Selected Real Problems in Power Engineering

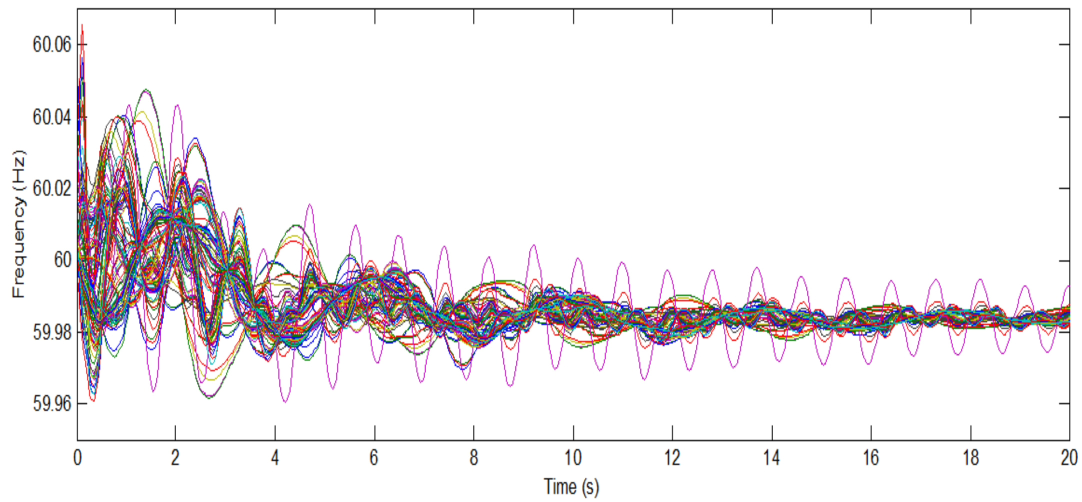
1. **Wide-area power grid stability monitoring**
   – Power-angle curves of a transmission line
2. **Fault-inducted delayed voltage recovery issues**
   – Characteristics of induction motors
   – Reactive power control using SVC and STATCOM
3. **Wind turbines**
   – Induction generators and power electronics convertors
4. **Prevention of voltage collapse**
   – Power-voltage curves of a transmission line

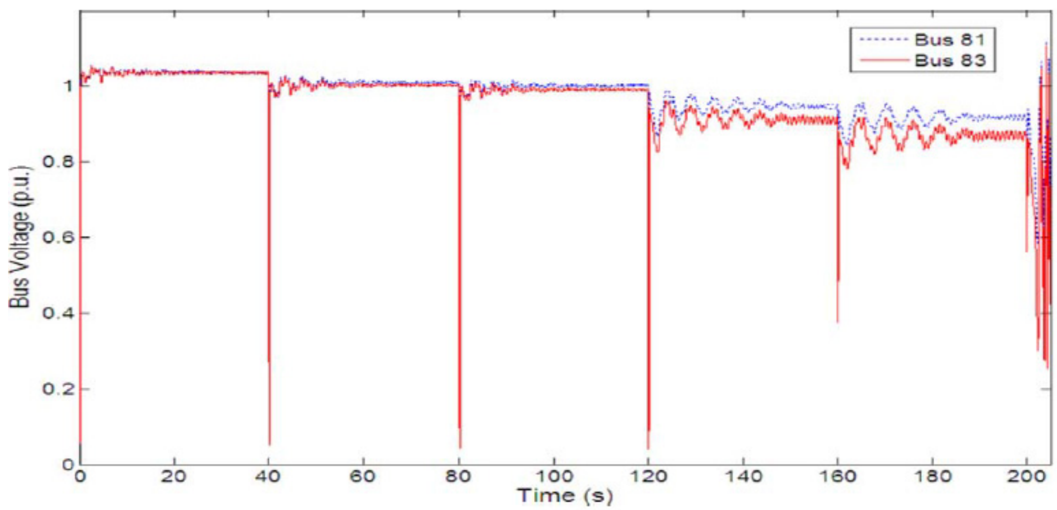
Requirements for a reliable electric power service

- Voltage and frequency must be maintained within close tolerances

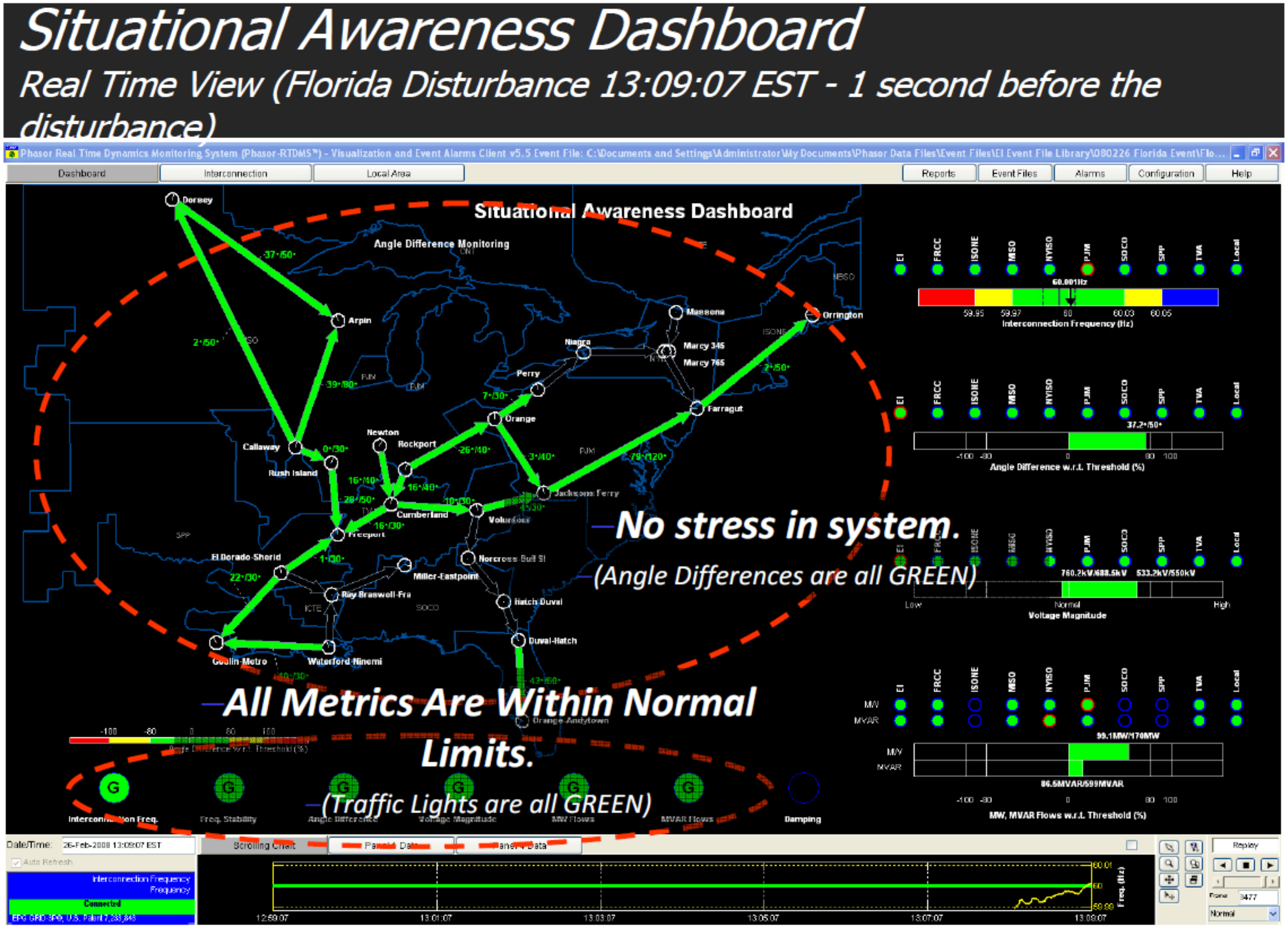
- Synchronous generators must be kept running in parallel with adequate capacity to meet the load demand

- Maintain the "integrity" of the bulk power network (avoid cascading outages)



