UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

The Australian Power Institute

API Masterclass

Reactive Power Management and Voltage Stability

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Drivers for managing reactive power

1.1 Characteristics of modern power systems

For a number of years, load growth was not matched by expansion of the transmission system.

- Transmission lines are being operated at higher loading levels.
- It is not unusual for thermal limits to exceed the surge impedance loading (SIL).
  - At SIL, the reactive power consumed by the line reactance is equal to the reactive power generated by the line susceptance.
  - At higher loading, transmission lines become net consumers of reactive power.

Load composition is changing.

- Significant increase in residential air-conditioners.
  - Many single-phase induction motors that stall for voltage dips of a few cycles.
- Greater use of power electronics.
  - Examples: motor drives, server farms, energy efficient lighting, plug-in electric vehicles.
  - Respond very quickly, effectively giving a constant power characteristic.
  - Load trips when voltage deviates beyond low and high voltage thresholds.
- Lighting example:
  - Incandescent, $I = V/R$, current drops as voltage drops.
  - Compact fluorescent, $I = P/V$, current increases as voltage drops.

Newer generating sources provide less/different reactive support.

- Modern synchronous generators have higher power factor rating, to save costs.
- Increased reliance on wind and solar (PV) generation.
  - Reactive power capability is vastly different from that of conventional generation.

Reactive power doesn't "flow" across transmission/distribution networks very well.

- A lack of local reactive support leads to local voltage reduction.

When a transmission line trips, power flow increases on adjacent lines, resulting in increased reactive demand, and reduced voltages.

- In a voltage collapse situation, the transmission system is incapable of sustaining the pre-disturbance power flow level, and voltages steadily decline.
- Protection operation progressively trips lines/feeders, weakening the power system.

Voltage collapse may take various forms. But in all cases, a deficiency of reactive power leads to abnormal voltage drops.

1.2 Examples of voltage collapse

France, December 19, 1978.

- The load rise between 0700 and 0800 was 4,600 MW, compared with around 3,000 MW on previous days.
- Voltages deteriorated after 0800, due to OLTC action.
  - Low voltages caused a reduction in MW production.
  - By 0820, voltages on the eastern 400 kV system ranged from 342 kV to 374 kV.
- Cascading protection operation began at 0826, after an overload relay tripped a major 400 kV line.
- Load loss was about 29 GW.

Sweden, December 27, 1983.

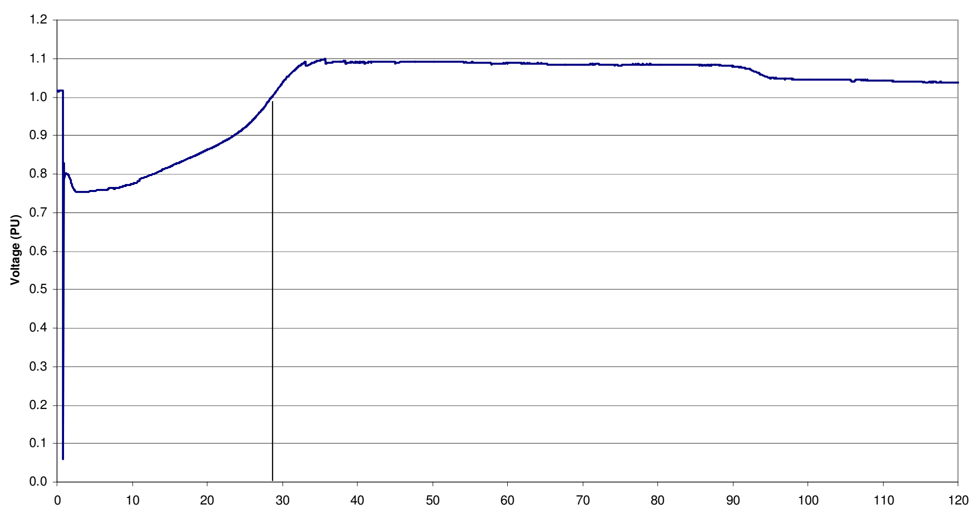
- A disconnector failure resulted in loss of a substation and two 400 kV transmission lines.
- About 8 seconds later, a 220 kV line tripped on overload.
- On-load tap changer (OLTC) actions were meant to raise distribution voltages, but instead reduced transmission voltages, leading to higher currents.
- About 50 seconds after the fault, another 400 kV line tripped.
- Cadcading protection operation led to islanding of southern Sweden.
- Load loss was about 11,400 MW.

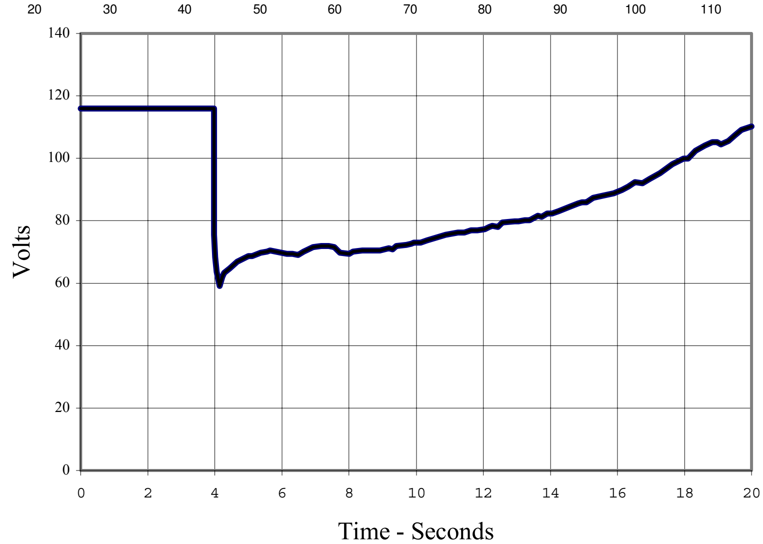
North-eastern America, August 14, 2003.

- Not officially an instance of voltage collapse, but reactive power issues played a significant role.
- Initial voltages were quite low (0.95-1.00 pu), but officially not abnormal.
- Then a generating unit tripped on incorrect over-excitation protection.
- Line overloads led to excessive sagging, and line tripping.
- Higher flows on adjacent feeders initiated zone 3 distance protection.
- Once the cascade was underway, there was no stopping it.
- See slides.

Air-conditioner induced incidents

- Numerous incidents: Southern California, Phoenix, Miami and others.
  - See Diaz de Leon and Taylor (2002), NERC report (2009).
- Initiating event causes residential air-conditioners to stall.
  - For voltages below about 65%, compressor motors stall in around 3-5 cycles.
- Stalled motors draw 4-6 times normal current, so voltages remain depressed.
- Thermal protection trips stalled motors after 5-10 seconds.





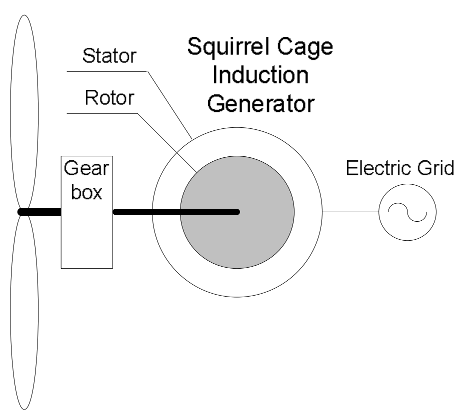
Voltage collapse in a mining environment

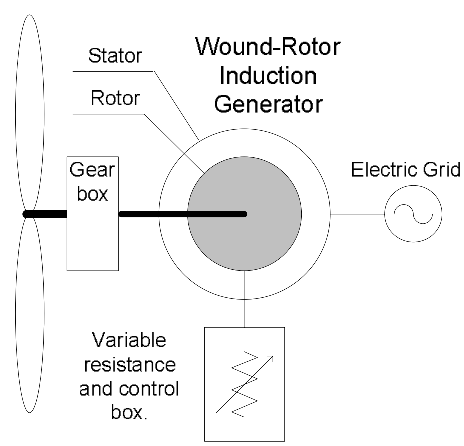
- Long radial supply system, relatively large impedance between the load and the nearest strong supply point.
- Load dominated by induction motors.
- Continuous miner (bucket wheel digger) encountered harder material, drawing higher current which caused a voltage reduction.

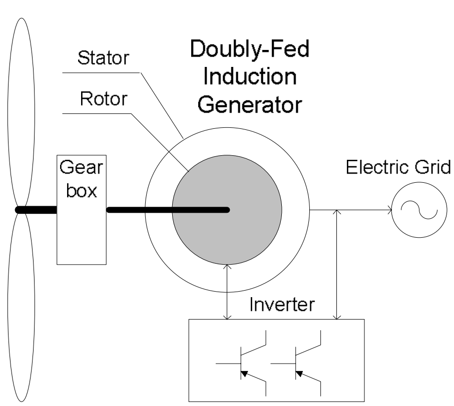
- This reduction in voltage was sufficiently low and long that other induction motors stalled, drawing high current across the weak system.
- Protection was tripped by a combination of low voltages and high currents.

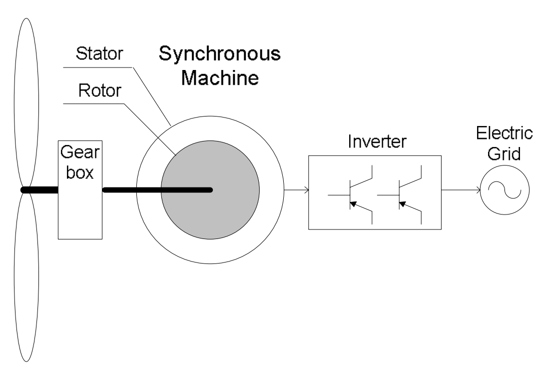
1.3 Wind power issues

- Wind farms tend to be connected at relatively weak points in the system (low fault level.)
  - High line resistance complicates voltage control strategies.
- Generation varies considerably, causing voltage variations.
  - This can lead to excessive tap changing.
- The impedance of the collector system, between the wind turbine generators (WTGs) and the collector bus, makes it difficult to use the WTG reactive power capability for voltage control at the point of common coupling.
- Early designs used induction machines that required substantial reactive support.
  - Newer doubly fed induction generator (DFIG) designs and inverter-connected synchronous machines provide voltage control at the generator terminals, but coordination with other voltage control devices is quite challenging.



