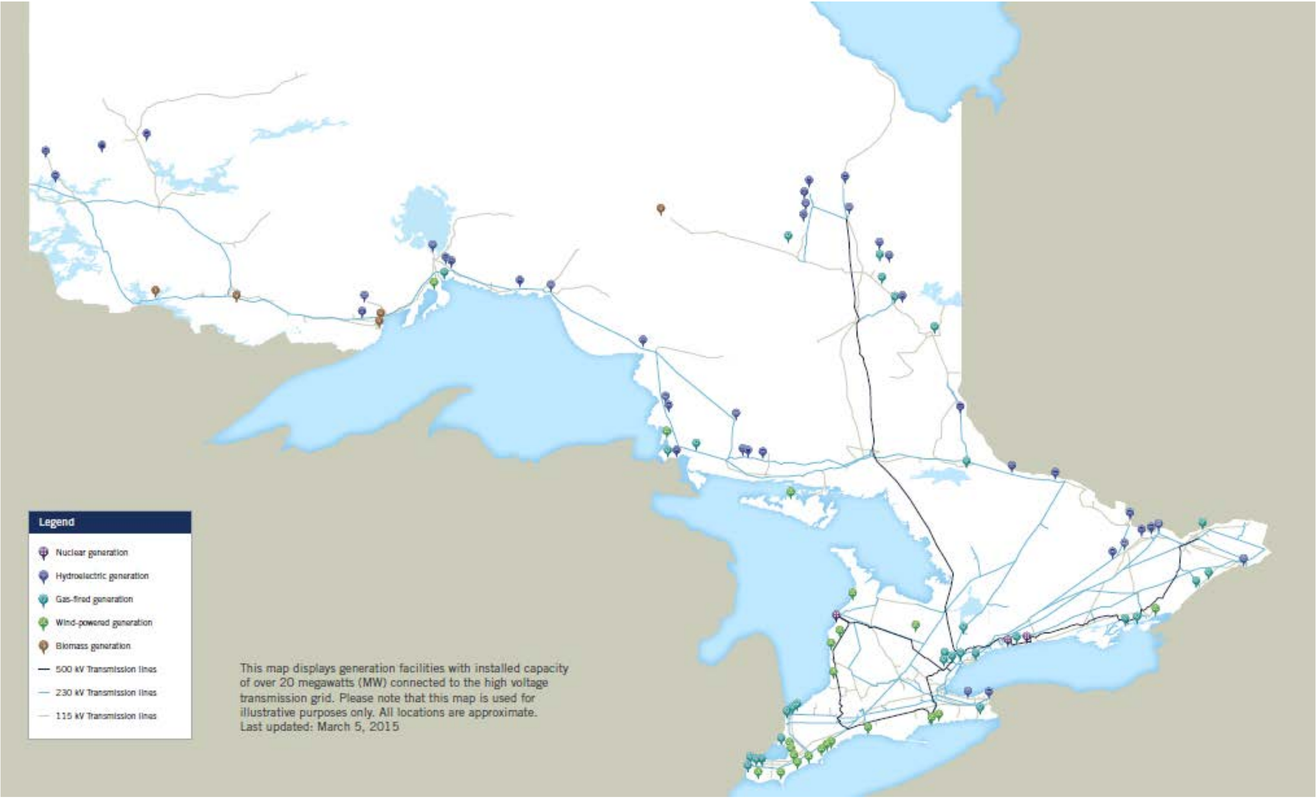
Load

100 MVA

Transformer PowerStream (Alectra)

Power System

- Ontario’s grid:



This map displays generation facilities with installed capacity of over 20 megawatts (MW) connected to the high voltage transmission grid. Please note that this map is used for illustrative purposes only. All locations are approximate.
Last updated: March 5, 2015

Power System

- Generator station:
  - Synchronous machine, exciter, primary voltage regulator and stabilizer.
  - Turbine (e.g. thermal, gas, hydro) and primary frequency controls (governor).
  - Fuelling system and controls (e.g. boiler, reservoir, valves)
  - Owned and run by generation companies or GENCOS (e.g. OPG).

Power System

- Transmission system:
  - High voltage transmission lines: overhead wires and towers, underground cables.
  - Transformers: step-up or step-down voltage levels to reduce transmission losses.
  - Switching stations (buses/nodes): connections, breakers, protections, etc.
  - Owned and maintained by transmission companies or TRANSCOS (e.g. Hydro One).

Power System

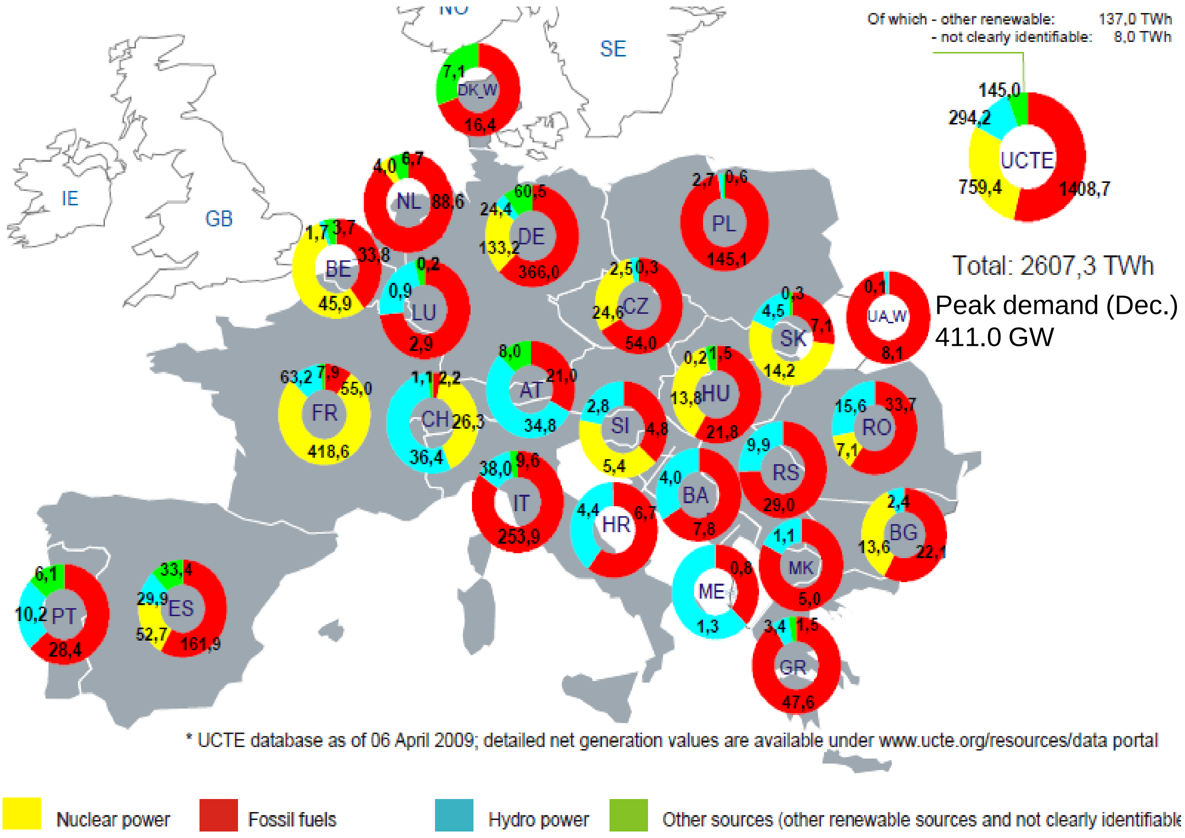
- Loads:
  - Large industrial customers and distribution networks.
  - Represent aggregate models of the distribution grid, including motors, lighting, heating, feeders, etc.
  - Owned by large customers and/or local distribution companies or LDCs (e.g. Toronto Hydro)

Power System

- Renewable Energy (RE) generation:
  - Mostly wind and SPV generation:
    - Wind mostly at the transmission system level as wind farms.
    - Solar mostly at the distribution system level as rooftop and ground-mounted.
  - Wind generation more significant than SPVG at most jurisdictions, with a few exceptions where solar resources are high (e.g. Hawaii, Arizona, Australia).
  - Mostly interfaced to the system through power electronic converters.
  - Generation technologies are relatively mature but new installations, connection standards, and controls are still under development, with system impacts not yet fully understood and thus being still studied.
  - Mostly privately owned by GENCOS (wind farms) and consumers (SPVG rooftop/ground-mounted).

Supply Technologies

- Europe’s electrical energy supply and demand [UCTE/ENTSO-E]:

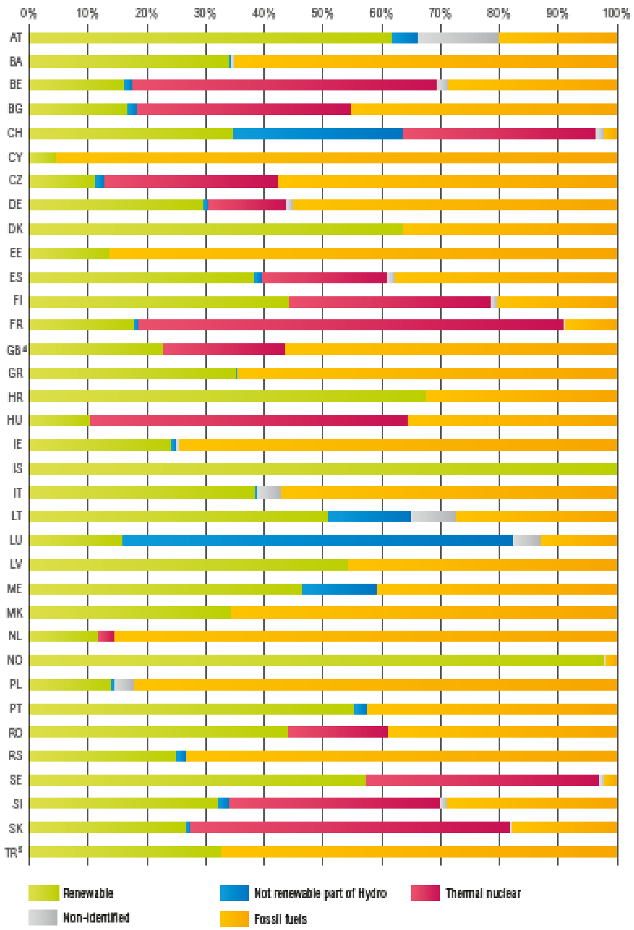


Total: 2607,3 TWh

Peak demand (Dec.) 411.0 GW

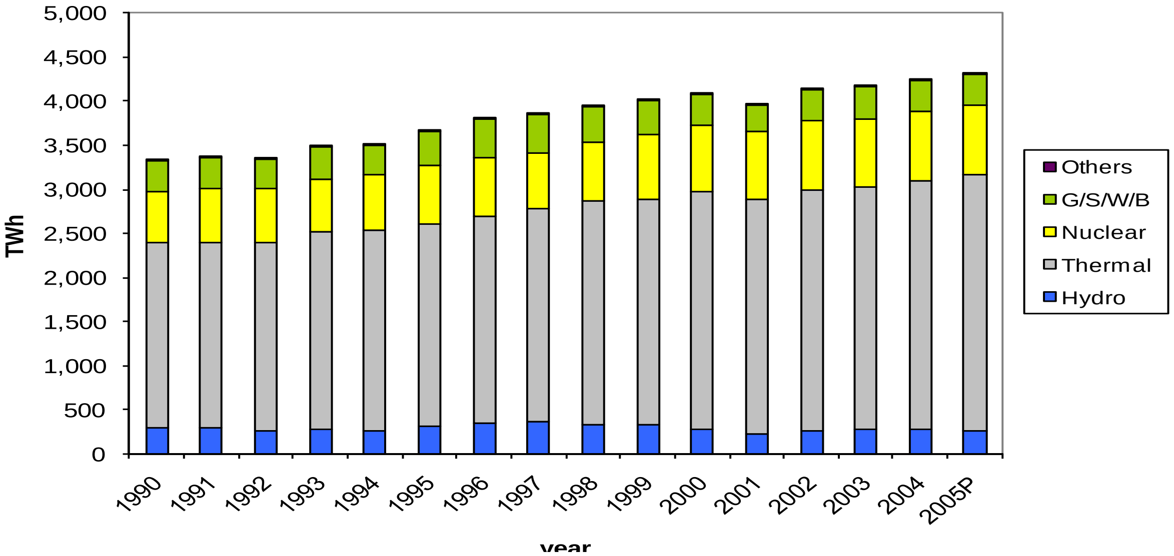
* UCTE database as of 06 April 2009; detailed net generation values are available under www.ucte.org/resources/data portal

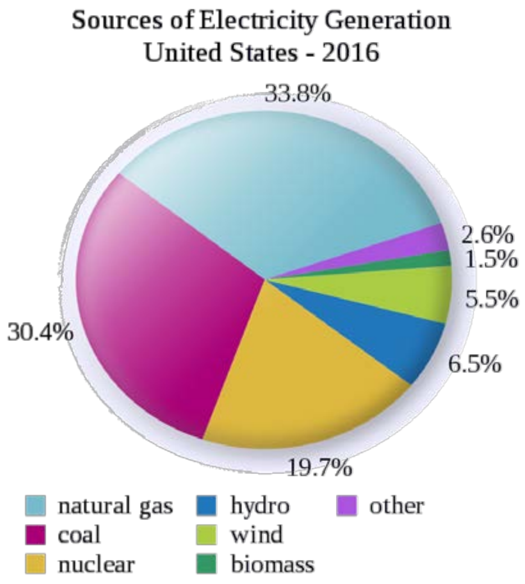
Share of energy produced of each member TSOs’ country 2016 in %⁴

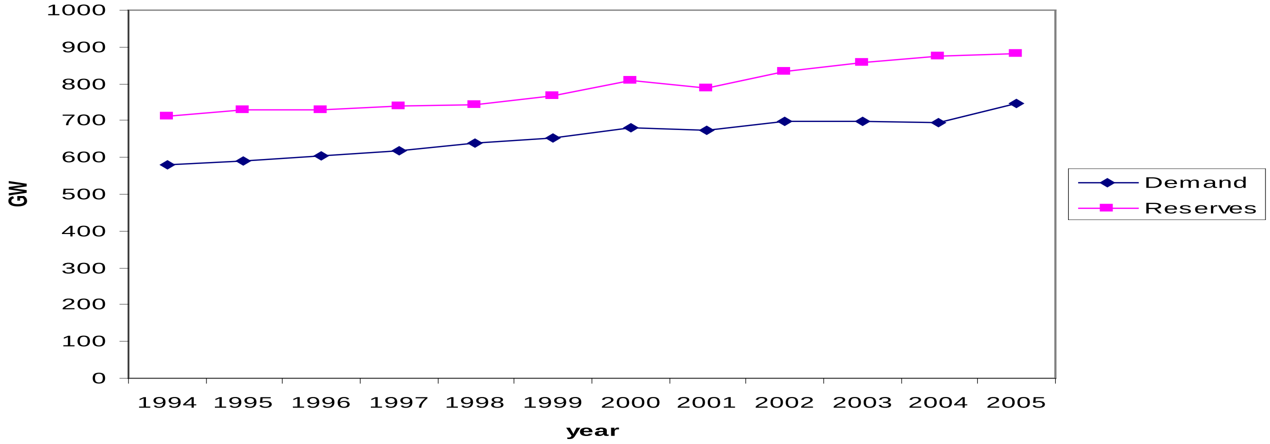


Supply Technologies

- US electricity supply and demand [US gov.]:

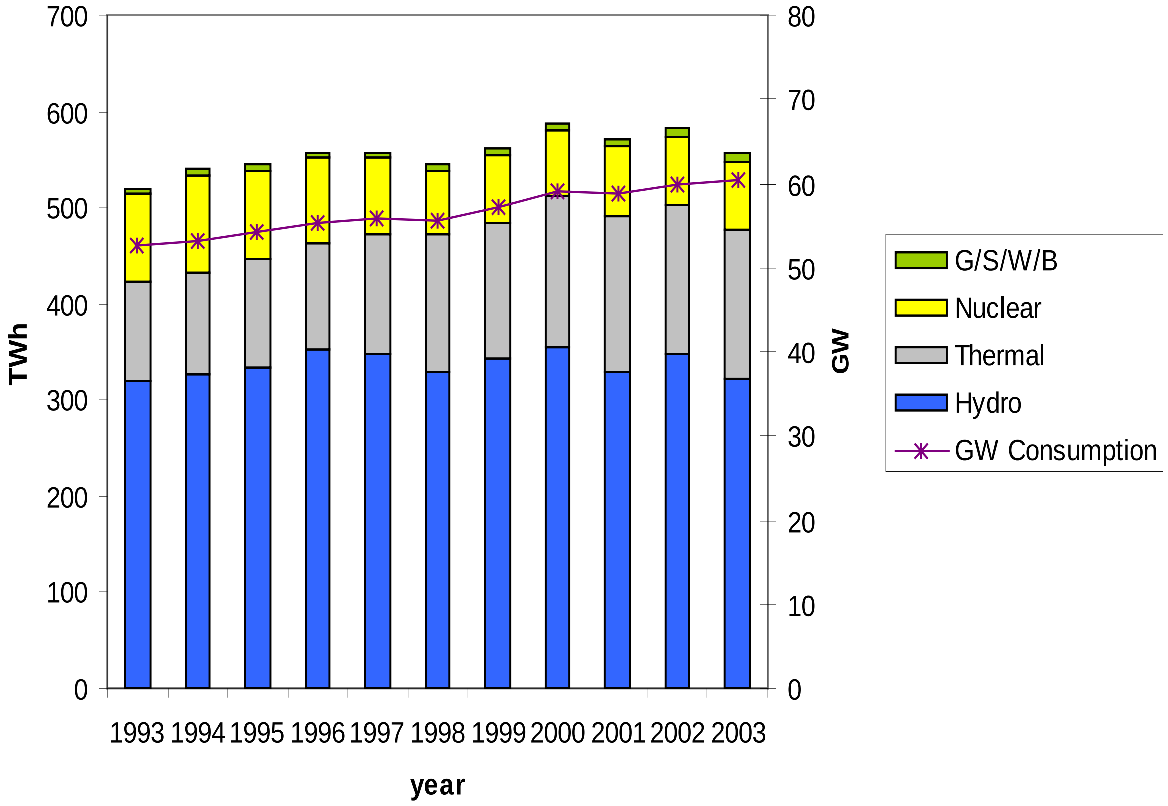


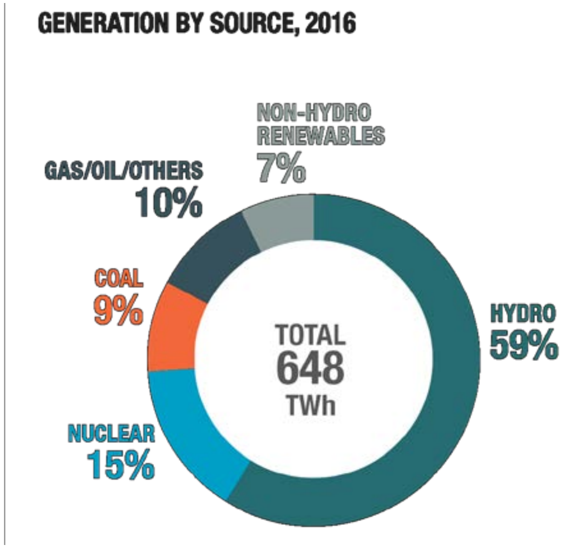




Supply Technologies

- Canada's electricity supply and demand [NRC]:

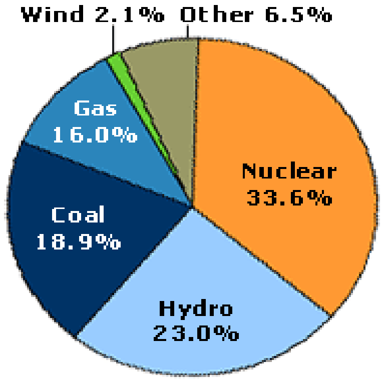


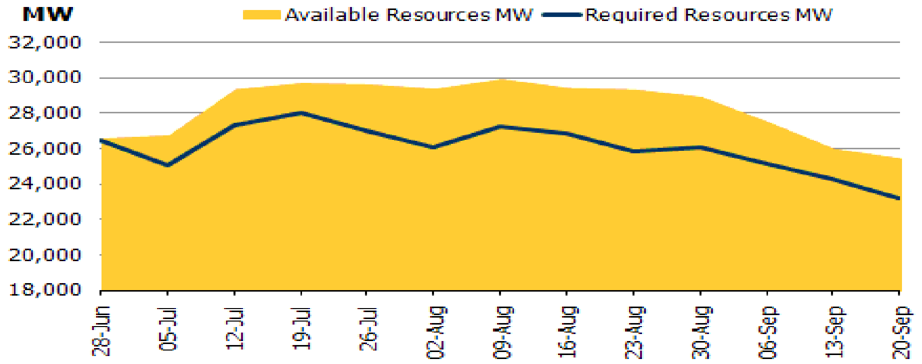


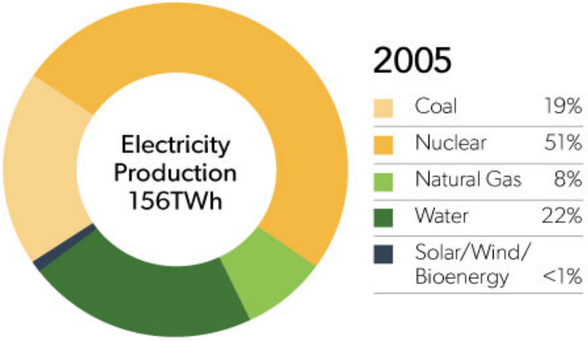
Supply Technologies

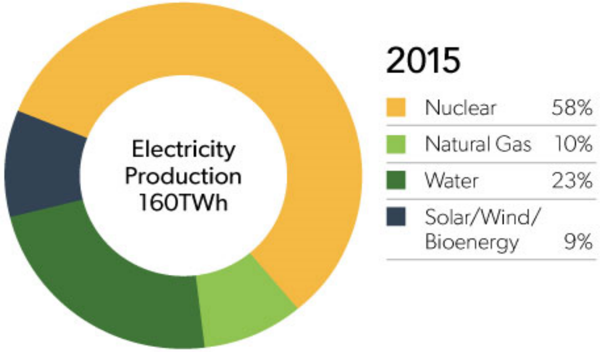
- Supply and demand in Ontario-Canada [IESO, ON gov.]:

2009









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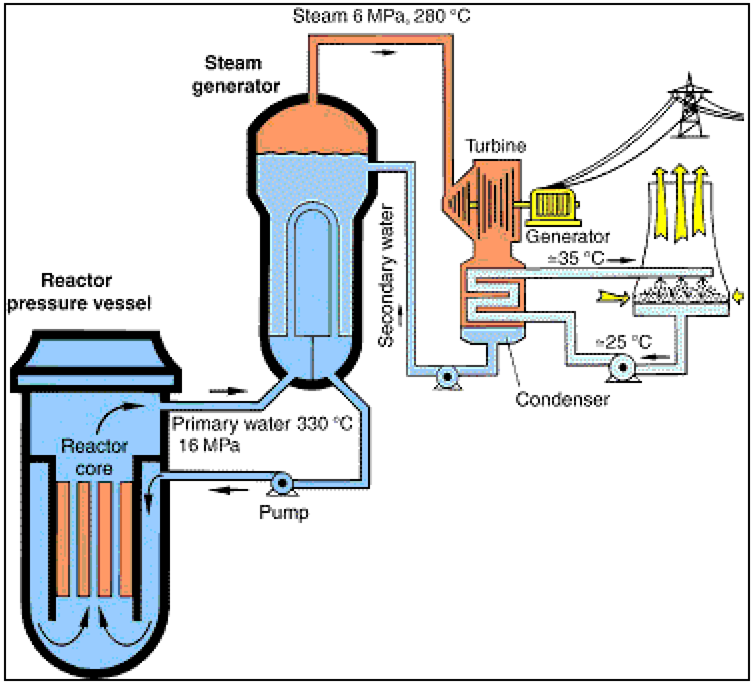
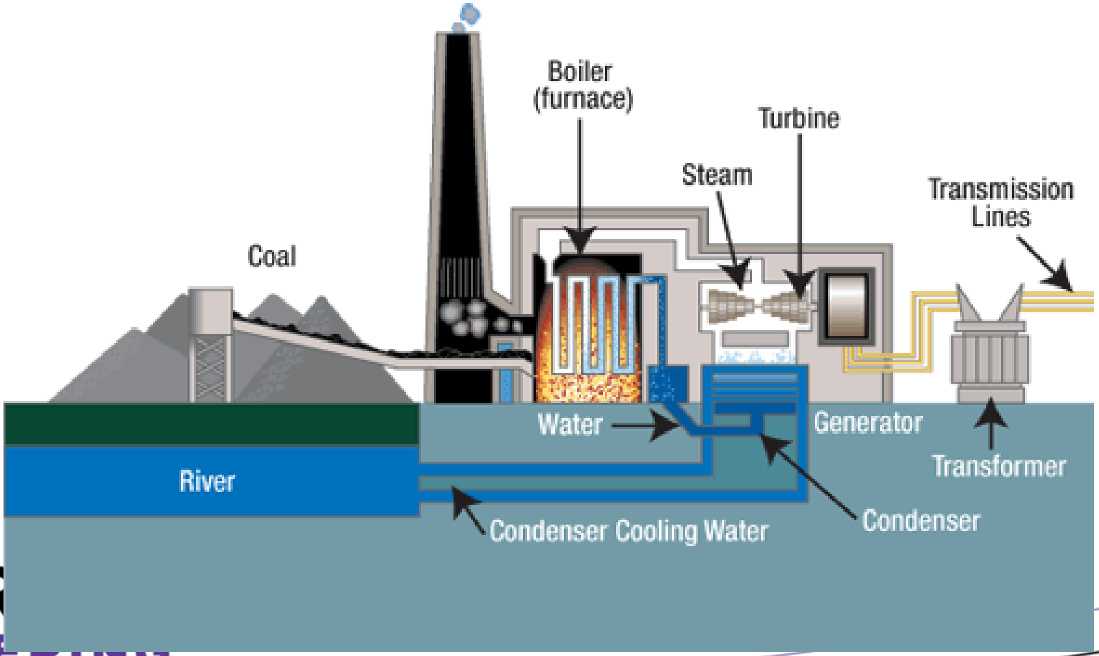
Supply Technologies

- Nuclear power generation [European Nuclear Society]:
  - Clean from green house gases emissions point of view.
  - To supply base load since does not control *f*.



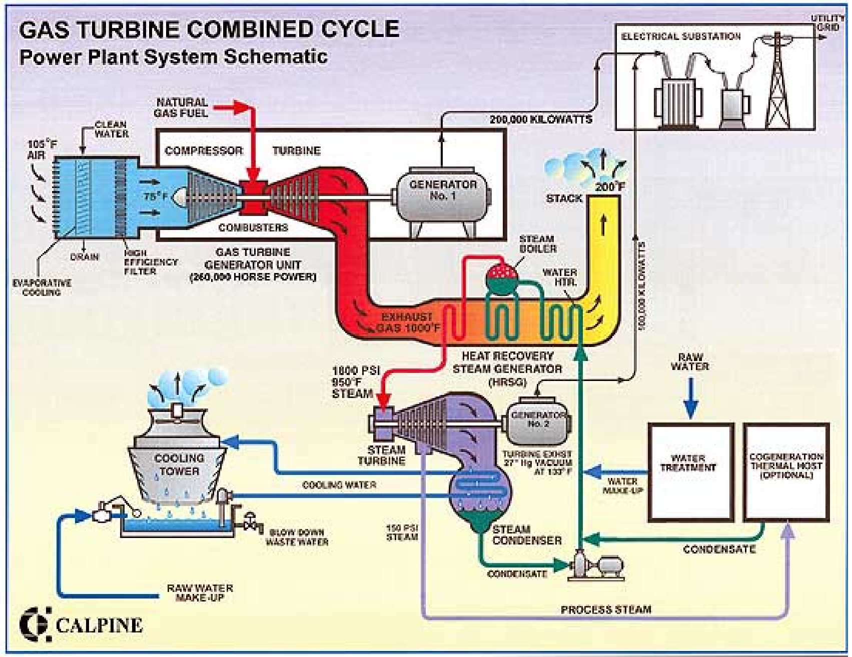
Supply Technologies

- Coal plant (thermal) [TVA]:
  - – “Dirty” from GHG point of view.
  - – Mainly to supply base load given slow response.



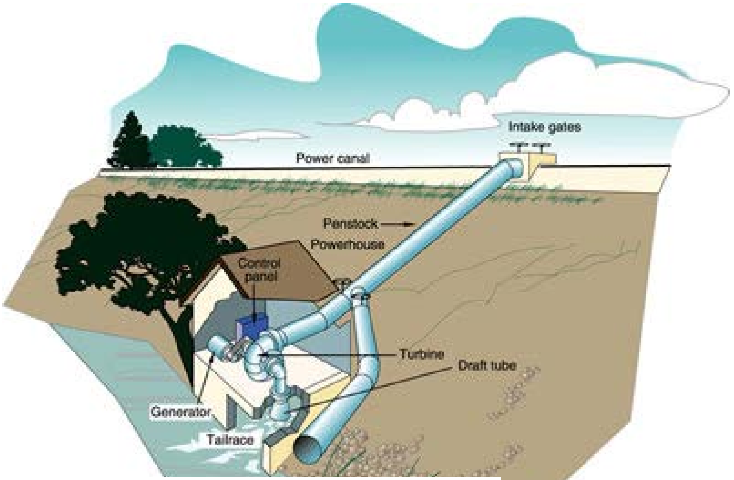
Supply Technologies

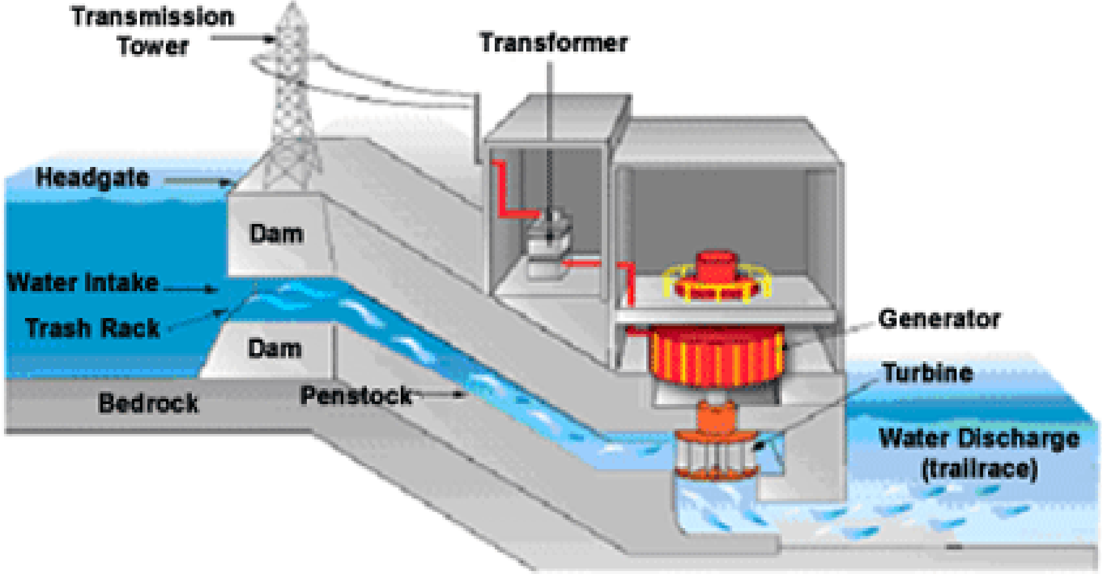
- Combined-cycle plant (thermal) [power-technology.com]:
  - Gas + steam turbine.
  - Cleaner that coal plants.
  - To supply base (steam) and peak load (gas).



Supply Technologies

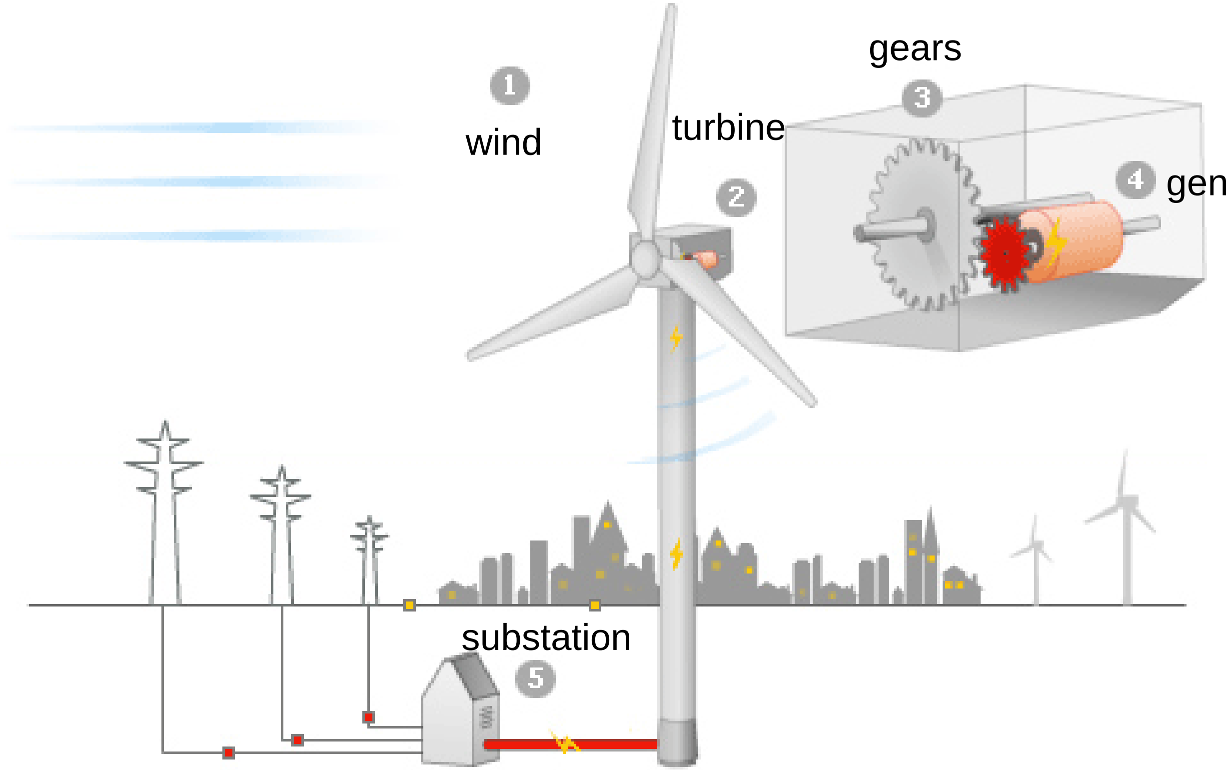
- Hydro plant [US DOE]:
  - Large and small (run of the river).
  - Supplies base and peak load (fast response)





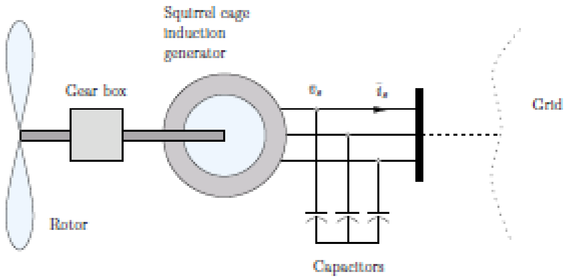
Supply Technologies

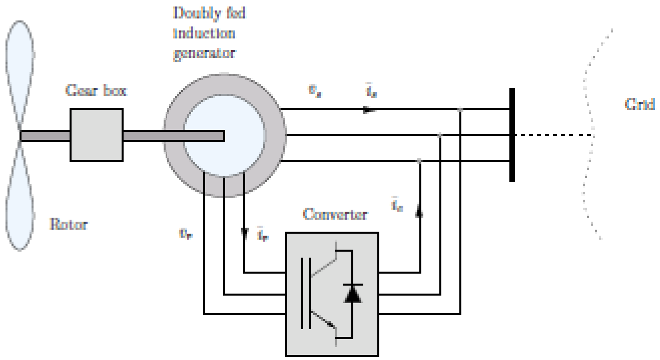
- Wind power [EON]: Clean, but not yet dispatchable.

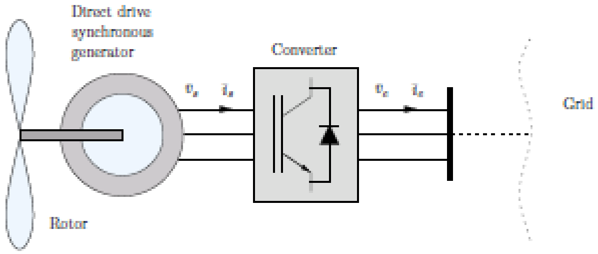


Supply Technologies

- Types of wind power units [PSAT]:

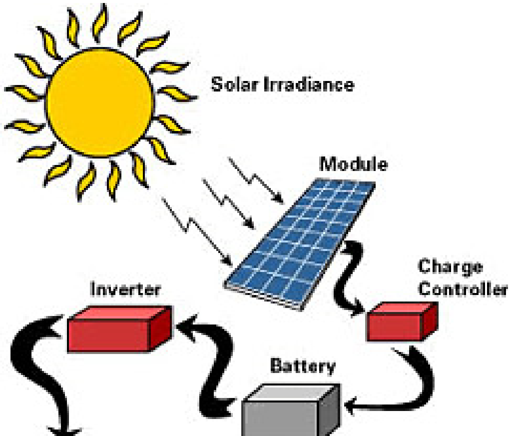


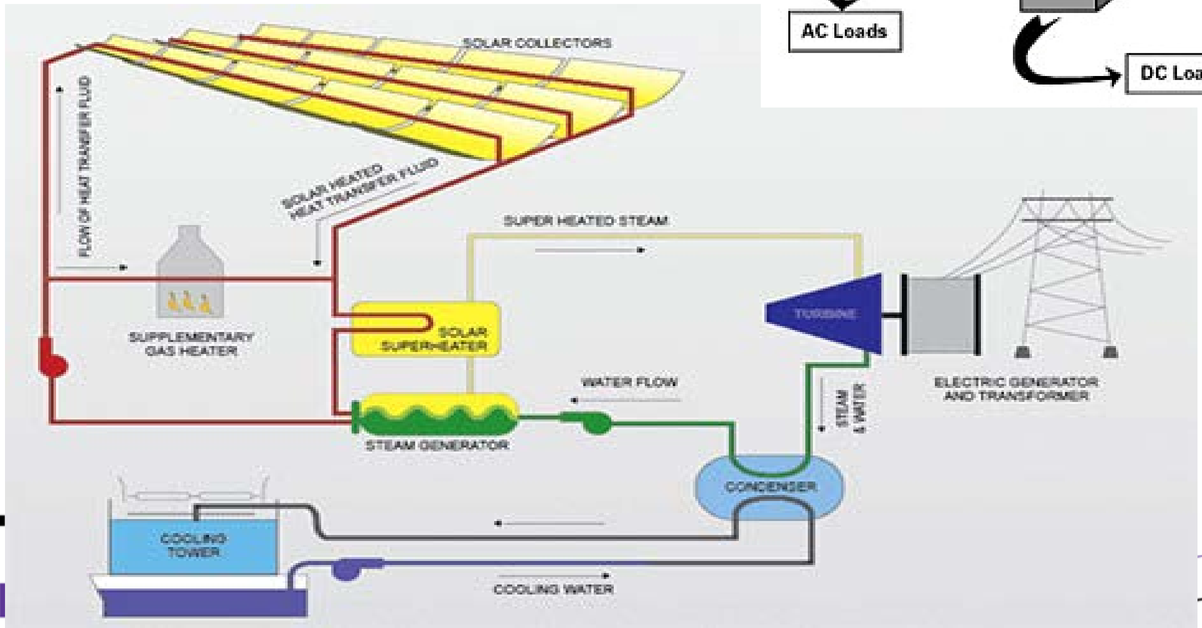




Supply Technologies

- Solar power:
  - PV [an-energy-efficient-home.com] and thermal [acciona-energia.com]
  - Dispatchable with energy storage systems.