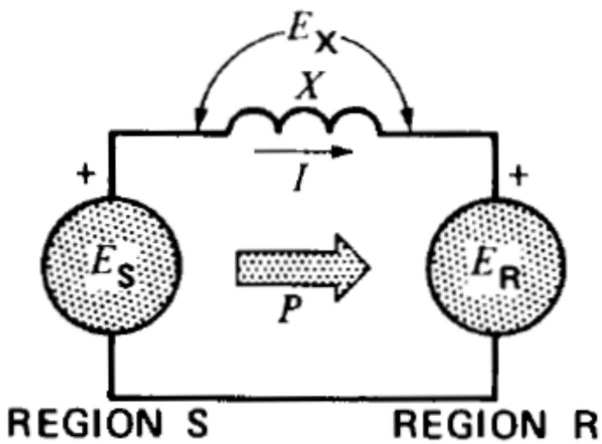


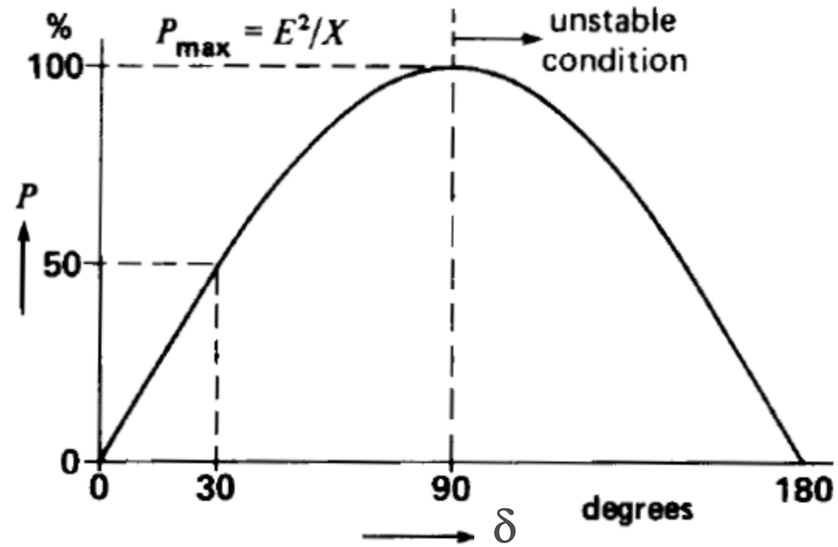
1 - Wide-Area Power Grid Stability Monitoring



From Terry Bilke's presentation at NASPI working group meeting in 2009

Inductive line connecting two systems





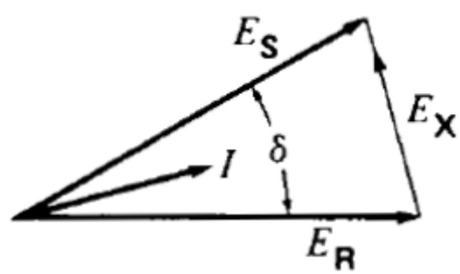


Figure 25.30a
Power versus angle characteristic.

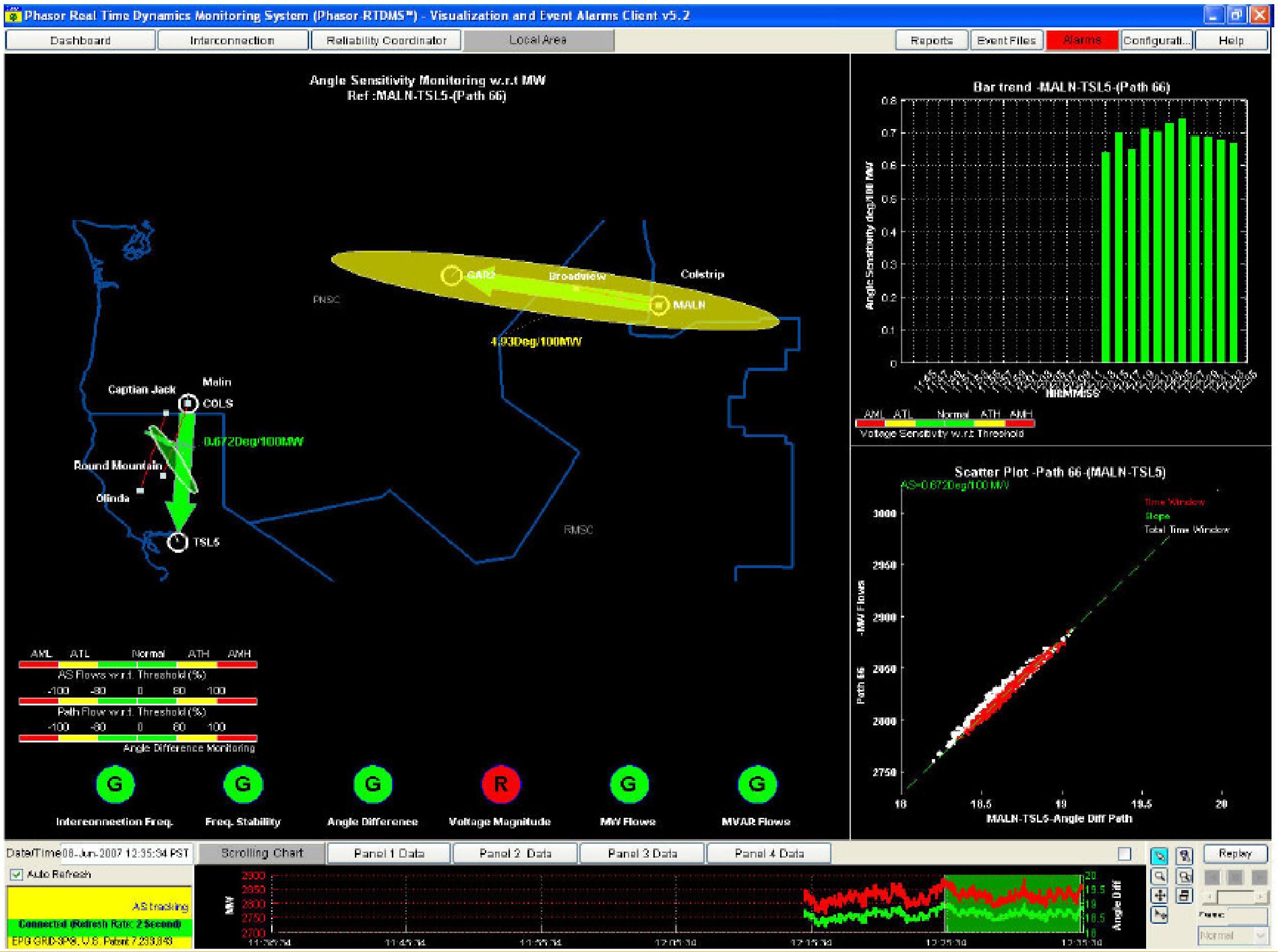
$$P = \frac{|E_S||E_R|}{X}\sin\delta \quad \leq P_{\max} = \frac{|E_S||E_R|}{X} \approx \frac{|E|^2}{X}$$

$$P \approx \frac{|E_S||E_R|}{X}\delta(\text{in rad}), \text{ if } \delta \text{ is small}$$

Angle Sensitivity Monitoring Display

Mapping 'Angular Separation' to 'MW Flows' (Example: 0.6 °/100 MW)