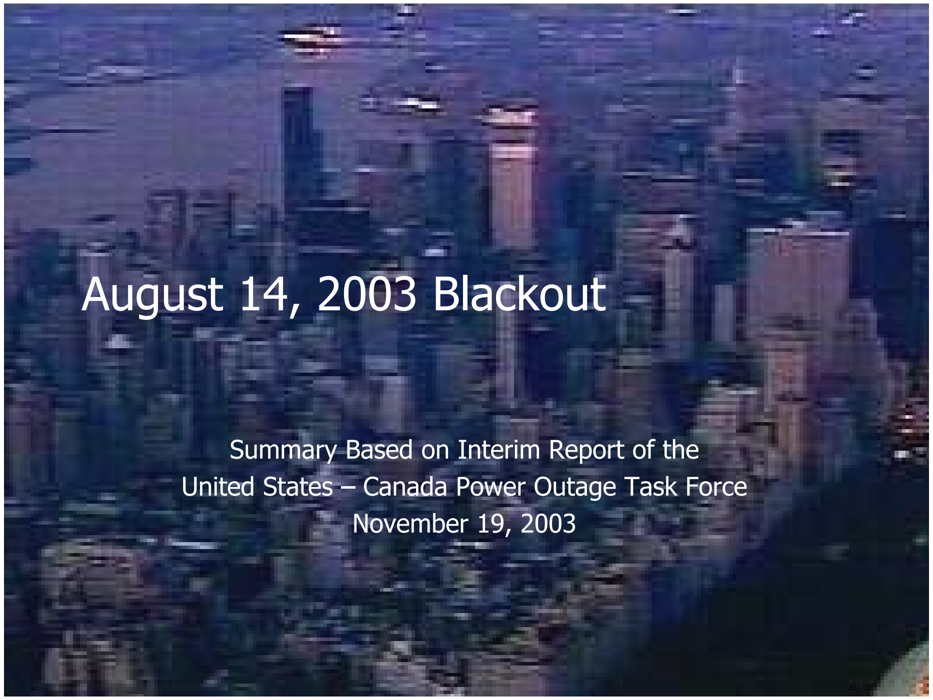




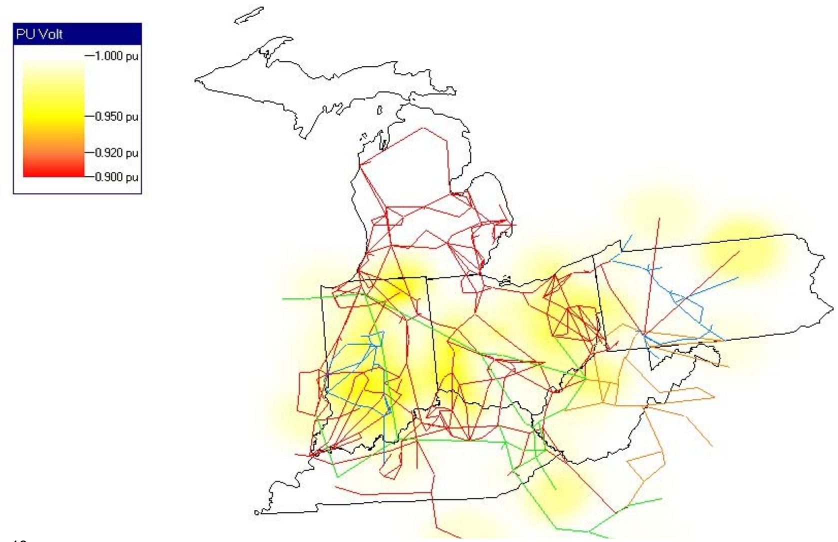


1.4 Solar (PV) generation on distribution networks

- High voltages can occur during periods of light load and high PV power generation.
- Grid-connection inverters operate at unity power factor (zero reactive power) due to AS 4777, though this standard is under review.
  - The corresponding standard in the US is IEEE 1547. It is also under review.

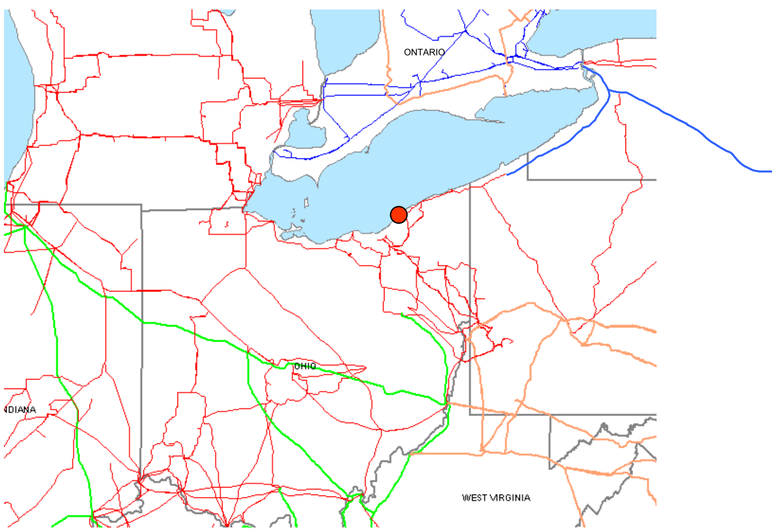


Voltages Prior to 15:05 EDT August 14



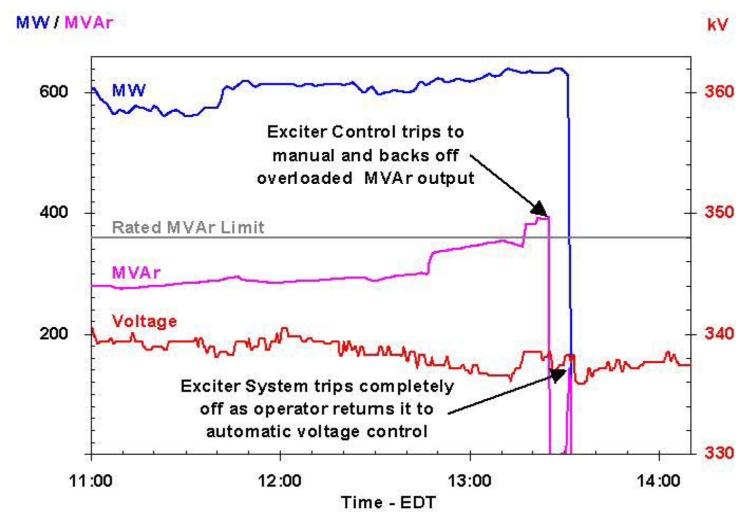
18

East Lake 5 Trip: 1:31:34 PM



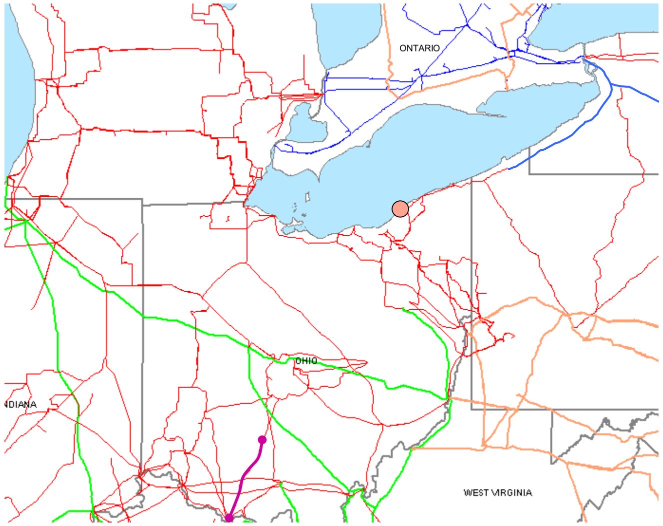
22

East Lake 5 Exciter Failure Causes Trip

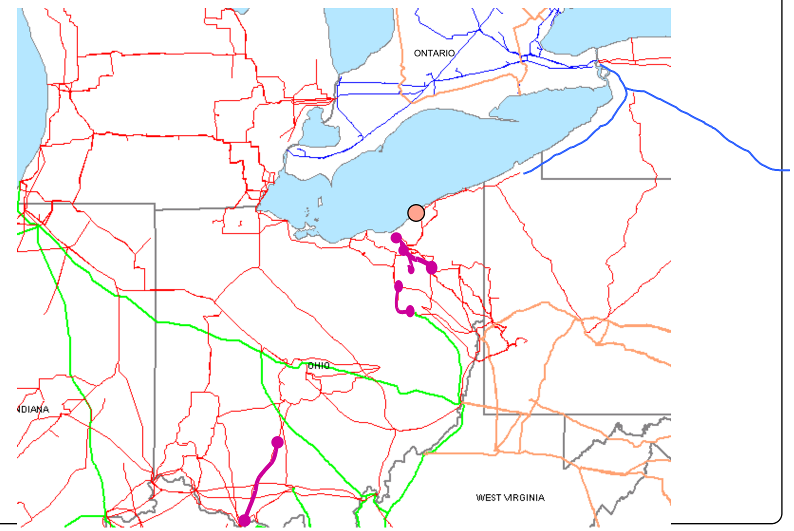


23

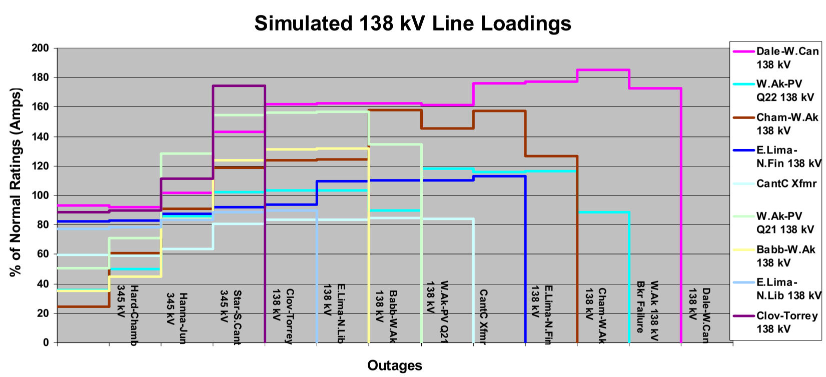
Stuart Atlanta Trip: 2:02 PM



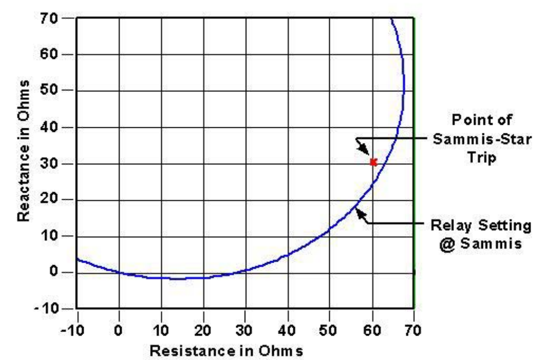
Situation after Initial Trips 3:05:41 – 3:41:35