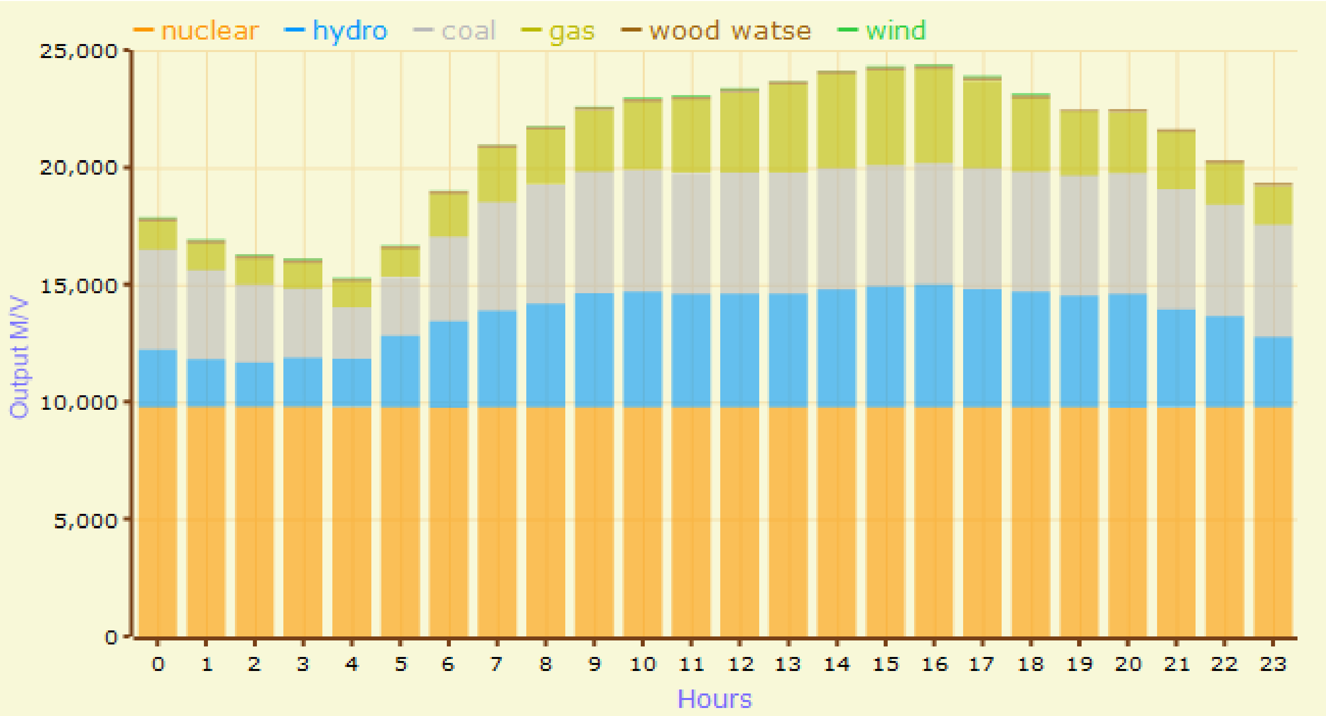




Supply Technologies

- Load supply in Ontario by generator type [MEI]:

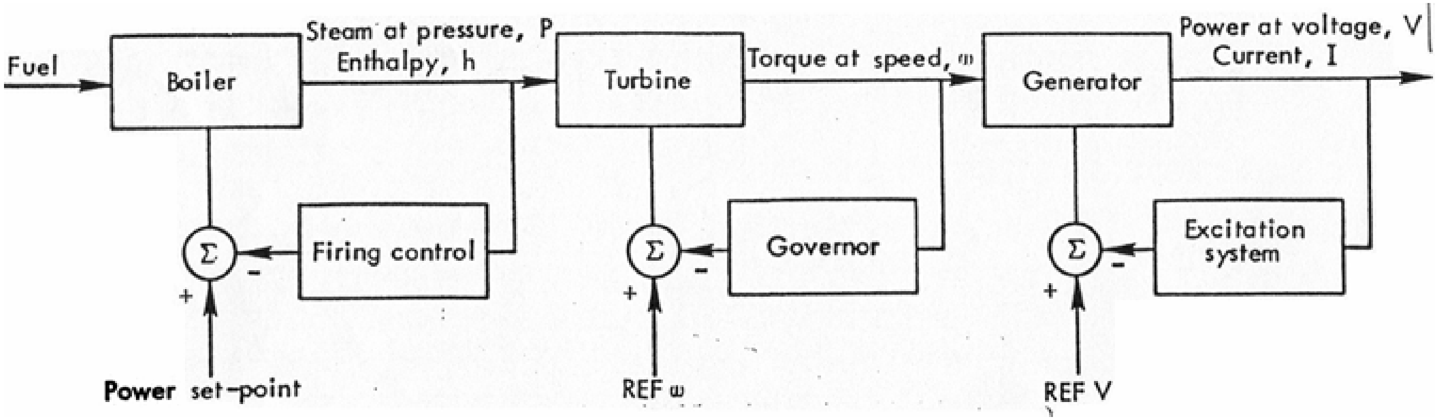
Generator Output - June 26, 2007



This chart excludes electricity imports.

Generator

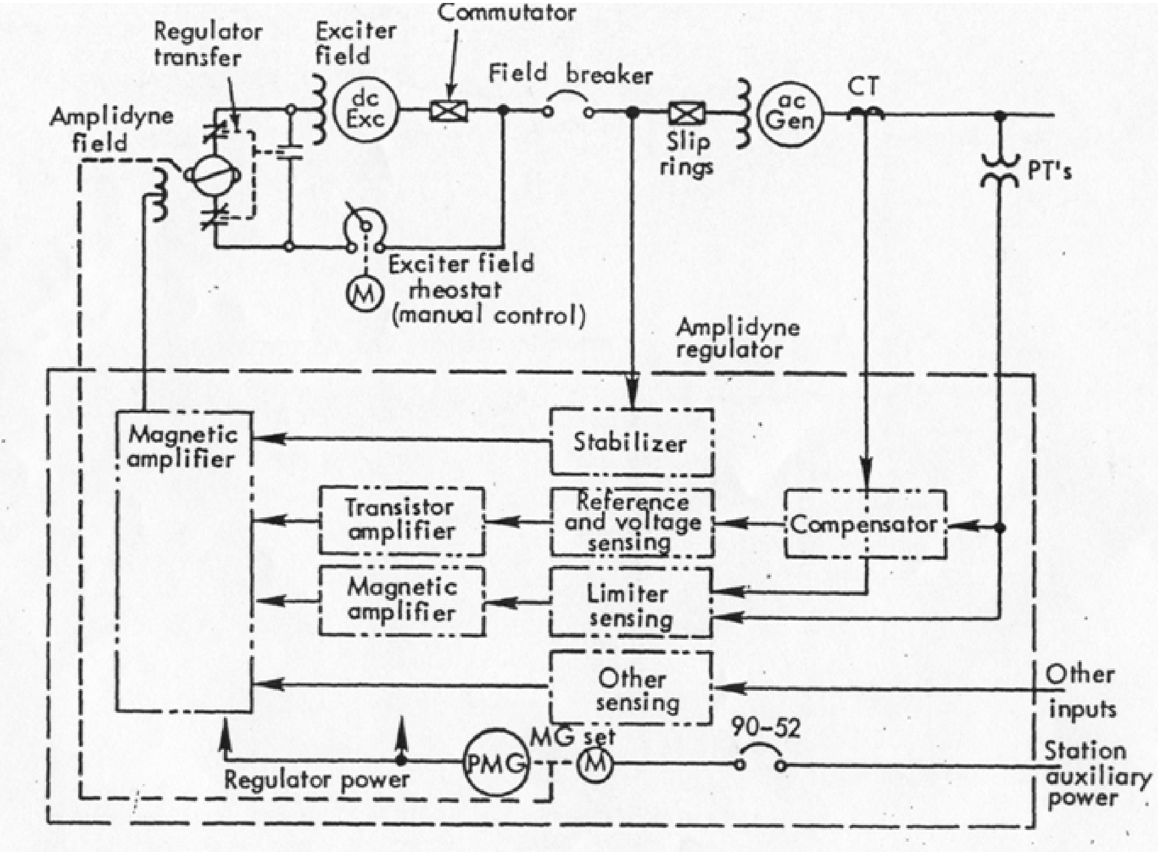
- Generator components:



  - Generator:
    - Synchronous machine: AC stator and DC rotor.
    - Excitation system: DC generator or static converter plus voltage regulator and stabilizer.

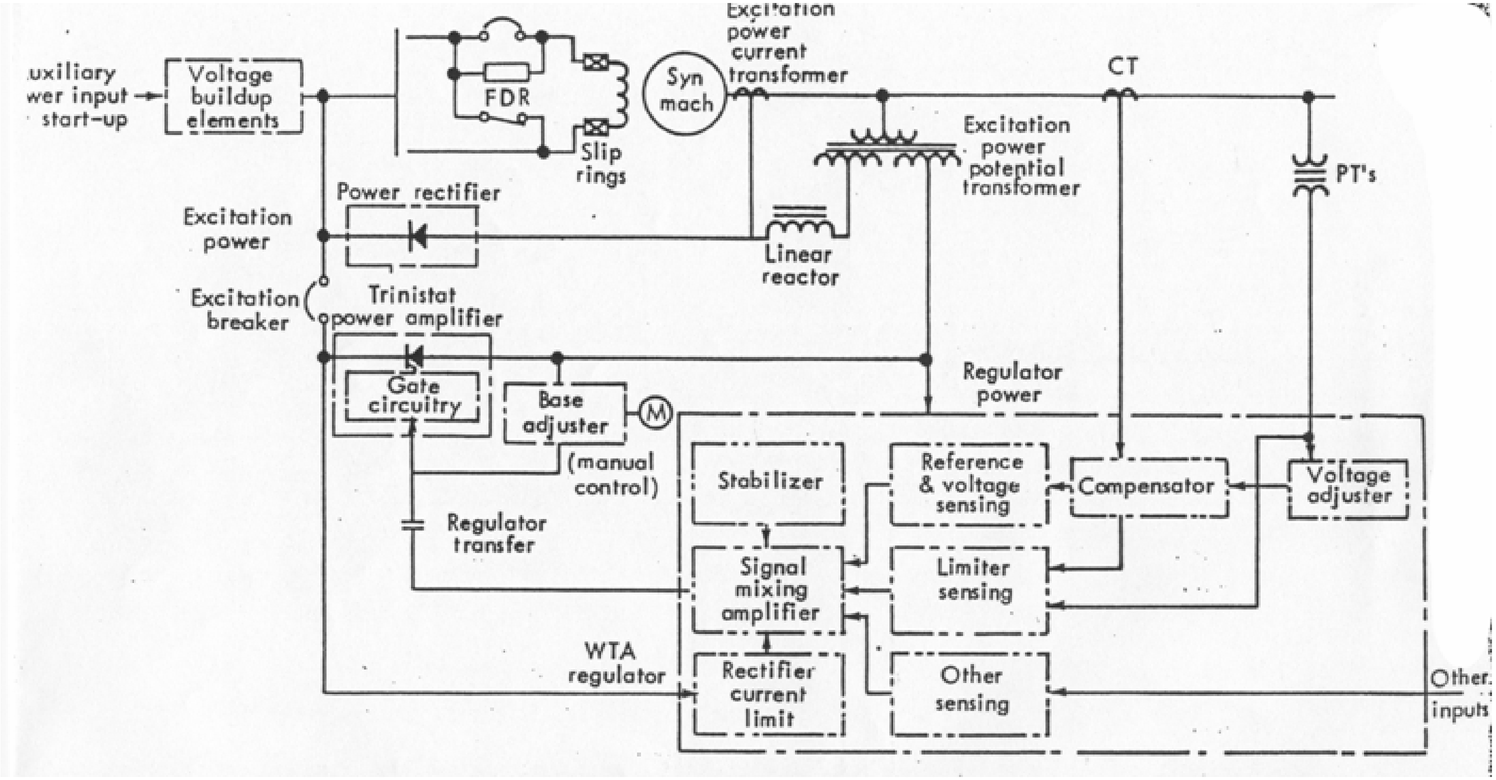
Generator

- Generator with DC exciter and associated controls:

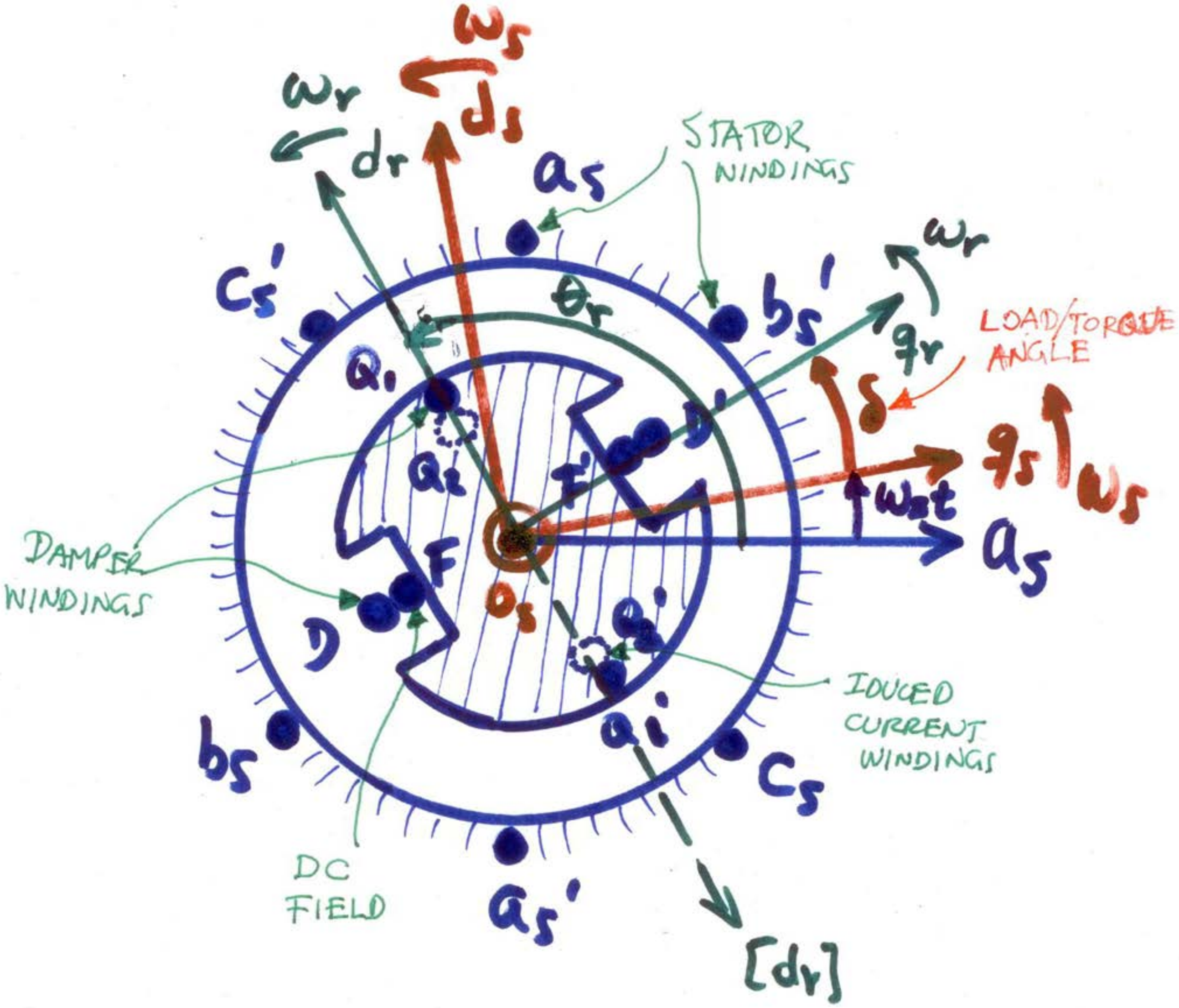


Generator

- Generator with static exciter and associated controls:



Synchronous Machine



Number of poles: $N_P = 2$

Synchronous Machine

- Electrical (inductor) equations:

$$\begin{aligned}[v] &= [R]\,[i] + \frac{\mathrm{d}}{\mathrm{d}t}[\lambda] \\ &= [R]\,[i] + \frac{\mathrm{d}}{\mathrm{d}t}[L(\theta_r)]\,[i]\end{aligned}$$

$$T_e = \frac{1}{2}\,[i]^T\,\frac{\mathrm{d}[L(\theta_r)]}{\mathrm{d}\theta_r}\,[i]$$

where $[v] = [v_{as}\ v_{bs}\ v_{cs}\ v_F\ v_D\ v_{Q1}\ v_{Q2}]^T$ and similarly for $[i]$ and $[\lambda]$.

- Mechanical (Newton's) equations:

$$\begin{aligned}J\,\frac{\mathrm{d}}{\mathrm{d}t}\omega_r + D\omega_r &= T_m - T_e \\ \frac{\mathrm{d}}{\mathrm{d}t}\theta_r &= \omega_r\end{aligned}$$

Synchronous Machine

- Park’s transformation equations:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = P_T^T \begin{bmatrix} v_{os} \\ v_{ds} \\ v_{qs} \end{bmatrix} \qquad \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} = P_T^T \begin{bmatrix} i_{os} \\ i_{ds} \\ i_{qs} \end{bmatrix}$$

$$P_T = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\theta_r & \cos(\theta_r - 120^\circ) & \cos(\theta_r + 120^\circ) \\ \sin\theta_r & \sin(\theta_r - 120^\circ) & \sin(\theta_r + 120^\circ) \end{bmatrix}$$

Synchronous Machine

- Detailed *dqo* equations:
  - Stator equations:

$$\begin{bmatrix} v_{os} \\ v_{ds} \\ v_{qs} \end{bmatrix} = -\begin{bmatrix} R_s & & \\ & R_s & \\ & & R_s \end{bmatrix}\begin{bmatrix} i_{os} \\ i_{ds} \\ i_{qs} \end{bmatrix} - \omega_r \begin{bmatrix} 0 \\ \lambda_{qs} \\ -\lambda_{ds} \end{bmatrix} - \frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} \lambda_{os} \\ \lambda_{ds} \\ \lambda_{qs} \end{bmatrix}$$

  - Rotor equations:

$$\left[\begin{array}{c} v_F \\ 0 \\ \hline 0 \\ 0 \end{array}\right] = \left[\begin{array}{cc|cc} R_F & & & \\ & R_D & & \\ \hline & & R_{Q1} & \\ & & & R_{Q2} \end{array}\right]\left[\begin{array}{c} i_F \\ i_D \\ \hline i_{Q1} \\ i_{Q2} \end{array}\right] + \frac{\mathrm{d}}{\mathrm{d}t}\left[\begin{array}{c} \lambda_F \\ \lambda_D \\ \hline \lambda_{Q1} \\ \lambda_{Q2} \end{array}\right]$$

Synchronous Machine

- Magnetic flux equations:

$$
\begin{bmatrix} \lambda_{os} \\ \lambda_{ds} \\ \lambda_{qs} \\ \hline \lambda_F \\ \lambda_D \\ \lambda_{Q1} \\ \lambda_{Q2} \end{bmatrix}
=
\left[\begin{array}{ccc|cccc}
L_o & & & & & & \\
 & L_d & & M_d & M_d & & \\
 & & L_q & & & M_q & M_q \\
\hline
 & M_d & & L_F & M_d & & \\
 & M_d & & M_d & L_D & & \\
 & & M_q & & & L_{Q1} & M_q \\
 & & M_q & & & M_q & L_{Q2}
\end{array}\right]
\begin{bmatrix} i_{os} \\ i_{ds} \\ i_{qs} \\ \hline i_F \\ i_D \\ i_{Q1} \\ i_{Q2} \end{bmatrix}
$$

Synchronous Machine

- Mechanical equations:

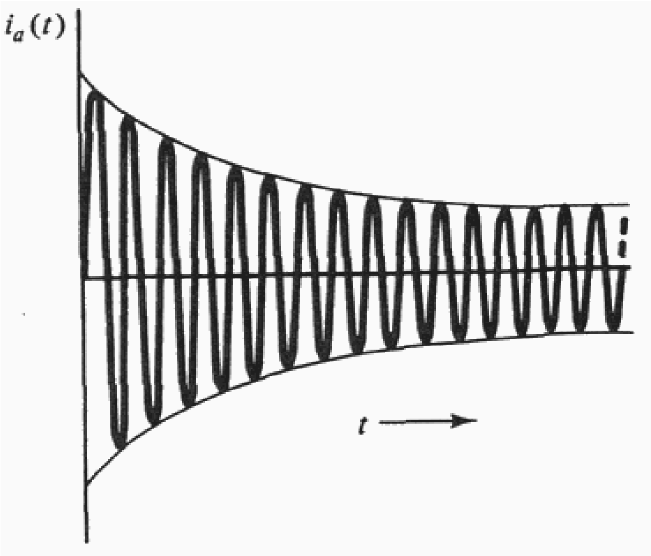
$$J \, \frac{\mathrm{d}}{\mathrm{d}t}\omega_r + D \, \omega_r = T_m - T_e$$

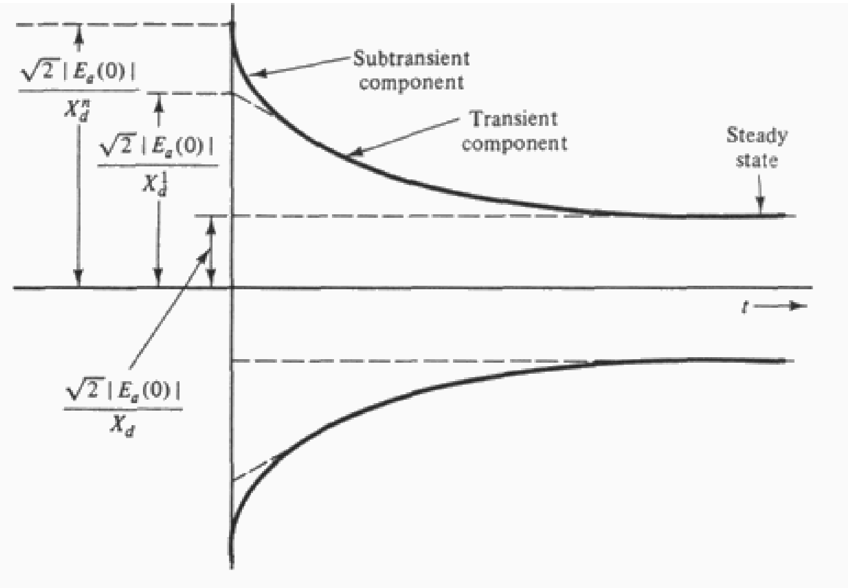
$$\frac{\mathrm{d}}{\mathrm{d}t}\theta_r = \omega_r$$

$$T_e = \frac{N_P}{2} \left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs} \right)$$

Synchronous Machine

- 3-phase short circuit at generator terminals:





$E_a(0)$ is the open-circuit RMS phase voltage

Simplified Models

- Assuming balanced operation (null zero sequence), the detailed machine model can be reduced to phasor models useful for stability and steady state analysis.
- Phasor models are based on the following assumptions:
  - The rotor speed does not deviate “much” from the synchronous speed, i.e. $\omega_r \approx \omega_s = (2/P)\ 2\ \pi\ f_o$, i.e. $\theta_r = \omega_s t + \pi/2 + \delta$
  - The rate of change in rotor speed is “small”, i.e. $|d\omega_r/d\ t\ | \approx 0$.

Simplified Models

- Subtransient models capture the full machine electrical dynamics, including the “few” initial cycles (ms) associated with the damper windings.
- Transient models capture the machine electrical dynamics starting with the field and induced rotor core current transient response. Damper windings transients are neglected.
- Steady sate models capture the machine electrical response when all transients have disappeared after “a few” seconds.

Subtransient Model

1. External phase voltages and currents, assuming $v_{as} = \sqrt{2}V_{as}\cos\left(\omega_s t + \theta_{V_{as}}\right)$:

$$\begin{aligned}
V_{as}^2 &= V_{qs}^2 + V_{ds}^2 = \left(\frac{v_{qs}}{\sqrt{3}}\right)^2 + \left(\frac{v_{ds}}{\sqrt{3}}\right)^2 \\
\theta_{V_{as}} &= \tan^{-1}\left(\frac{V_{ds}}{V_{qs}}\right) + \delta \\
I_{as}^2 &= I_{qs}^2 + I_{ds}^2 = \left(\frac{i_{qs}}{\sqrt{3}}\right)^2 + \left(\frac{i_{ds}}{\sqrt{3}}\right)^2 \\
\theta_{I_{as}} &= \tan^{-1}\left(\frac{I_{ds}}{I_{qs}}\right) + \delta
\end{aligned}$$

2. Subtransient "internal" voltages associated with the damper windings (D and Q1):

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}E_q'' &= \frac{1}{T_{do}''}\left[E_q' + \left(X_d' - X_d''\right)I_{ds} - E_q''\right] \\
\frac{\mathrm{d}}{\mathrm{d}t}E_d'' &= \frac{1}{T_{qo}''}\left[E_d' - \left(X_q' - X_q''\right)I_{qs} - E_d''\right] \\
E_q'' - V_{qs} &= r_s I_{qs} - X_d'' I_{ds} \\
E_d'' - V_{ds} &= r_s I_{ds} + X_q'' I_{qs}
\end{aligned}$$

Subtransient Model

3. Transient "internal" voltages associated with the field (F) and rotor-core induced current windings (Q2):

$$\frac{\mathrm{d}}{\mathrm{d}t}E'_q = \frac{1}{T'_{do}}\left[E_f + \left(X_d - X'_d\right)I_{ds} - E'_q\right]$$

$$\frac{\mathrm{d}}{\mathrm{d}t}E'_d = \frac{1}{T'_{qo}}\left[-\left(X_q - X'_q\right)I_{qs} - E'_d\right]$$

4. Mechanical equations:

$$\frac{\mathrm{d}}{\mathrm{d}t}\Delta\omega_r = \frac{1}{M}[P_m - \underbrace{V_{as}I_{as}\cos\left(\theta_{V_{as}} - \theta_{I_{as}}\right)}_{P_e} - D\Delta\omega_r]$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\delta = \Delta\omega_r = \omega_r - \omega_s$$

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Subtransient Model

- The subtransient reactances (X_q'', X_d'') and open circuit time constants (T_{qo}'', T_{do}''), as well as the transient reactances (X_q', X_d') and open circuit time constants (T_{qo}', T_{do}') are directly associated with the machine internal resistances and inductances.
- In practice, most of these constants are determined from short circuit tests.
- All the E voltages are "internal" machine voltages directly associated with the "internal" phase angle δ.
- The internal field voltage E_f is directly proportional to the actual field dc voltage, and is typically controlled by the voltage regulator.
- The mechanical power P_m is controlled through the governor.

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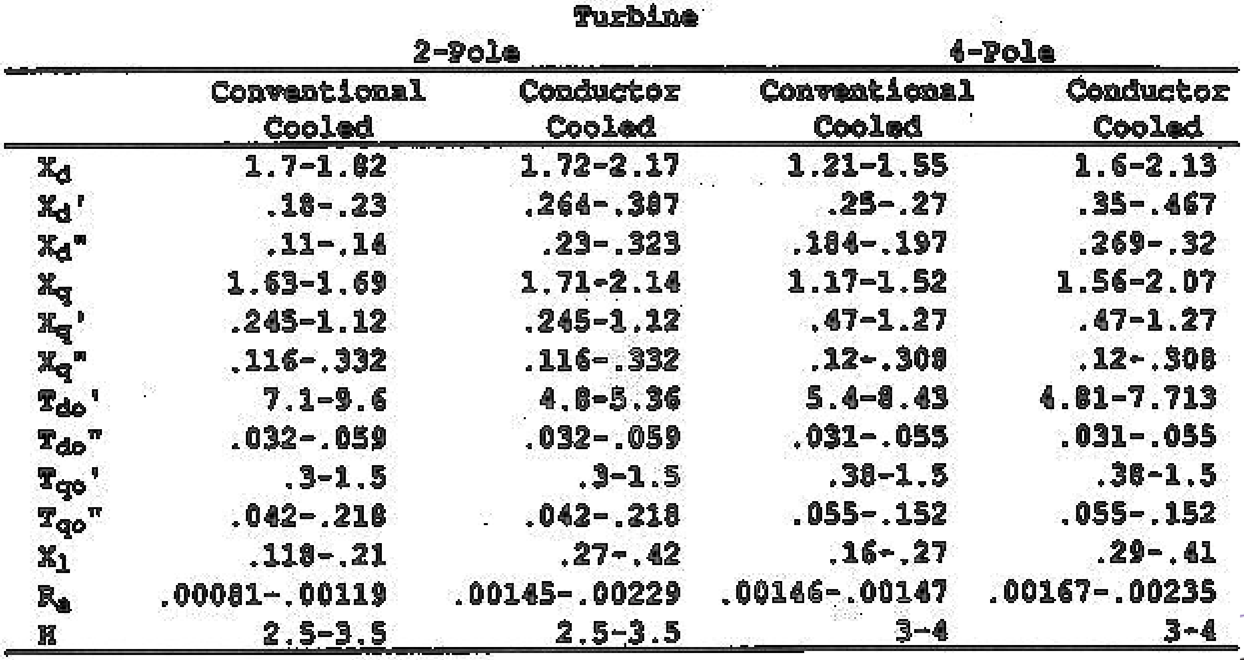
Subtransient Model

- Typical machine parameters:

$$H = \pi f_o M = J \omega_o / S_B$$

$$X_o = 0.1 \text{ to } 0.7 \text{ of } X_d''$$

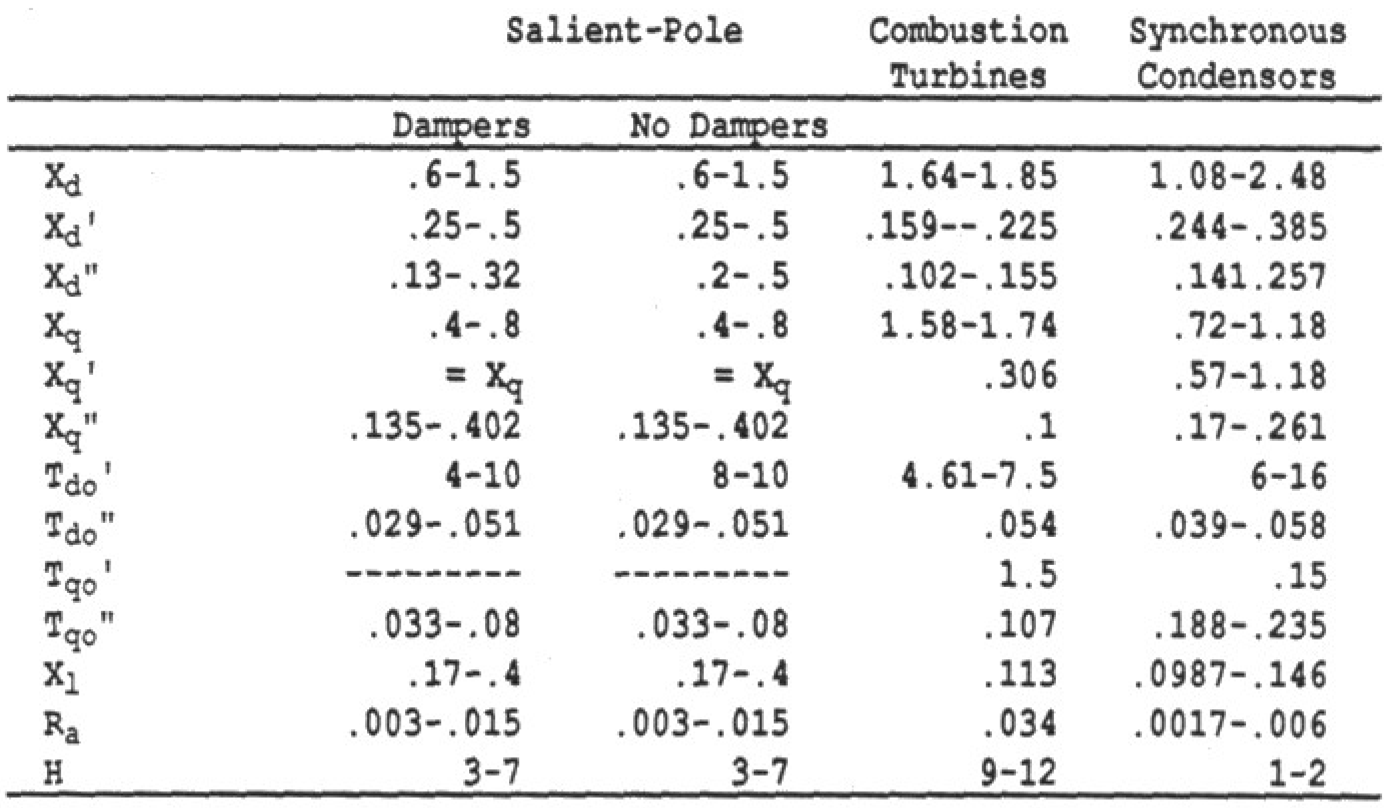
$$r_s = R_a$$



Turbine

	2-Pole		4-Pole	
	Conventional Cooled	Conductor Cooled	Conventional Cooled	Conductor Cooled
X_d	1.7-1.82	1.72-2.17	1.21-1.55	1.6-2.13
X_d'	.18-.23	.264-.387	.25-.27	.35-.467
X_d''	.11-.14	.23-.323	.184-.197	.269-.32
X_q	1.63-1.69	1.71-2.14	1.17-1.52	1.56-2.07
X_q'	.245-1.12	.245-1.12	.47-1.27	.47-1.27
X_q''	.116-.332	.116-.332	.12-.308	.12-.308
T_{do}'	7.1-9.6	4.8-5.36	5.4-8.43	4.81-7.713
T_{do}''	.032-.059	.032-.059	.031-.055	.031-.055
T_{qo}'	.3-1.5	.3-1.5	.38-1.5	.38-1.5
T_{qo}''	.042-.218	.042-.218	.055-.152	.055-.152
X_l	.118-.21	.27-.42	.16-.27	.29-.41
R_a	.00081-.00119	.00145-.00229	.00146-.00147	.00167-.00235
H	2.5-3.5	2.5-3.5	3-4	3-4

Subtransient Model



	Salient-Pole		Combustion Turbines	Synchronous Condensors
	Dampers	No Dampers		
X_d	.6-1.5	.6-1.5	1.64-1.85	1.08-2.48
X_d'	.25-.5	.25-.5	.159--.225	.244-.385
X_d''	.13-.32	.2-.5	.102-.155	.141.257
X_q	.4-.8	.4-.8	1.58-1.74	.72-1.18
X_q'	$= X_q$	$= X_q$	.306	.57-1.18
X_q''	.135-.402	.135-.402	.1	.17-.261
T_{do}'	4-10	8-10	4.61-7.5	6-16
T_{do}''	.029-.051	.029-.051	.054	.039-.058
T_{qo}'	---------	---------	1.5	.15
T_{qo}''	.033-.08	.033-.08	.107	.188-.235
X_l	.17-.4	.17-.4	.113	.0987-.146
R_a	.003-.015	.003-.015	.034	.0017-.006
H	3-7	3-7	9-12	1-2

Transient Model

- Obtained by eliminating the damper winding dynamic equations as follows:

1. External phase voltages and currents, assuming $v_{as} = \sqrt{2}V_{as}\cos\left(\omega_s t + \theta_{V_{as}}\right)$:

$$\begin{aligned} V_{as}^2 &= V_{qs}^2 + V_{ds}^2 = \left(\frac{v_{qs}}{\sqrt{3}}\right)^2 + \left(\frac{v_{ds}}{\sqrt{3}}\right)^2 \\ \theta_{V_{as}} &= \tan^{-1}\left(\frac{V_{ds}}{V_{qs}}\right) + \delta \end{aligned}$$

$$\begin{aligned} I_{as}^2 &= I_{qs}^2 + I_{ds}^2 = \left(\frac{i_{qs}}{\sqrt{3}}\right)^2 + \left(\frac{i_{ds}}{\sqrt{3}}\right)^2 \\ \theta_{I_{as}} &= \tan^{-1}\left(\frac{I_{ds}}{I_{qs}}\right) + \delta \end{aligned}$$

Transient Model

2. Transient "internal" voltages associated with the field (F) and rotor-core induced current windings (Q2):

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}E'_q &= \frac{1}{T'_{do}}\left[E_f + \left(X_d - X'_d\right) I_{ds} - E'_q\right] \\
\frac{\mathrm{d}}{\mathrm{d}t}E'_d &= \frac{1}{T'_{qo}}\left[- \left(X_q - X'_q\right) I_{qs} - E'_d\right] \\
E'_q - V_{qs} &= r_s I_{qs} - X'_d I_{ds} \\
E'_d - V_{ds} &= r_s I_{ds} + X'_q I_{qs}
\end{aligned}$$

3. Mechanical equations:

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}\Delta\omega_r &= \frac{1}{M}[P_m - \underbrace{V_{as} I_{as} \cos\left(\theta_{V_{as}} - \theta_{I_{as}}\right)}_{P_e} - D\Delta\omega_r] \\
\frac{\mathrm{d}}{\mathrm{d}t}\delta &= \Delta\omega_r = \omega_r - \omega_s
\end{aligned}$$

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Transient Model

- The damping D in the mechanical equations, which is typically a small value, is assumed to be large to indirectly model the significant damping effect of these windings on ω_r.
- It’s the typical model used in stability studies.