Monitor
- *key corridor or*
- *generation*



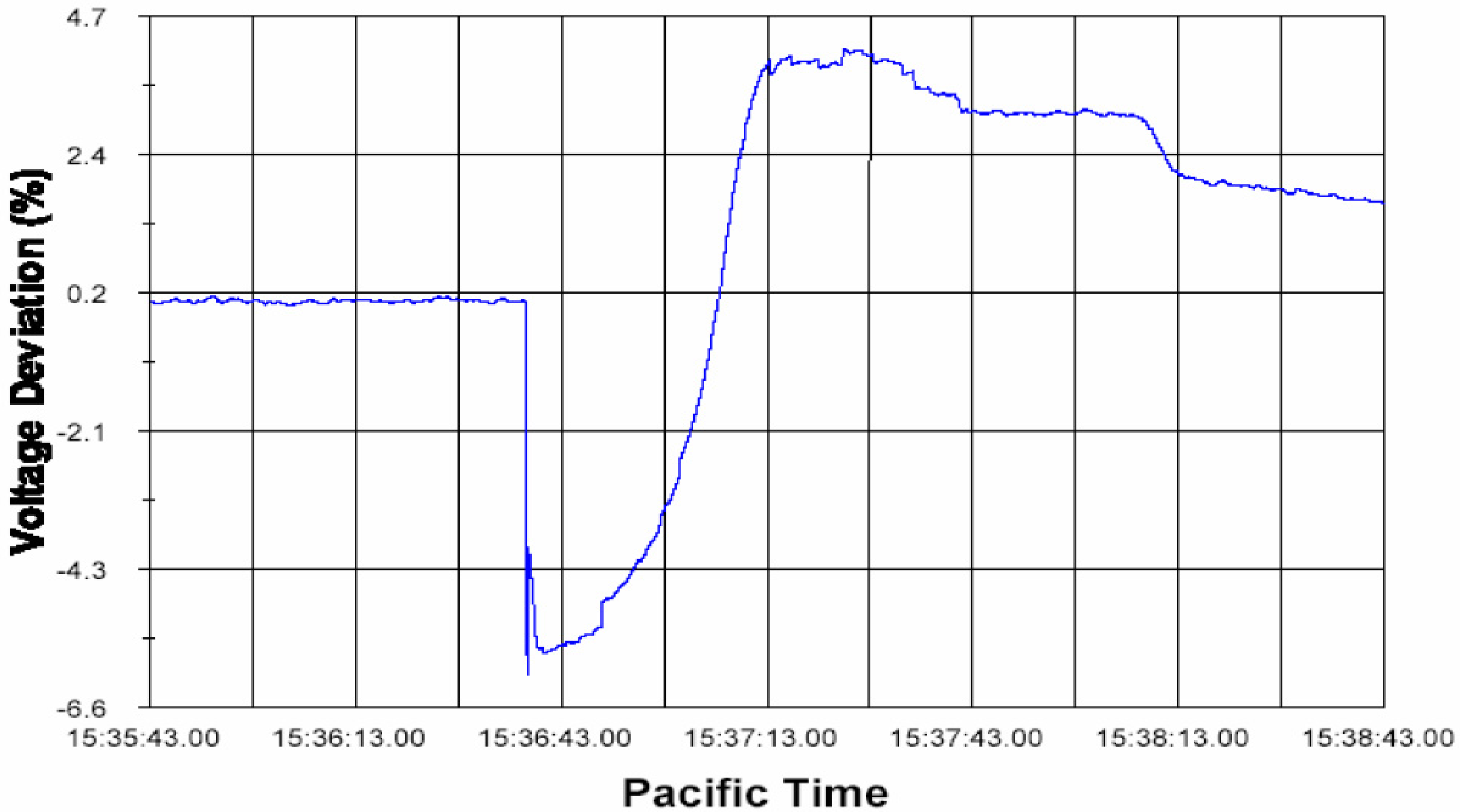
Estimated angle sensitivities (in degree/100 MW)

Scatter plot of the P-Angle curve

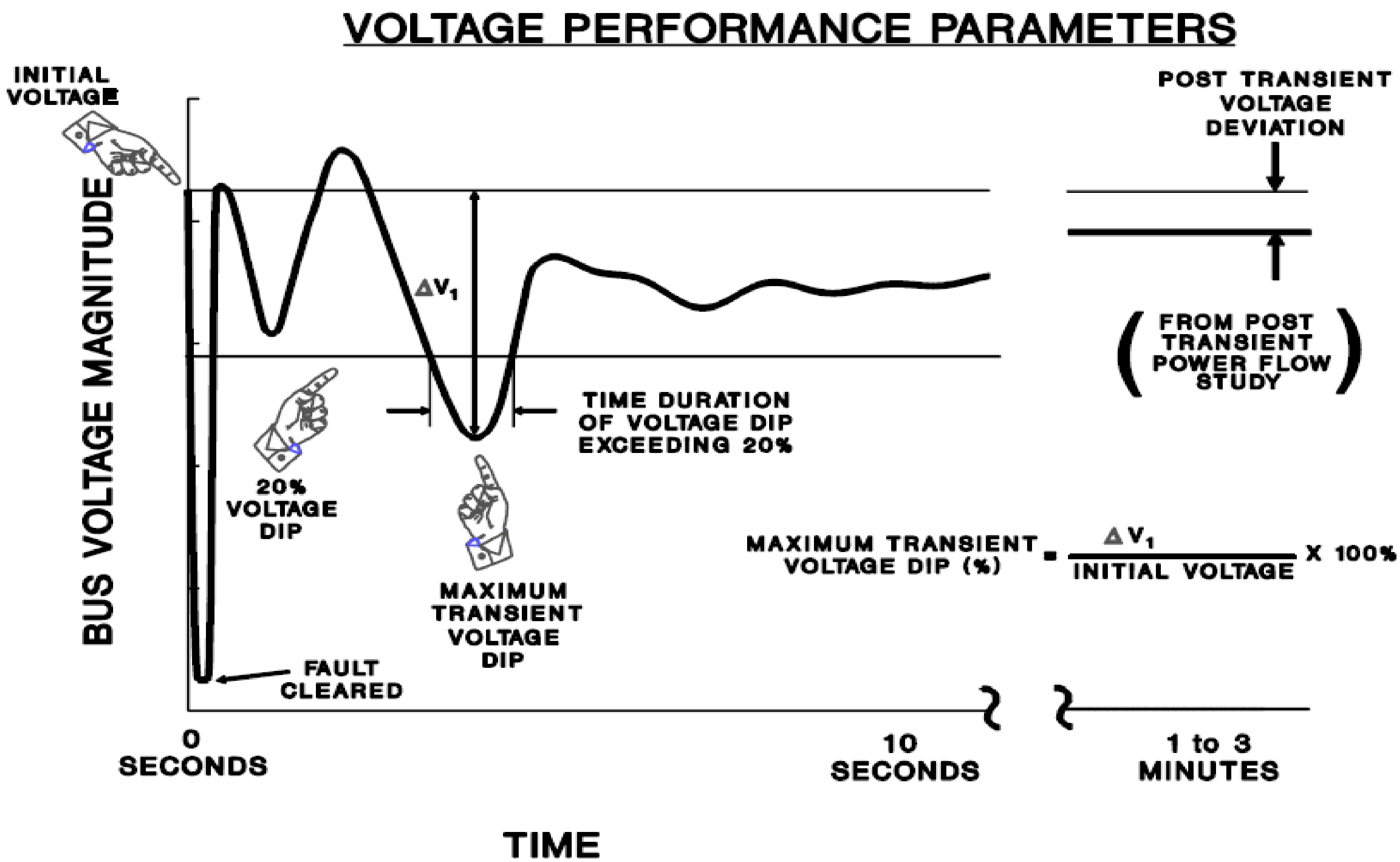
From Terry Bilke's presentation at NASPI working group meeting in 2009

2 – Fault-Induced Delayed Voltage Recovery (FIDVR)

- FIDVR issues are increasingly reported with the growth of induction motor loads, e.g. air conditioners.
- For example, a power utility company Southern California Edison has experienced delayed voltage recovery problems due to its high percentage of air conditioner loads. The high load currents and VAR demands caused up to 30s delays for the voltage to recover following the fault clearing operation



NERC Reliability Criteria



- Following a single contingency, voltage dip should not exceed 25% and should not exceed 20% for more than 20 cycles at load buses