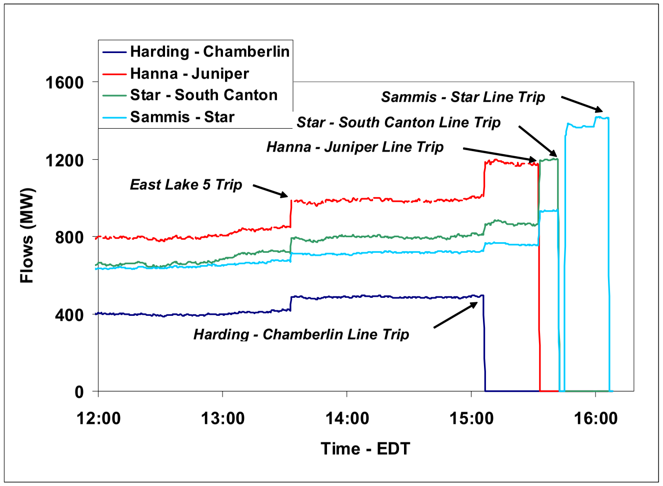
138 kV Lines Overload and Cascade Near Akron



Sammis-Star Zone 3 Relay Operates on Steady State Overload

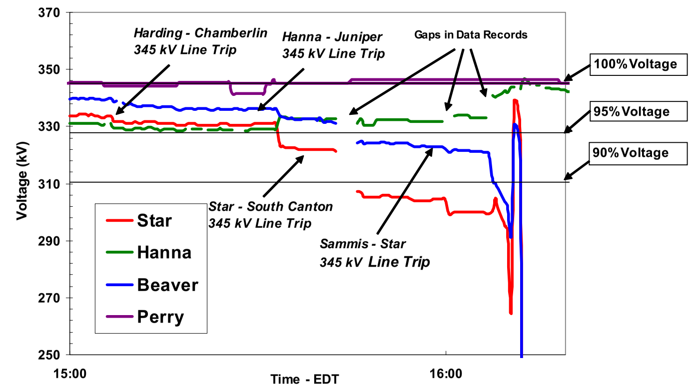


Actual Loading on Critical Lines



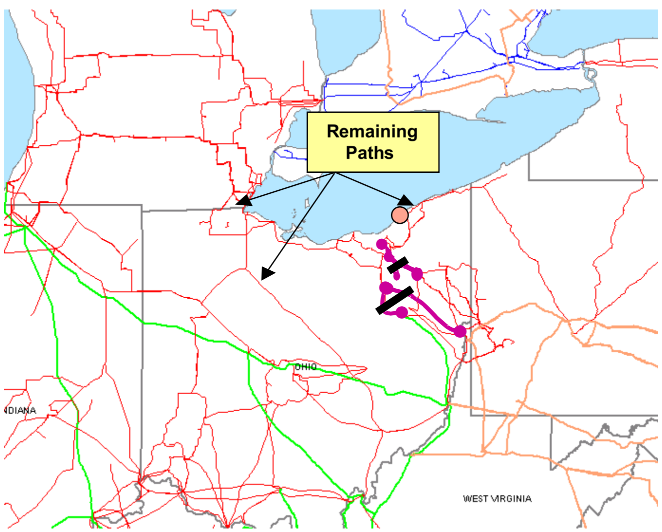
40

Actual Voltages Leading to Sammis-Star



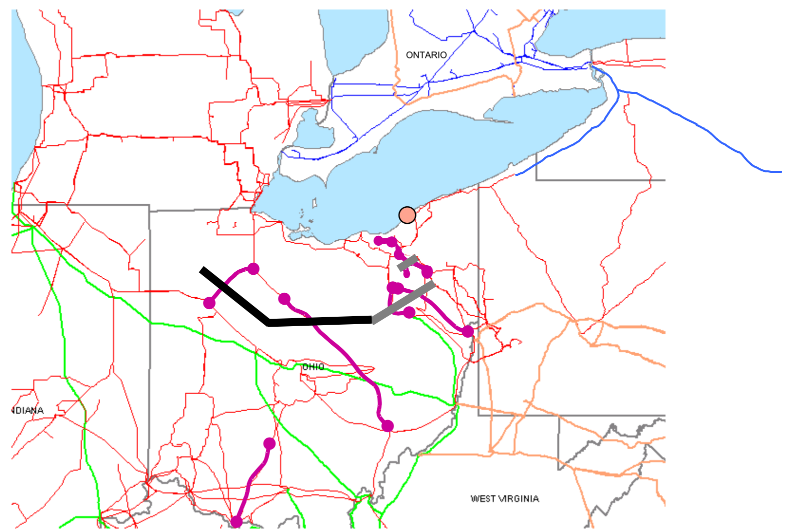
41

Major Path to Cleveland Blocked after Loss of Sammis-Star 4:05:57.5 PM



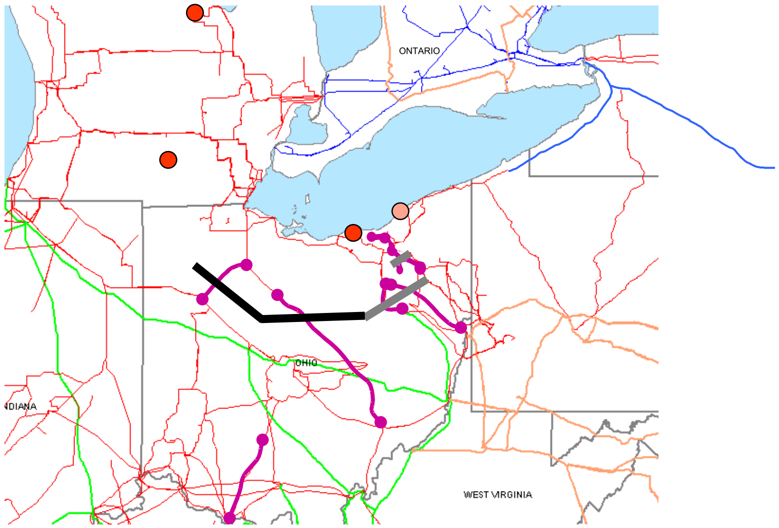
42

345 kV Lines Trip Across Ohio to West

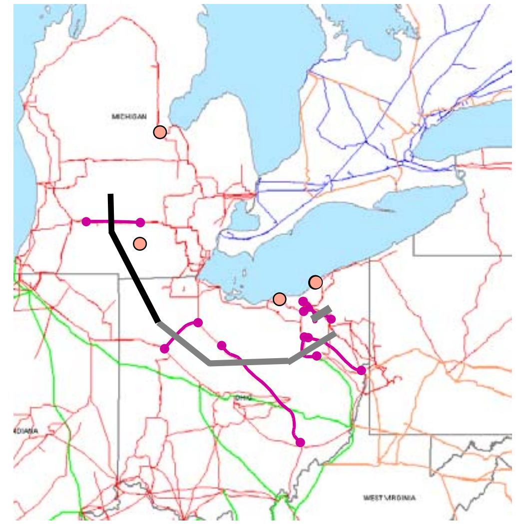


43

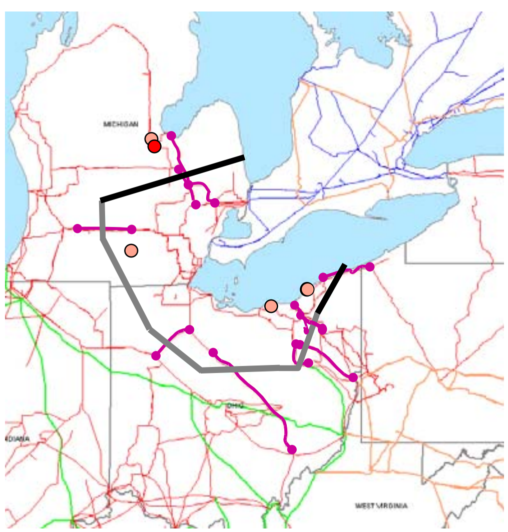
Generation Trips 4:09:08 – 4:10:27 PM



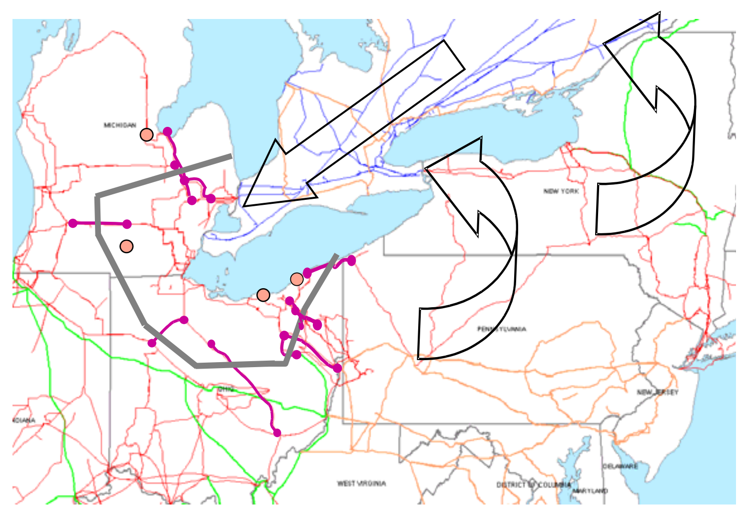
345 kV Transmission Cascade Moves North into Michigan 4:10:36 – 4:10:37 PM