Transient Model

- Neglecting the induced currents in the rotor (winding Q2):

$$\begin{aligned} X'_q &= X_q \\ T'_{qo} &= 0 \end{aligned} \quad \Rightarrow \quad E'_d = 0$$

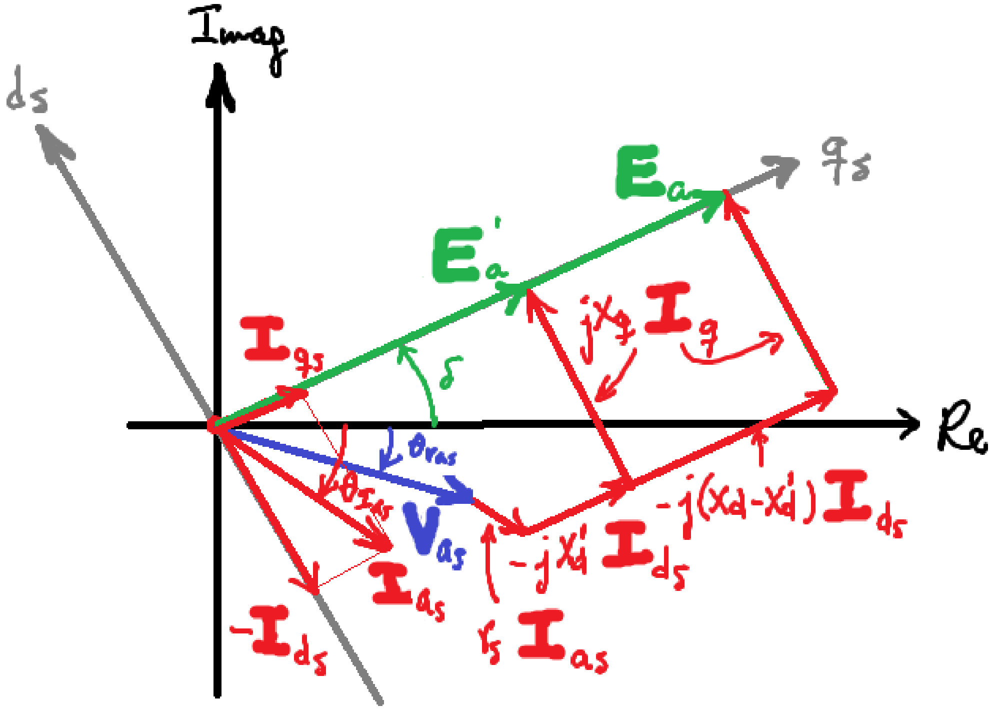
leads to the transient equations:

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}E'_a &= \frac{1}{T'_{do}}\left[E_f + \underbrace{\left(X_d - X'_d\right) I_{ds} - E'_a}_{-E_a}\right] \\ E'_a\angle\delta &= V_{as}\angle\theta_{V_{as}} + r_s I_{as}\angle\theta_{I_{as}} + \\ & \quad jX'_d I_{ds}\angle(\delta + 90^\circ) + jX_q I_{qs}\angle\delta \\ E_a\angle\delta &= V_{as}\angle\theta_{V_{as}} + r_s I_{as}\angle\theta_{I_{as}} + \\ & \quad jX_d I_{ds}\angle(\delta + 90^\circ) + jX_q I_{qs}\angle\delta \\ I_{as}\angle\theta_{I_{as}} &= I_{ds}\angle(\delta + 90^\circ) + I_{qs}\angle\delta \end{aligned}$$

Transient Model

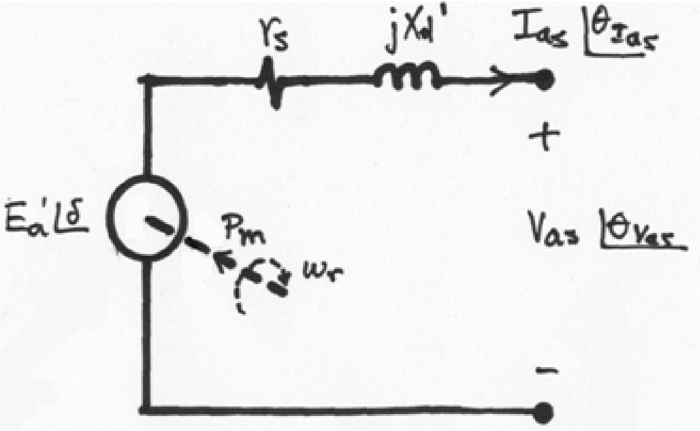
- The phasor diagram in this case is:

$$
\begin{aligned}
\boldsymbol{E}'_a &= \boldsymbol{V}_{as} + r_s \boldsymbol{I}_{as} + jX'_d \boldsymbol{I}_{ds} + jX_q \boldsymbol{I}_{qs} \\
\boldsymbol{E}_a &= \boldsymbol{V}_{as} + r_s \boldsymbol{I}_{as} + jX_d \boldsymbol{I}_{ds} + jX_q \boldsymbol{I}_{qs}
\end{aligned}
$$



Transient Model

- For faults near the generator terminals, the q axis has little effect on the system response, i.e. $I_{qs} \approx 0$.
- This results in the classical voltage source and transient reactance generator model used in most theoretical stability studies:



$$E_a' \angle \delta \;=\; V_{as} \angle \theta_{V_{as}} + (r_s + jX_d') I_{as} \angle \theta_{I_{as}}$$

Transient Model

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}E'_a &= \frac{1}{T'_{do}}\left[E_f \underbrace{-\left(X_d - X'_d\right) I_{as} - E'_a}_{-E_a}\right] \\
\frac{\mathrm{d}}{\mathrm{d}t}\Delta\omega_r &= \frac{1}{M}[P_m - \underbrace{V_{as}I_{as}\cos\left(\theta_{V_{as}} - \theta_{I_{as}}\right)}_{P_e} - D\Delta\omega_r] \\
\frac{\mathrm{d}}{\mathrm{d}t}\delta &= \Delta\omega_r = \omega_r - \omega_s
\end{aligned}
$$

where:

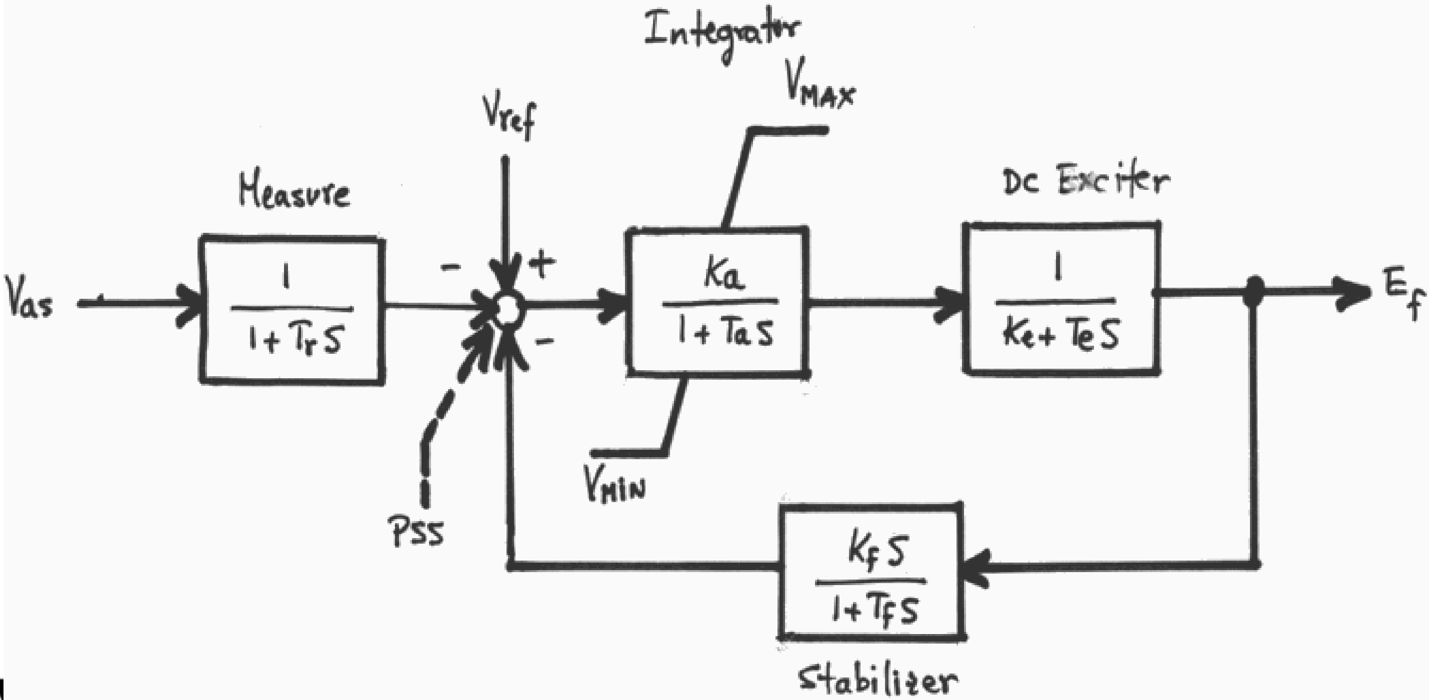
$$E_a\angle\delta \;=\; V_{as}\angle\theta_{V_{as}} + (r_s + jX_d)I_{as}\angle\theta_{I_{as}}$$

Transient Model

- A further approximation in some cases is used by neglecting the field dynamics, i.e. $T_{do}' = 0$.
- In this case, E_a' is a “fixed “ variable controlled directly through the voltage regulator via E_f, i.e. $E_a' = E_f$.
- The limits in the voltage regulator are used to represent limits in the field and armature currents.
- These limits can be “soft”, i.e. allowed to temporarily exceed the hard steady state limits, to represent under- and over-excitation.

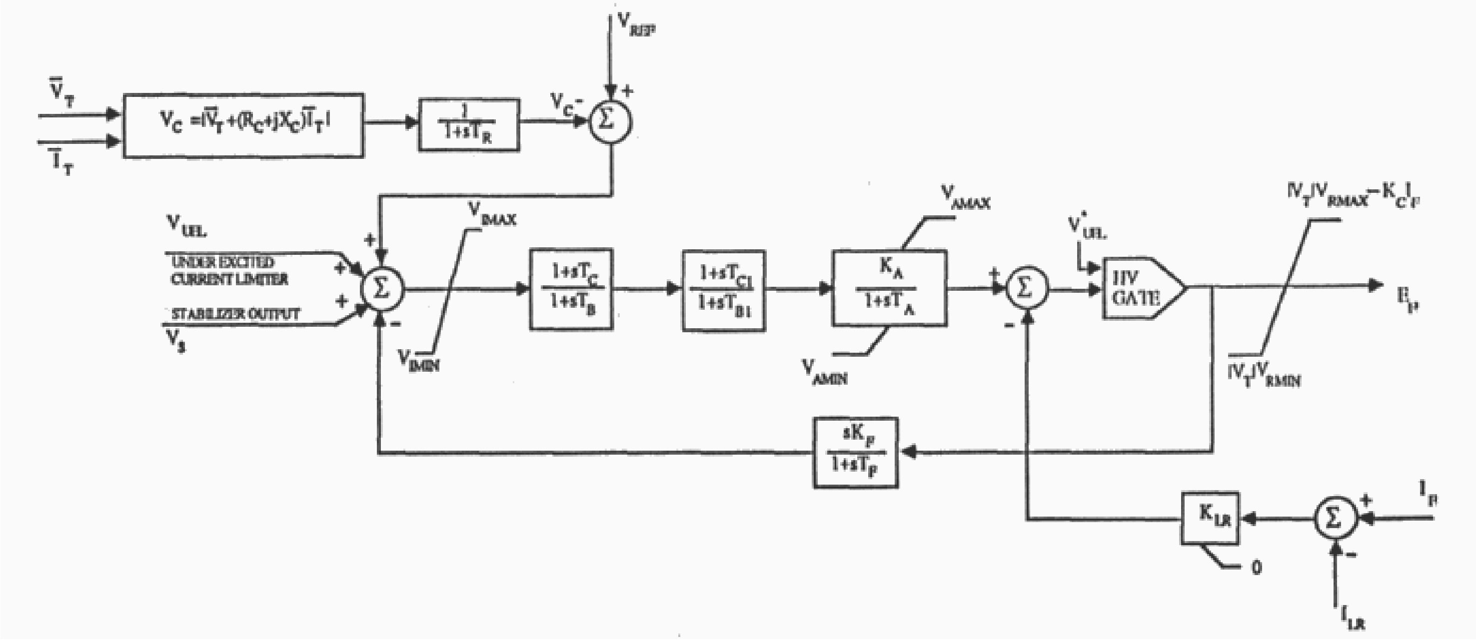
Controls

- A simple voltage regulator model (IEEE type 1):



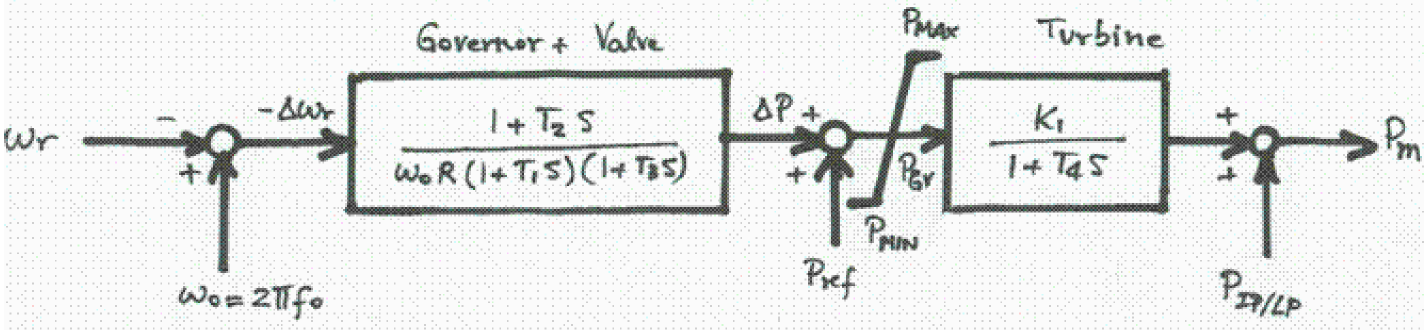
Controls

- A static voltage regulator model:



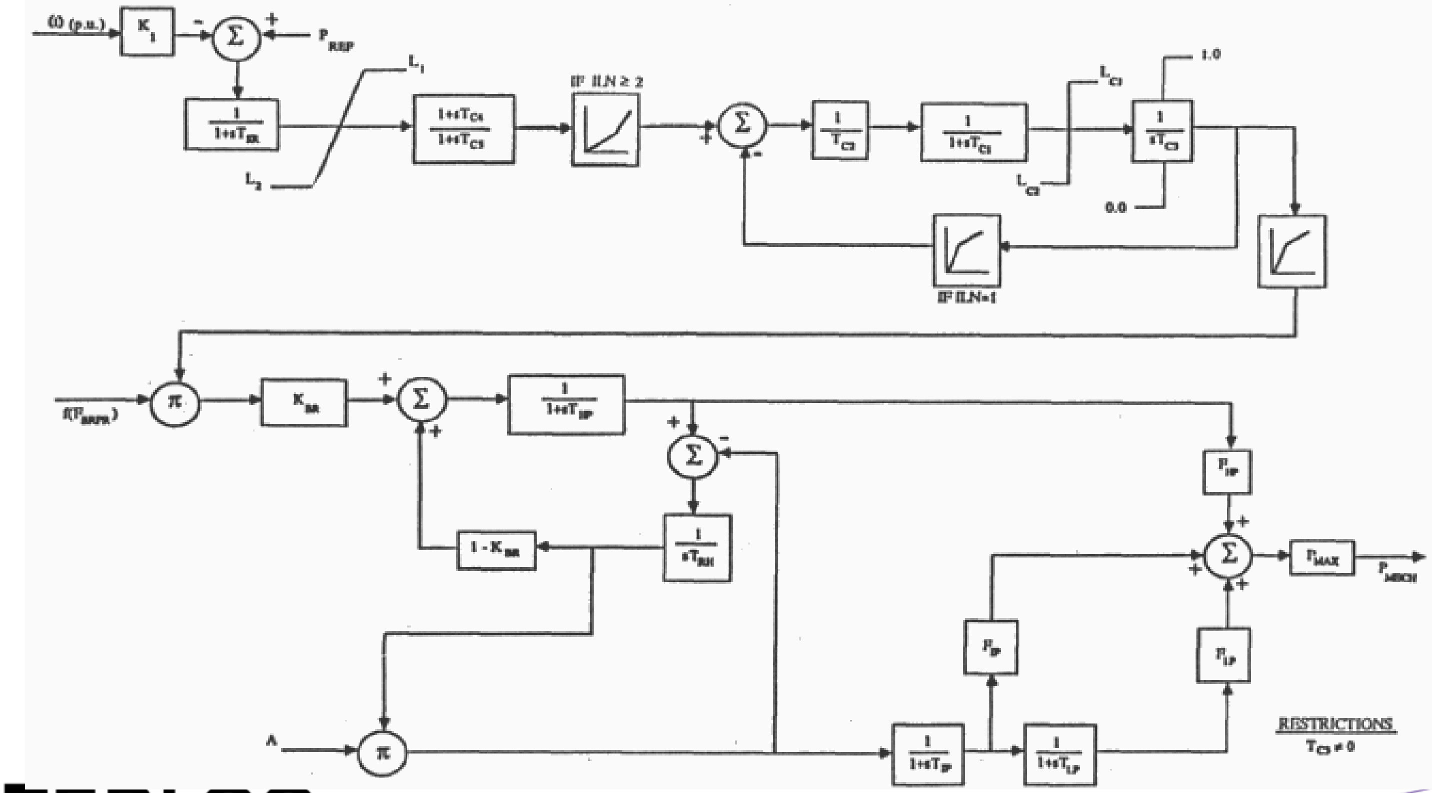
Controls

- A simple governor model (hydraulic valve plus turbine):



Controls

- A governor-steam turbine model:

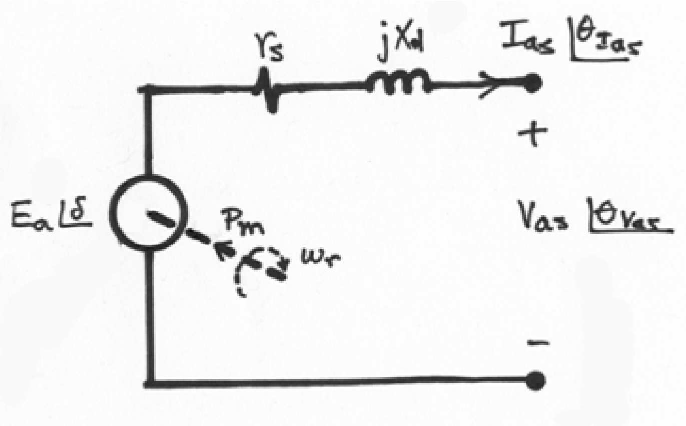


Steady State Model

- When all transients are neglected, the generator model becomes:

$$\begin{aligned} E_a\angle\delta &= V_{as}\angle\theta_{V_{as}} + r_s I_{as}\angle\theta_{I_{as}} \\ &\quad + jX_d I_{ds}\angle(\delta + 90^\circ) + jX_q I_{qs}\angle\delta \\ E_a &= E_f \\ I_{as}\angle\theta_{I_{as}} &= I_{qs}\angle\delta + jI_{ds}\angle\delta \end{aligned}$$

which, for a round rotor machine ($X_d = X_q$), leads to the classical steady state generator model:



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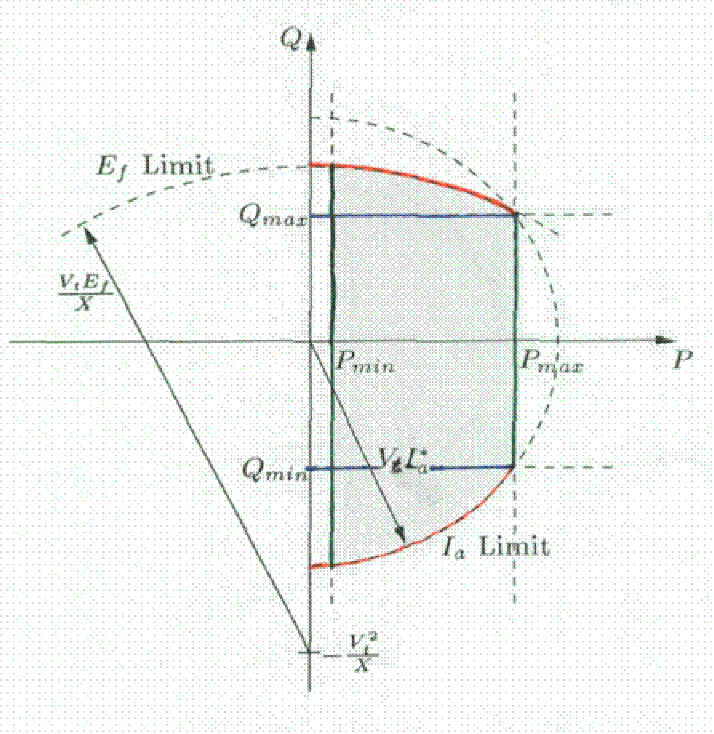
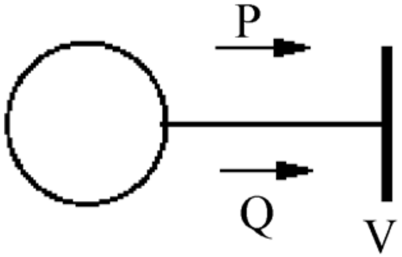
Steady State Model

- Based on this simple model, the field and armature current limits can be used to define the generator capability curves (for a given terminal voltage $V_{as} = V_t$):



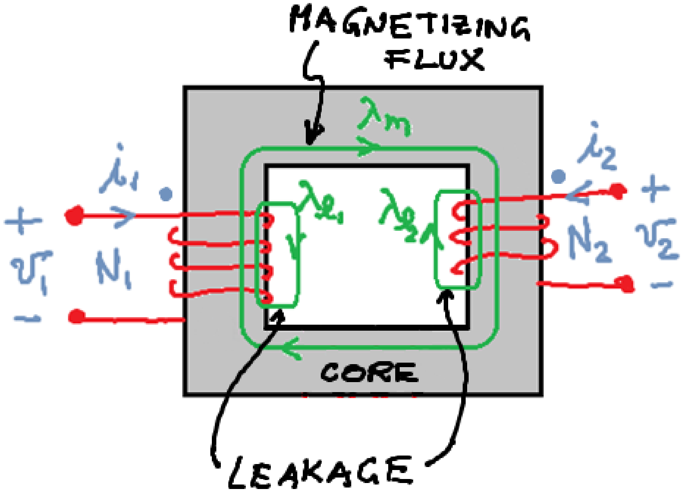
Steady State Model

- Considering the voltage regulator effect, the generator can be modeled as a constant terminal voltage within the generator reactive power capability, delivering constant power (P_m).
- This yields the PV generator model for power flow studies:



where $P = P_m$ = constant, and $V = V_t$ = constant for $Q_{min} \leq Q \leq Q_{max}$; otherwise, $Q = Q_{max/min}$ and V is allowed to change.

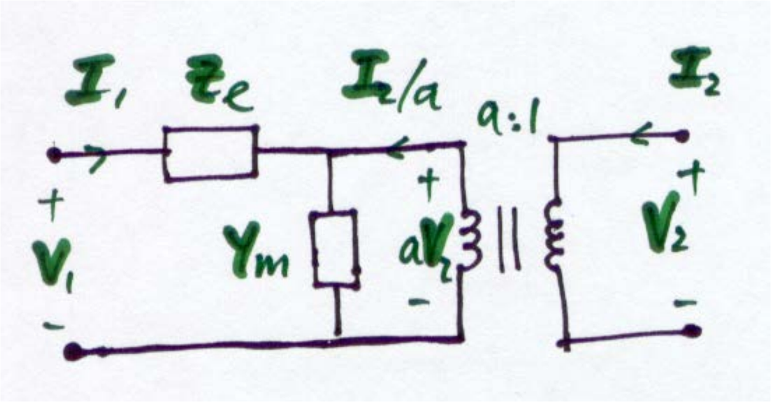
Single-phase Transformers



- The basic characteristics of this device are:
  - Flux leakage around the transformer windings is represented by a leakage inductance L_l.
  - The core is made of magnetic material and is represented by a magnetization inductance (L_m>>L_l), but saturates.
  - Losses in the windings (Cu wires) and core (hysteresis and induced currents) are represented with lumped resistances (r and G_m).
  - Steps up or down the voltage/current depending on the turn ratio $a = N_1/N_2 = V_1/V_2$

Single-phase Transformers

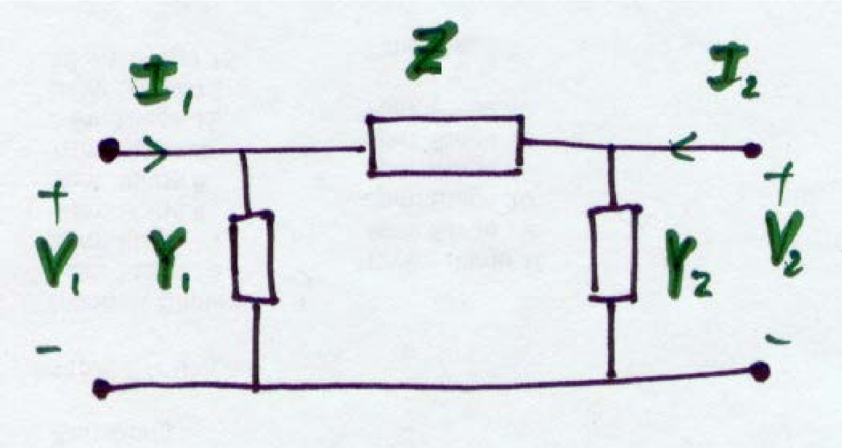
- The phasor equivalent circuit is, assuming $\boldsymbol{Z}_m >> \boldsymbol{Z}_{l1}$:



$$\begin{aligned}\begin{bmatrix} \boldsymbol{V}_1 \\ \boldsymbol{I}_1 \end{bmatrix} &= \begin{bmatrix} a(1+\boldsymbol{Z}_l\boldsymbol{Y}_m) & \boldsymbol{Z}_l/a \\ a\boldsymbol{Y}_m & 1/a \end{bmatrix}\begin{bmatrix} \boldsymbol{V}_2 \\ -\boldsymbol{I}_2 \end{bmatrix} \\ &= \begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{D} \end{bmatrix}\begin{bmatrix} \boldsymbol{V}_2 \\ -\boldsymbol{I}_2 \end{bmatrix}\end{aligned}$$

Single-phase Transformers

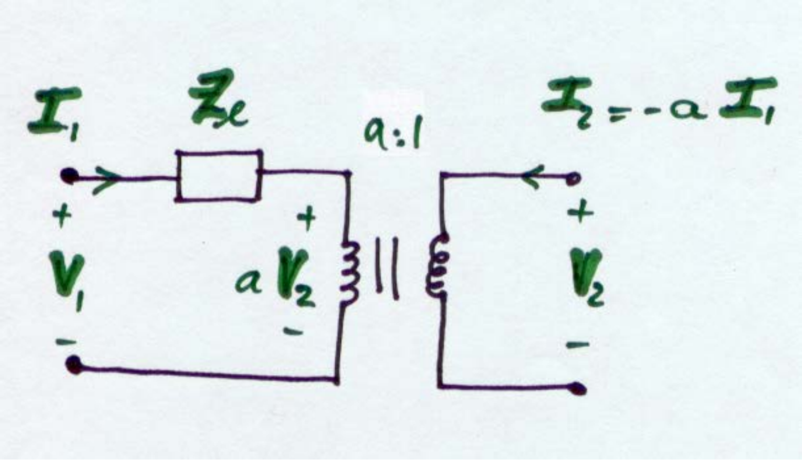
- Or Π form:



$$
\begin{aligned}
\boldsymbol{Z} &= \frac{\boldsymbol{Z}_l}{a} \\
\boldsymbol{Y}_1 &= (1-a)\frac{1}{\boldsymbol{Z}_l} \\
\boldsymbol{Y}_2 &= (a^2\boldsymbol{Z}_l\boldsymbol{Y}_m + a^2 - a)\frac{1}{\boldsymbol{Z}_l} \\
&\approx (a^2-a)\frac{1}{\boldsymbol{Z}_l} \quad \text{for} \quad \boldsymbol{Y}_m \approx 0
\end{aligned}
$$

Single-phase Transformers

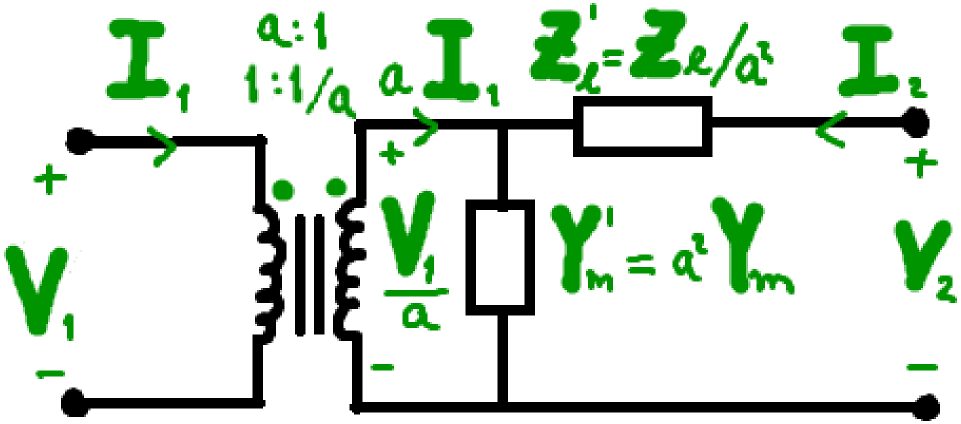
- Neglecting $\boldsymbol{Z}_m$ ($\boldsymbol{Y}_m$ is small given the core magnetic properties):



$$
\begin{aligned}
\boldsymbol{V}_1 &= \boldsymbol{Z}_l\,\boldsymbol{I}_1 + a\,\boldsymbol{V}_2\\
\boldsymbol{I}_2 &= -a\,\boldsymbol{I}_1
\end{aligned}
$$

Single-phase Transformers

- Some programs/data formats (e.g. PSAT and IEEE common format) model the transformer as follows:



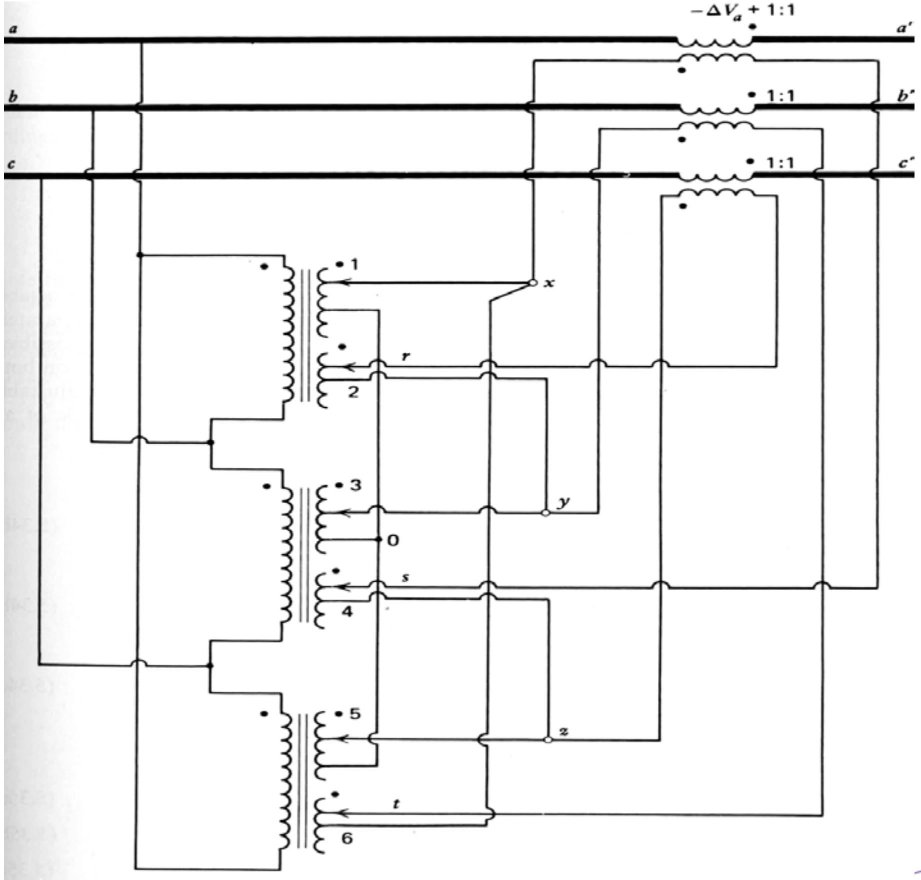
- This is equivalent to the previous model but seen from the secondary side.

Load Tap Changers (LTCs)

- Certain transformer have built-in Under-Load Tap Changers (ULTCs) or LTCs.
- This are either operated manually (locally or remote controlled) or automatically with a voltage regulator; the voltage control range is limited (approximately ± 10%) and on discrete steps (about ± 1%).
- The time response is in the order of minutes, with 1-2 min. delays, due to ULTCs being implemented using electromechanical systems.
- These are typically used to control the load voltage side, and hence are used at subtransmission substations.
- Nowadays, power electronic switches are used, leading to Thyristor Controller Voltage Regulators (TCVR), which are faster voltage controllers and are considered Flexible AC Transmission Systems (FACTS).
- These types of transformers are modeled using the same transformer models, but *a* may be assumed to be a discrete controlled variable through a voltage regulator with a dead-band.

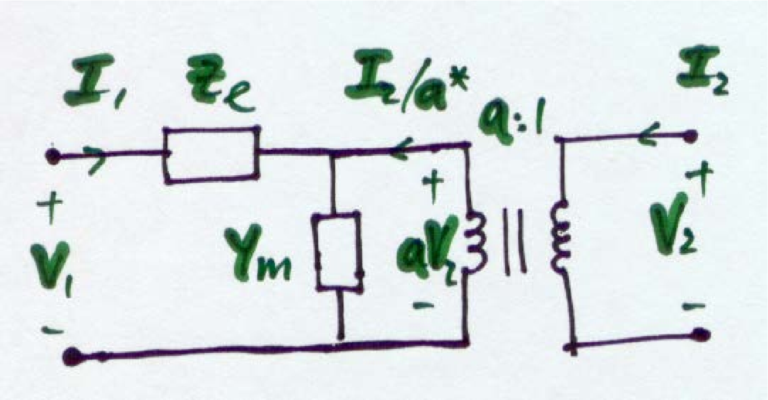
Phase Shifters

- Transformers with special connections and under-load tap changers can also be used for phase shift control and are known as Phase Shifters:



Phase Shifters

- These control the phase shift difference between the two terminal voltages within approximately $\pm 30^{o}$, thus increasing the power capacity of a transmission line.
- It is also used to eliminate “loop” currents, i.e. “normalize” a system (e.g. interconnection between Ontario and Michigan/NY).
- Phase shifters are modeled using a similar model but the tap is a phasor as opposed to a scalar:



$$\boldsymbol{a} = a\,\underline{/\alpha}$$

- A Π equivalent circuit cannot be used in this case.