Torque-Speed Curve: 5 hp motor

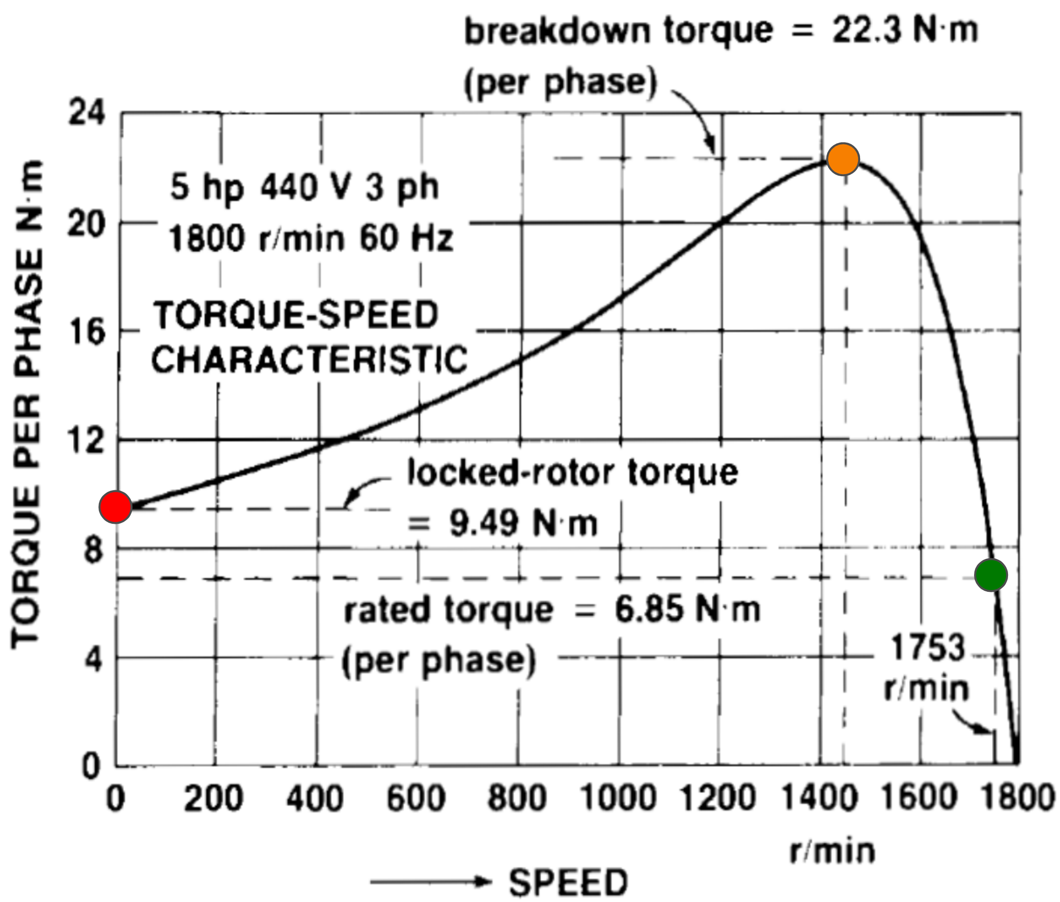


TABLE 15A TORQUE-SPEED CHARACTERISTIC

5 hp, 440 V, 1800 r/min, 60 Hz squirrel-cage induction motor

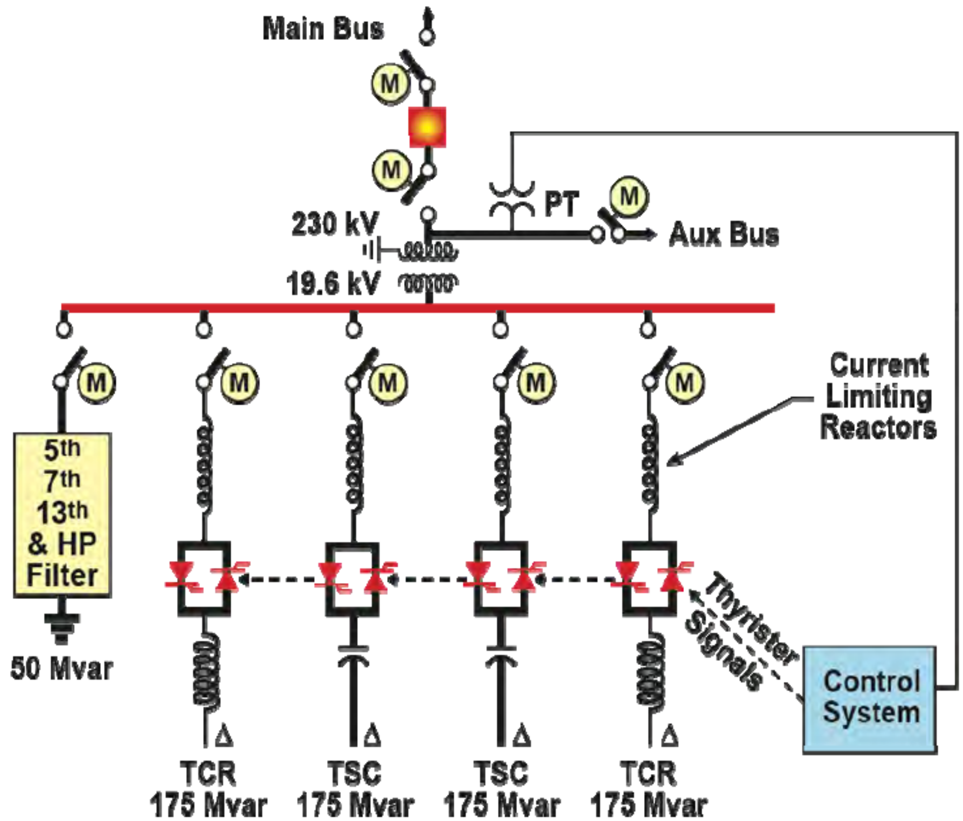
s	I_1	P_r	T	n
	[A]	[W]	[N·m]	[r/min]
0.0125	2.60	649	3.44	1777
0.025	5.09	1243	6.60	1755
0.026	5.29	1291	6.85	1753
0.05	9.70	2256	12.0	1710
0.1	17.2	3547	18.8	1620
0.2	26.4	4196	22.3	1440
0.4	33.9	3441	18.3	1080
0.6	36.6	2674	14.2	720
0.8	37.9	2150	11.4	360
1	38.6	1788	9.49	0

The rated power of 5 hp is developed at $s = 0.026$.

- When the motor is stalled, i.e. locked-rotor condition, the current is 5-6 times the full-load current, making I^2R losses 25-36 times higher than normal, so the rotor must never remain locked for more than a few second
- Small motors (15 hp and less) develop their breakdown torque at about 80% of n_s

Use of Static Var Compensators (SVC)

- Typically, a SVC installed at a bus is composed of
  - shunt reactors (reactive loads) and capacitors (reactive sources) connected via high-speed thyristor switches
  - a control system adjusts the amount of reactors or capacitors in-service to maintain the bus voltage at a target level