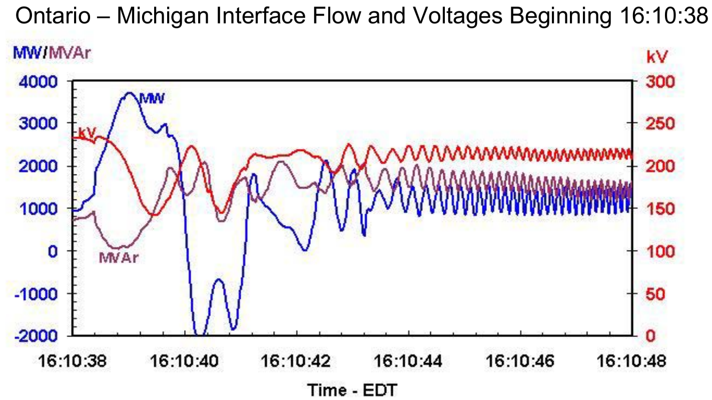
Northern Ohio and Eastern Michigan Served Only from Ontario after 4:10:37.5 – 4:10:38.6 PM



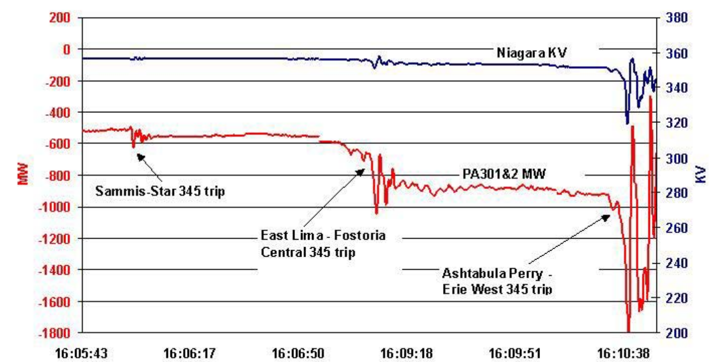
Power Transfers Shift at 4:10:38.6 PM



Eastern Eastern Michigan (Detroit) Unstable Voltage and Frequency Collapse and Pole Slipping



Conditions at Niagara Indicate Progressively Worsening Stability Conditions with Prior Events



Near-Term Industry Actions

Responses from Control Areas and Reliability Coordinators Due December 15

- Voltage support/reactive supply
- Reliability communications
- Computer failure response & notifications
- Emergency action plans and capabilities
- Operator training for emergencies
- Vegetation management

Basic concepts

2.1 What is reactive power?

Instantaneous power is given by

$$p(t) = v(t)i(t)$$

where

$$v(t) = \sqrt{2}\, V_{rms} \cos(\omega t + \theta_v)$$
$$i(t) = \sqrt{2}\, I_{rms} \cos(\omega t + \theta_i).$$

Manipulation using trigonometric identities gives

$$p(t) = P\Big(1 + \cos\big(2(\omega t + \theta_v)\big)\Big) + Q \sin\big(2(\omega t + \theta_v)\big)$$

where

$$P = V_{rms} I_{rms} \cos(\theta_v - \theta_i)$$
$$Q = V_{rms} I_{rms} \sin(\theta_v - \theta_i).$$

Apparent power is given by $V_{rms} I_{rms}$.

Average (active or real) power is given by

$$P_{ave} = \frac{1}{T} \int_T p(t) dt = P.$$

The Q term is referred to as *reactive power*, and is a measure of the apparent power that is not contributing to energy delivery.

For example, the following figure shows $i(t)$ lagging $v(t)$ by 30^o. This gives $P = 0.433$ and $Q = 0.25$.

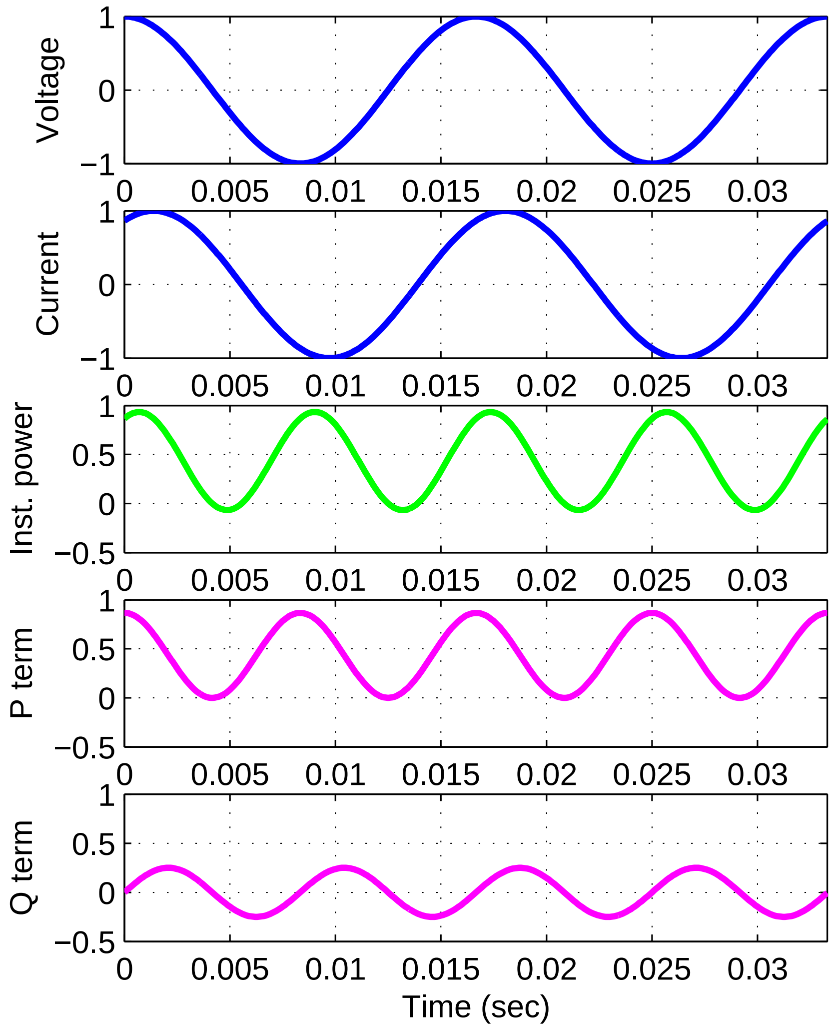
In terms of phasors, $V = V_{rms} \angle \theta_v$ and $I = I_{rms} \angle \theta_i$, complex power is given by

$$S = P + jQ = V I^*$$

where $|S|$ is the apparent power.

Power factor:

- Lagging, P and Q have the same sign.
- Leading, P and Q have opposite signs.
  - These definitions hold for both load and generation.



Voltage
1
0
−1
Current
Inst. power
0.5
−0.5
P term
Q term
0
0.005
0.01
0.015
0.02
0.025
0.03
Time (sec)

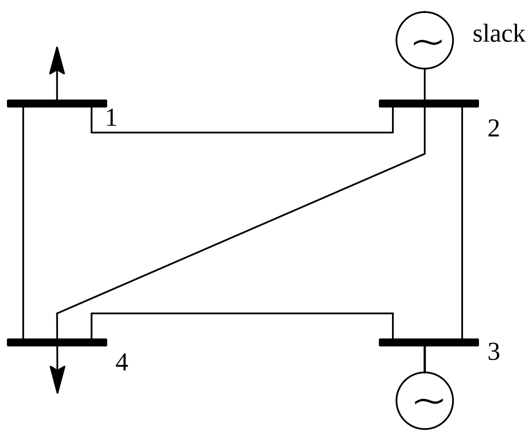
2.2 Voltage - reactive power coupling

The power balance equations can be written,

$$P_i^{sp} = P_i(\theta, V) = V_i \sum_{k=1}^{n} V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik})$$
$$Q_i^{sp} = Q_i(\theta, V) = V_i \sum_{k=1}^{n} V_k (G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik})$$

where the phasor voltage at the i-th bus is $V_i \angle \theta_i$, angle differences are given by $\theta_{ik} = \theta_i - \theta_k$, and $Y_{ik} = G_{ik} + jB_{ik}$ is the (ik)-th element of the *network admittance matrix* defined by

$$Y_{ii} = \sum_{\substack{k=0 \\ k \neq i}}^{n} y_{ik} = \text{ self admittance of node } i$$
$$Y_{ik} = -y_{ik} = \text{ mutual admittance between nodes } i \text{ and } k.$$



The power flow sensitivities are provided by the Jacobian,

$$\begin{bmatrix} \Delta P^{sp} \\ \Delta Q^{sp} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}$$

where, for $i \neq k$,

$$\frac{\partial P_i}{\partial \theta_k} = V_i V_k (G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik})$$
$$\frac{\partial P_i}{\partial V_k} = V_i (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik})$$
$$\frac{\partial Q_i}{\partial \theta_k} = -V_i V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik})$$
$$\frac{\partial Q_i}{\partial V_k} = V_i (G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik})$$

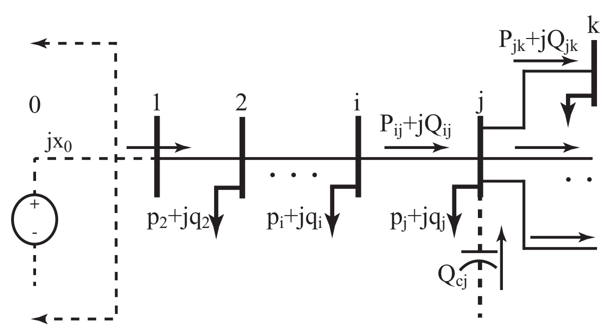
and

$$\frac{\partial P_i}{\partial \theta_i} = -B_{ii}V_i^2 - Q_i$$
$$\frac{\partial P_i}{\partial V_i} = G_{ii}V_i + P_i/V_i$$
$$\frac{\partial Q_i}{\partial \theta_i} = -G_{ii}V_i^2 + P_i$$
$$\frac{\partial Q_i}{\partial V_i} = -B_{ii}V_i + Q_i/V_i$$

Under "normal" power system conditions, $G_{ik} \approx 0$ and $\theta_{ik} \approx 0$. It follows that $\frac{\partial P_i}{\partial V_k}$ and $\frac{\partial Q_i}{\partial \theta_k}$ are small, and power flow behaviour is dominated by the $P - \theta$ and $Q - V$ couplings.