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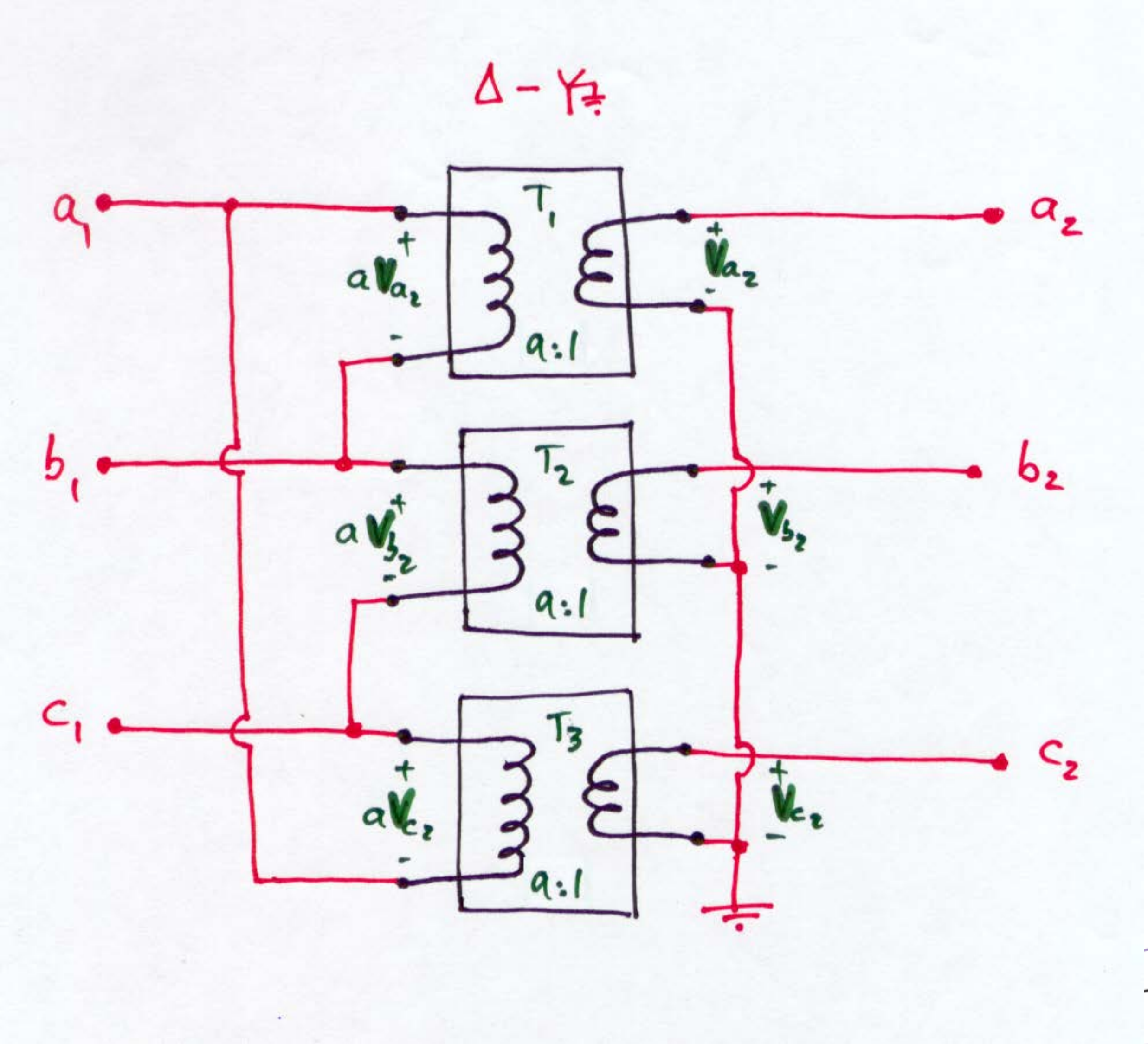
Three-phase Transformers



Three-phase Transformers

- The 3 single-phase transformers form a 3-phase bank that induces a phase shift, depending on the connection:

$$\begin{aligned}
\boldsymbol{V}_{ab_1} &= a\,\boldsymbol{V}_{a_2} \\
\boldsymbol{V}_{ab_2} &= \sqrt{3}\angle 30^\circ\,\boldsymbol{V}_{a_2} \\
\Rightarrow \boldsymbol{V}_{ab_1} &= \frac{a}{\sqrt{3}\angle 30^\circ}\,\boldsymbol{V}_{ab_2} \\
\boldsymbol{a} &= \frac{a}{\sqrt{3}}\angle -30^\circ \\
\boldsymbol{a}_{pu} &= a_{pu}\angle -30^\circ
\end{aligned}$$

Three-phase Transformers

$$\begin{aligned} \text{Y-}\Delta\text{:} \quad \boldsymbol{a} &= \sqrt{3}a \angle 30^\circ \\ \boldsymbol{a}_{pu} &= a_{pu} \angle 30^\circ \end{aligned}$$

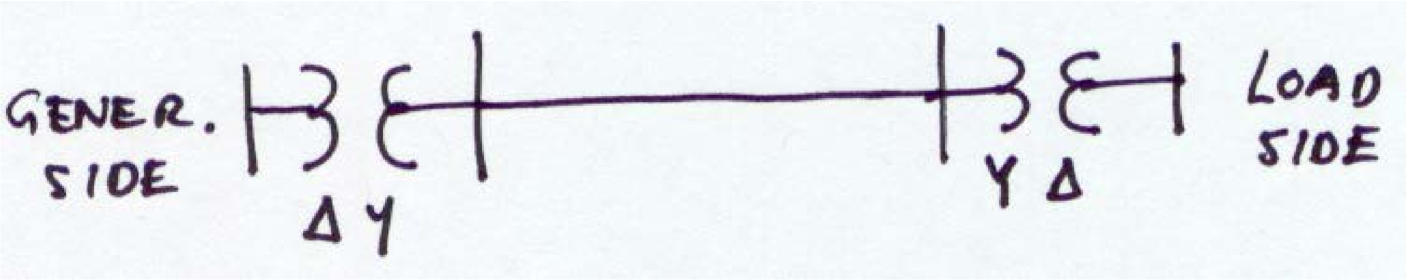
$$\begin{aligned} \Delta\text{-Y:} \quad \boldsymbol{a} &= \frac{a}{\sqrt{3}} \angle -30^\circ \\ \boldsymbol{a}_{pu} &= a_{pu} \angle -30^\circ \end{aligned}$$

$$\text{Y-Y:} \quad \boldsymbol{a} = a$$

$$\Delta\text{-}\Delta\text{:} \quad \boldsymbol{a} = a$$

Three-phase Transformers

- In balanced, “normal” systems, the net phase shift between the generation and load sides is zero, and hence is neglected during system analyses:

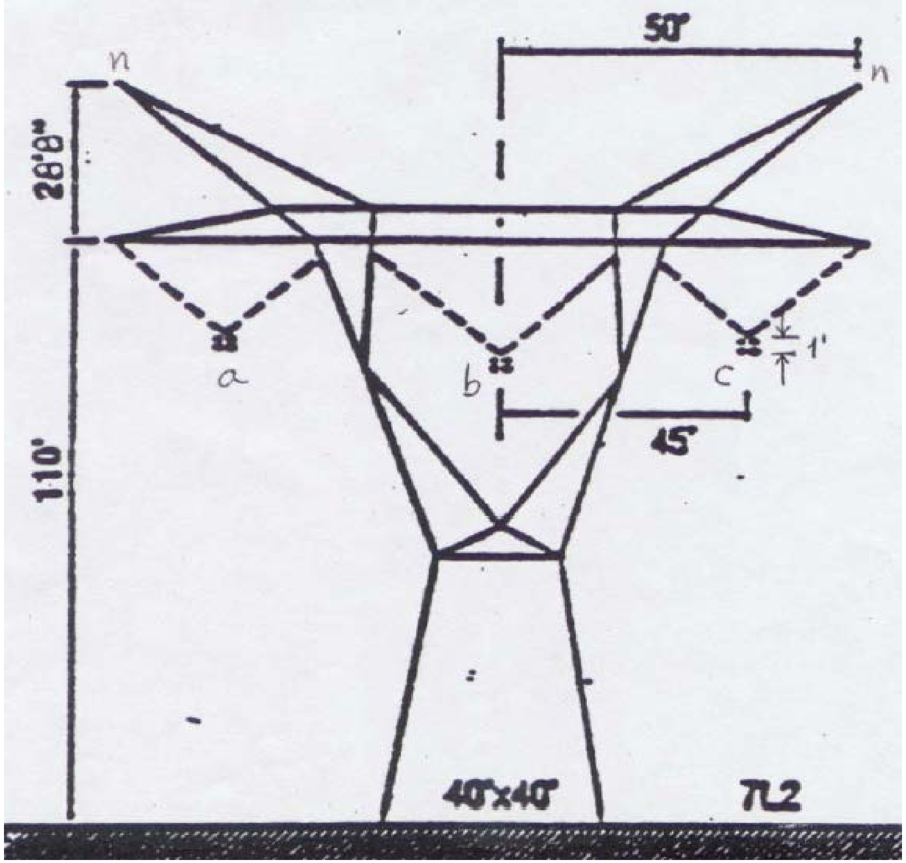


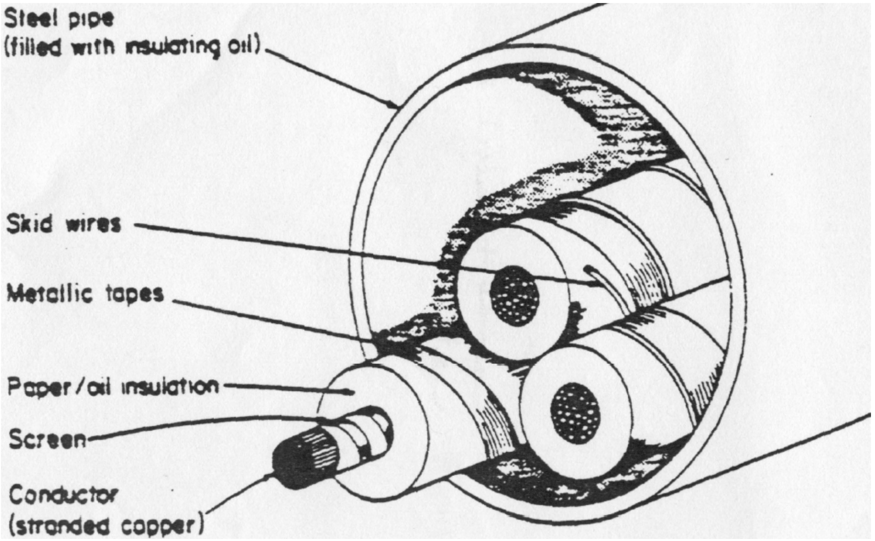
- In these systems, the p.u. per-phase models of the transformers are identical to the equivalent single-phase transformer models.

Saturation

- The magnetization inductance L_m changes with the magnetization current due to saturation of the magnetic core.
- Saturation occurs due to a reduction on the number of “free” magnetic dipoles in the enriched core.
- This results in the core behaving more like air than a magnet, i.e. magnetic “conductivity” decreases.
- It’s typically represented using a piece-wise linear model.

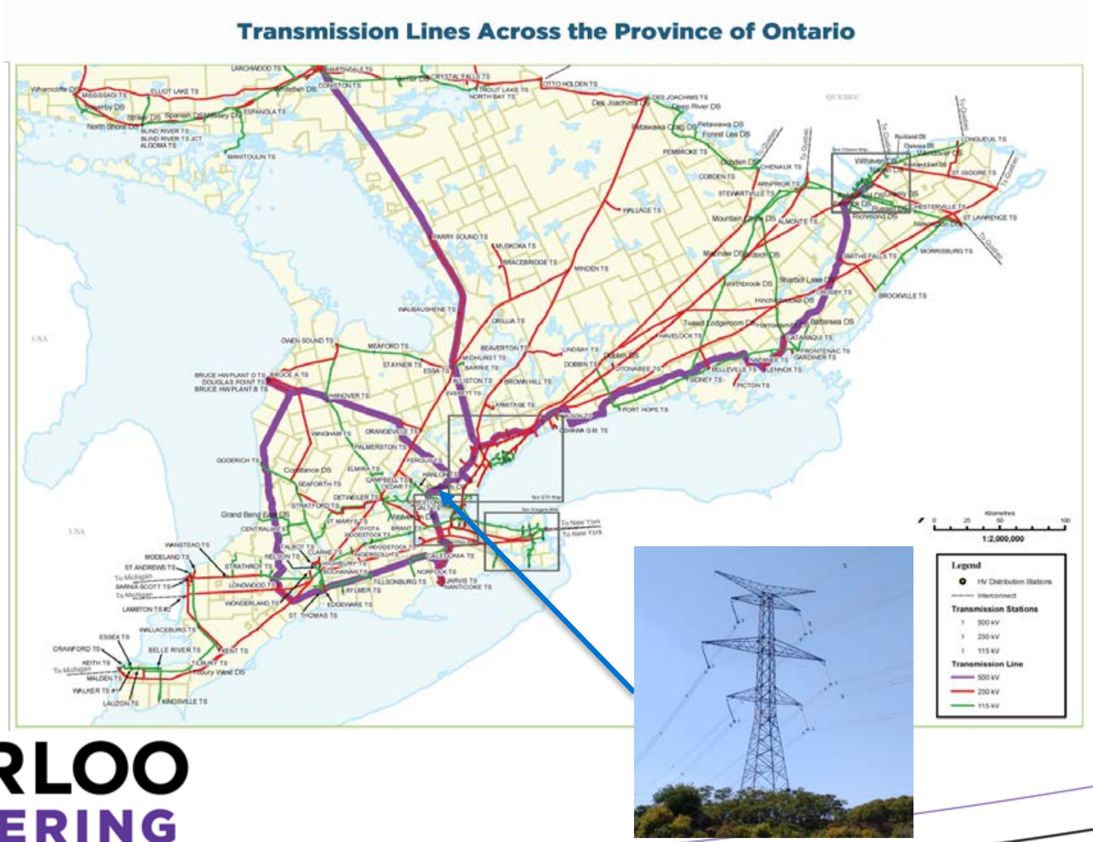
Transmission Lines (and Cables)





Transmission Lines

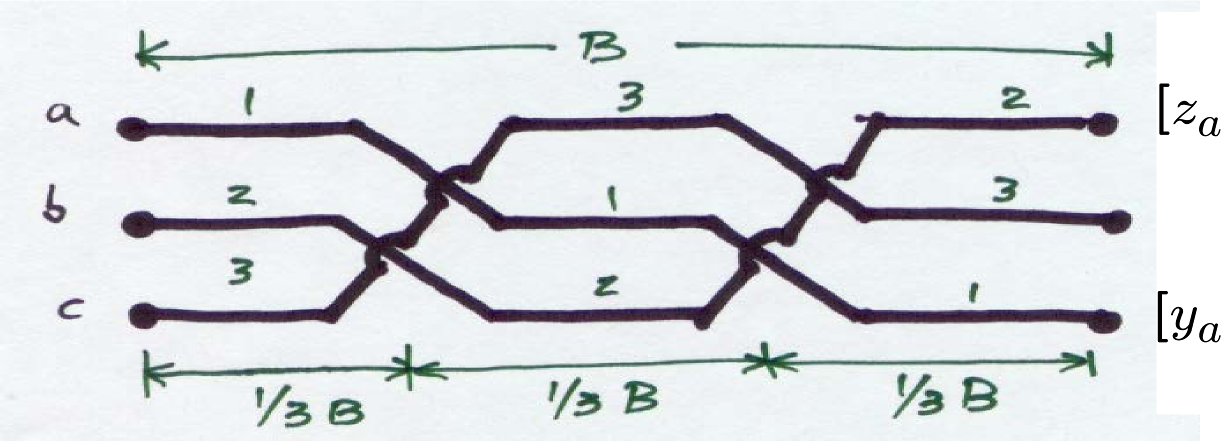
- In transmission systems, most lines are overhead lines, like for example the 500 kV near the 401 in Milton:



Transmission Lines Across the Province of Ontario

Transmission Lines

- If a line is transposed to balance the phases, the length of the barrel *B* must be much less than the wavelength (*s/f* ≈ 5,000 km @ 60 Hz **)** *B* ≈ 50 km), thus leading to:



$$[z_{abc}] = \begin{bmatrix} z_s & z_m & z_m \\ z_m & z_s & z_m \\ z_m & z_m & z_s \end{bmatrix}$$

$$[y_{abc}] = \begin{bmatrix} y_s & y_m & y_m \\ y_m & y_s & y_m \\ y_m & y_m & y_s \end{bmatrix}$$

Transmission Lines

- Sequence transformation: $V_{opn} = T_s^{-1} V_{abc}$
  $I_{opn} = T_s^{-1} I_{abc}$

$$T_s = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \boldsymbol{a}^2 & \boldsymbol{a} \\ 1 & \boldsymbol{a} & \boldsymbol{a}^2 \end{bmatrix} \quad \Rightarrow T_s^{-1} = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \boldsymbol{a} & \boldsymbol{a}^2 \\ 1 & \boldsymbol{a}^2 & \boldsymbol{a} \end{bmatrix}$$

$$\boldsymbol{a} = 1\angle 120^\circ$$

$$\Rightarrow [z_{opn}] = T_s^{-1}[z_{abc}]T_s$$

$$= \begin{bmatrix} \boldsymbol{z}_s + 2\boldsymbol{z}_m & 0 & 0 \\ 0 & \boldsymbol{z}_s - \boldsymbol{z}_m & 0 \\ 0 & 0 & \boldsymbol{z}_s - \boldsymbol{z}_m \end{bmatrix} = \begin{bmatrix} \boldsymbol{z}_o & & \\ & \boldsymbol{z}_p & \\ & & \boldsymbol{z}_n \end{bmatrix}$$

$$\boldsymbol{z}_p = \boldsymbol{z}_n \qquad \boldsymbol{z}_o \approx 3\boldsymbol{z}_p$$

- Similarly for $[y_{opn}] = T_s^{-1} [y_{abc}] T_s$.

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Transmission Lines

- Positive sequence (per-phase) phasor model:

$$\begin{bmatrix} \boldsymbol{V}_1 \\ \boldsymbol{I}_1 \end{bmatrix} = \begin{bmatrix} \cosh \gamma d & \boldsymbol{Z}_c \sinh \gamma d \\ 1/\boldsymbol{Z}_c \sinh \gamma d & \cosh \gamma d \end{bmatrix} \begin{bmatrix} \boldsymbol{V}_2 \\ -\boldsymbol{I}_2 \end{bmatrix}$$

$$= \begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{D} \end{bmatrix} \begin{bmatrix} \boldsymbol{V}_2 \\ -\boldsymbol{I}_2 \end{bmatrix}$$

$$\cosh \gamma d = \frac{e^{\gamma d} + e^{-\gamma d}}{2}$$

$$\sinh \gamma d = \frac{e^{\gamma d} - e^{-\gamma d}}{2}$$

$$\gamma = \sqrt{\boldsymbol{z}\,\boldsymbol{y}} \quad \rightarrow \quad \text{propagation constant}$$

$$\boldsymbol{Z}_c = \sqrt{\frac{\boldsymbol{z}}{\boldsymbol{y}}} \quad \rightarrow \quad \text{characteristic impedance}$$

Transmission Lines

$$\boldsymbol{z} = r + j\omega l \qquad \boldsymbol{y} = j\omega c$$

$$r = \frac{r_{\text{tables}}}{N_b} \ [\Omega/\text{m}] \qquad l = \frac{\mu_o}{2\pi} \ln \frac{D_m}{R_b'} \ [\text{H/m}] \qquad c = \frac{2\pi\epsilon_o}{\ln \frac{D_m}{R_b}} \ [\text{F/m}]$$

$$\mu_o = 4\pi \times 10^{-7} \ [\text{H/m}] \qquad \epsilon_o = 8.854 \times 10^{-12} \ [\text{F/m}]$$

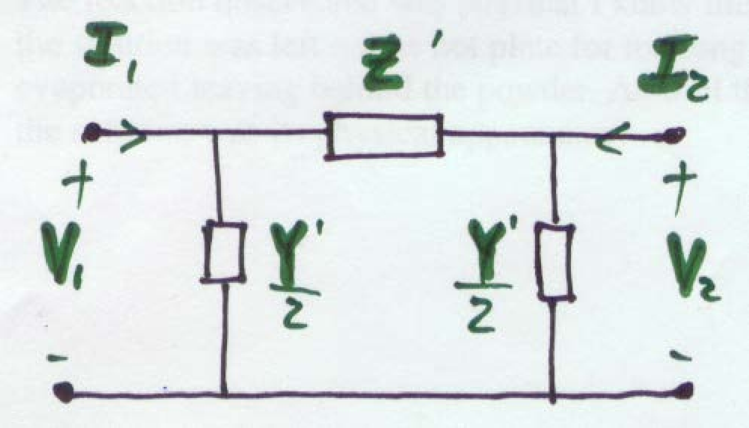
D_m is the GMD of the 3 phases: $D_m = \sqrt[3]{d_{ab}\, d_{ac}\, d_{bc}}$

R_b' is the GMR of the bundled (N_b) and wires: $R_b' = \sqrt[N_b]{R' d_{12}\, d_{13} \cdots d_{1N_b}}$

R_b is the GMR of the bundled: $R_b = \sqrt[N_b]{R\, d_{12}\, d_{13} \cdots d_{1N_b}}$

Transmission Lines

- This can be converted into the Π equivalent circuit:



$$Z' = \underbrace{\boldsymbol{z}\, d}_{\boldsymbol{Z}} \frac{\sinh \gamma d}{\gamma d}$$

$$\boldsymbol{Y}' = \underbrace{\boldsymbol{y}\, d}_{\boldsymbol{Y}} \frac{\tanh(\gamma d/2)}{\gamma d/2}$$

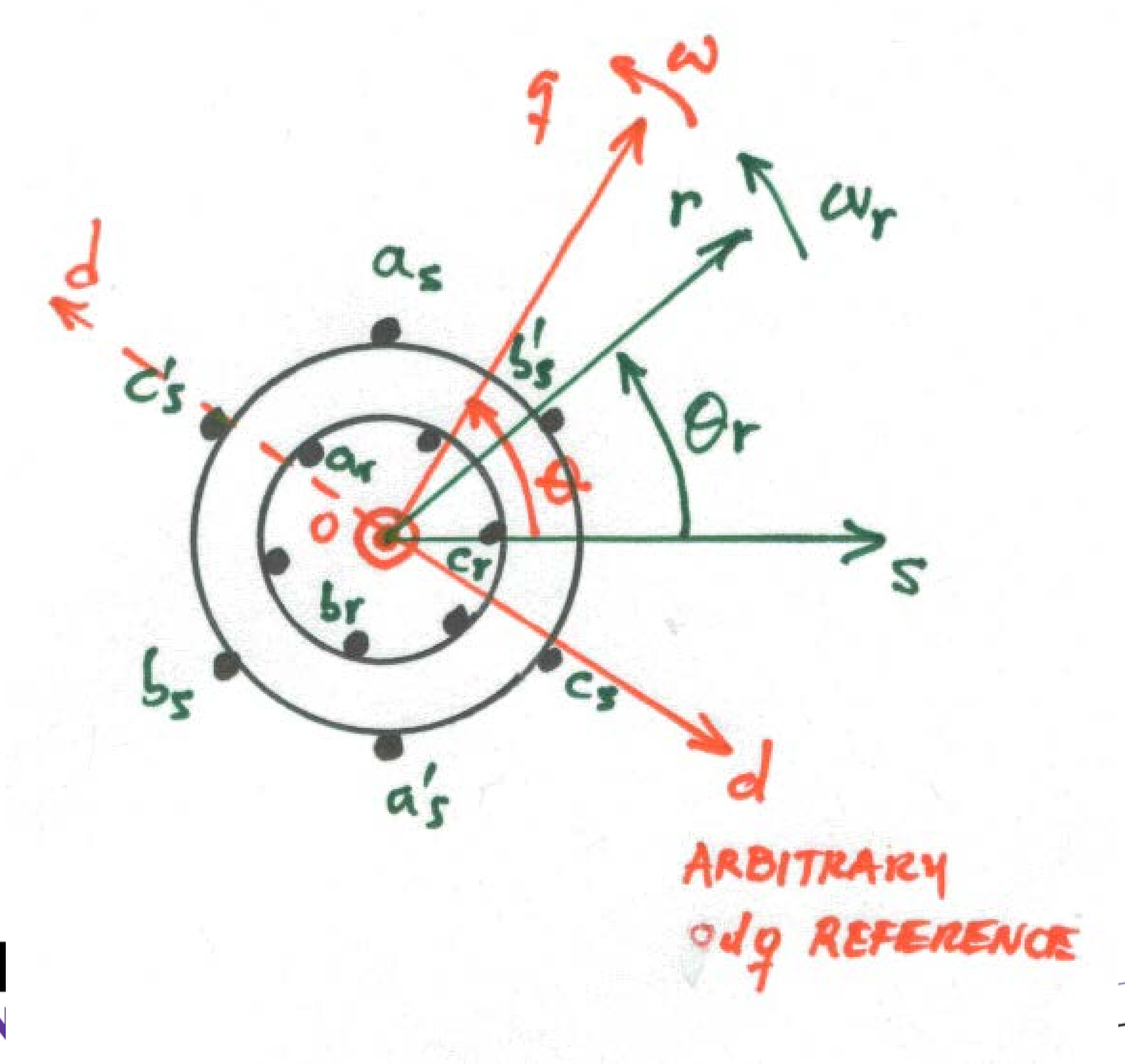
$$\text{for } d < 250\text{km} \Rightarrow \boldsymbol{Z}' \approx \boldsymbol{Z} \qquad \boldsymbol{Y}' \approx \boldsymbol{Y}$$

$$\text{for } d < 100\text{km} \Rightarrow \boldsymbol{Z}' \approx \boldsymbol{Z} \qquad \boldsymbol{Y}' \approx 0$$

Loads

- Load classification by demand level:
  - Residential: lighting and heating (RL + controls); AC (motor + controls); appliances (small motors + controls)
  - Commercial: similar types of devices as residential.
  - Industrial: motor drives (induction and dc motor-based mostly); arc furnaces; lighting; heating; others (e.g. special motor drives).
- By type:
  - RLC + controls
  - Drives: ac/dc motors + electronic controls
  - Special (e.g. arc furnaces).
- Most controls are implemented using a variety of power electronic converters.
- Aggregate load models are necessary at the transmission system modeling level; only large loads are represented with their actual models.

Induction Motor



Induction Motor

- Assuming a balanced, fundamental frequency ($\omega = \omega_o$) system, the model can be reduced to a p.u. “transient” model (3rd order model):

$$
\begin{aligned}
\boldsymbol{V}_{as} &= V_{as_R} + jV_{as_I} \\
\boldsymbol{I}_{as} &= I_{as_R} + jI_{as_I}
\end{aligned}
$$

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}E'_R &= \omega_o\, S\, E'_I - \frac{1}{T'_o}\left[E'_R + \left(X_S - X'\right) I_{as_I}\right] \\
\frac{\mathrm{d}}{\mathrm{d}t}E'_I &= -\omega_o\, S\, E'_R - \frac{1}{T'_o}\left[E'_I - \left(X_S - X'\right) I_{as_R}\right] \\
V_{as_R} - E'_R &= r_S I_{as_R} - X' I_{as_I} \\
V_{as_I} - E'_I &= r_S I_{as_I} + X' I_{as_R}
\end{aligned}
$$

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}S &= \frac{1}{H}(T_L - T_e + D\omega_o - DS) \\
T_e &= \frac{1}{\omega_o}(E'_R I_{as_R} + E'_I I_{as_R}) \\
T_L &= f(S)
\end{aligned}
$$

Induction Motor

$$S = \frac{\omega_o - \omega_r}{\omega_o} \rightarrow \text{slip}$$

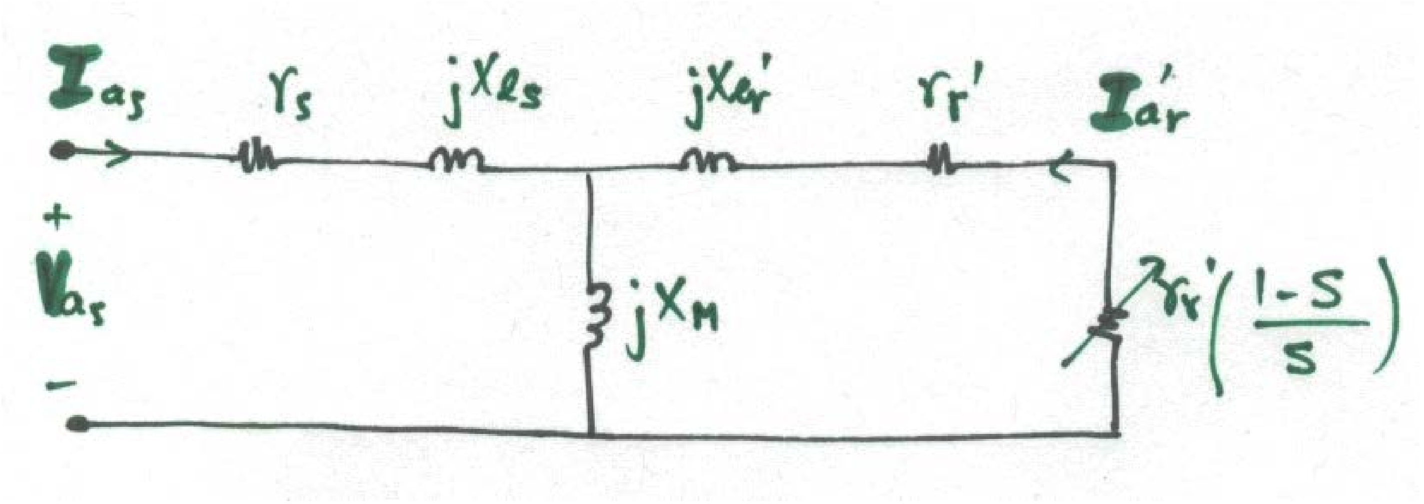
$$X_S = X_{ls} + X_M \rightarrow \text{stator reactance}$$

$$X' = X_{ls} + \frac{X'_{lr} X_M}{X'_{lr} + X_M} \rightarrow \text{transient reactance}$$

$$T'_o = \frac{X'_{lr} + X_M}{\omega_o r'_r} \rightarrow \text{open circuit transient time constant}$$

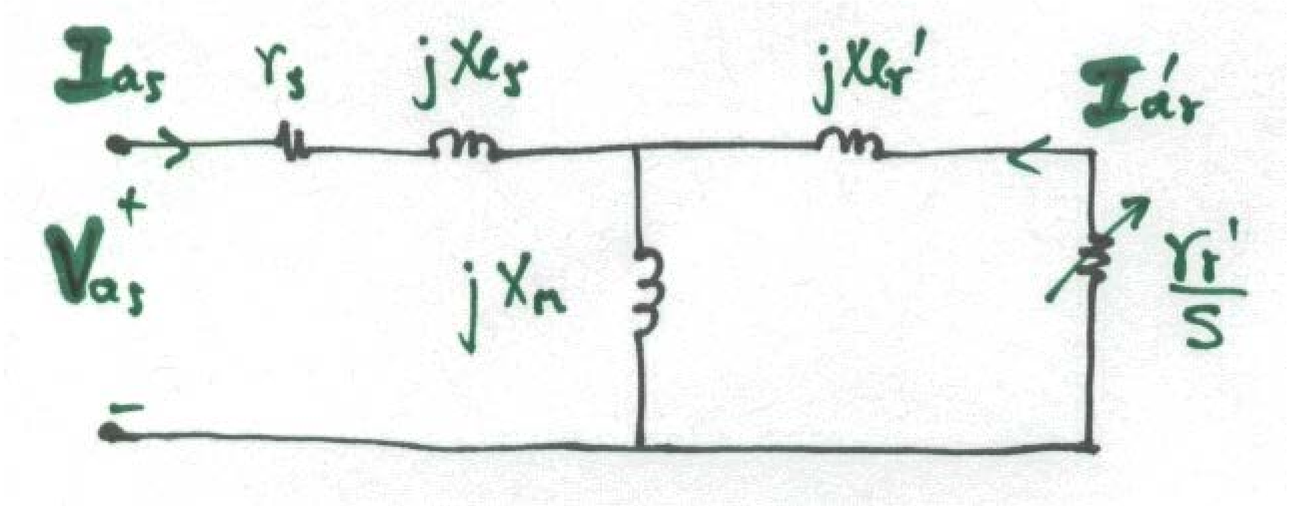
Induction Motor

- If the electromagnetic transients are neglected, the system can be reduced to the following quasi-steady state equivalent circuit model:



Induction Motor

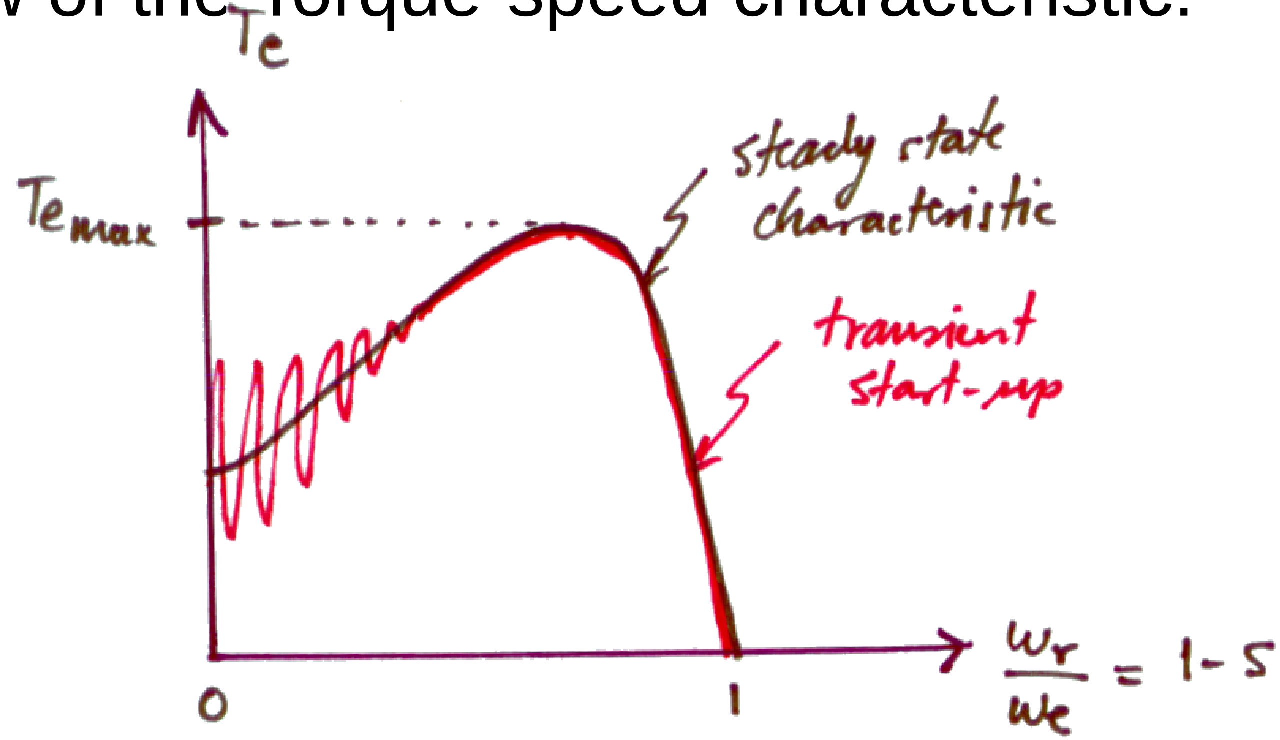
- Or equivalently:



- Plus the mechanical equations.

Induction Motor

- This simplification can be justified from the point of view of the Torque-speed characteristic:



Induction Motor

- If the mechanical dynamics are ignored, the slip S becomes a fixed value, and hence the equivalent circuit can be reduced to a simple equivalent reactive impedance, i.e. a Z load.
- For loads with multiple IMs, an equivalent motor model can be used to represent these motors.
- Neglecting the motor dynamic equations in large or equivalent aggregate motors can lead to significant modeling errors, as the transient model and mechanical time constants can be on the same range as the generator time constants.
- Double-cage IMs can be modeled by introducing an additional inductance on the rotor side, which leads to a “subtransient” model.

Impedance Load Models

- Ignoring “fast” and “slow” transients, certain loads can be represented using an equivalent impedance.
- A Z load model is typically used for a variety of dynamic analysis of power systems.
- Using these load models, an equivalent impedance can be readily obtained for all loads connected at a particular bus at the transmission system level.
- ULTCs are used to connect distribution systems (subtransmission and LV systems and the loads connected to these) to the transmission system to control the steady state voltage on the load side.

Power Load Models

- Hence, for “slow” dynamic analysis of balanced, fundamental frequency system models:

$$\begin{aligned} P_L &= V_L^2\, G_L = P_{Lo}\left(\frac{V_L}{V_{Lo}}\right)^2 \\ Q_L &= V_L^2\, B_L = Q_{Lo}\left(\frac{V_L}{V_{Lo}}\right)^2 \end{aligned}$$

$$V_L \approx V_{Lo} \;\Rightarrow\; \begin{aligned} P_L &\approx P_{Lo} \\ Q_L &\approx Q_{Lo} \end{aligned}$$

- This is typically referred as a constant PQ model.