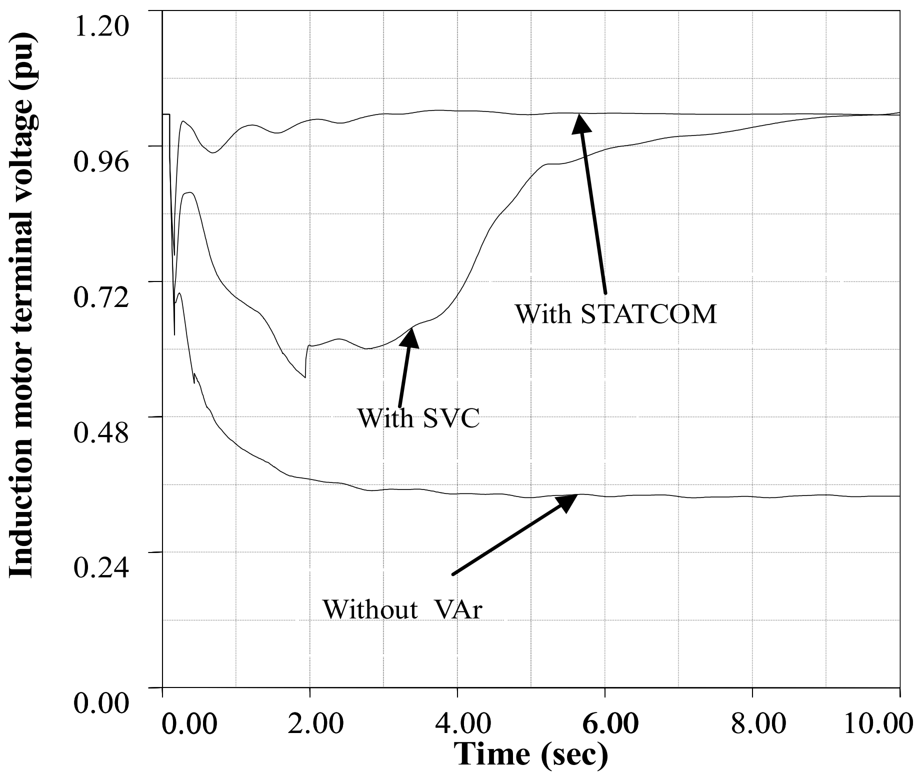
TCR - Thyristor-controlled reactor

TSC - Thyristor-switched capacitor

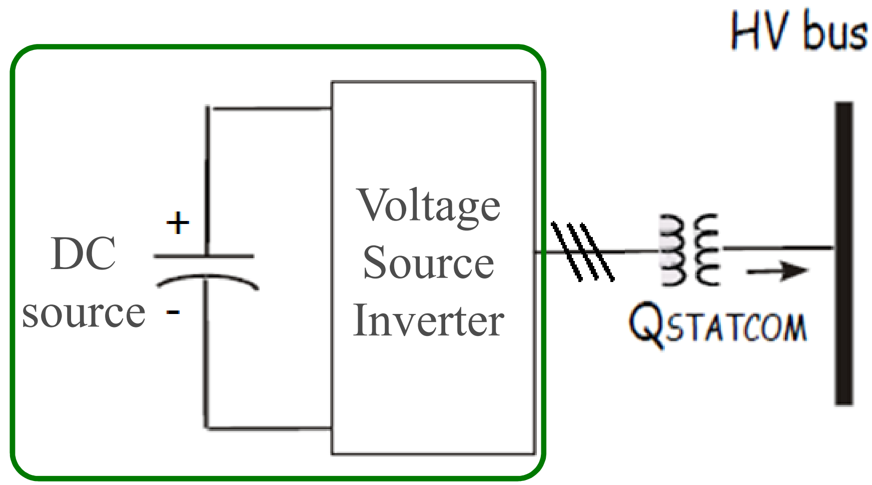
HP filer - High-pass filter to absorb high frequency harmonics caused by thyristor switches

Use of STATCOM

- Unlike a passive SVC, a STATCOM (static synchronous compensator) has an internal voltage source to provides constant output current even at very low voltages.



B. Sapkota, et al, "Dynamic VAR planning in a large power system using trajectory sensitivities," IEEE Trans. Power Systems, 2010.



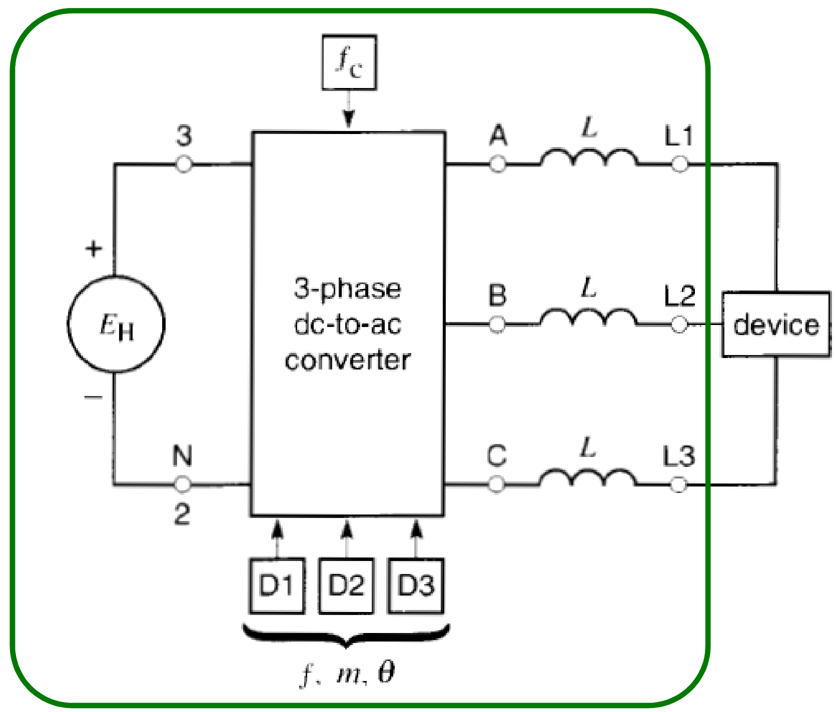
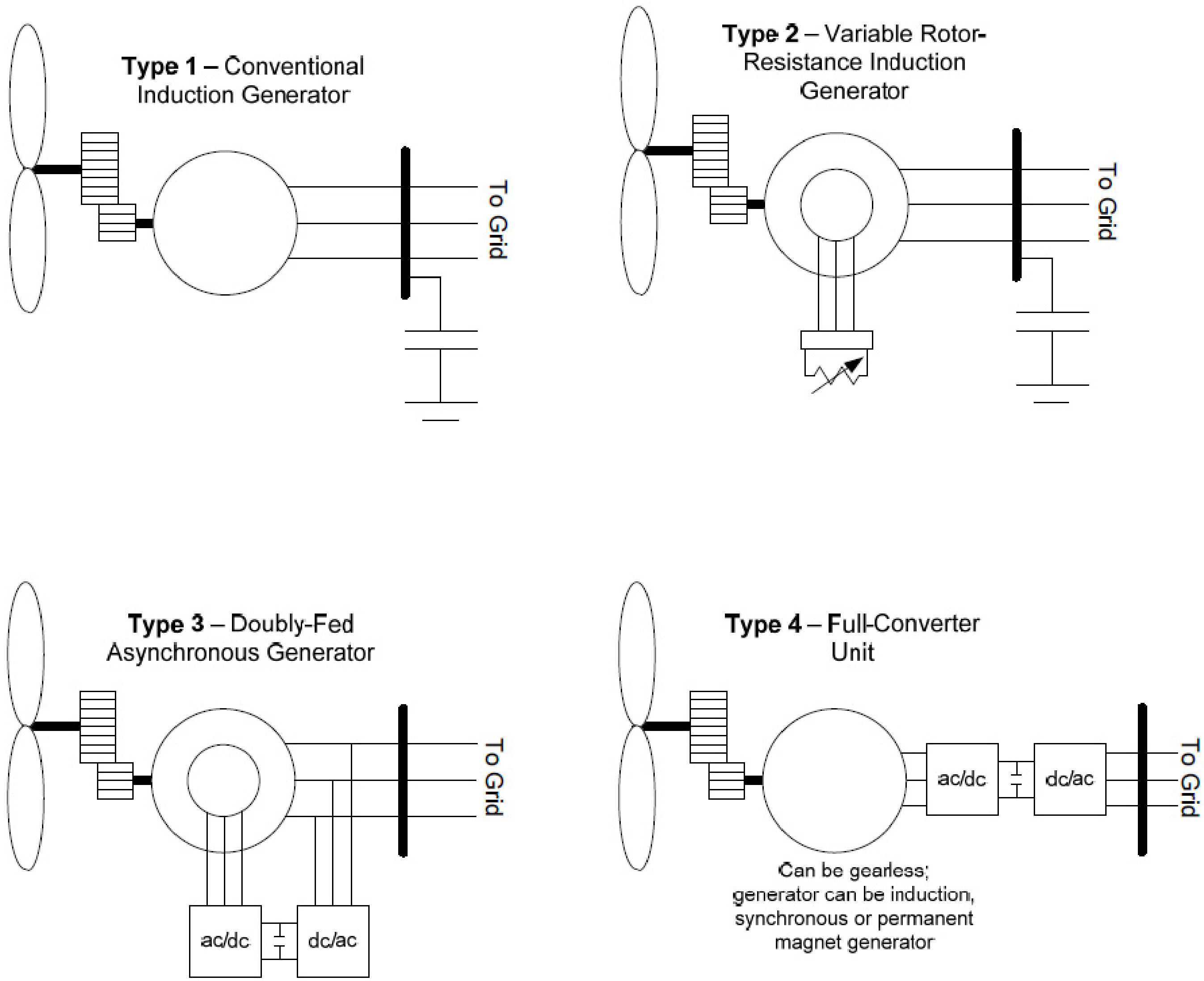


Figure 21.87
Schematic diagram of a dc-to-ac 3-phase switching converter.