- When the network is heavily loaded, θ_{ik} may not be small.
- For distribution and sub-transmission networks, R/X ratios are higher, so ignoring G_{ik} may not provide a good approximation.

2.3 Radial networks



For a radial network, the power flow equations can be written in the recursive form:

$$P_{ij} = \sum_{k \in \mathcal{C}_j} P_{jk} + r_{ij}\left(P_{ij}^2 + Q_{ij}^2\right)/V_i^2 + p_j$$
$$Q_{ij} = \sum_{k \in \mathcal{C}_j} Q_{jk} + x_{ij}\left(P_{ij}^2 + Q_{ij}^2\right)/V_i^2 + q_j - b_j V_j^2$$
$$V_j^2 = V_i^2 - 2\left(r_{ij}P_{ij} + x_{ij}Q_{ij}\right) + \frac{\left(r_{ij}^2 + x_{ij}^2\right)\left(P_{ij}^2 + Q_{ij}^2\right)}{V_i^2}$$

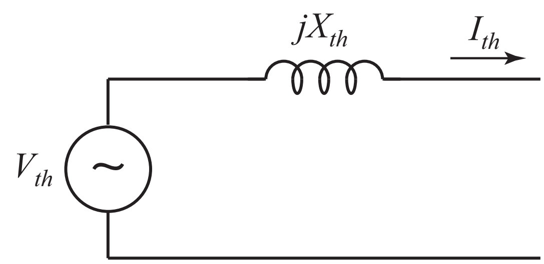
where $\mathcal{C}_j$ is the set of nodes connected "downstream" of node j, and each branch impedance is $z_{ij} = r_{ij} + jx_{ij}$.

This set of equations can be solved using a simple forward/backward iterative algorithm.

2.4 Back of the envelope per unit calculations

Relationship between fault level and system impedance

- Consider the Thévenin equivalent seen from a particular location (in per unit.)



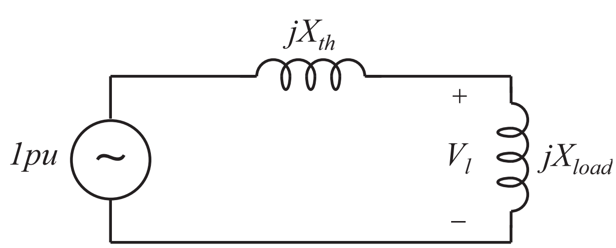
- A three phase to ground fault at the chosen location is equivalent to applying a short circuit to the terminals of the Thévenin equivalent, giving

$$I_{th} = \frac{V_{th}}{jX_{th}}$$

- Assume $V_{th} \approx 1$ pu.
- The fault level in per unit is given by

$$\begin{aligned} \text{Fault level } &= S_{fl} = |V_{th}||I_{th}| \\ &= \frac{1}{X_{th}} \end{aligned}$$

Voltage variation with load



- Assume the load is a reactance, $S_{load} = \frac{V^2}{jX_{load}}$.
- In per unit, $X_{load} = \frac{1}{|S^0_{load}|}$ where S^0_{load} is the value of the load at nominal voltage.
- Consider a load that varies in the range 0 to 20 MVA at a location where the fault level is 200 MVA.
- Using a per unit base of 100 MVA gives

$$X_{th} = \frac{1}{2}, \quad X_{load} \text{ ranges between } \frac{1}{0} \text{ and } \frac{1}{0.2}.$$

The load voltage therefore ranges between 1 pu (for no load) and

$$V = \frac{X_{load}}{X_{load} + X_{th}} = \frac{5}{5 + 0.5} = 0.91 \text{ pu.}$$

- Consider the connection of a capacitor of 5 MVAr instead of the load. In per unit, $X_{load} = -\frac{1}{0.05} = -20$ pu, so the voltage will be

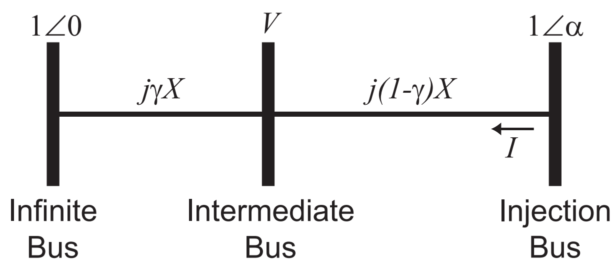
$$V = \frac{-20}{-20 + 0.5} = 1.0256 \text{ pu.}$$

  Notice that adding a capacitor to an inductive system will always cause a voltage rise.

  – This becomes more complicated when resistance in the supply system is significant.

2.5 Voltage - active power coupling

The following radial system can be used to establish a rule of thumb relating active power injection, fault level at the injection point, and voltage drop at points along the radial feeder.



Assumptions:

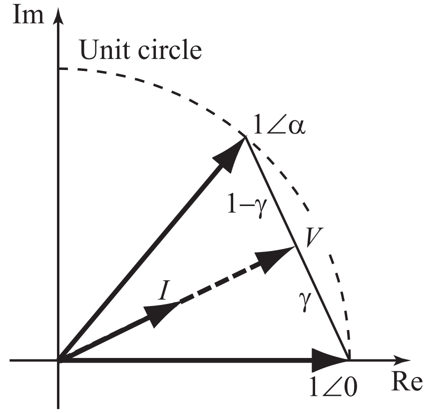
1. The injection point voltage is held at 1 pu by local reactive support.
2. The radial system in lossless.
3. The distance between the infinite bus and the intermediate bus is the fraction γ of the total feeder length, with $0 \leq \gamma \leq 1$.
4. The load/injection at the intermediate bus is negligible in comparison with the injection at the end bus, and therefore may be neglected.

From the figure,

$$I = \frac{1\angle\alpha - 1\angle 0}{jX} = \frac{V - 1\angle 0}{j\gamma X} \tag{1}$$

$$\Rightarrow \quad V = 1\angle 0 + \gamma(1\angle\alpha - 1\angle 0). \tag{2}$$

The vector diagram corresponding to (2) is shown below. As γ varies from 0 to 1, V follows the straight line from $1\angle 0$ to $1\angle\alpha$. From (1), the current I is always at right angles to the vector $1\angle\alpha - 1\angle 0$.



The voltage magnitude $|V|$ at the intermediate bus is smallest when $\gamma = 0.5$, which corresponds to the angle of V being $\alpha/2$. For this case, it follows from trigonometry that

$$\cos\left(\frac{\alpha}{2}\right) = |V|, \tag{3}$$

and that V and I are aligned. Furthermore, the active power injection is given by

$$P = S_{fl}\sin(\alpha) \tag{4}$$

where $S_{fl} = 1/X$ is the fault level at the injection point.

The power factor of the injected active/reactive power is determined by the angle between the voltage $1\angle\alpha$ and current I. That angle is $\alpha/2$, so the power factor is $\cos(\alpha/2)$.

- Notice from (3) that the power factor therefore has the same value as the voltage $|V|$ at the mid-point bus.

Example

Assume the maximum allowable voltage drop at any point along the feeder is 5%. Equation (3) gives

$$\cos\left(\frac{\alpha}{2}\right) = 0.95$$
$$\Rightarrow \qquad \alpha = 36.39^o.$$

From (4), it follows that

$$\frac{P}{S_{fl}} = \sin(36.39) = 0.59.$$

Therefore the maximum allowable active power injection is 59% of the fault level. Another way of interpreting this result is that variation in active power from maximum output (59% of the fault level) to zero will cause a voltage fluctuation of 5% at the feeder mid-point.

In order to maintain the injection bus voltage at 1 pu, the source will need to be capable of operating at a power factor of 0.95 lagging. □

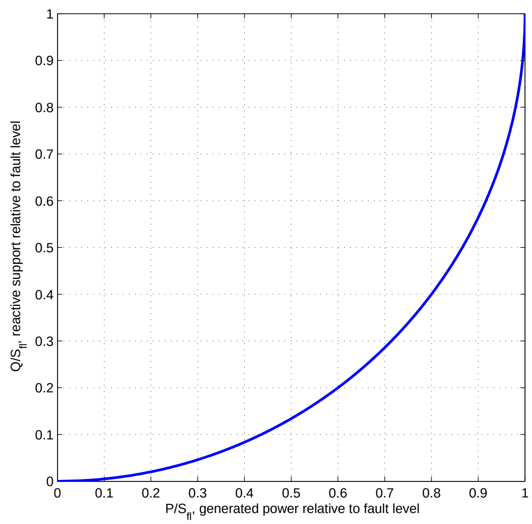
The reactive power required to support the injection bus voltage at 1 pu is given by

$$Q = S_{fl}(1 - \cos\alpha).$$

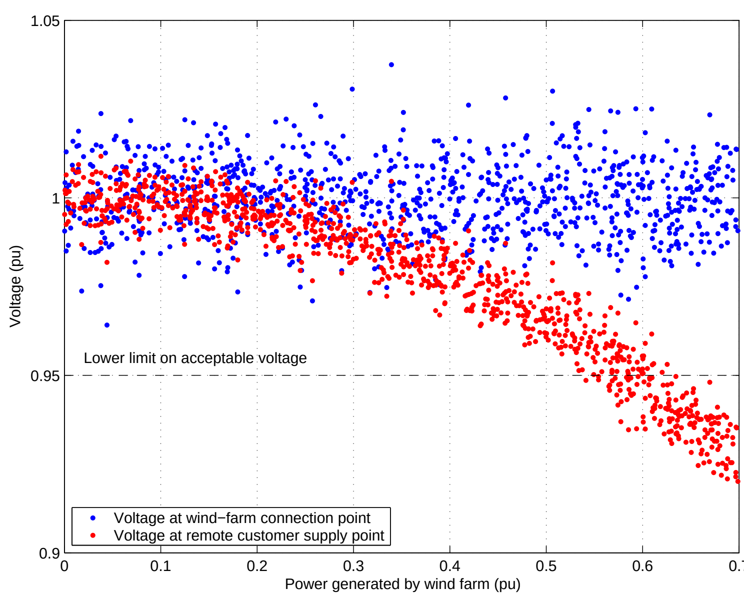
Combining with (3), the relationship between the active power P injected, and reactive support Q can be written