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Power Load Models

- Load recovery of certain loads (e.g thermostatic) with respect to voltage changes can be modeled as:

$$\frac{\mathrm{d}x(t)}{\mathrm{d}t} = -\frac{x(t)}{T_p} + P_{Lo}\left[\frac{V_L(t)}{V_{Lo}}\right]^{N_{ps}} - P_{Lo}\left[\frac{V_L(t)}{V_{Lo}}\right]^{N_{pt}}$$

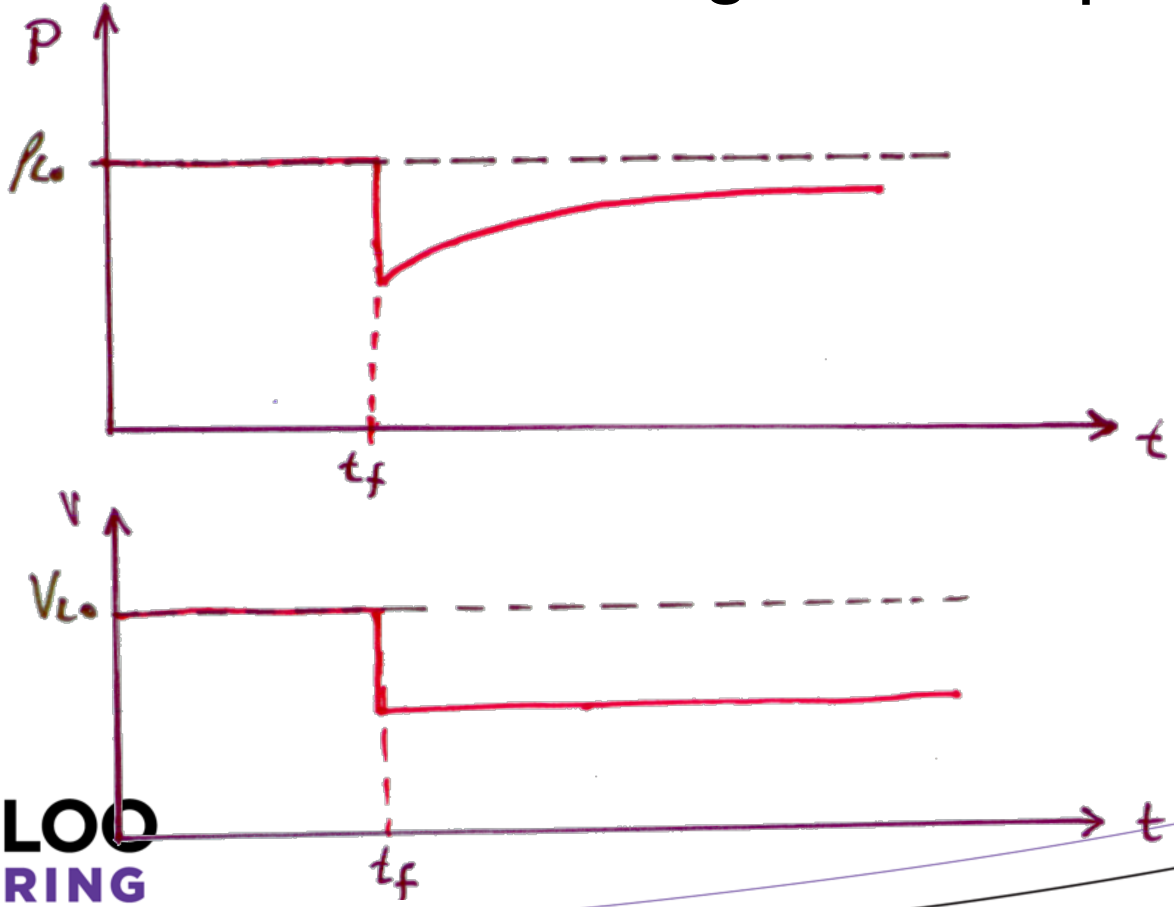
$$P_L(t) = \frac{x(t)}{T_p} + P_{Lo}\left[\frac{V_L(t)}{V_{Lo}}\right]^{N_{pt}}$$

$$\frac{\mathrm{d}y(t)}{\mathrm{d}t} = -\frac{y(t)}{T_q} + Q_{Lo}\left[\frac{V_L(t)}{V_{Lo}}\right]^{N_{qs}} - Q_{Lo}\left[\frac{V_L(t)}{V_{Lo}}\right]^{N_{qt}}$$

$$Q_L(t) = \frac{y(t)}{T_q} + Q_{Lo}\left[\frac{V_L(t)}{V_{Lo}}\right]^{N_{qt}}$$

Power Load Models

- This results in the following time response:



Power Load Models

- Certain loads have been shown to behave in steady state as follows:

$$\left.\begin{aligned} P_L &= K_P\, V_L^{\alpha_P}\, f_L^{\beta_P} \approx P_{Lo} \left(\frac{V_L}{V_{Lo}}\right)^{\alpha_P} \\ Q_L &= K_Q\, V_L^{\alpha_Q}\, f_L^{\beta_Q} \approx Q_{Lo} \left(\frac{V_L}{V_{Lo}}\right)^{\alpha_Q} \end{aligned}\right\} \rightarrow \text{as } f \approx f_o$$

Type	α_P	α_Q	β_P	β_Q
Filament lamps	1.6	0	0	0
Fluorecent lamps	1.2	3	-1	-2.8
Heater	2	0	0	0
IM at half load	0.2	1.6	1.5	-0.3
IM at full load	0.1	0.6	2.8	1.8
Reduction furnace	1.9	2.9	-0.5	0
Aluminum plant	1.8	2.2	-0.3	0.6

Power Load Models

- ZIP model:

$$\begin{aligned} P_L &= P_{L_Z}\left(\frac{V_L}{V_{Lo}}\right)^2 + P_{L_I}\left(\frac{V_L}{V_{Lo}}\right) + P_{L_P} \\ Q_L &= Q_{L_Z}\left(\frac{V_L}{V_{Lo}}\right)^2 + Q_{L_I}\left(\frac{V_L}{V_{Lo}}\right) + Q_{L_P} \end{aligned}$$

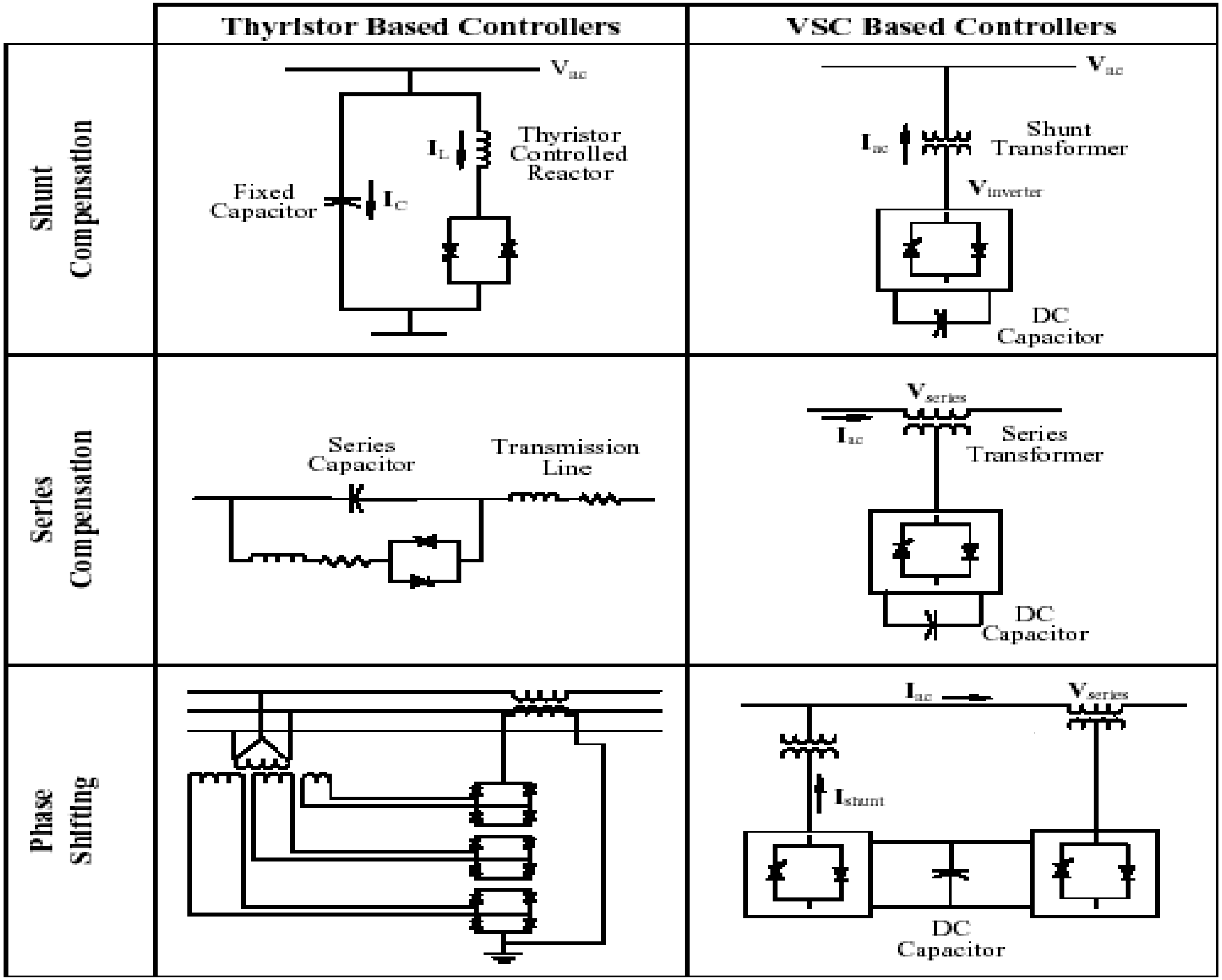
Power Load Models

- Mixed dynamic model:

$$\begin{aligned} P_L &= K_{pf}\, f + K_{pv}\left[V_L^{\alpha} + T_{pv}\,\frac{\mathrm{d}V_L}{\mathrm{d}t}\right] \\ &\approx P_{Lo} + K_{pv}\left[(V_L - V_{Lo})^{\alpha} + T_{pv}\,\frac{\mathrm{d}V_L}{\mathrm{d}t}\right] \end{aligned}$$

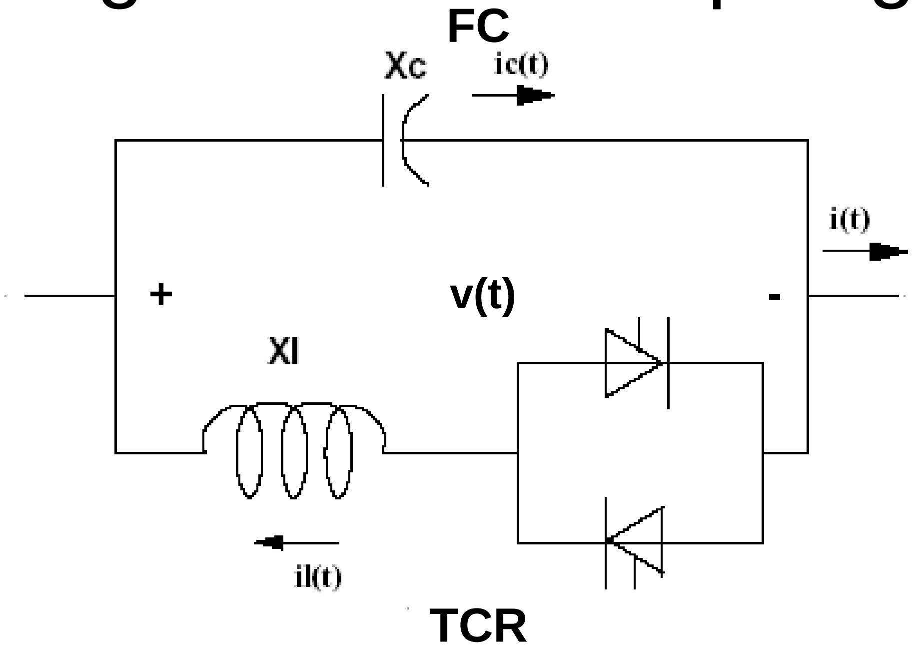
$$\begin{aligned} Q_L &= K_{qf}\, f + K_{qv}\left[V_L^{\beta} + T_{qv}\,\frac{\mathrm{d}V_L}{\mathrm{d}t}\right] \\ &\approx Q_{Lo} + K_{qv}\left[(V_L - V_{Lo})^{\beta} + T_{qv}\,\frac{\mathrm{d}V_L}{\mathrm{d}t}\right] \end{aligned}$$

FACTS


Thyristor Based Controllers
VSC Based Controllers
Shunt Compensation
Series Compensation
Phase Shifting
V_{ac}
I_L
Thyristor Controlled Reactor
Fixed Capacitor
I_C
V_{ac}
I_{ac}
Shunt Transformer
V_{inverter}
DC Capacitor
Series Capacitor
Transmission Line
V_{series}
I_{ac}
Series Transformer
DC Capacitor
I_{ac}
V_{series}
I_{shunt}
DC Capacitor

TCR-FC

- SVC and TCSC controllers are based on the following basic circuit topology:



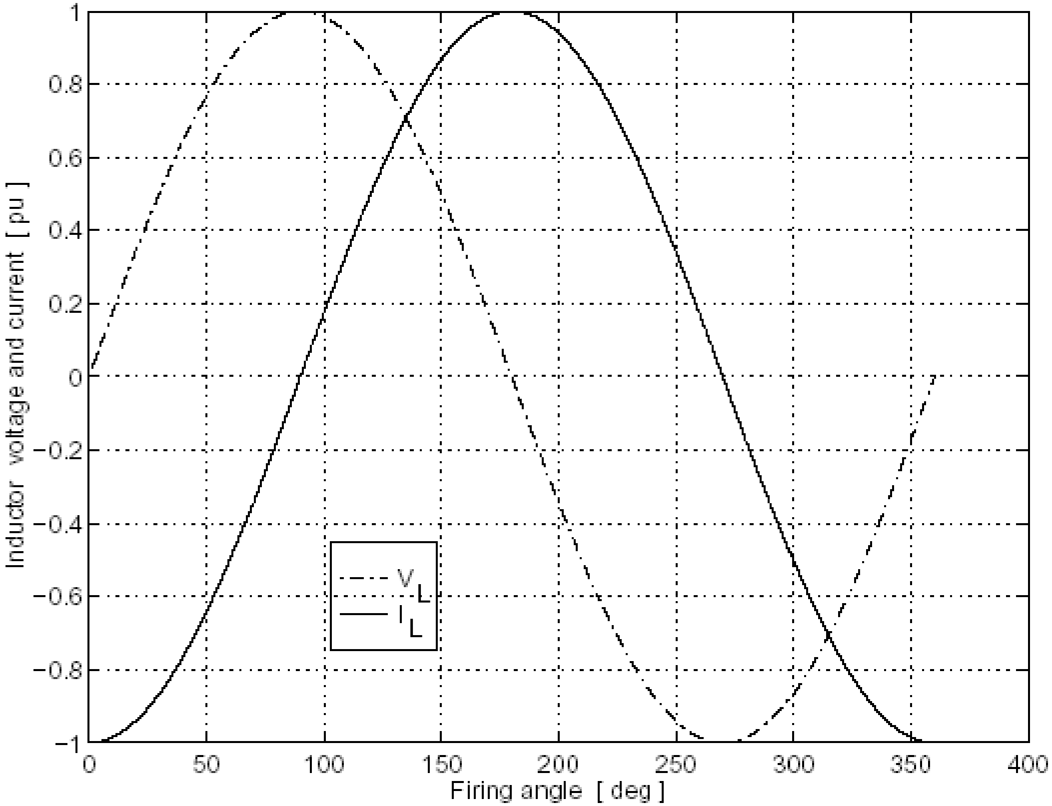
TCR-FC

- Each thyristor is “fired” every half cycle.
- The firing angle *α* is “synchronized” with respect to the zero-crossing of the voltage (or current).
- Hence, $90^o \leq \alpha \leq 180^o$ for the TCR, since:

$$\begin{aligned} v(t) &= \sqrt{2}V\,\mathsf{sin}(\omega t) \\ \Rightarrow\; i_L(t) &= -\frac{1}{L}\int v(t)\mathsf{d}t \\ &= -\sqrt{2}I\,\mathsf{cos}(\omega t) \end{aligned}$$

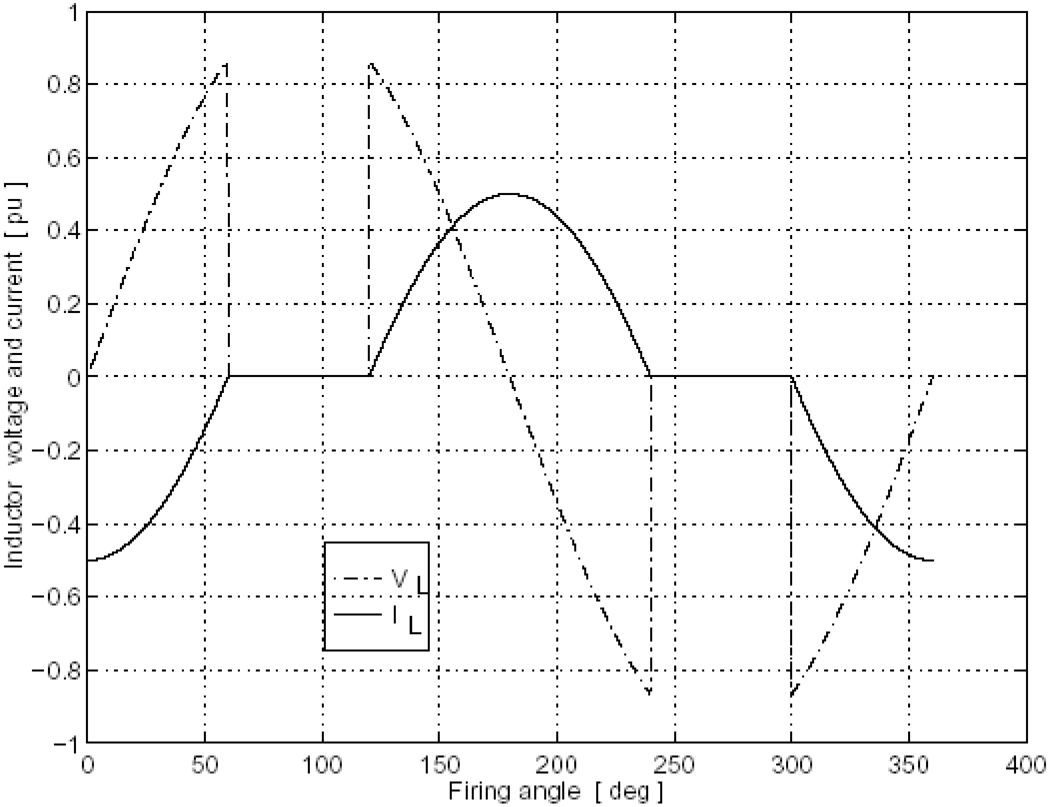
TCR-FC

- For $\alpha = 90^o \Rightarrow$ full X_l (inductive)



TCR-FC

- For $\alpha = 120^o \Rightarrow$ less inductive, more capacitive



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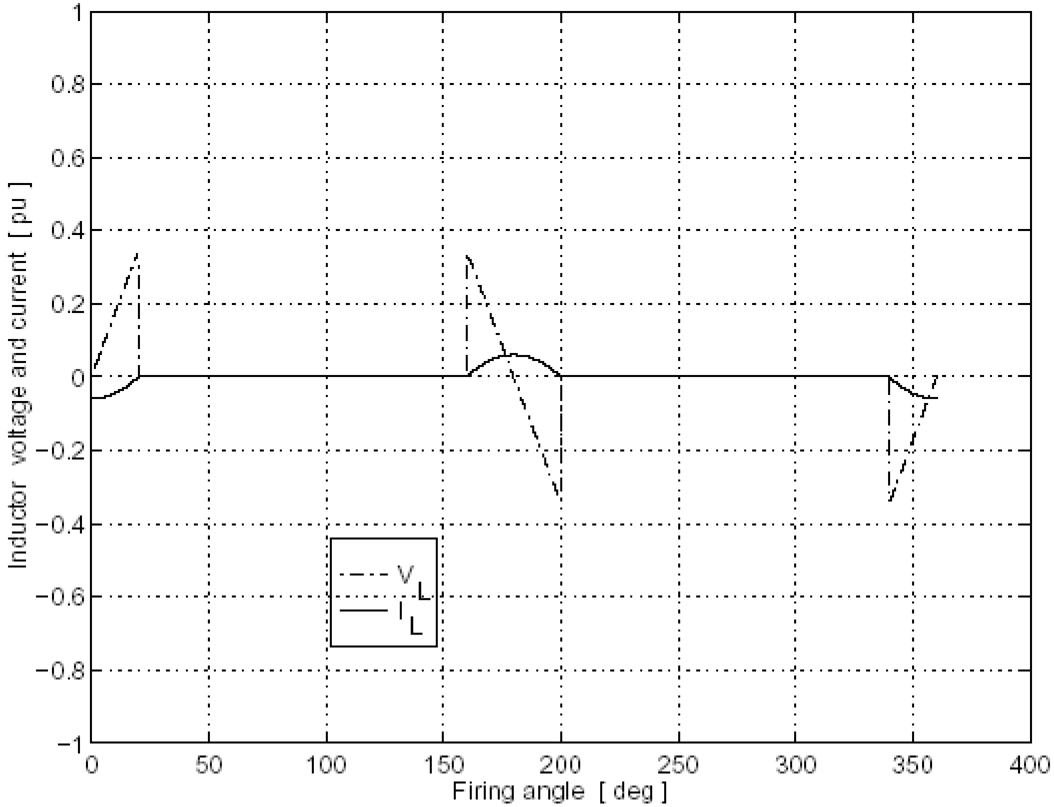
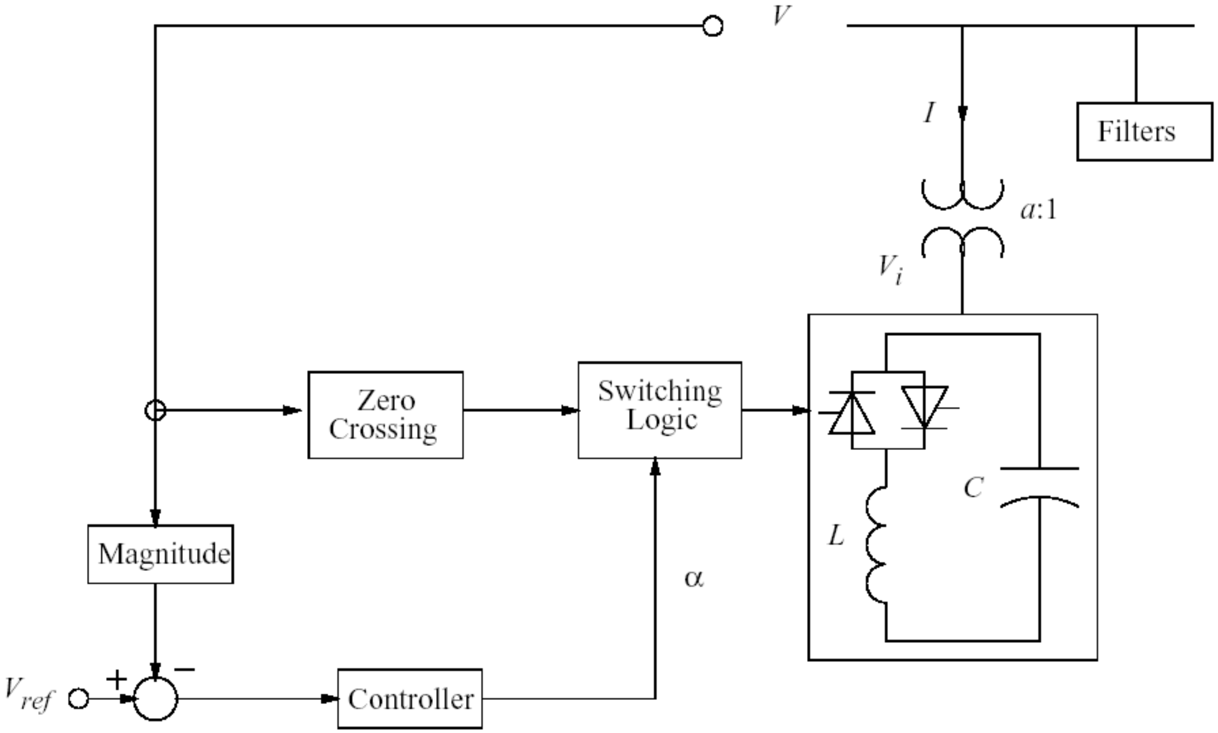
TCR-FC

- For $\alpha = 160^{o} \Rightarrow$ mostly capacitive, since $i_l(t) \approx 0$



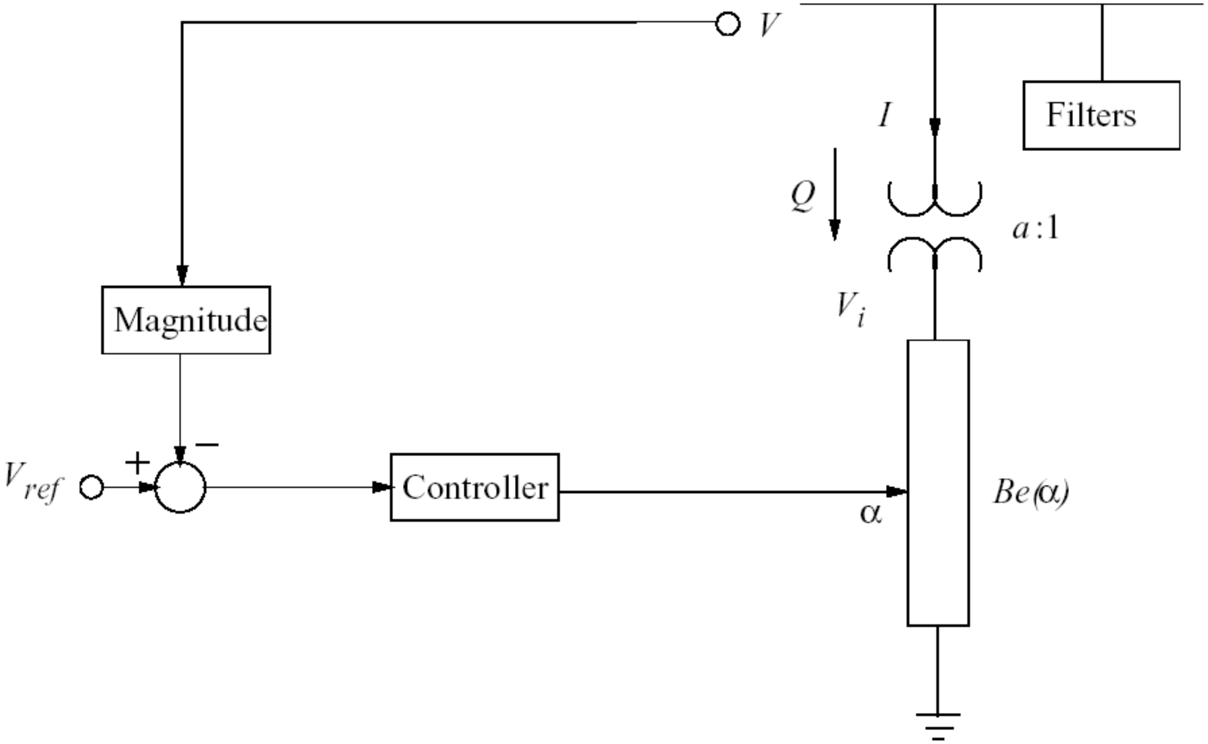
SVC



V
I
Filters
a:1
V_i
Zero Crossing
Switching Logic
C
L
Magnitude
α
V_{ref}
+
−
Controller

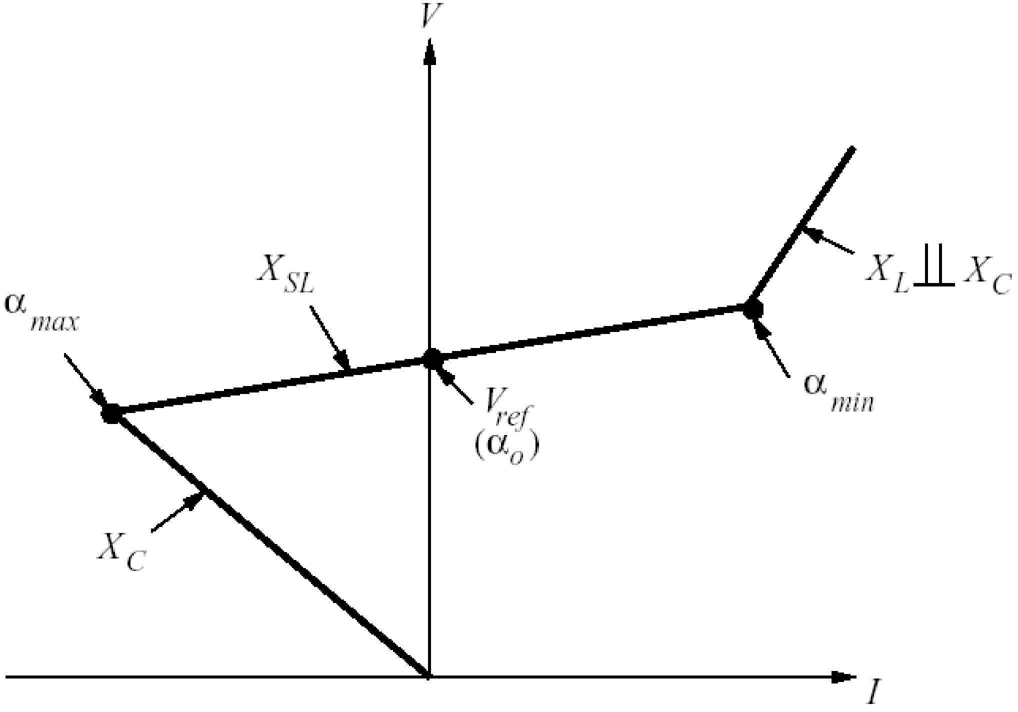
SVC

- Assuming a sinusoidal bus voltage under balanced, fundamental frequency operation, the controller can be modeled as:

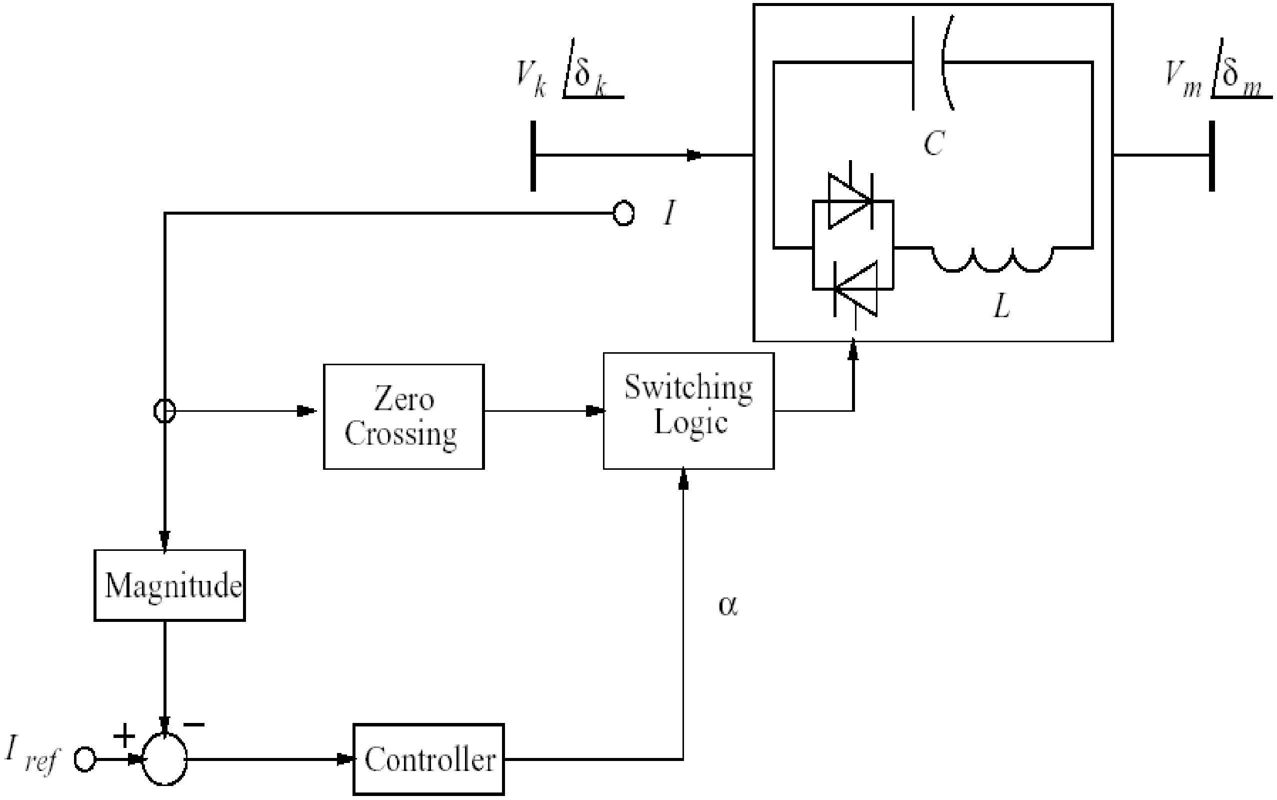


SVC

- This yields the following steady state control characteristic:

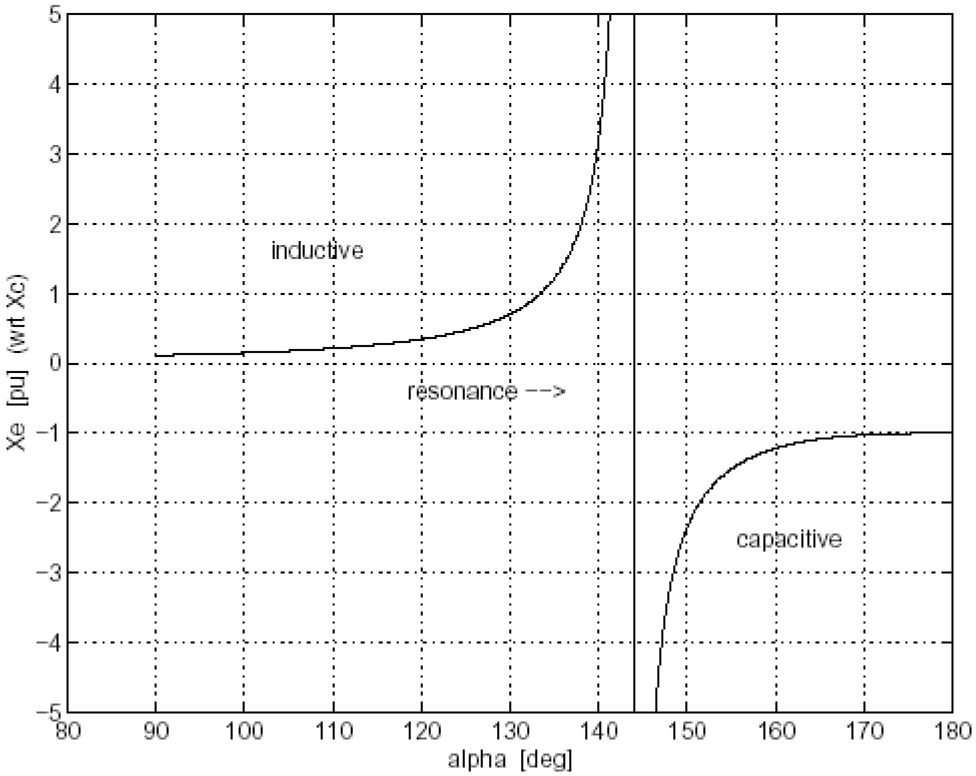


TCSC


$V_k \angle \delta_k$
C
$V_m \angle \delta_m$
I
L
Zero Crossing
Switching Logic
Magnitude
α
I_{ref}
+
−
Controller

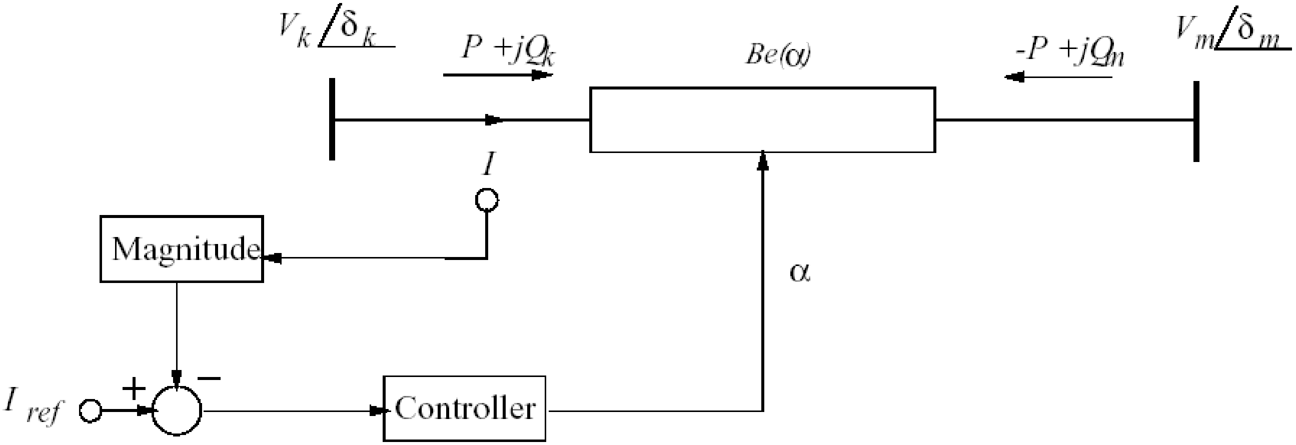
TCSC

- The controller has a resonant point that must to be avoided, as the controller becomes an open circuit:



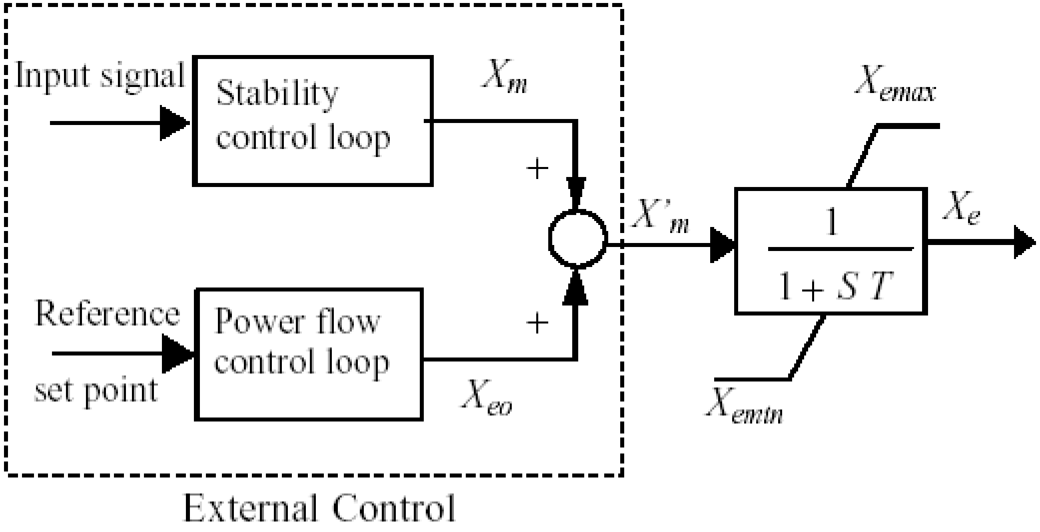
TCSC

- Thus, the controller limits on *α* have two regions to avoid the resonant point (harmonics are high near this point).
- Assuming a sinusoidal line current, the balanced, fundamental frequency model for this controllers is:



TCSC

- Most stability programs use a variable impedance model to represent the TCSC, with limits defined by the corresponding *α* limits.
- The typical control for this type of model is:



TCSC

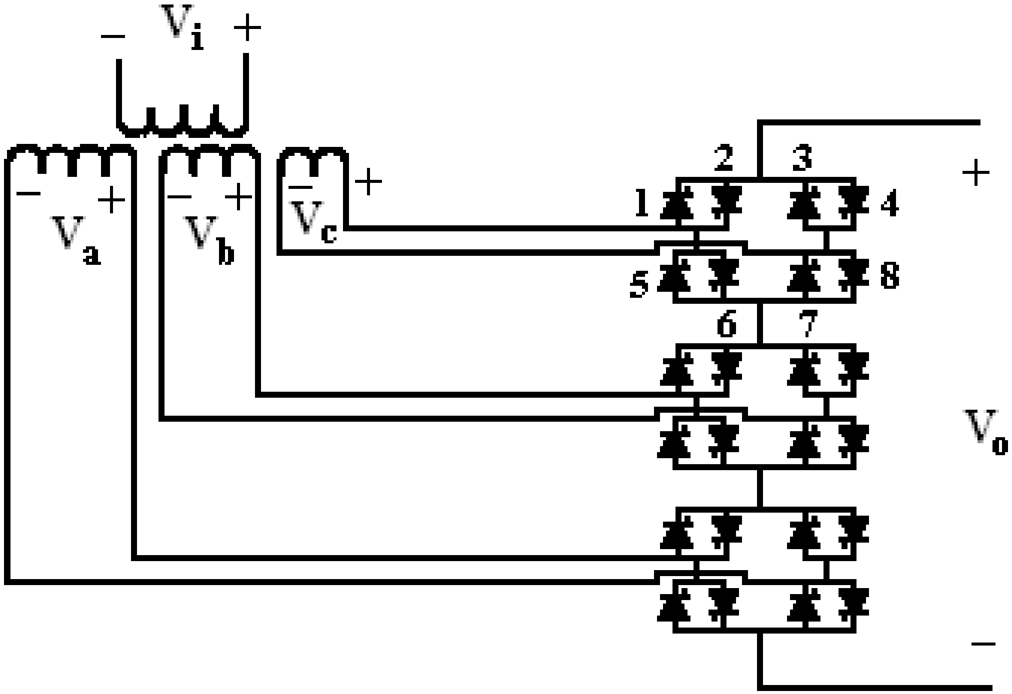
- The power flow or “slow” control is designed to maintain a constant controller impedance.
- The stability or “fast” control is usually designed to reduced system oscillations after contingencies.
- The typical use of this type of controller in practice is for the control of inter-area oscillations (e.g. North-South ac interconnection in Brazil).
- For simple series compensation, MSC are a much cheaper option; however, these can lead to Sub-synchronous Resonance (SSR) problems.