3 – Wind Turbines



From EPRI report “Proposed Changes to the WECC WT4 Generic Model for Type 4 Wind Turbine Generators”, 12, 2011

Asynchronous generator

Connect the 5 hp, 1800 r/min, 60Hz motor to a 440 V, 3-phase line and drive it at a speed of 1845 r/min

$s=(n_s\text{-n})/n_s=(1800\text{-}1845)/1800= -0.025 <0$

$R_2/\text{s}=1.2/(-0.025)= -48\Omega <0$

The negative resistance indicates the actual power flow from the rotor to the stator

Power flow from the rotor to the stator:

$|E|= 440/1.73=254$ V

$|I_1|=|E|/ |-48+1.5+ j6|=254/46.88= 5.42$A

$\boldsymbol{P_r=|I_1|^2R_2/s= -1410}$ **W** (in fact, rotor → stator)

Mech. power & torque inputs to the shaft:

$P_{jr}=|I_1|^2R_2=35.2$ W

$\boldsymbol{P_m=P_r+P_{jr}}=1410 + 35.2=1445$W

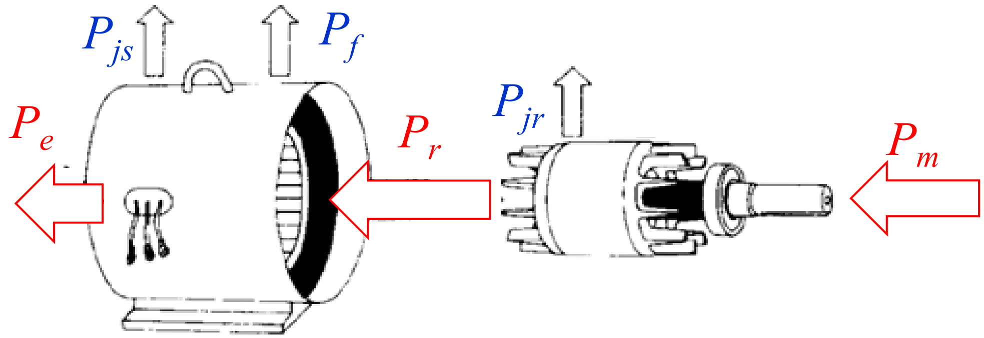
$T=3\times9.55 \times P_m/n=22.3$ N·m

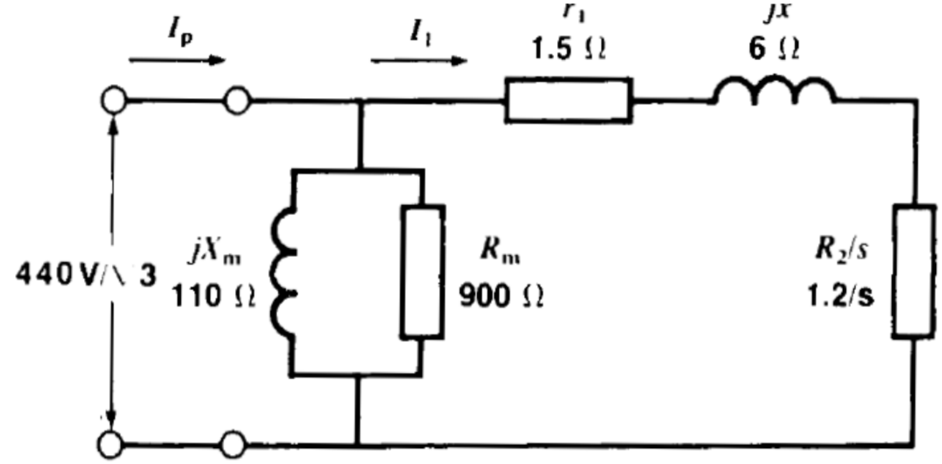
Total active power delivered to the line:

$P_{js}=|I_1|^2r_1=44.1$ W, $P_f=|E|^2/R_\text{m}=71.1$ W

$\boldsymbol{P_e=P_r-P_{js}-P_f}= 1410\text{-}44.1\text{-}71.7=1294$ W

$P_{3\phi}=3P_e=3882$W





Reactive power absorbed from the line:

$Q_{3\phi}=(|I_1|^2x+|E|^2/X_\text{m})\times3=(176+586)\times3=2286$ var

Complex power delivered to the line:

$S_{3\phi}=P_{3\phi} - Q_{3\phi}=3882 - \text{j}2286$ VA

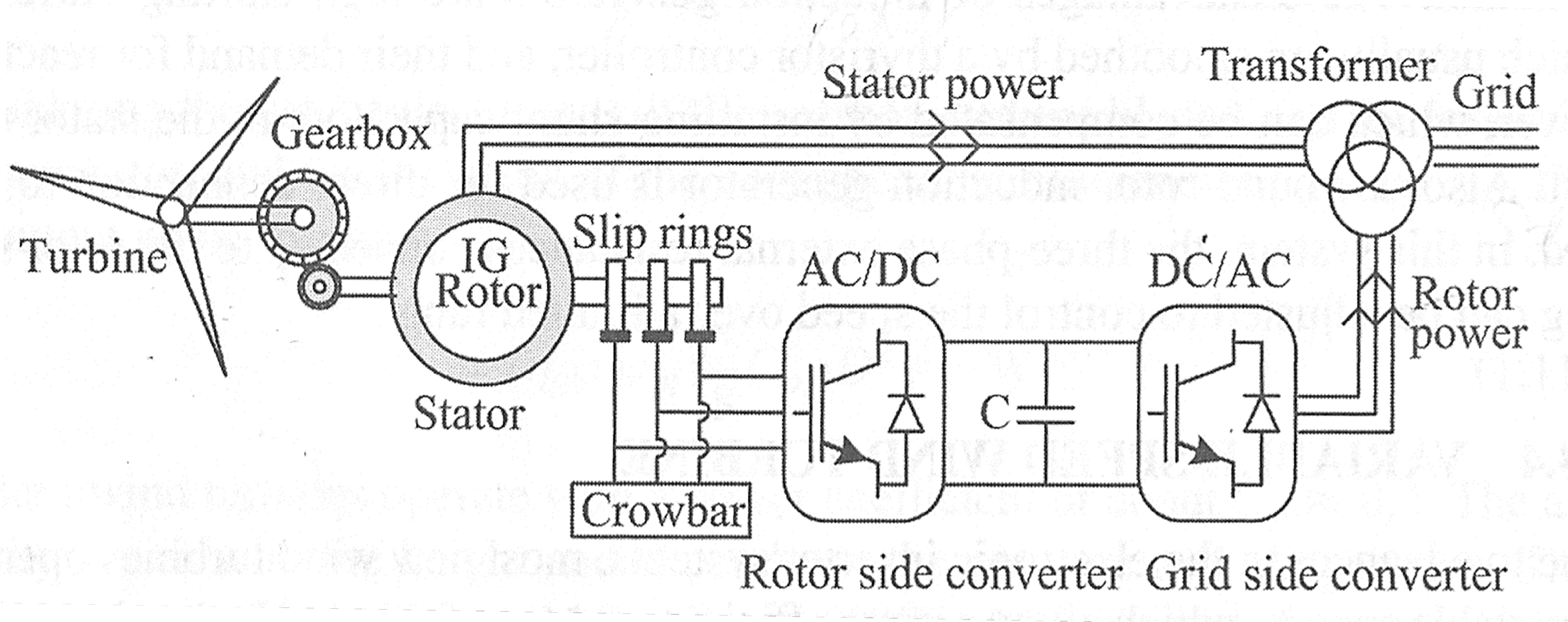
$\cos\theta=86.2\%$

Efficiency of this asynchronous generator

$\eta=P_e/P_m=1294/1445=89.5\%$

DFIG Wind Turbine

- A Doubly-Fed Induction Generator (DFIG) wind turbine can deliver energy to the power grid from both the stator and rotor windings through power electronics converters.
- By means of the converters, it can be a reactive power source of the grid like a STATCOM