$$\left(\frac{P}{S_{fl}}\right)^2 + \left(1 - \frac{Q}{S_{fl}}\right)^2 = 1$$

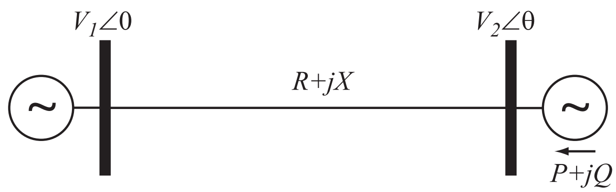
which describes a circle with centre at $\frac{P}{S_{fl}} = 0$, $\frac{Q}{S_{fl}} = 1$, and radius of 1. This is shown in the following figure. Notice that little reactive support is required when P is small (relative to S_{fl}). However, the reactive support requirements grow rapidly as P increases. In fact, for $P/S_{fl} > 1/\sqrt{2} \approx 0.7$, every extra MW of generation requires more than a MVAr of reactive support.



Example: variability in wind generation produces voltage fluctuations of the form shown in the following figure.



2.6 Resistance in the network

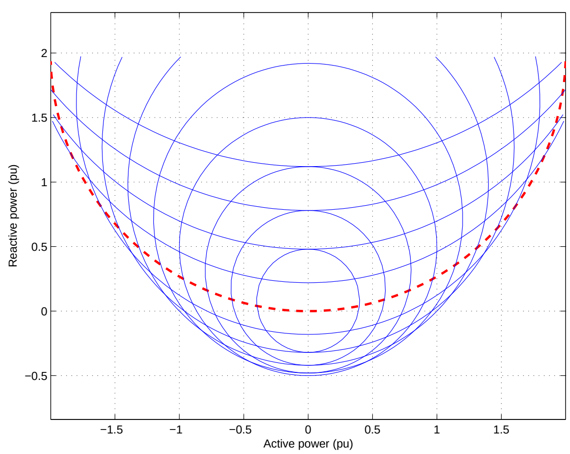


The relationship between injected power $P + jQ$ and the bus voltage magnitude V_2 is given by,

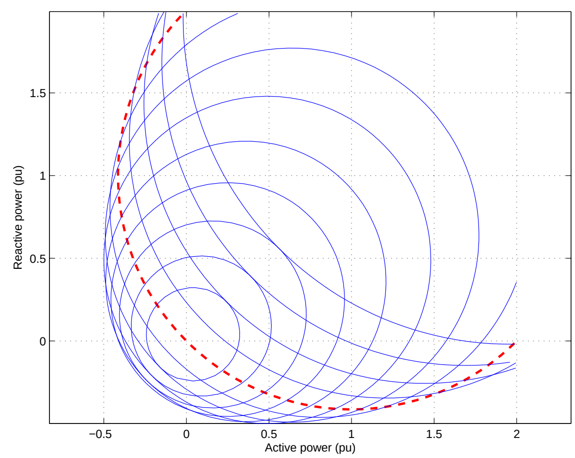
$$\left(\frac{V_2^2 R}{R^2 + X^2} - P\right)^2 + \left(\frac{V_2^2 X}{R^2 + X^2} - Q\right)^2 = \frac{V_1^2 V_2^2}{R^2 + X^2}$$

where all quantities are given in per unit.

This relationship is illustrated below for $V_1 = 1.0$ pu and $X = 0.5$ pu, and two line resistance cases, $R = 0.0$ pu and $R = 0.5$ pu.



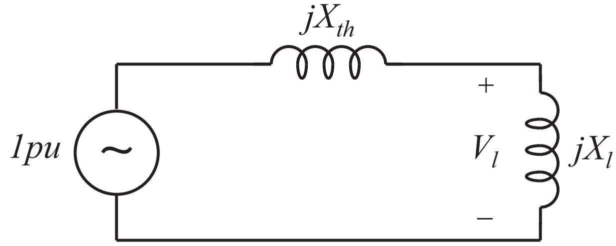
(a) $R = 0.0$ pu, $X = 0.5$ pu.



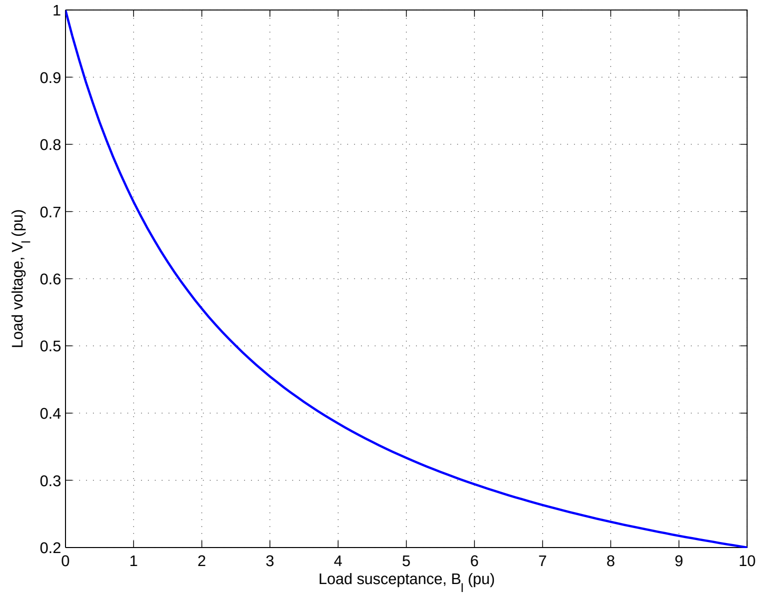
(b) $R = 0.5$ pu, $X = 0.5$ pu.

2.7 Maximum loading

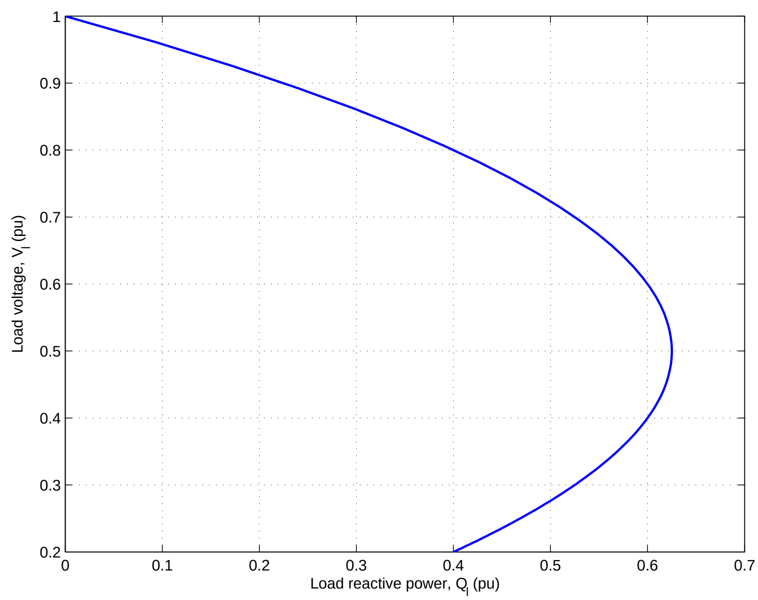
Keep in mind the Thévenin equivalent model



- The relationship between load voltage V_ℓ and reactive demand $B_\ell = 1/X_\ell$ has the form shown in the following figure.

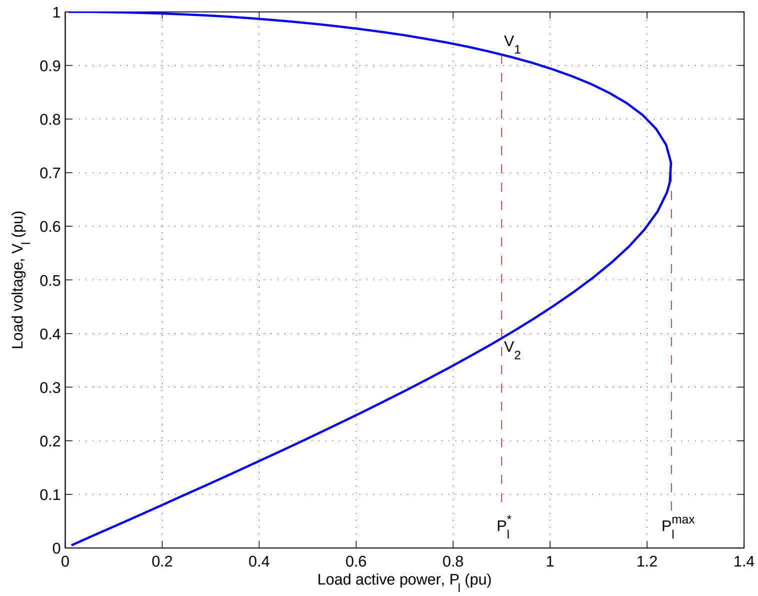


- The corresponding relationship between V_ℓ and reactive power $Q_\ell = B_\ell V_\ell^2$ is quite different though.



- Recall the maximum power transfer theorem from undergraduate circuit analysis.