TCVR & TCPAR

- TCVR and TCPAR are basically ULTC and phase-shifters, respectively, with thyristor switching as opposed to electromechanical switching.
- Thus, these controllers have better dynamic response, i.e. smaller time constants, than the corresponding electromechanical-based devices.
- Controls are typically discrete, but with certain designs these can be continuous.

TCVR & TCPAR

- The typical topology is:

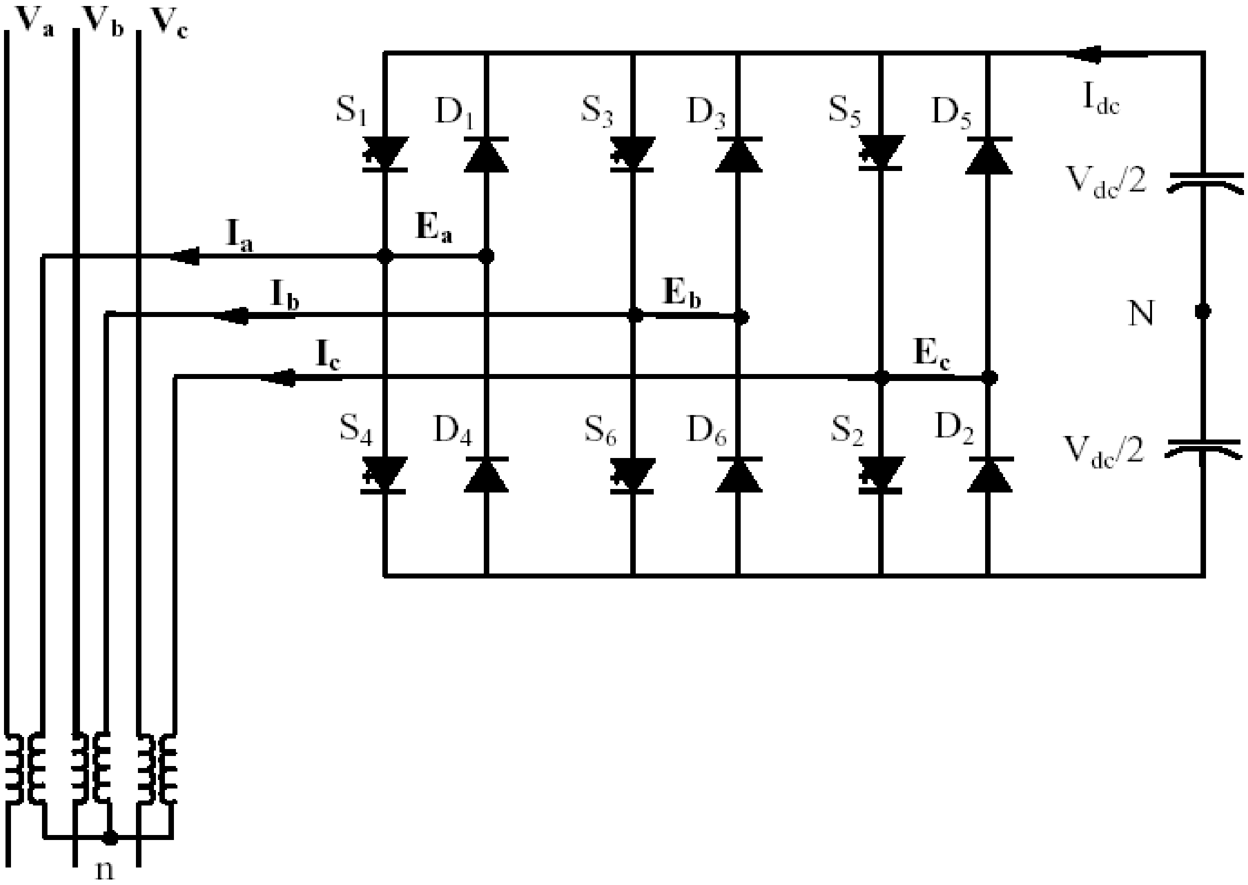


TCVR & TCPAR

  - Valves 1 and 7 (positive cycle), and 2 and 8 (negative cycle) add V_c to V_o.
  - Valves 3 and 5 (positive cycle), and 4 and 6 (negative cycle) add $-V_c$ to V_o.
  - Valves 1 and 5 (positive cycle), and 2 and 6 (negative cycle) cancel V_c; similarly for 3-4 and 7-8.
- These devices are typically modeled as ULTC and phase-shifters in dynamic and steady state studies.

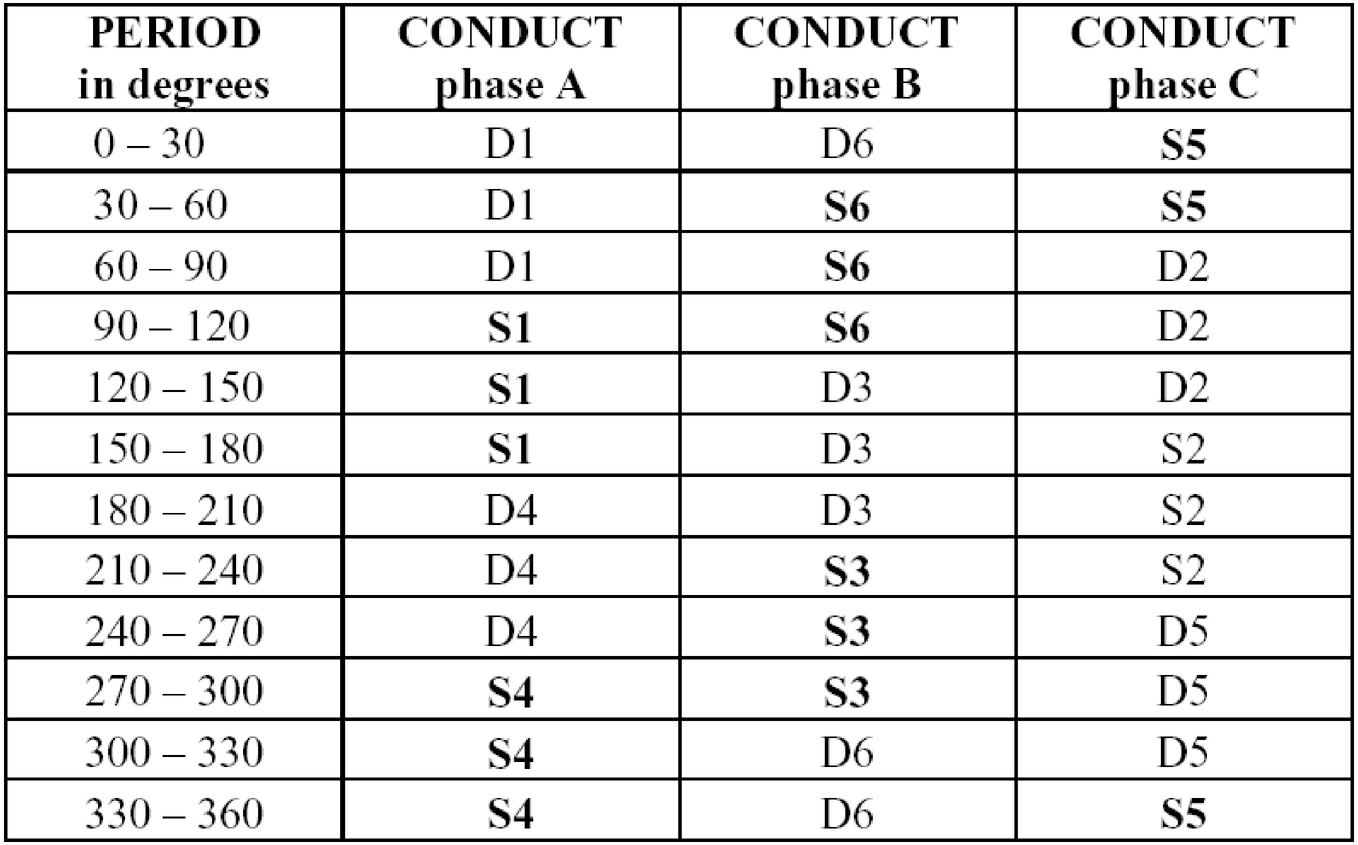
VSC

- Typical six pulse VSC with IGBT/GTO switches:



VSC

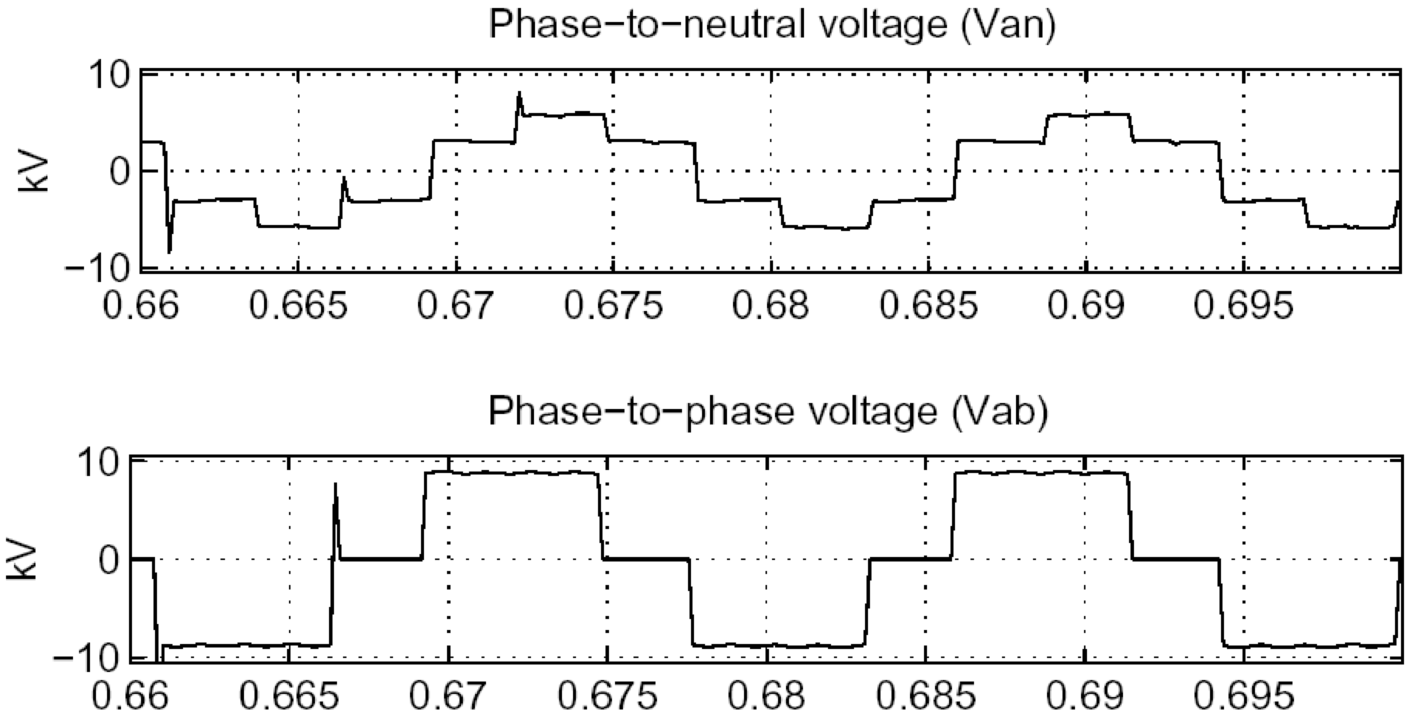
- Switching scheme:



PERIOD in degrees	**CONDUCT phase A**	**CONDUCT phase B**	**CONDUCT phase C**
0 – 30	D1	D6	**S5**
30 – 60	D1	**S6**	**S5**
60 – 90	D1	**S6**	D2
90 – 120	**S1**	**S6**	D2
120 – 150	**S1**	D3	D2
150 – 180	**S1**	D3	S2
180 – 210	D4	D3	S2
210 – 240	D4	**S3**	S2
240 – 270	D4	**S3**	D5
270 – 300	**S4**	**S3**	D5
300 – 330	**S4**	D6	D5
330 – 360	**S4**	D6	**S5**

VSC

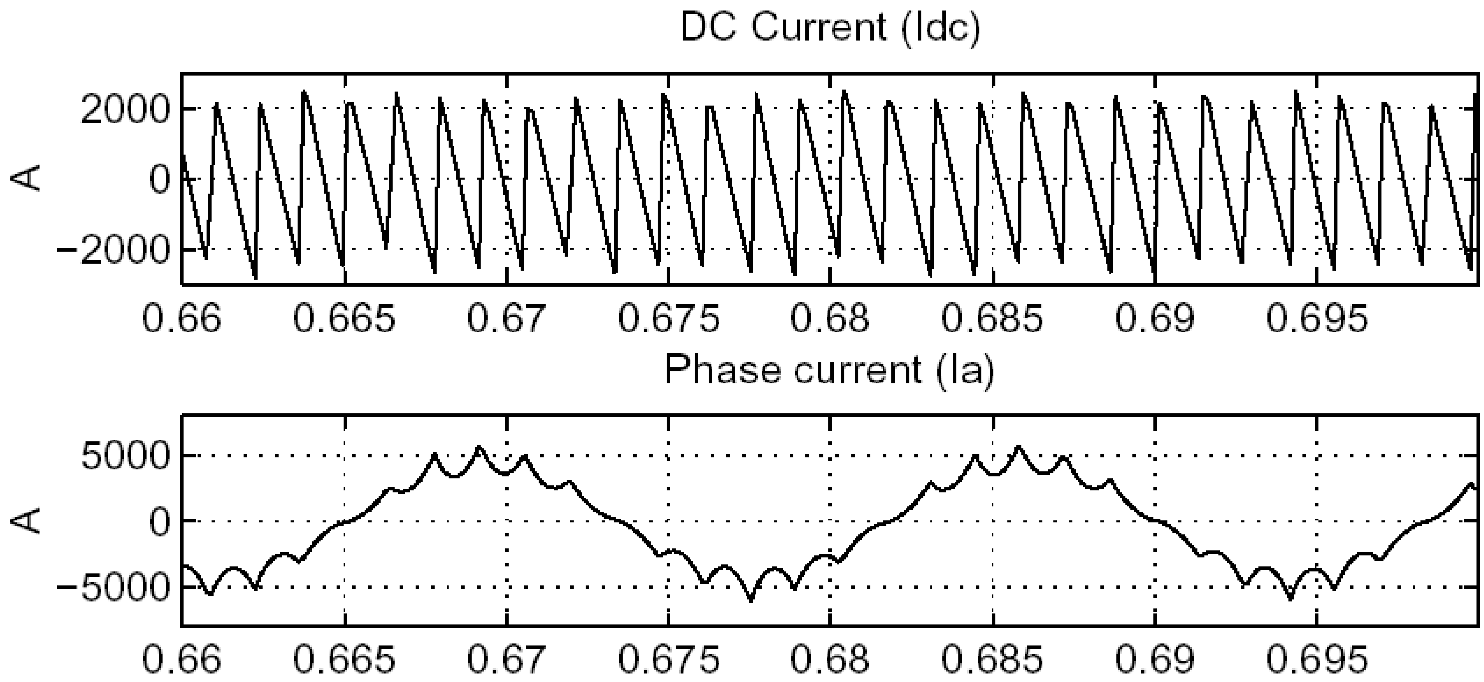
- Modeling full commutation:



Phase−to−neutral voltage (Van)

Phase−to−phase voltage (Vab)

VSC

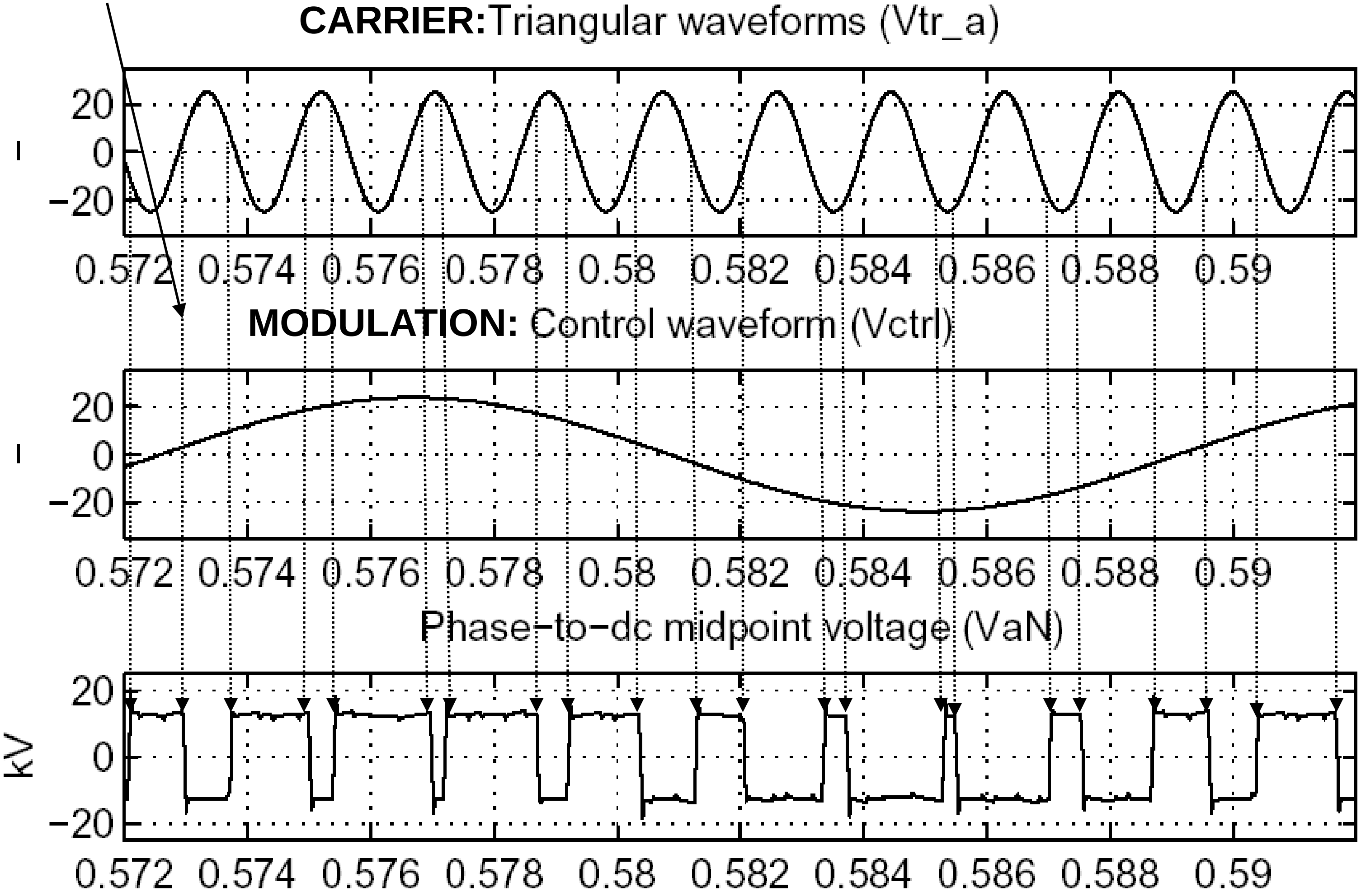


- Observe the high content of harmonics in the ac voltages and currents.

VSC

- Pulse-width modulation (PWM) control techniques may also be used (“popular” in low voltage level applications).
- Beside the control advantages, this technique eliminates certain lower harmonics, although it creates high level harmonics.
- For example, for a 6-pulse VSC:

VSC



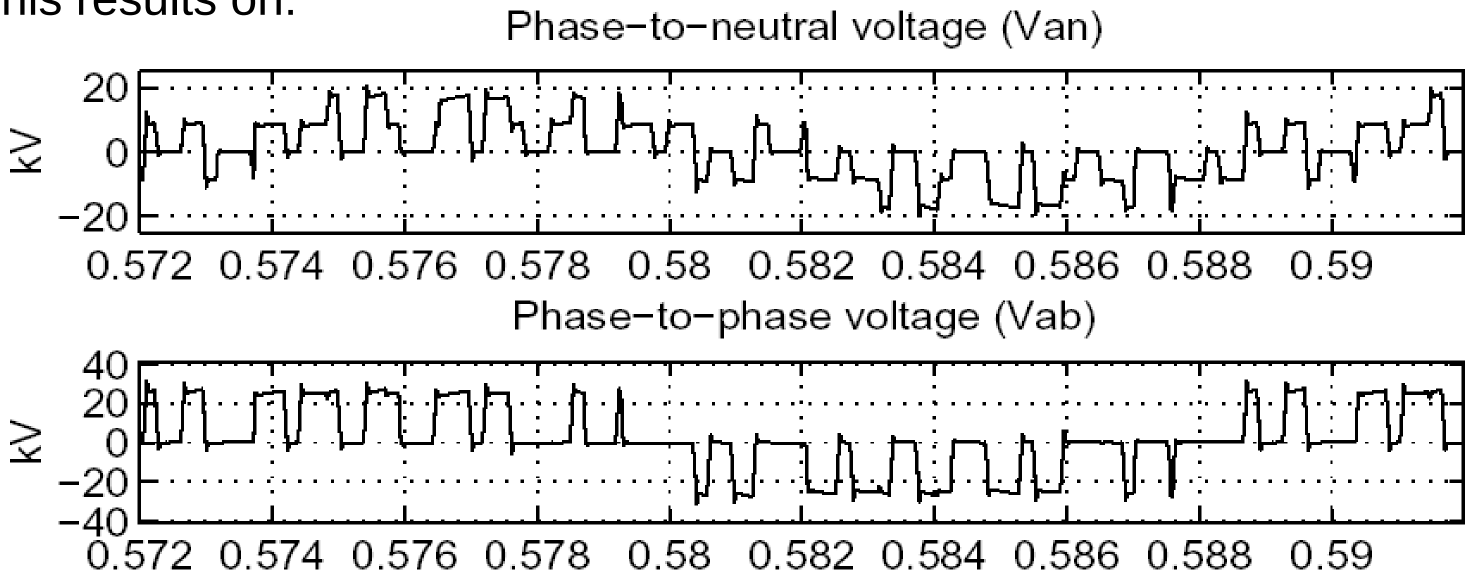
Fire valves when carrier and modulation signals cross

CARRIER: Triangular waveforms (Vtr_a)

MODULATION: Control waveform (Vctrl)

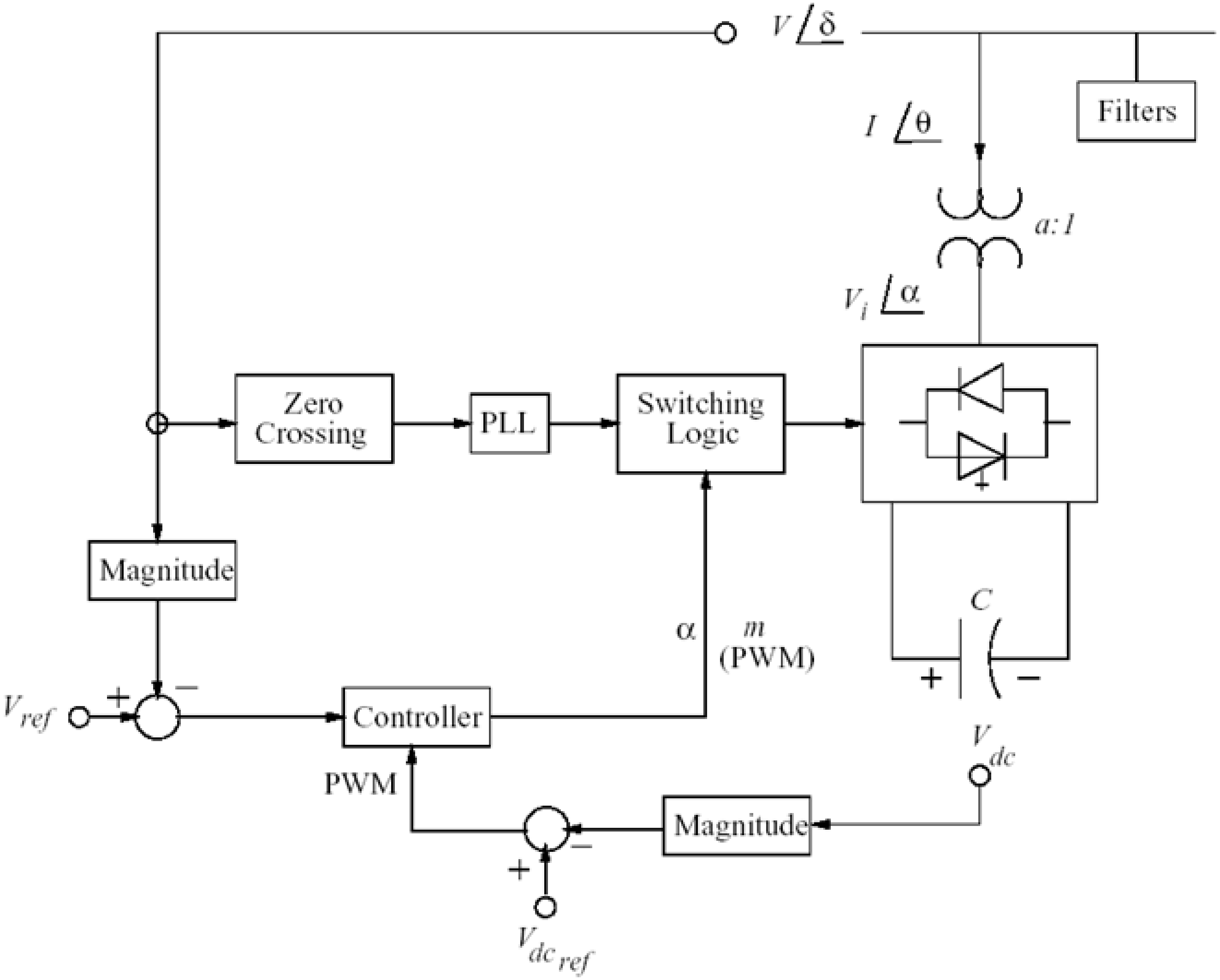
VSC

- This results on:



- Changing the modulation ratio, i.e. the magnitude of the modulation signal, results in changes of the ac voltage magnitudes.
- Shifting the modulation signal leads to phase shifts on the ac voltages.

STATCOM



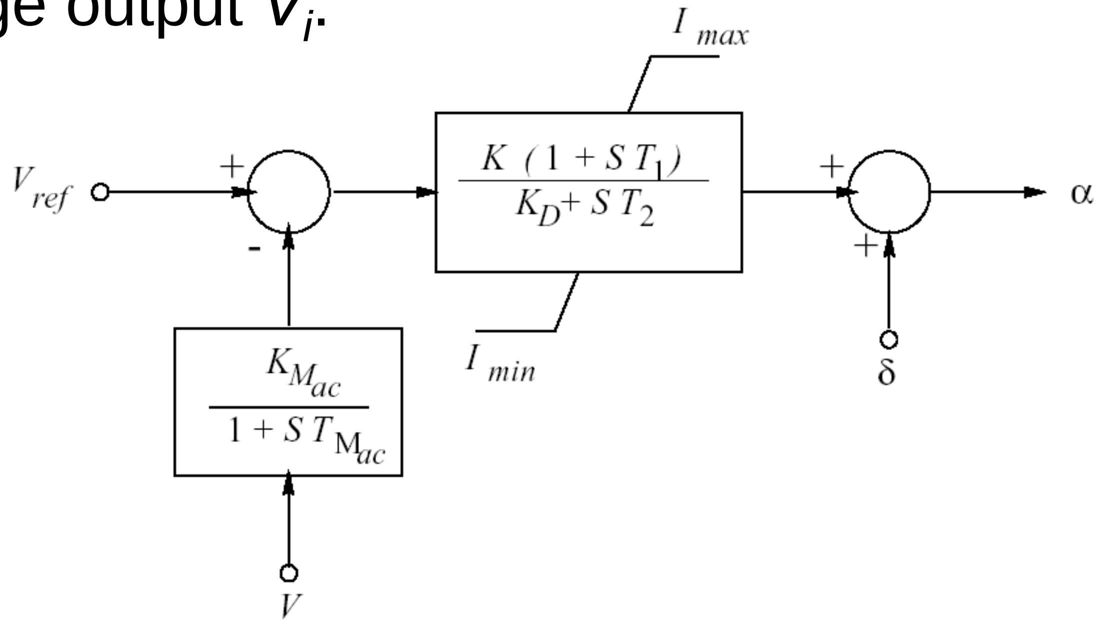
$V\angle\delta$
Filters
$I\angle\theta$
$a:1$
$V_i\angle\alpha$
Zero Crossing
PLL
Switching Logic
Magnitude
α
m (PWM)
C
+
−
V_{ref}
+
−
Controller
PWM
V_{dc}
Magnitude
+
−
$V_{dc\,ref}$

STATCOM

- It is basically a VSC controlling the bus voltage.
- The phase-locked loop (PLL) is needed to reduce problems with spurious zero voltage crossings associated with the high harmonic content of the signals for this controller, especially with PWM controls.

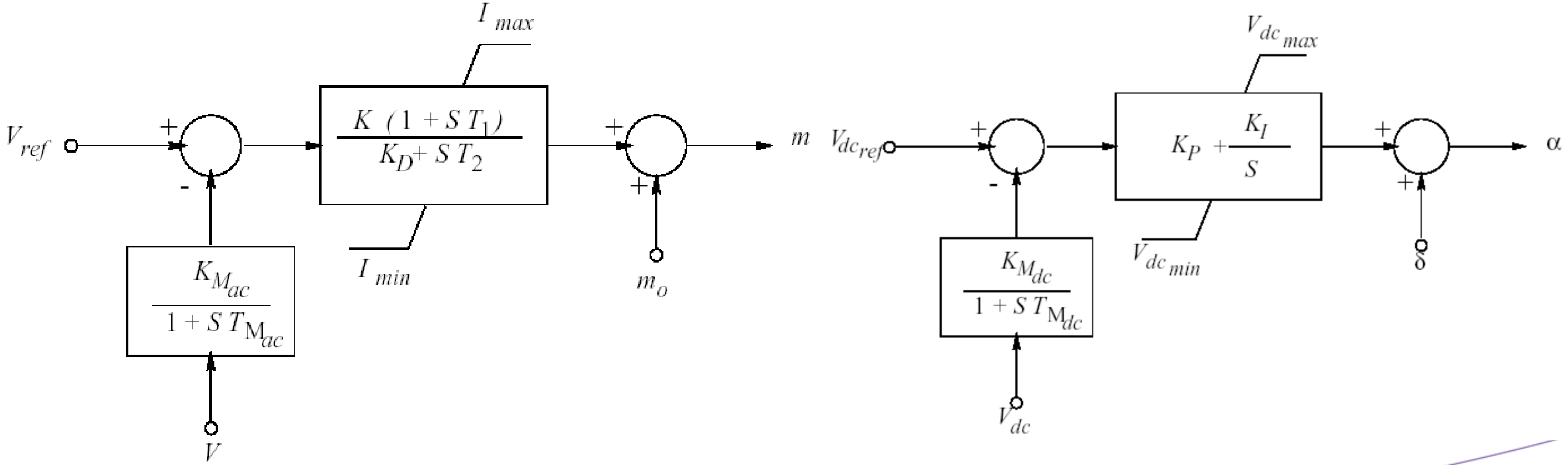
STATCOM

- Two types of controls can be implemented:
  - Phase control in a multi-pulse VSC: By controlling the phase angle of the voltage, the capacitor can be charged ($\alpha < \delta \Rightarrow$ controller absorbs P) or discharged ($\alpha > \delta \Rightarrow$ controller delivers P), thus controlling the voltage output V_i.



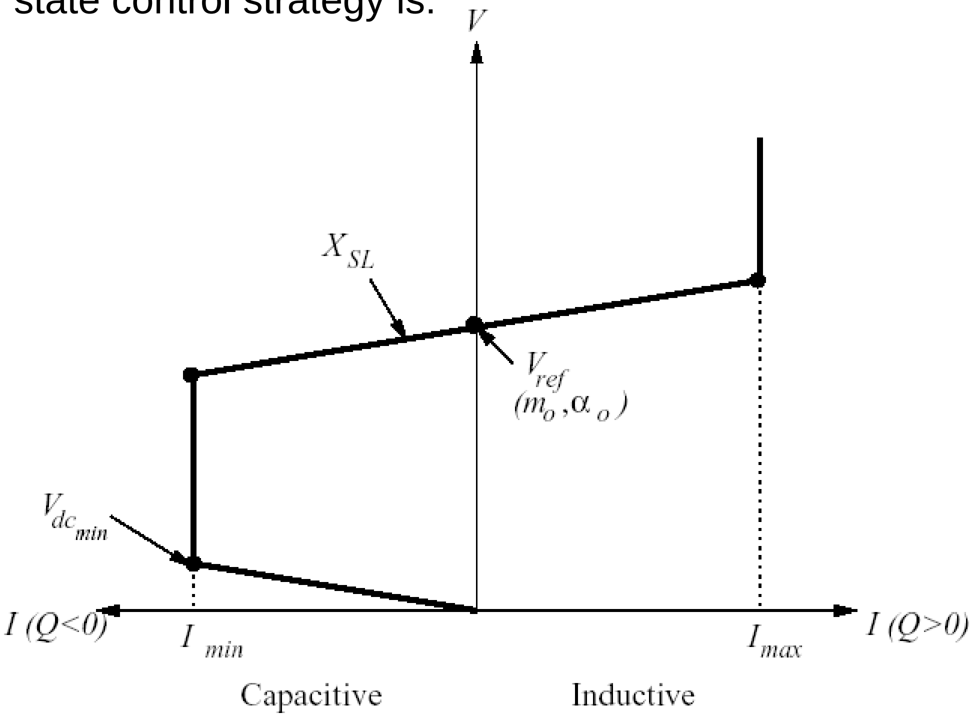
STATCOM

- PWM control in a 6-pulse VSC: the voltage output V_i can be controlled through the modulation ratio m independently of its phase angle α, which in turn controls V_{dc}.



STATCOM

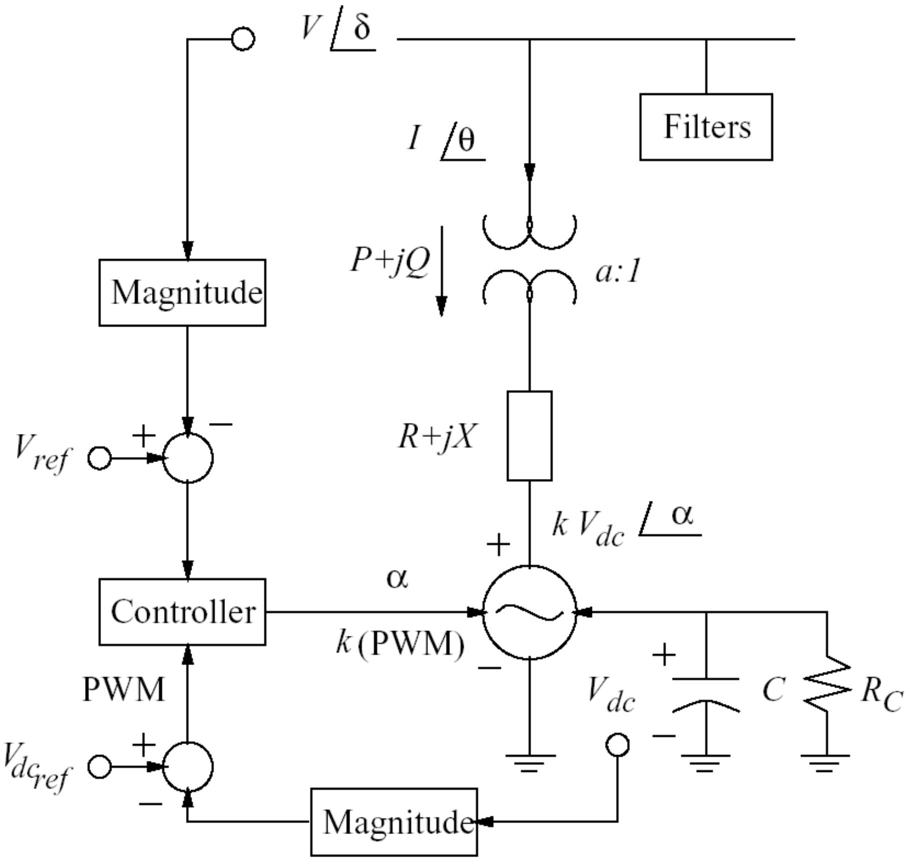
- The typical steady state control strategy is:



- The current limits are due to the valve current limitations.