4 - Voltage Collapse - July 2nd, 1996 Western Cascading Event

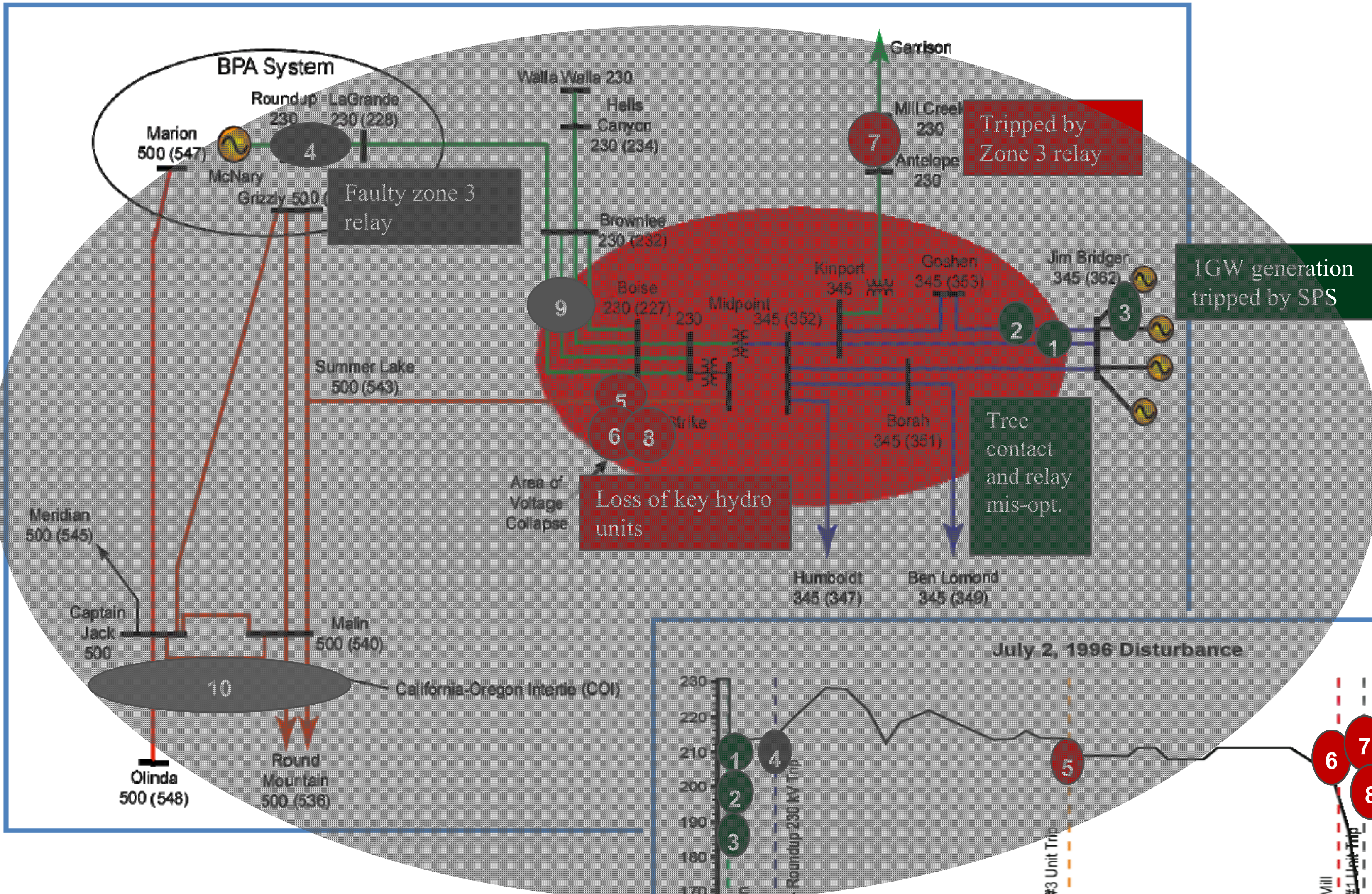


Figure 6-22. One-Line Diagram for July 2, 1996 Disturbance

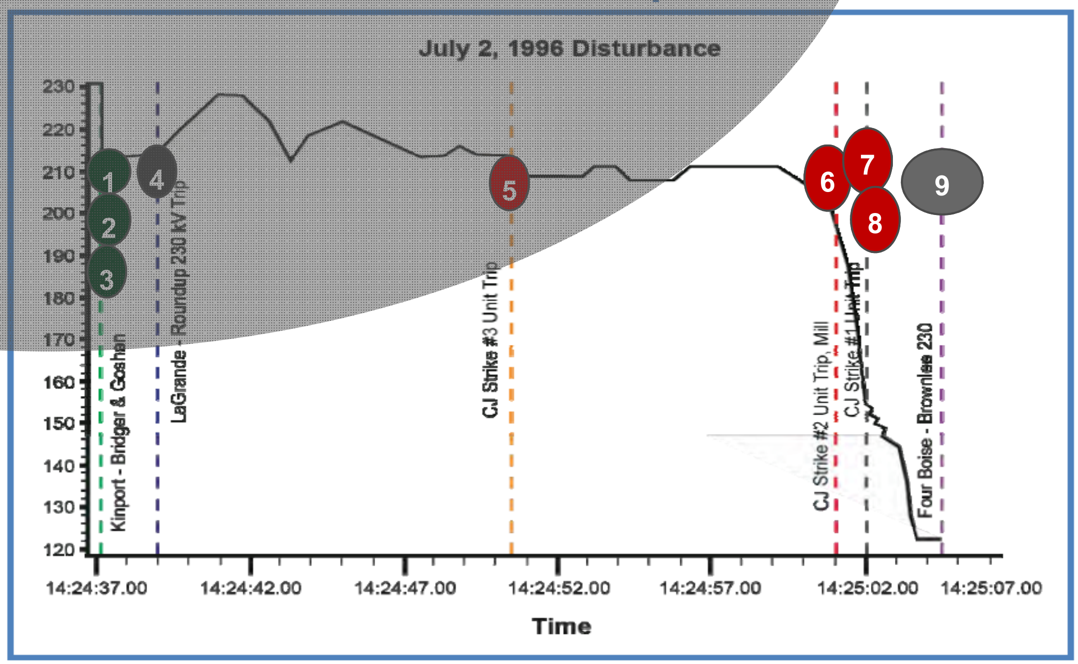


Figure 6-23. Boise 230 kV Voltage Collapse

Inductive line

$$P = |I|^2 (kX) = \left| \frac{E_S}{jX + kX} \right|^2 kX$$

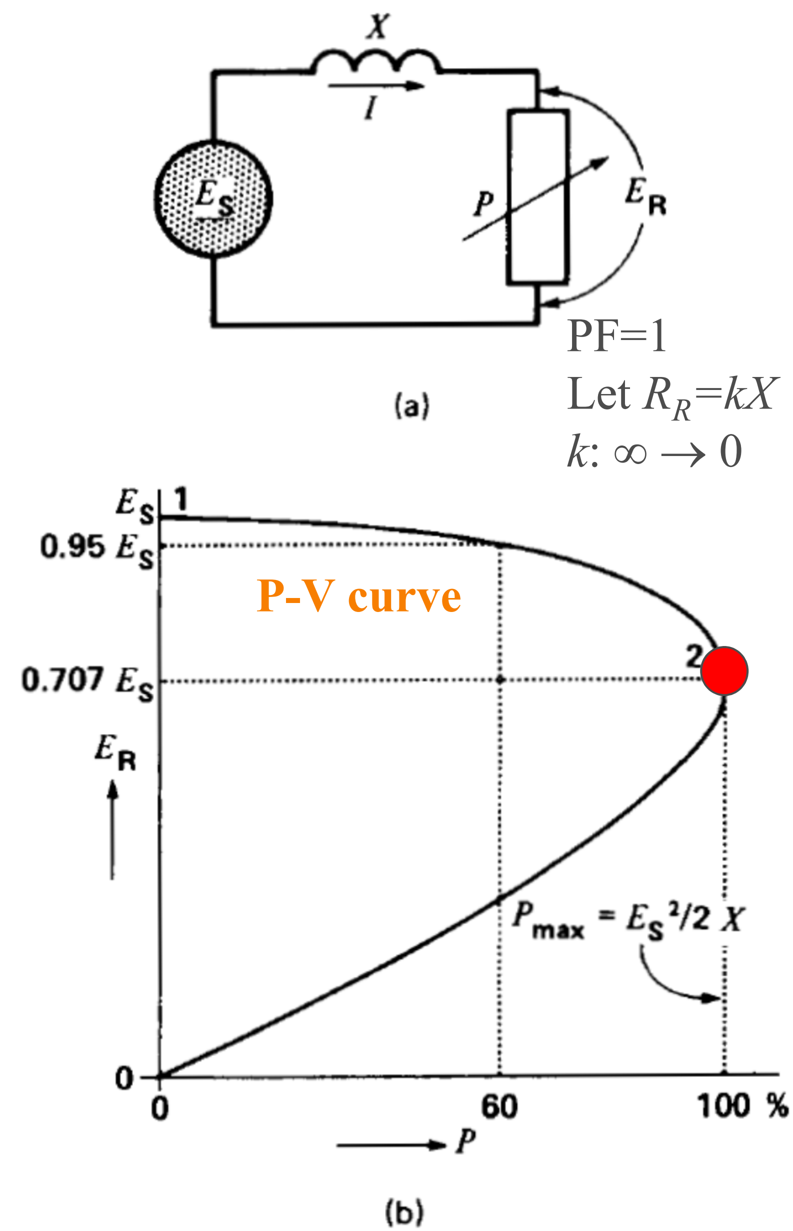
$$= \frac{|E_S|^2}{X\,|k - 1/k + 2j\,|} \le \frac{|E_S|^2}{2X}$$