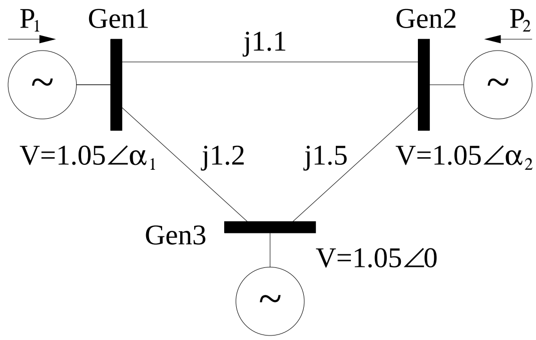
The relationship between P_ℓ and V_ℓ is qualitatively similar to Q_ℓ versus V_ℓ.



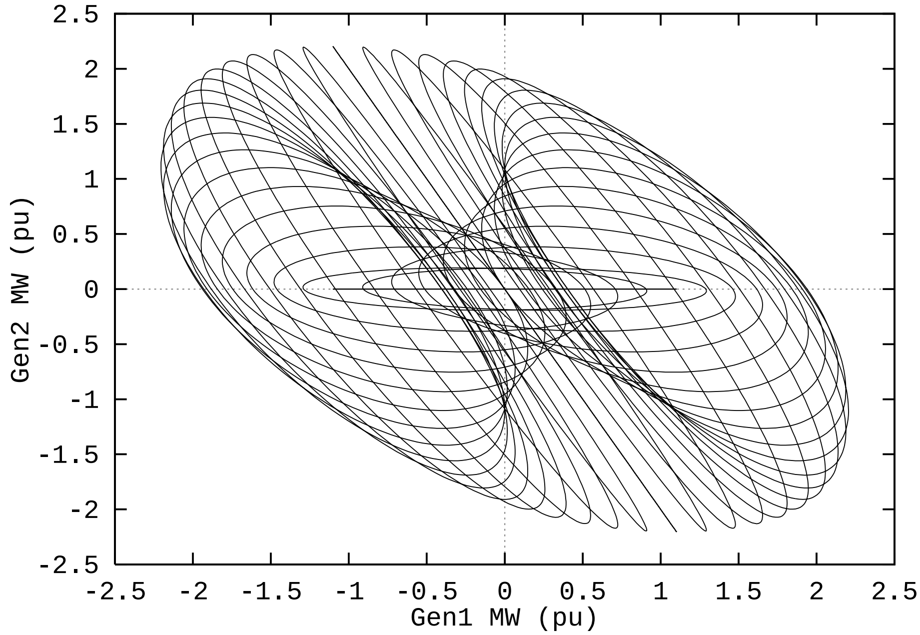
- Notice that a certain value of load P_ℓ^* can be supplied at two different voltages V_1 and V_2.
  - Two power flow solutions exist.
  - Both can be obtained in a laboratory circuit.
  - Only the high voltage solution is feasible in a power system, as protection would operate prior to reaching the lower voltage V_2.
- As load P_ℓ increases, V_1 decreases but V_2 increases.
- As the maximum load P_ℓ^{max} is approached, the voltage V_1 falls more rapidly.
  - Voltage becomes increasingly sensitive to changes in P_ℓ.
- If the system is forced to supply power greater than P_ℓ^{max}, it will fail in some way.
  - Unmodelled dynamics will cause voltage collapse.

The boundedness of power flow solutions is an important aspect of voltage instability.

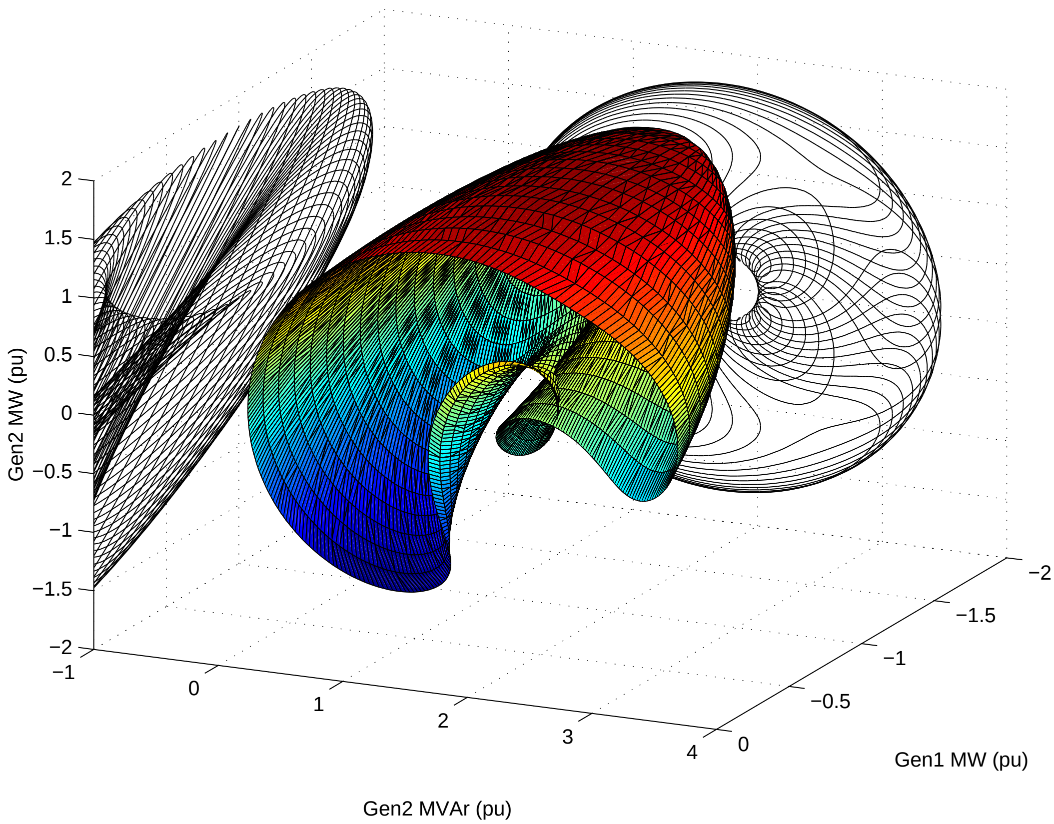
- Consider a three generator system.



- With the slack bus at Generator 3, the relationship between active power injections P_1 and P_2 is given by the following bounded shape.



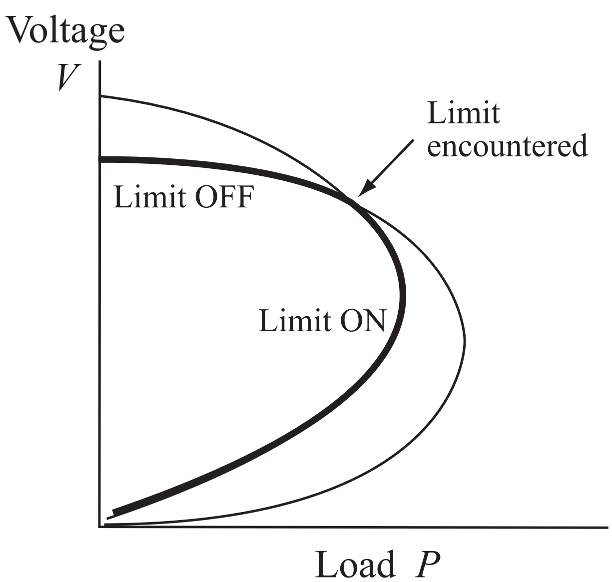
- The shape becomes even more interesting when the reactive power at Generator 2 is also shown.

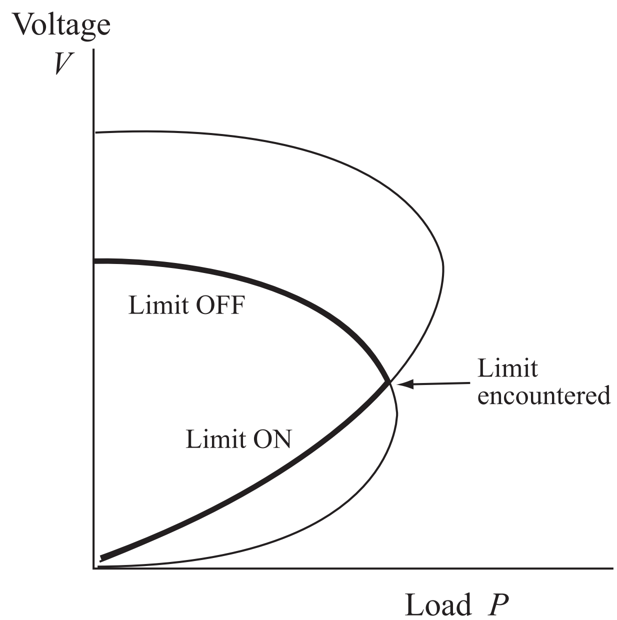


2.8 Reactive power limits

The previous examples assumed that the source can supply unlimited reactive power.