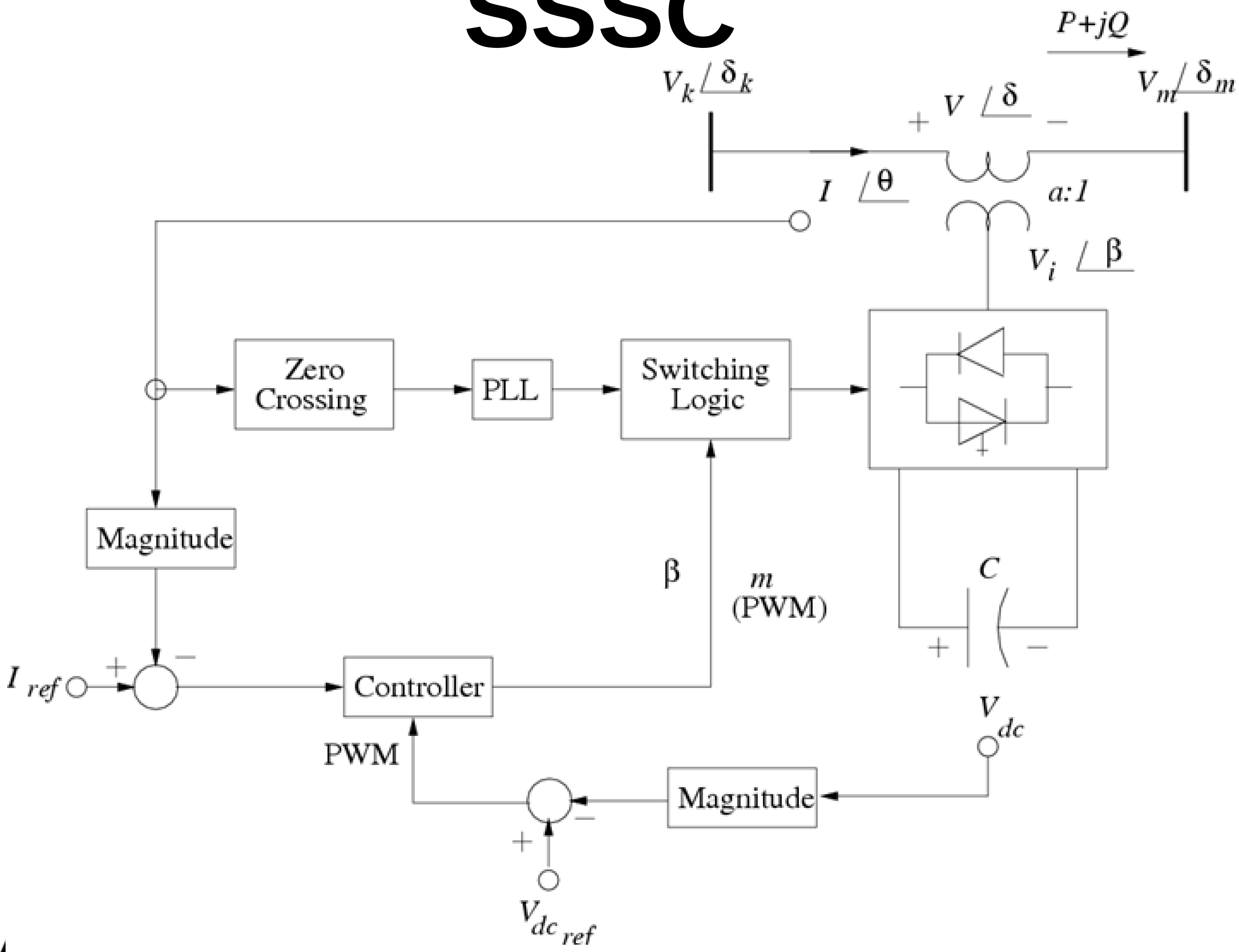
STATCOM

- Assuming balanced, fundamental frequency operation, the controller can be modeled as:



$$\dot{V}_{dc} = \frac{V\ I}{C\ V_{dc}}\cos(\delta - \theta) - \frac{G_C}{C}\,V_{dc} - \frac{R}{C}\,\frac{I^2}{V_{dc}}$$

SSSC

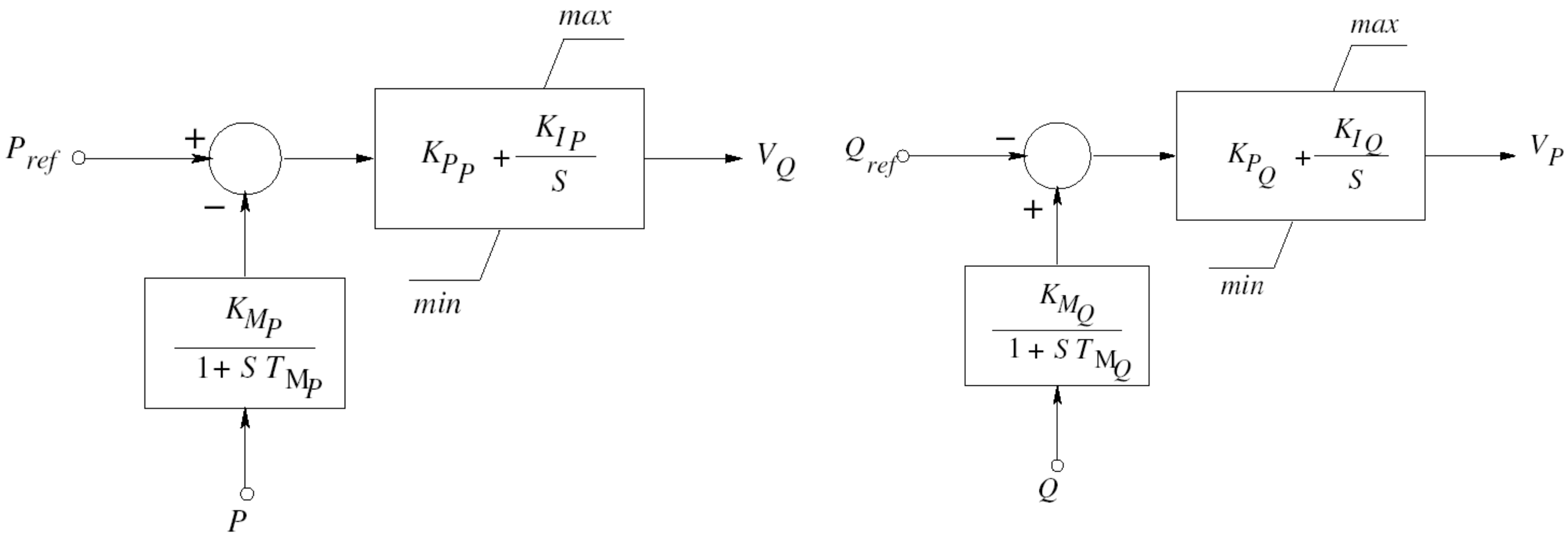

P+jQ
$V_k \angle \delta_k$
$V \angle \delta$
+
−
$V_m \angle \delta_m$
$I \angle \theta$
a:1
$V_i \angle \beta$
Zero Crossing
PLL
Switching Logic
Magnitude
β
m (PWM)
C
+
−
I_{ref}
+
−
Controller
PWM
V_{dc}
Magnitude
−
+
$V_{dc\ ref}$

SSSC

- Similar to the STATCOM but connected in series and synchronized with respect to the line current.
- A phase angle β control charges and discharges of the capacitor, thus controlling the output voltage V_i.
- PWM controls can be decoupled or coupled:

SSSC

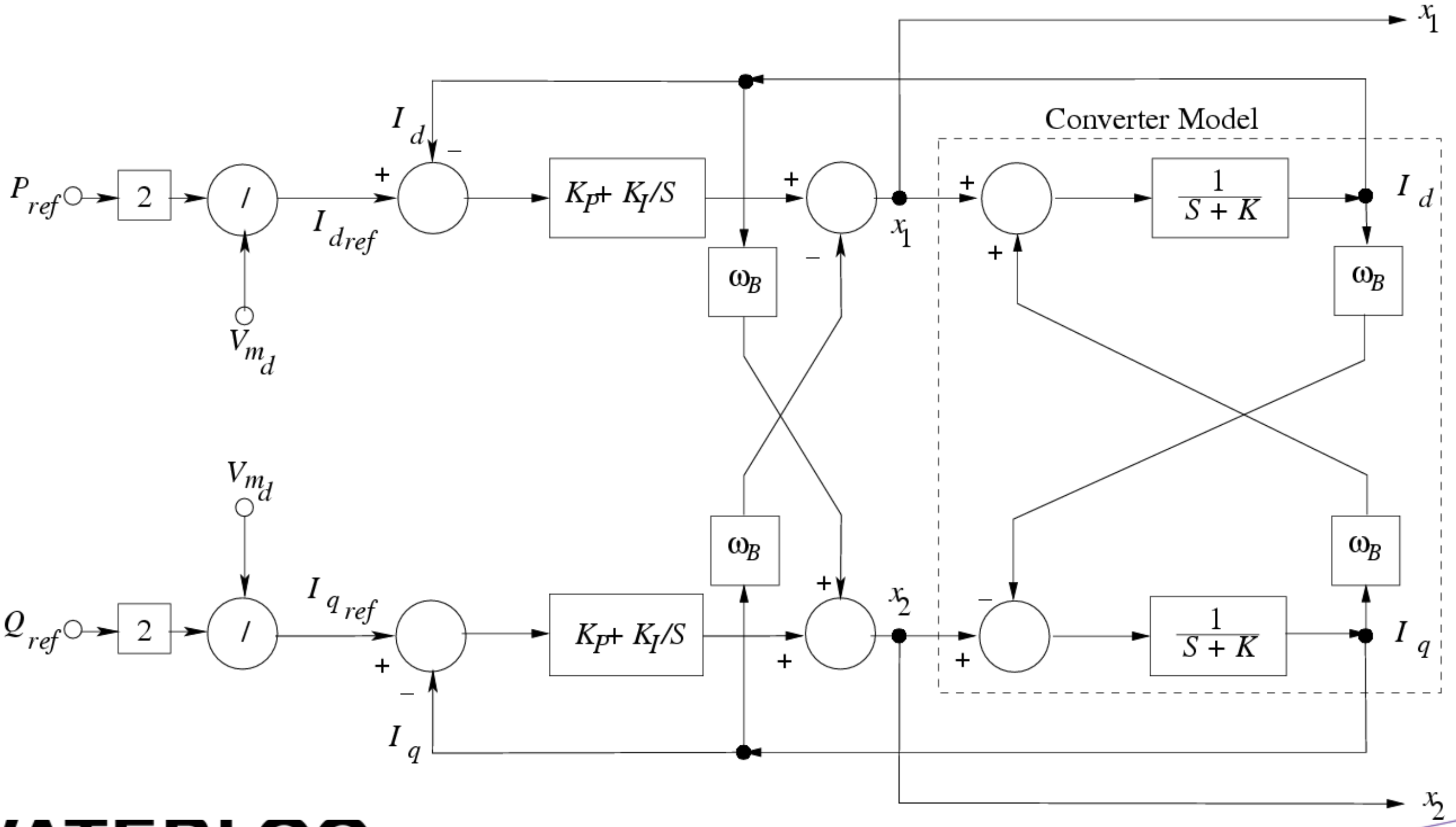
– Decoupled PWM controls:



$$V_i = \sqrt{V_P^2 + V_Q^2} \qquad m = \sqrt{\frac{8}{3}}\,\frac{V_i}{V_{dc}} \qquad \Delta\beta = -\tan^{-1}\left(\frac{V_Q}{V_P}\right)$$

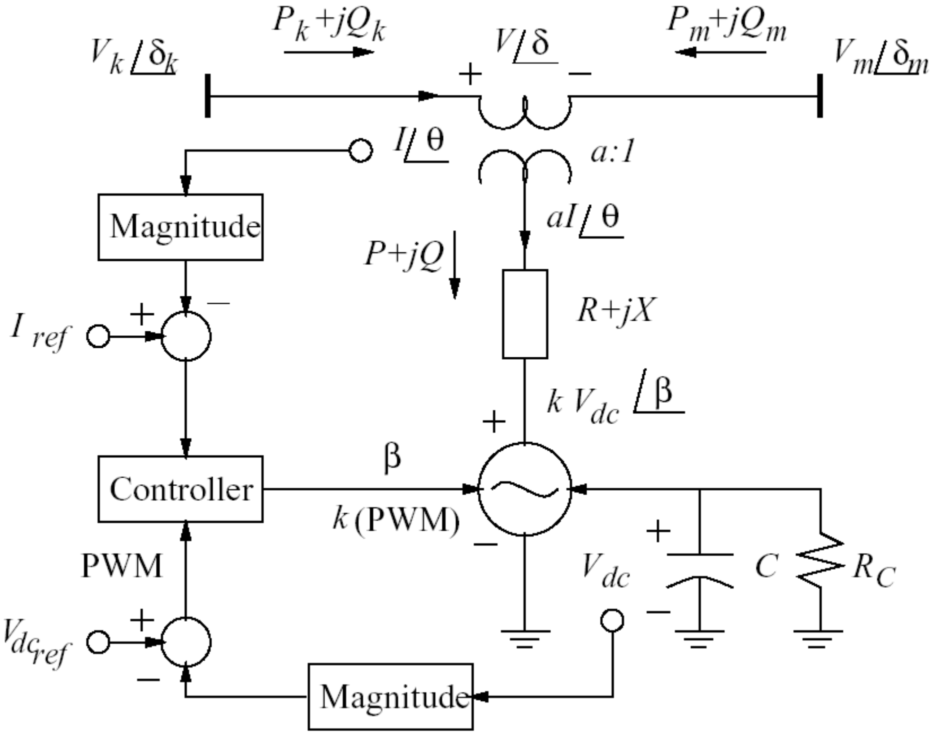
SSSC

- – Coupled PWM controls (better overall performance):



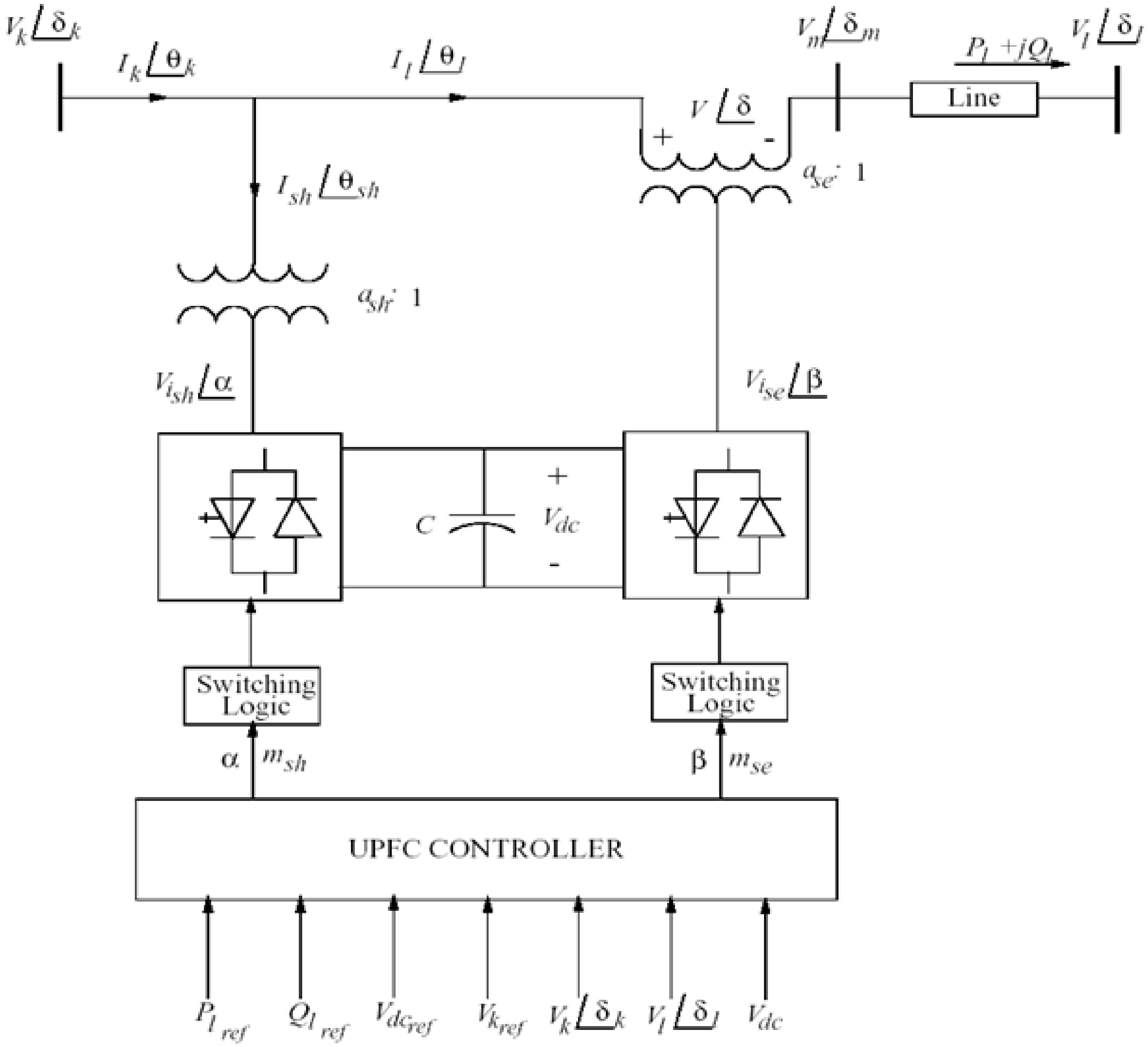
SSSC

- Assuming balanced, fundamental frequency operation, the controller can be modeled as:



$$\dot{V}_{dc} = \frac{V\ I}{C\ V_{dc}} \cos(\delta - \theta) - \frac{G_C}{C}\ V_{dc} - \frac{R}{C}\ \frac{I^2}{V_{dc}}$$

UPFC

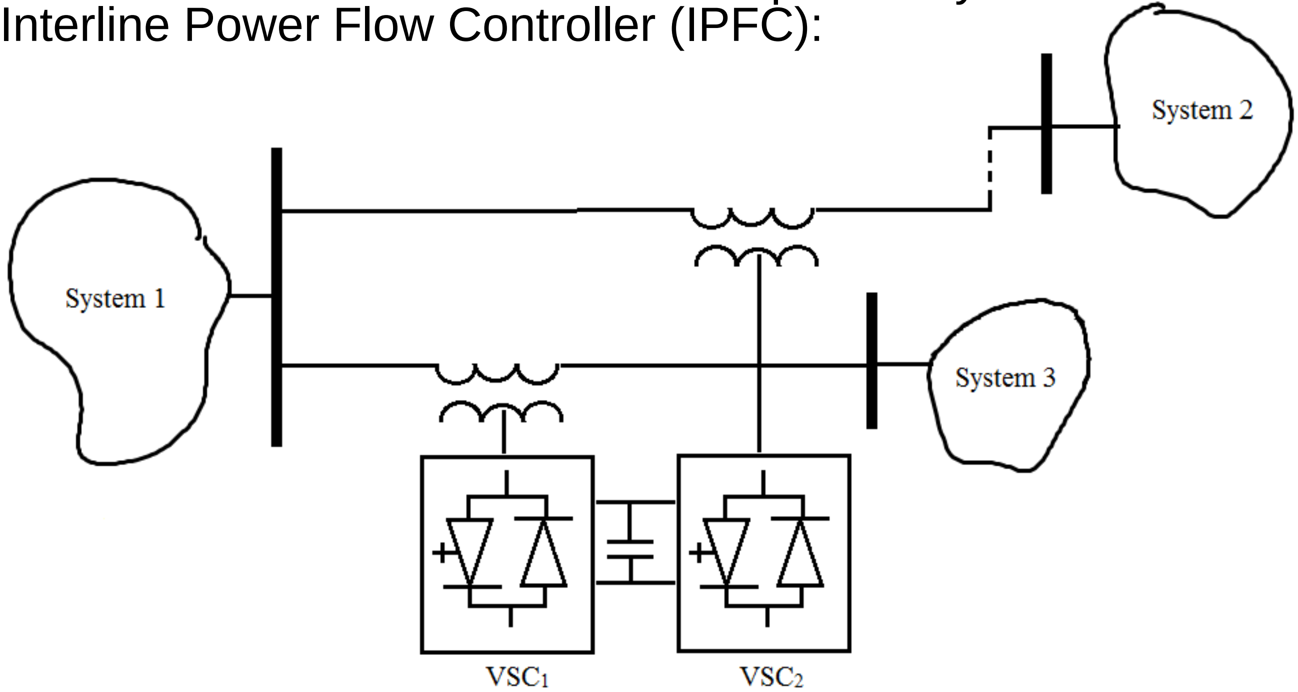

$V_k\angle\delta_k$
$I_k\angle\theta_k$
$I_l\angle\theta_l$
$V_m\angle\delta_m$
P_l+jQ_l
$V_l\angle\delta_l$
Line
$V\angle\delta$
+
-
a_{se}: 1
$I_{sh}\angle\theta_{sh}$
a_{sh}: 1
$V_{ish}\angle\alpha$
$V_{ise}\angle\beta$
C
+
V_{dc}
-
Switching Logic
Switching Logic
α
m_{sh}
β
m_{se}
UPFC CONTROLLER
$P_{l\ ref}$
$Q_{l\ ref}$
V_{dcref}
V_{kref}
$V_k\angle\delta_k$
$V_l\angle\delta_l$
V_{dc}

UPFC

- This controller is basically the STATCOM and SSSC combined, with independent controls, especially for PWM:
  - The STATCOM controls the sending-end voltage V_k and dc voltage V_{dc}.
  - The SSSC controls the power on the line P_l and Q_l.
- There is a “demo” UPFC controller in Ohio (AEP-EPRI venture).

IPFC

- A combination of 2 SSSCs connected independently to 2 lines is referred to as an Interline Power Flow Controller (IPFC):

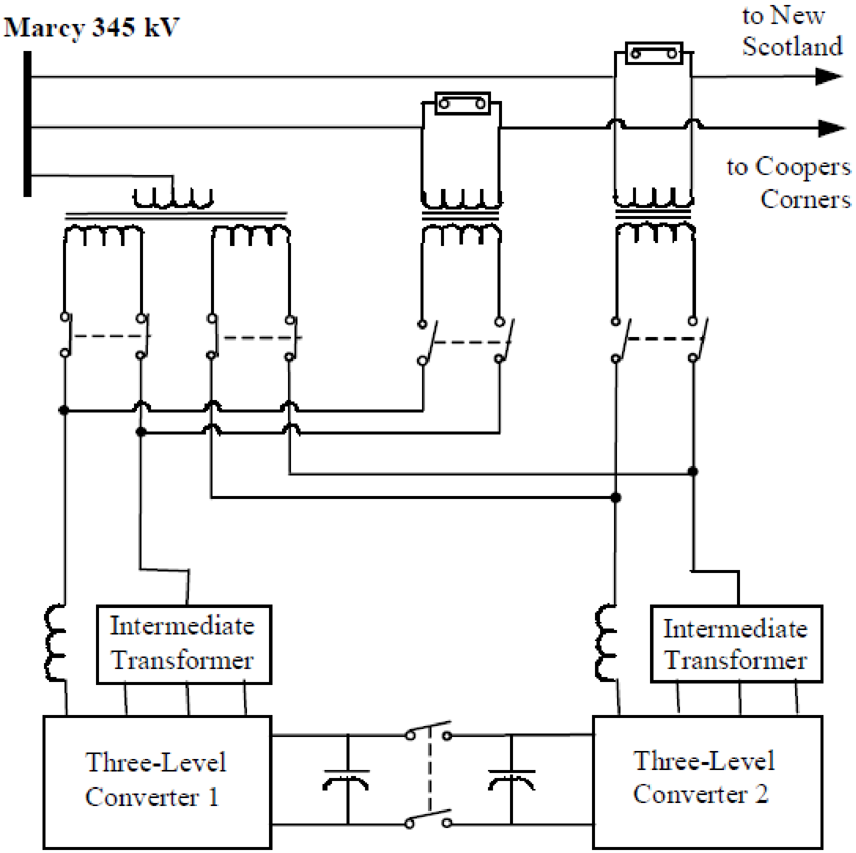


- In this case the power on both lines can be controlled independently.

CSC

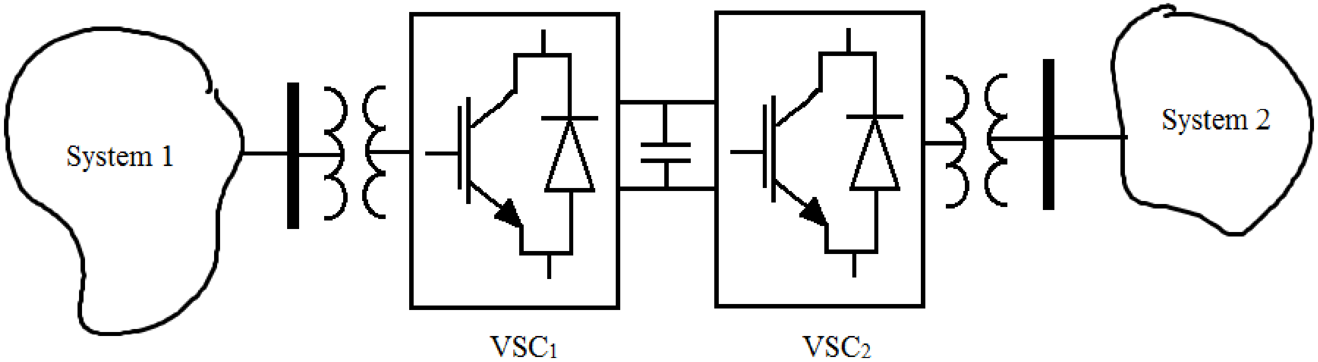
- A combination of 2 SSSC and 2 STATCOMS connected to 2 independent lines is referred to as a Convertible Static Compensator (CSC).
- In this case the control possibilities are many, as it can work as a STATCOM, SSSC, UPFC and IPFC.
- The CSC has been implemented in NY to relief congestion (NYPA-EPRI venture) [E. Uzunovic et al, “NYPA convertible static compensator (CSC) application phase I: STATCOM,” *Proc. Trans. & Dist. Conf. and Expo.*, vol. 2, 2001, pp. 1139-1143]:

CSC


Marcy 345 kV
to New Scotland
to Coopers Corners
Intermediate Transformer
Intermediate Transformer
Three-Level Converter 1
Three-Level Converter 2

HVDC Light

- Based on VSCs as opposed to the current sourced converters (CSCs) used in classical HVDC:



- IGBTs (Insulated-gate bipolar transistors have a FET gate and a BJT switch) instead of GTOs are used as switches; have lower losses, higher frequency switching capacity, are cheaper, but have less reverse voltage blocking capacity.
- These switches allow using PWM controls, which yield greater control flexibility.

HVDC Light

- The reduced reverse voltage blocking capacity of IGBTs versus GTOs reduces the overall power capacity of the link; this is the reason for the “light” label.
- The overall costs of the link are lower, allowing for wider applications of this technology.
- Classical HVDC is most cost effective at power ranges above ~250 MW, whereas HVDC Light ratings are typically in the order of a few tens of MW (the technology current upper limits are 1,200 MW and ±320 kV).
- Visit http://www.abb.com/industries/us/9AAC30300394.aspx for more details and actual projects.

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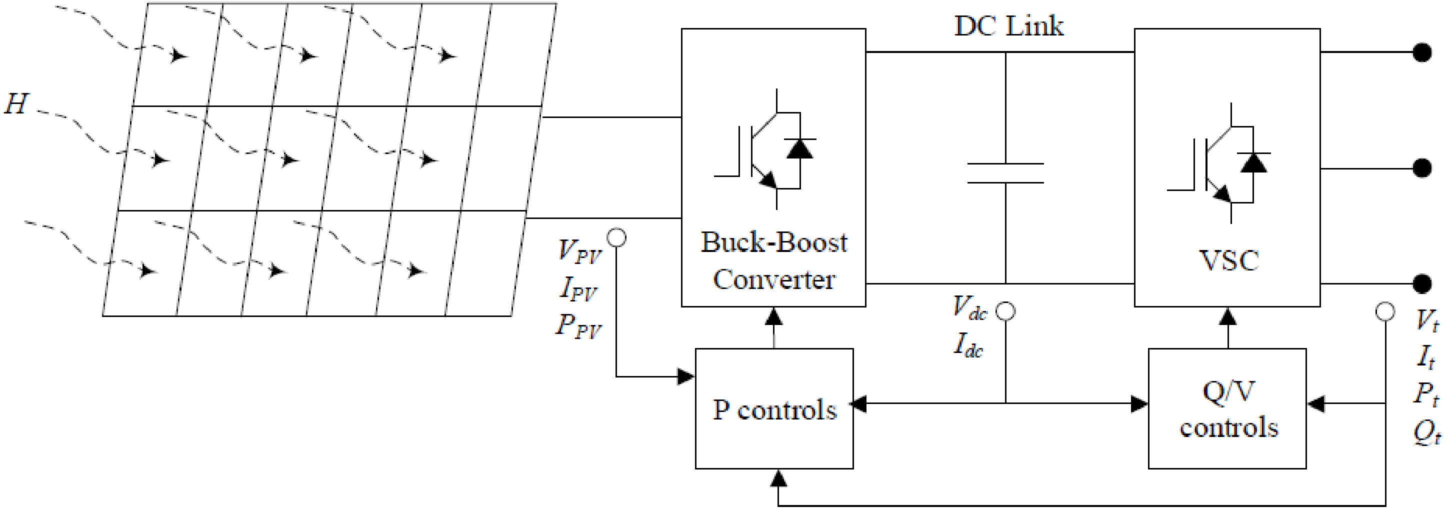
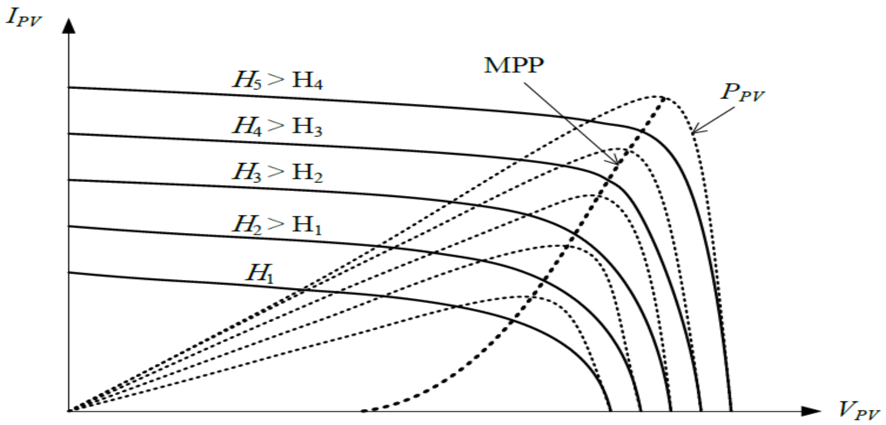
SPVG

~100 MW_{peak} solar farm connected to Bluewater Power distribution system



SPVG Controls

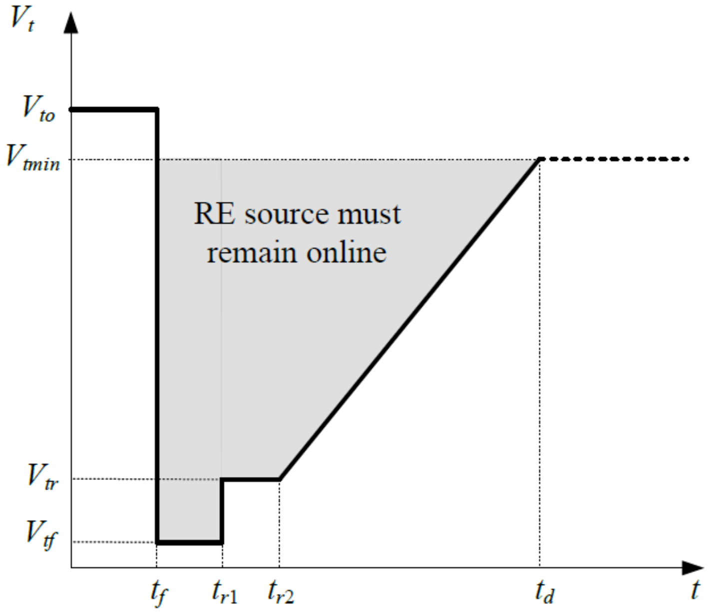
- Original PQ controls:
  - P output kept at maximum using an MPPT control of the dc-dc converter VI output:



  - Q = 0 (unity power factor) with Q/V control of PWM VSC, so it is not a Q load for the system with negative impact on voltage.

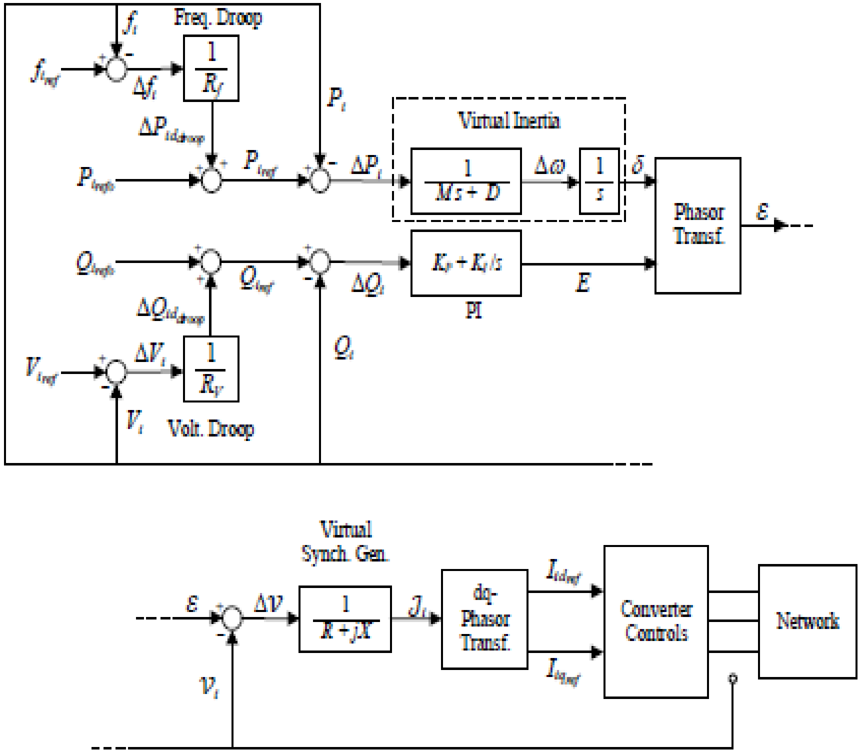
SPVG Controls

- RE generators were required to disconnect under faults, which created low voltage and frequency problems with loss of power.
- Now they are required to provide reactive power during fault conditions via Low-Voltage Ride-Through (LVRT)/ or Fault Ride-Through (FTR) control, i.e. converter Q injection.
- More jurisdictions are now requiring full V output control like standard generators.



SPVG Controls

- Some jurisdictions are also requiring nowadays some frequency control:
    - MPPT control is deactivated to allow some limited P control, thus de-rating the generator.
    - Some manufactures are providing controls so that generator provide also virtual inertia, such as the Synchronous Power Controller (SPC):

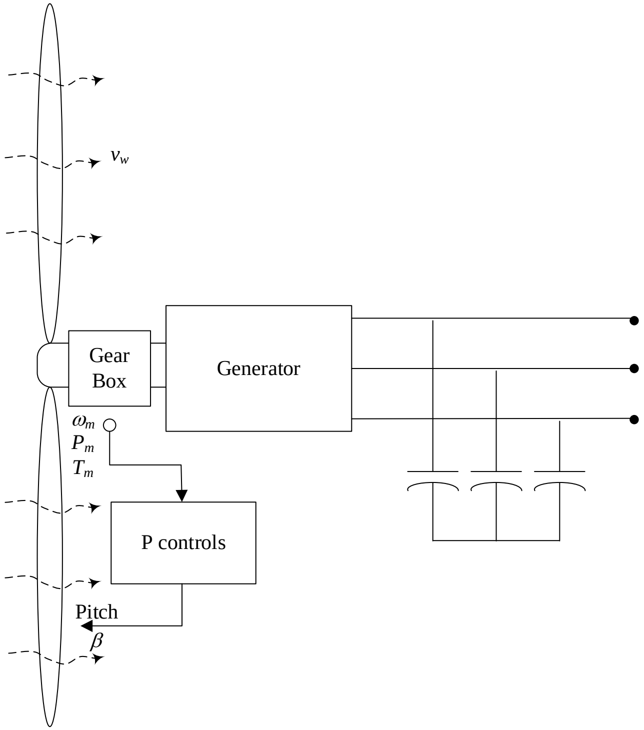


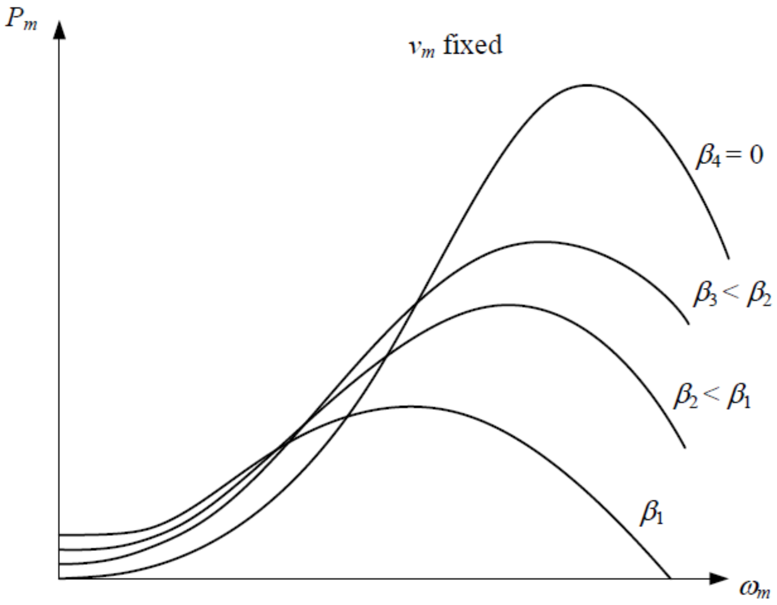
WG

- Ripley-Kincardine WG plant: 76 MW with 38x2 MW Enercon Tyep 4/D SGPM generators connected at 230kV.