When k=1, i.e. $R_R = X$

$P = P_{max} = |E_S|^2/2X$

where $|E_R| = |E_S|/\sqrt{2} = 0.707|E_S|$

and voltage collapse happens



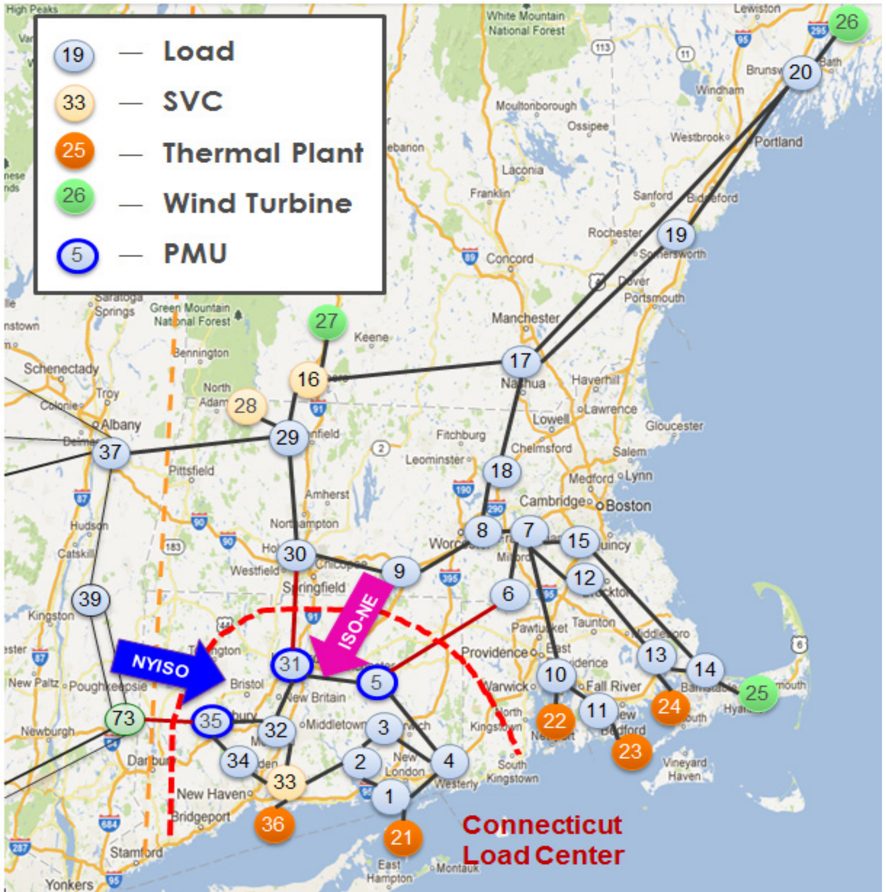
PF=1

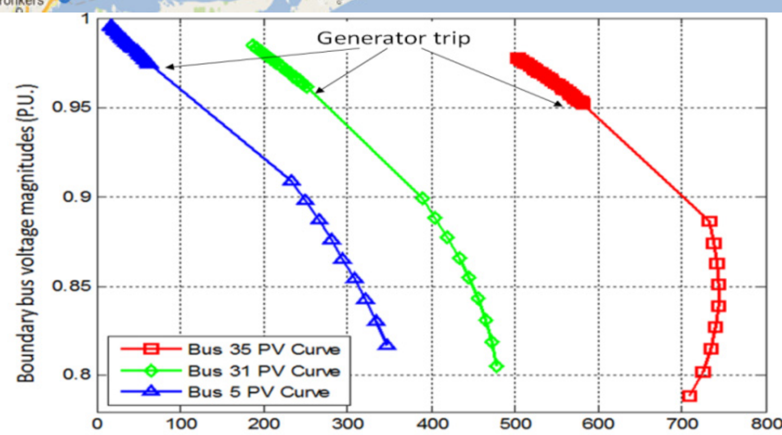
Let $R_R = kX$

k: $\infty \rightarrow 0$

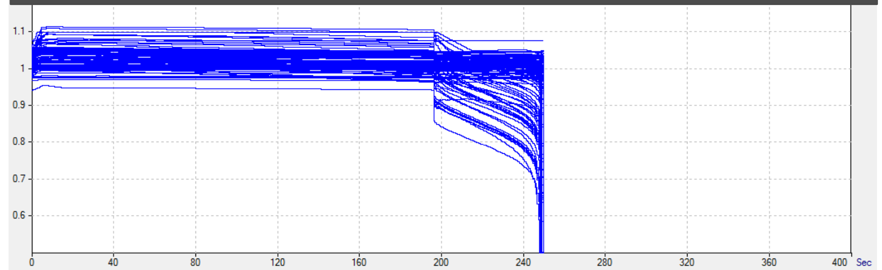
Figure 25.22
Characteristics of an inductive line.

Prevention of Voltage Collapse

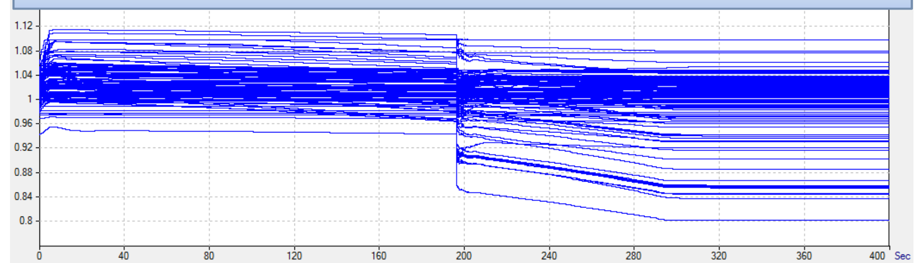




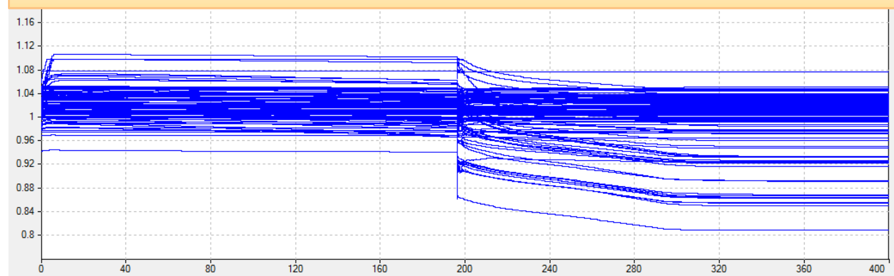
Voltage Collapse after a Generator Trip



With Under-Voltage Load Shedding (Today's control)



With Centralized Control of SVCs



Dispatch more VAR from Wind Turbines