WG

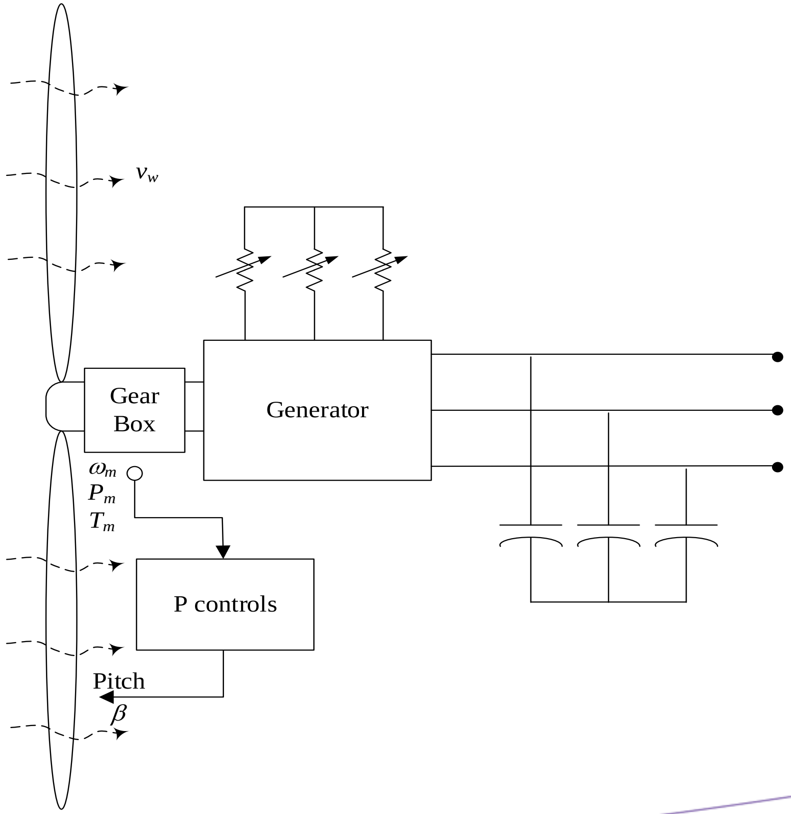
- Type 1/A: Fixed speed with pitch control.





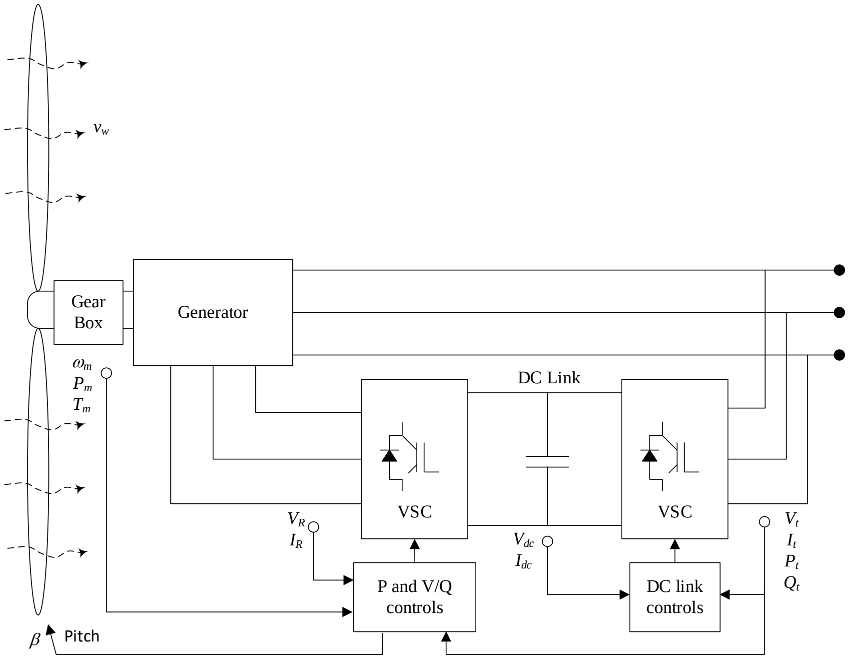
WG

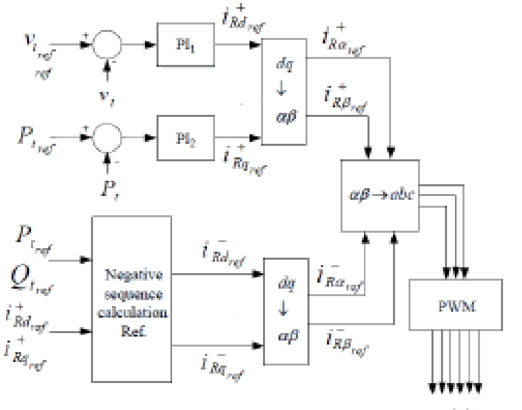
- Type 2/B: Doubly Fed Induction Generator (DFIG) with variable speed through variable rotor resistance, plus pitch control.



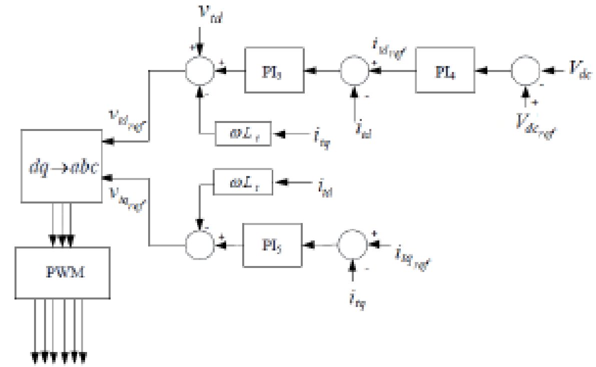
WG

- Type 3/C: DFIG with rotor converters plus pitch controls.





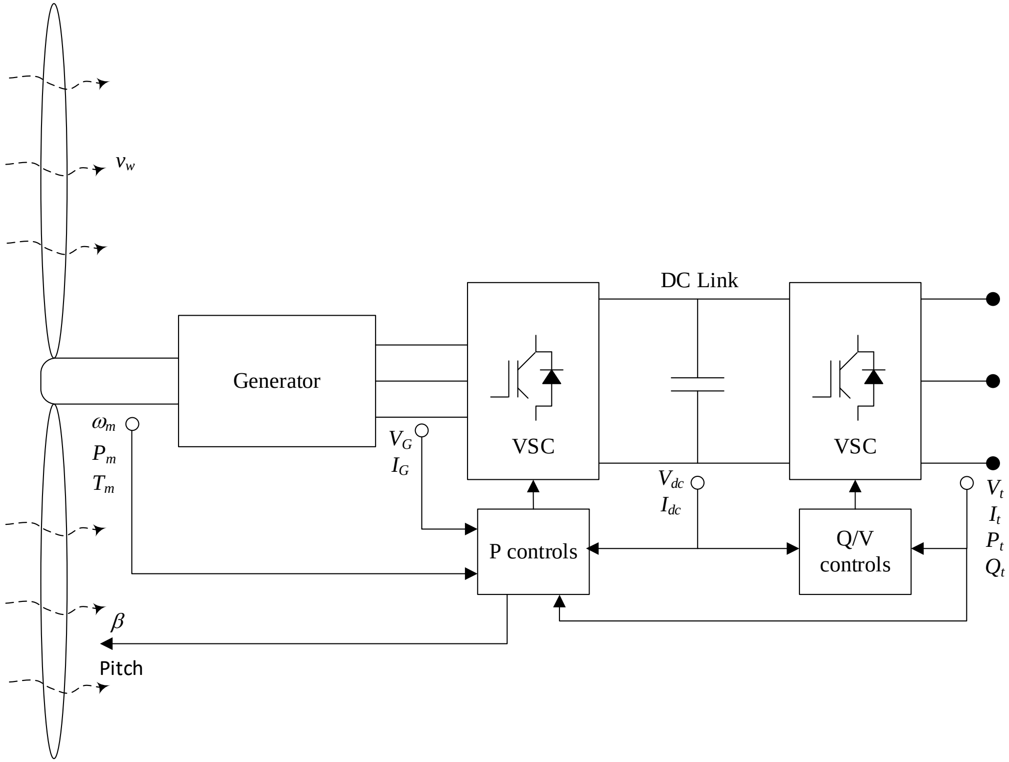
Rotor-side VSC



Grid-side VSC

WG

- Type 4/D: Permanent Magnet Synchronous Generator (PMSG) or IG with ac-dc-ac full converter interface, similar to SPCG.

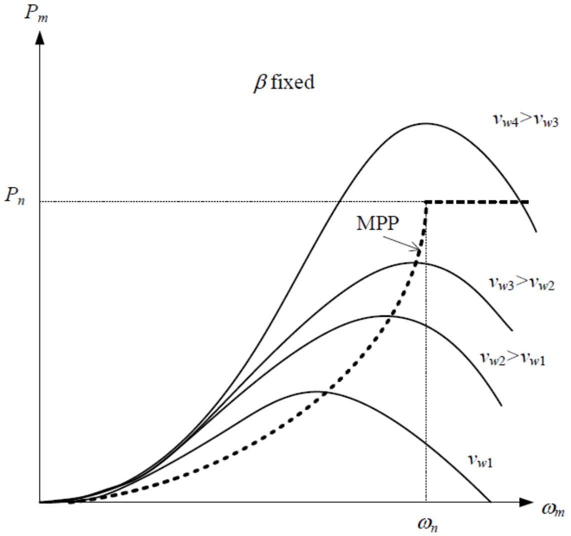


WG Controls

- Depend on technology:
  - Type 1/A: Only slow pitch controls to keep torque and/or turbine speed at rated values and/or within limits to avoid turbine problems.
  - Type 2/B: Slow pitch control plus some fast P control through variable resistors.
  - Type 3/C: Slow pitch control plus fast P and Q/V control through rotor ac-dc-ac converter.
  - Type 4/D: Slow pitch control plus fast P and Q/V control through full ac-dc-ac converter interface.

WG Controls

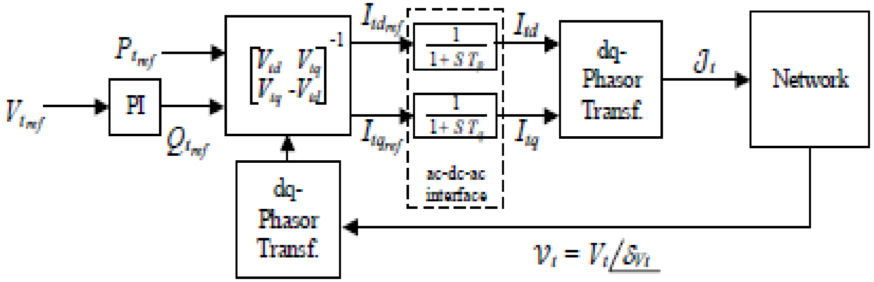
- Type 3/C and 4/D P control:
  - MPPT based on:



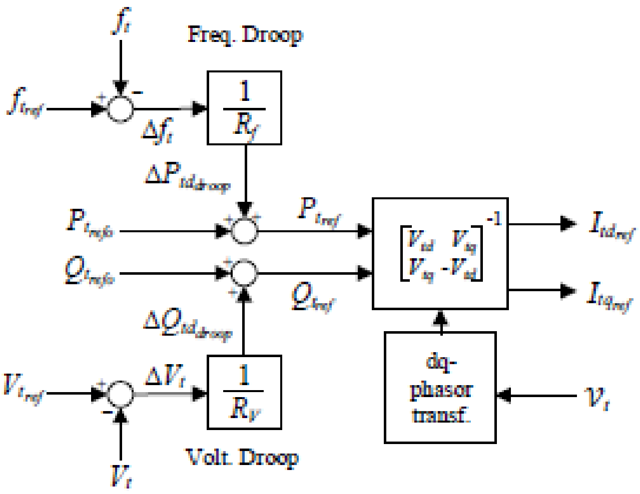
  - MPPT deactivated for some frequency control, de-rating the WG.

SPVG and WG Simplified Models

- Simplified model, based on WECC wind generator phasor (average) model:

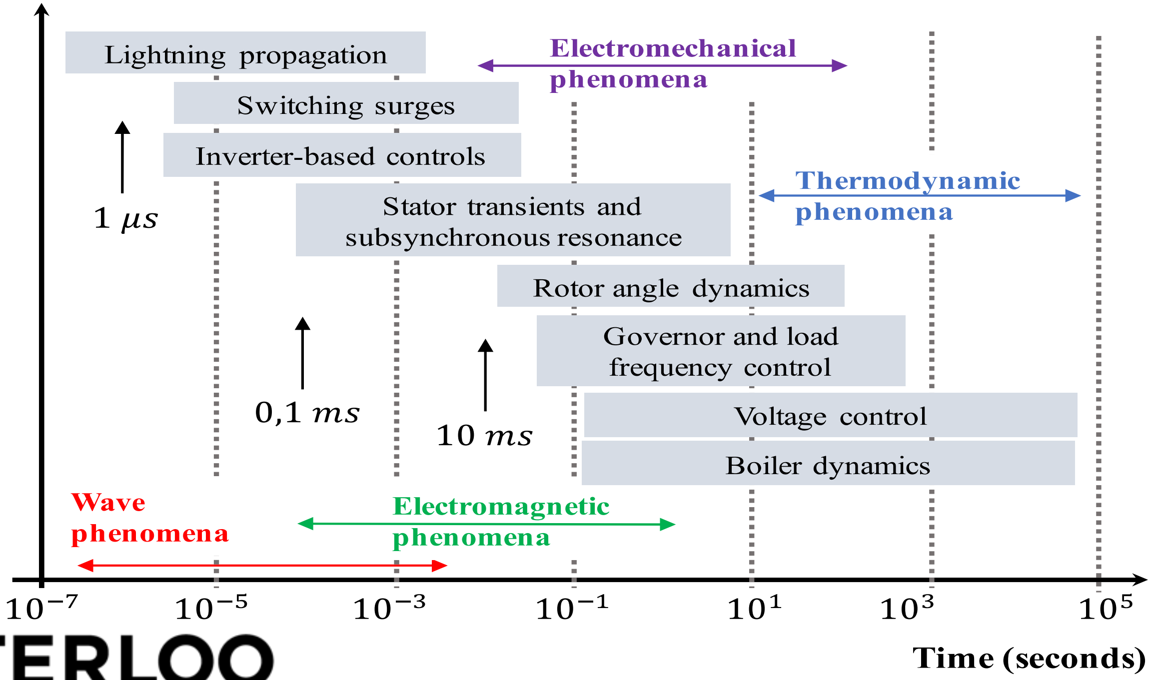


- V and f droop controls for this model:



Dynamic Grid Studies

- Time domains of dynamic studies (IEEE PES PSDPC TF on “Stability Definitions and Characterization of Dynamic Behavior in Systems With High Penetration Of Power Electronic Interfaced Technologies”):



Dynamic Grid Studies

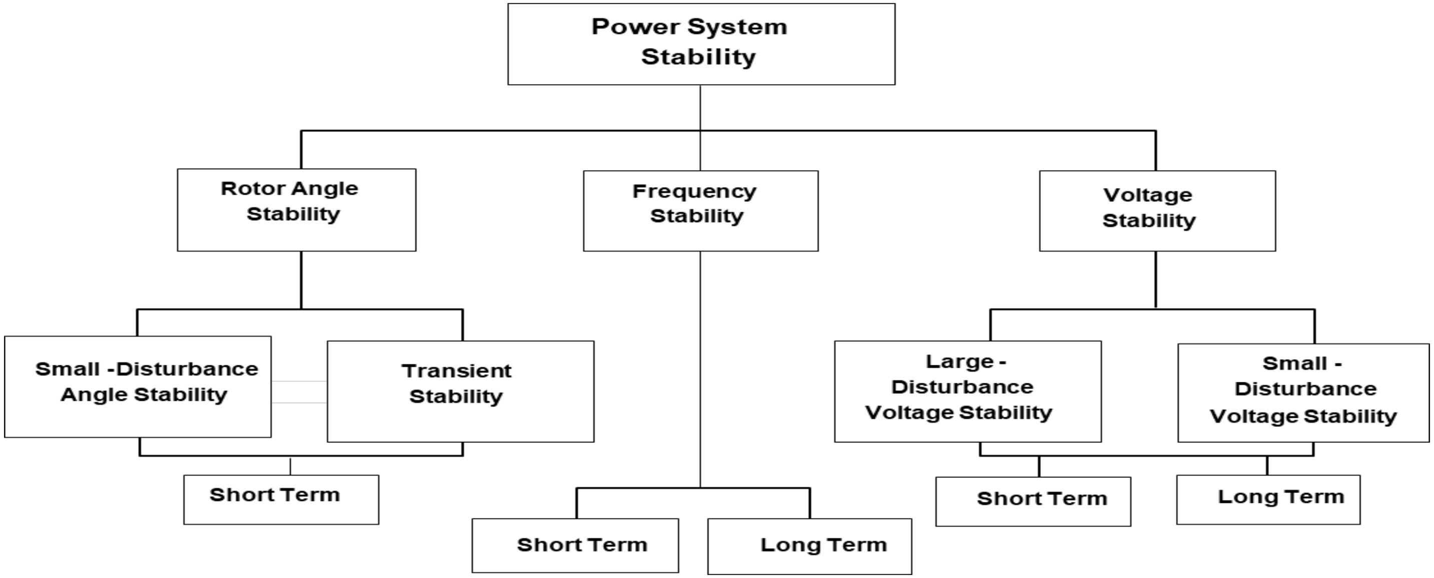
- Tools:
  - – Wave and electromagnetic phenomena: PSCAD/EMTDC, EMTP, ATP, and others.
  - – Electromechanical phenomena: DSATools, PSS/E, PSAT, DIgSILENT PowerFactory, and many others (e.g. ETAP).
  - – Thermodynamic phenomena: partially DSATools, PSS/E, and others.

Dynamic Grid Studies

- Techniques:
  - Steady and quasi-steady state:
    - Power flows.
    - PV curves.
    - Eigenvalues and eigenvectors.
  - Transients:
    - Detailed time-domain simulations for unbalanced and converter systems.
    - Transient stability simulations of phasor-based, balanced system models.

Dynamic Grid Studies

- Grid stability studies (IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, “Definition and Classification of Power System Stability”, *IEEE Trans. Power Systems* and *CIGRE Technical Brochure 231,* 2003):



Power System Stability

Rotor Angle Stability

Frequency Stability

Voltage Stability

Small -Disturbance Angle Stability

Transient Stability

Large - Disturbance Voltage Stability

Small - Disturbance Voltage Stability

Short Term

Short Term

Long Term

Short Term

Long Term

- These definitions and classification are being updated in the context of faster dynamics (e.g. converter-based systems).

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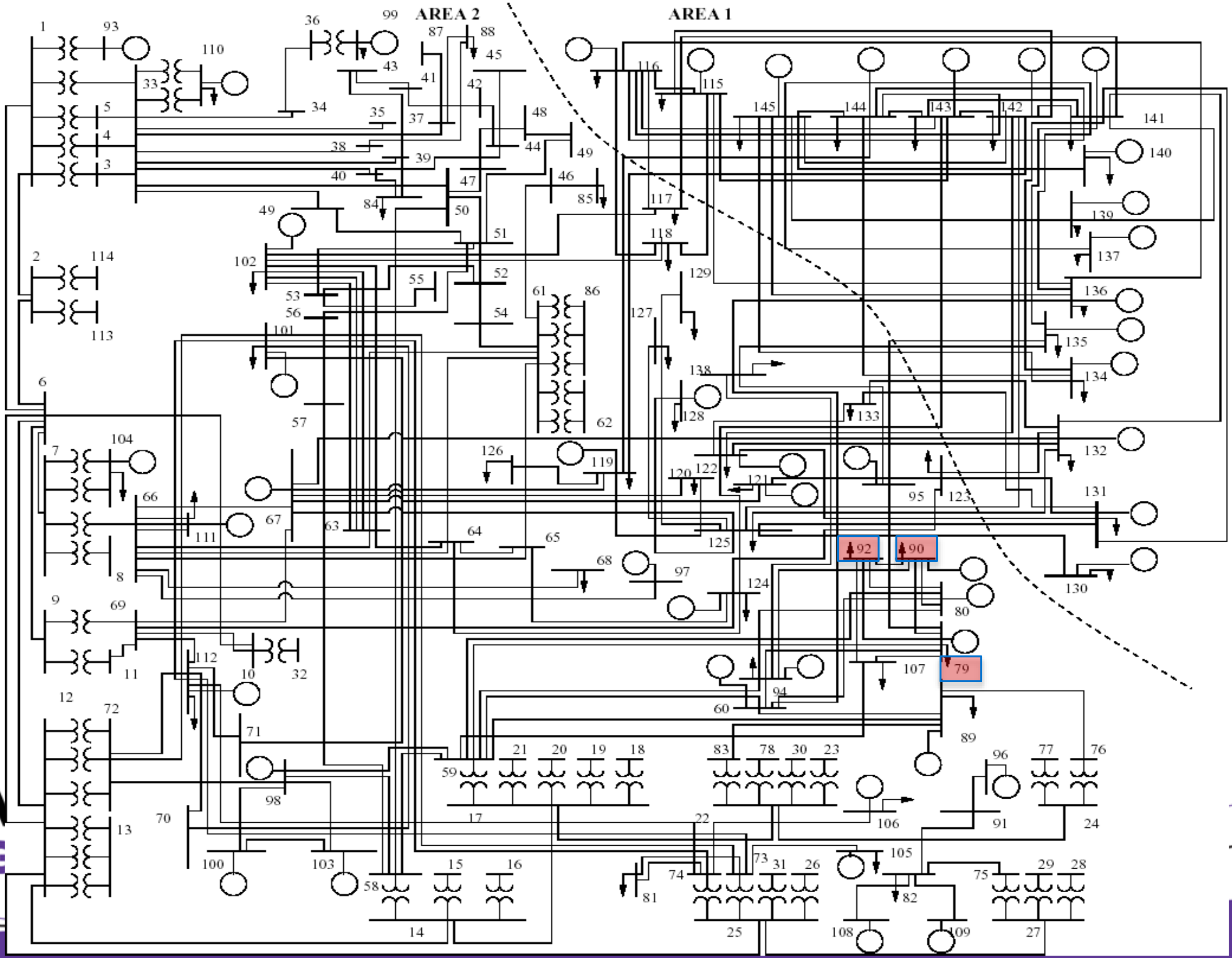
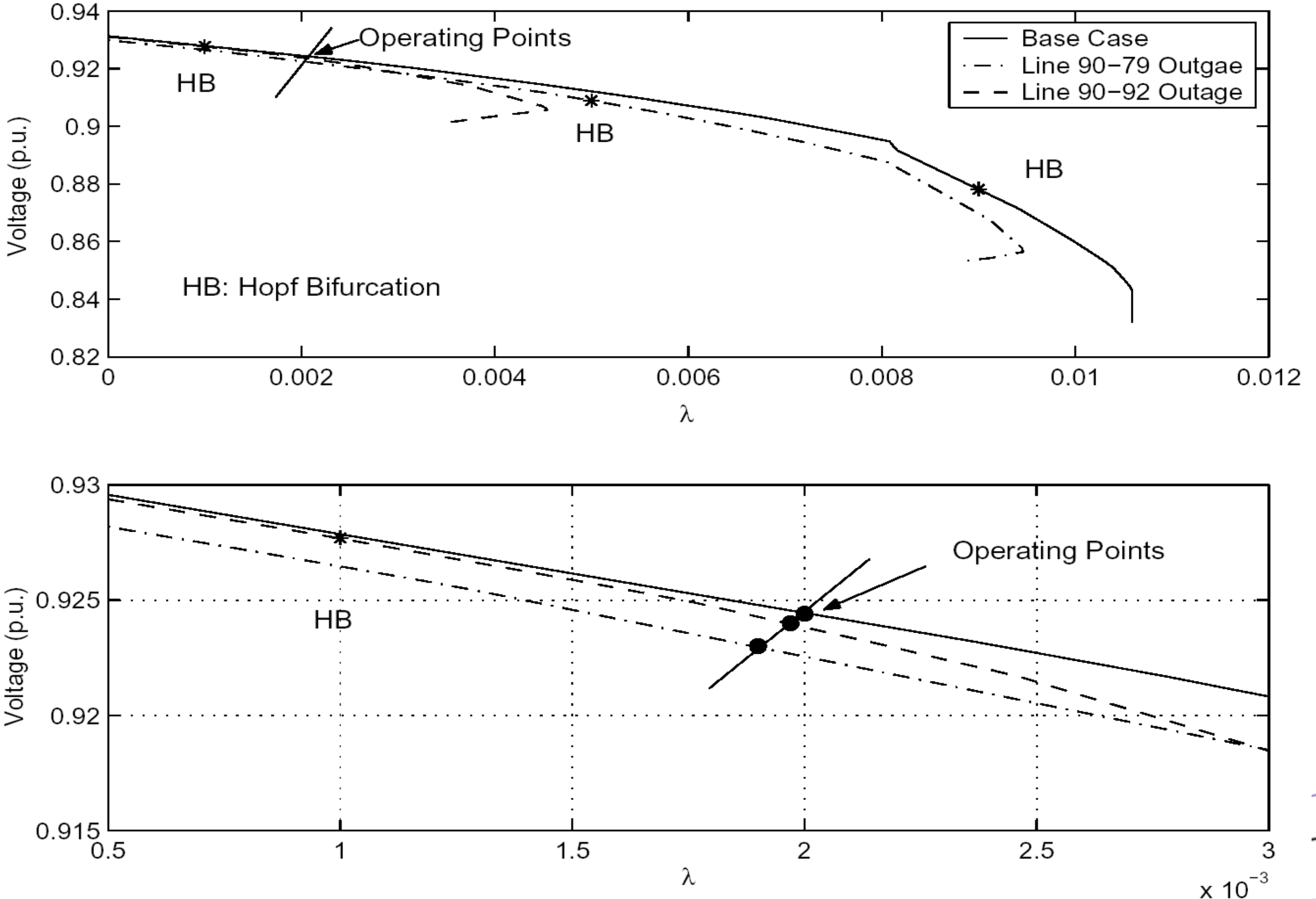
Dynamic Grid Study Example

- For the IEEE 145-bus, 50-machine test system:



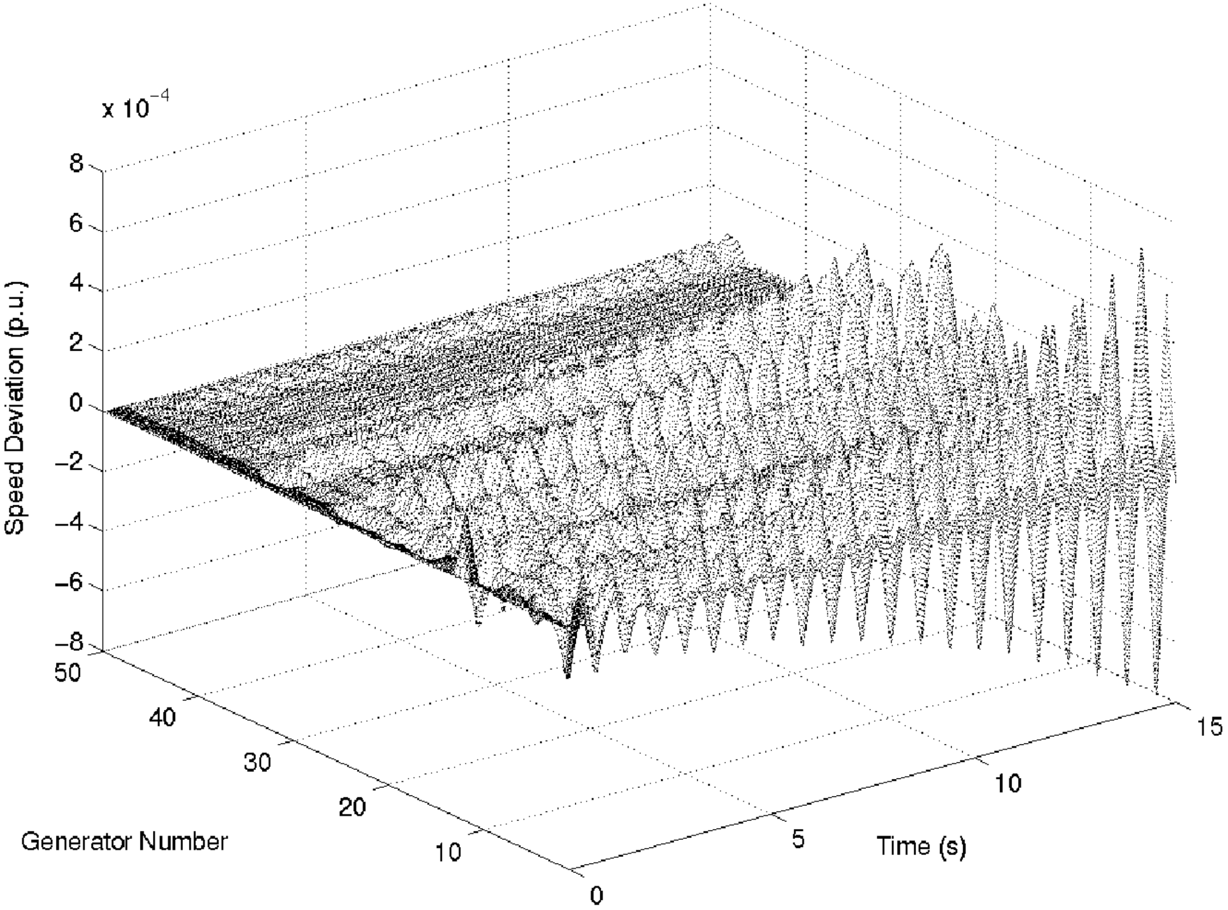
Dynamic Grid Study Example

- – For an impedance load model, the PV curves yield:



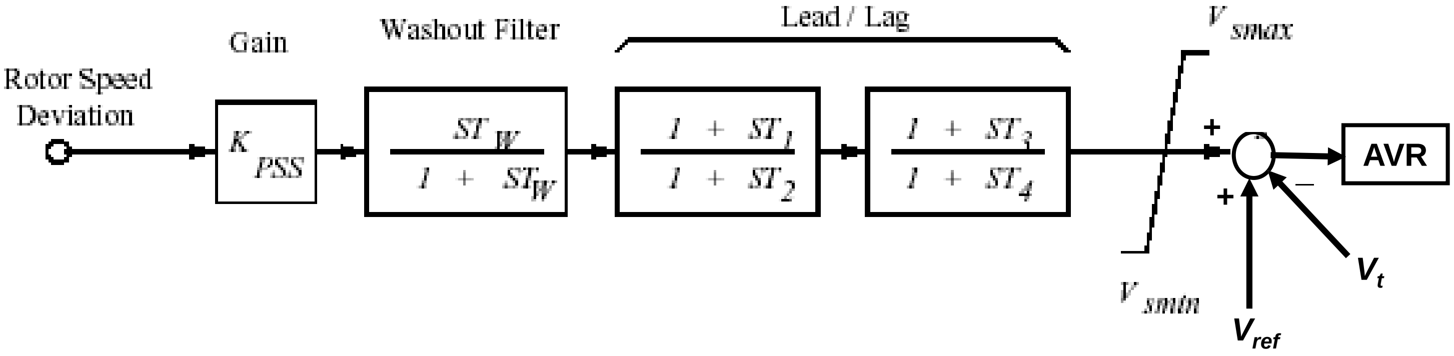
Dynamic Grid Study Example

- – Hence, a line 90-92 outage yields:



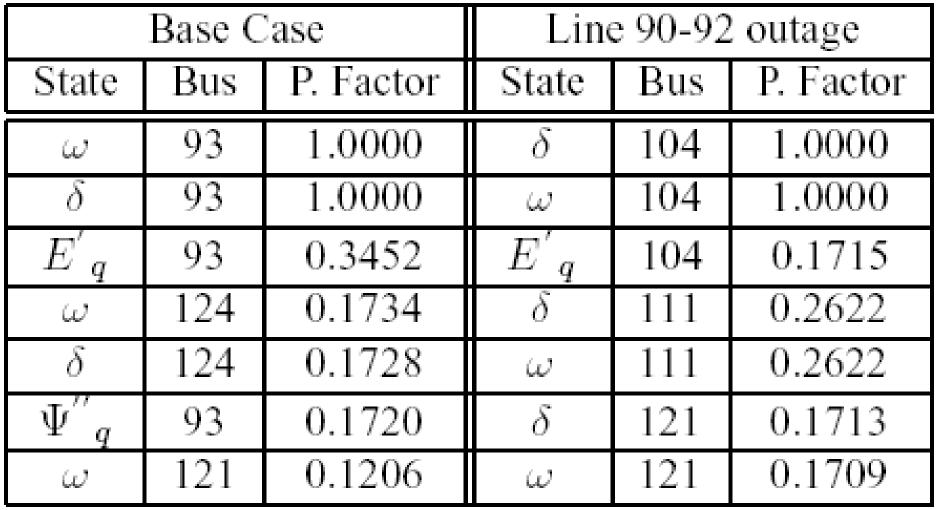
Dynamic Grid Study Example

- This has been typically solved by adding Power System Stabilizers (PSS) to the voltage controllers in “certain” generators, so that the equilibrium point is made stable, i.e. the Hopf is removed (FACTS may also be used to address this problem):

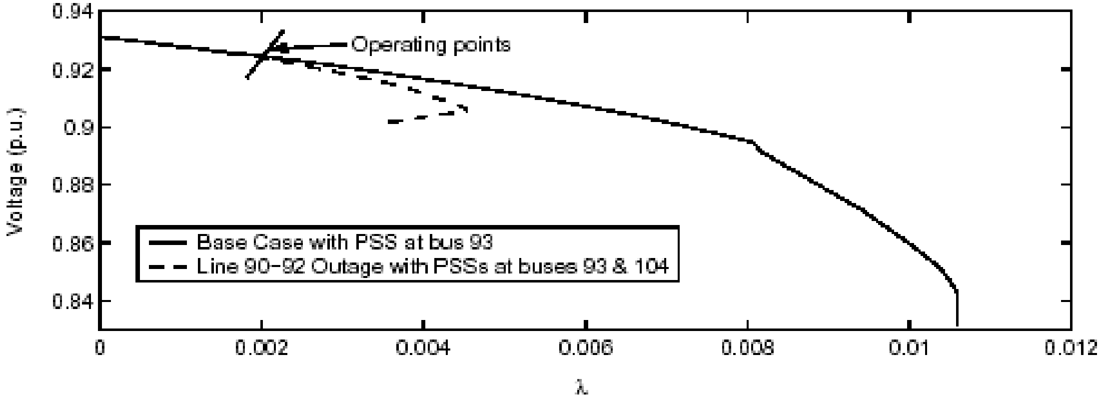


Dynamic Grid Study Example

- – A participation factor analysis in this case yields:

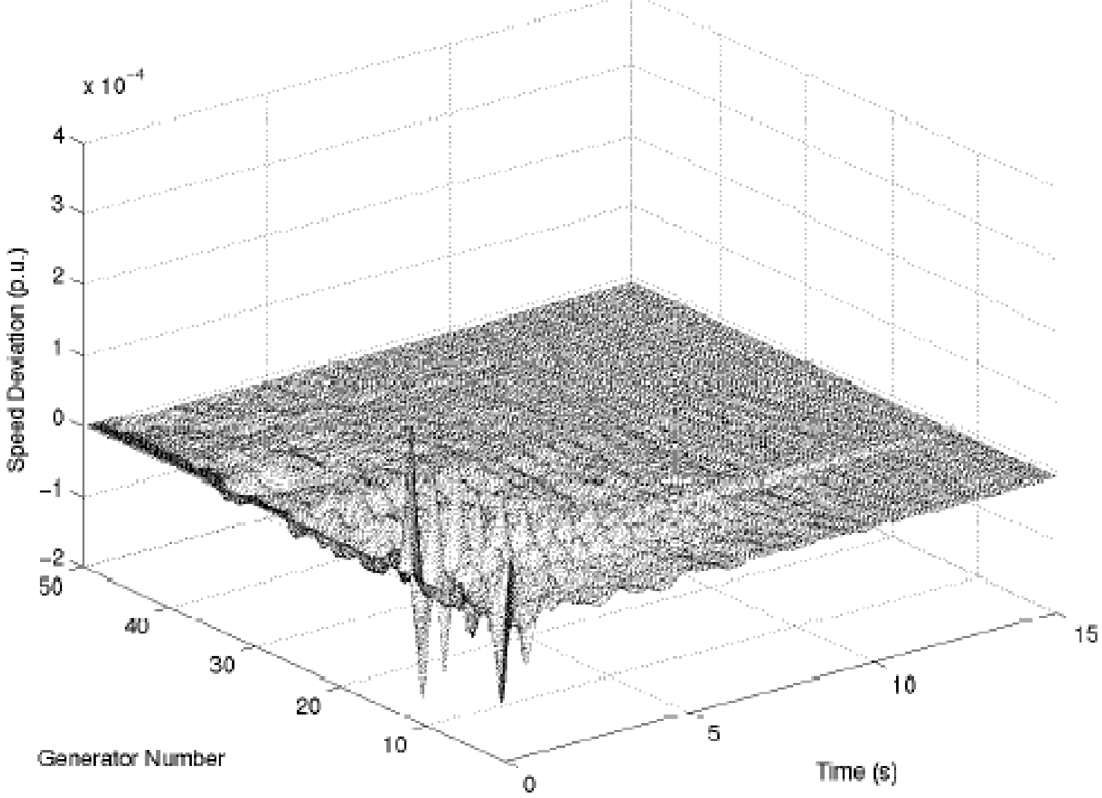


Base Case			Line 90-92 outage		
State	Bus	P. Factor	State	Bus	P. Factor
ω	93	1.0000	δ	104	1.0000
δ	93	1.0000	ω	104	1.0000
E'_q	93	0.3452	E'_q	104	0.1715
ω	124	0.1734	δ	111	0.2622
δ	124	0.1728	ω	111	0.2622
Ψ''_q	93	0.1720	δ	121	0.1713
ω	121	0.1206	ω	121	0.1709



Dynamic Grid Study Example

- The line 90-92 outage with PSS at generators 93 and 104 yields:



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Dynamic Grid Study Example

- More details regarding this example can be found in:

  N. Mithulananthan, C. A. Cañizares, J. Reeve, and G. J. Rogers, "Comparison of PSS, SVC and STATCOM Controllers for Damping Power System Oscillations," *IEEE Transactions on Power Systems*, Vol. 18, No. 2, May 2003, pp. 786-792.