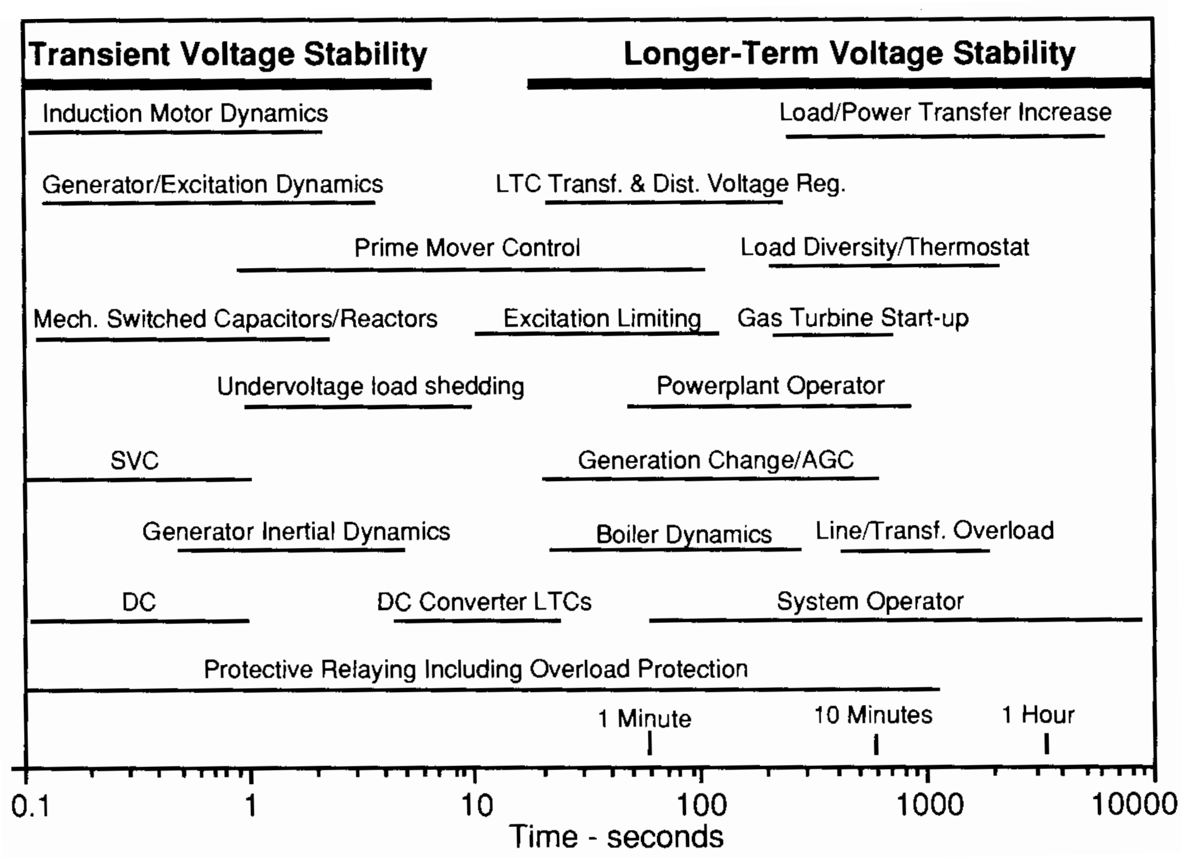
- When a source of reactive power, such as a generator, encounters a limit, it can no longer regulate voltage.
  - The Thévenin equivalent effectively undergoes a step change.
- Loss of voltage support reduces the power transfer capability of the system, and may result in immediate and unexpected loss of stability.





2.9 Short-term versus long-term voltage behaviour

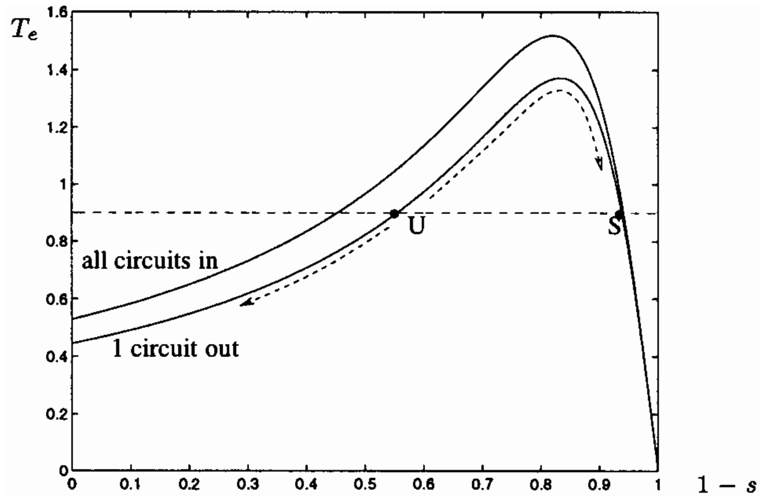
Short-term implies a time frame of seconds, while long-term implies minutes.



From Taylor, 1994.

Short-term voltage behaviour is driven by fast-acting devices such as induction motors and power electronic interfaces (HVDC for example.)

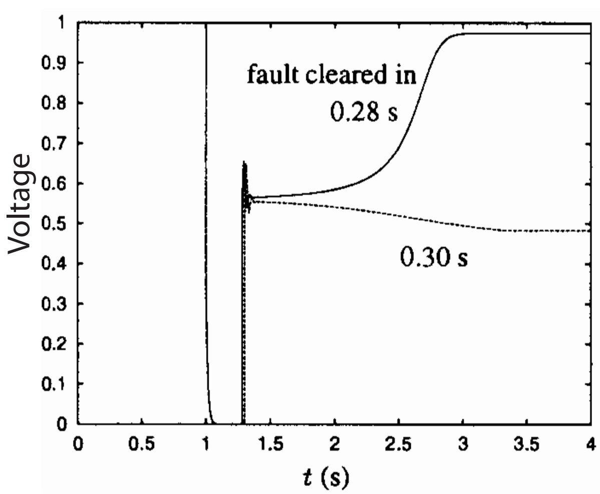
- Consider an induction motor with the following torque-slip curve.

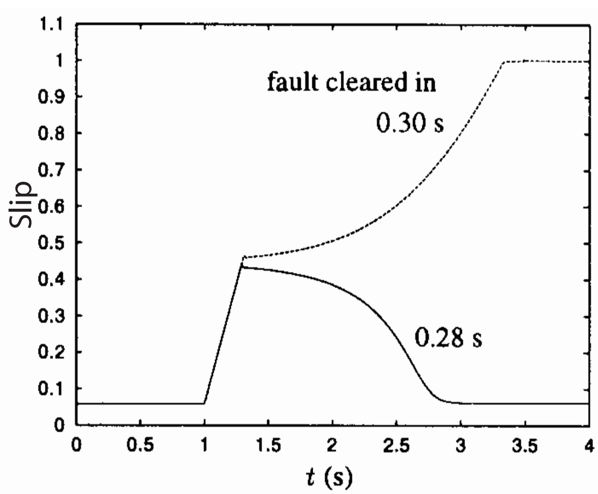


- Slip is driven by

$$\dot{s} \approx T_m - T_e$$

- When an induction motor is stalled, it looks like a high impedance fault on the system.
  - Current drawn is around 4-6 times full load current.



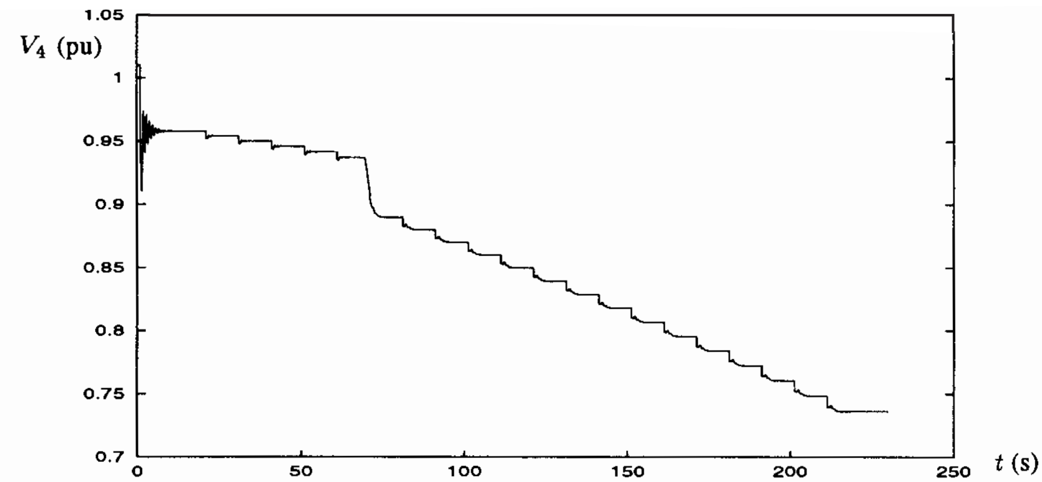


- Larger induction motors will have low voltage protection, which will operate. Smaller induction motors will often remain connected until thermal protection operates (around 5-10 seconds.)

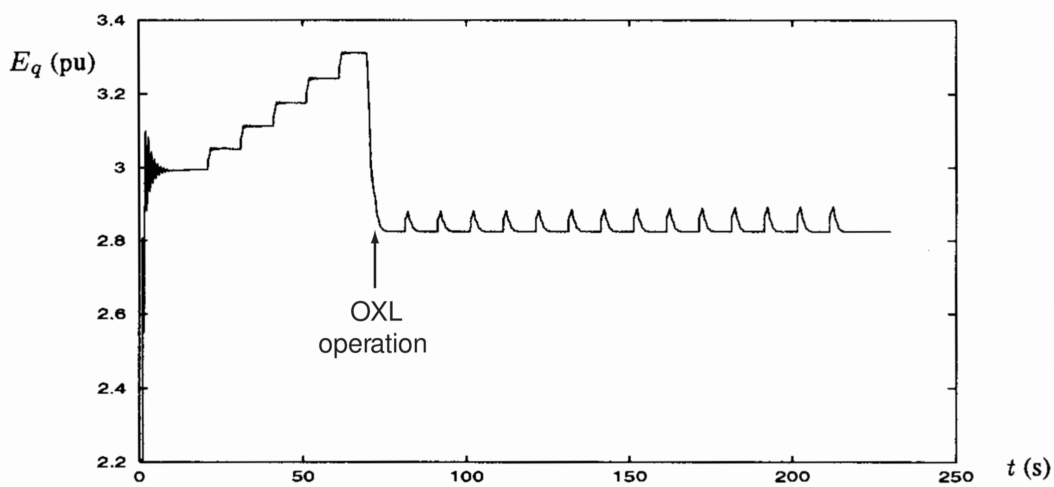
- Overcurrent protection may operate on the distribution system due to high stall currents.

Long-term voltage behaviour is dominated by on-load tap-changing transformers and generator over-excitation limiters.

- A weakening of the transmission system (loss of a line) causes a voltage drop.
  - Reactive support from line susceptance is reduced.
  - Currents increase, with resultant increases in I^2X reactive losses.
- Tap changers respond to lift distribution side voltages, but instead push transmission voltages lower, resulting in greater demand for reactive power.
- Generators seek to support their terminal bus voltages by increasing reactive power output. This requires greater field current. If field current becomes excessive, the generator over-excitation limiter (OXL) will act to reduce reactive power production, causing further voltage drops.



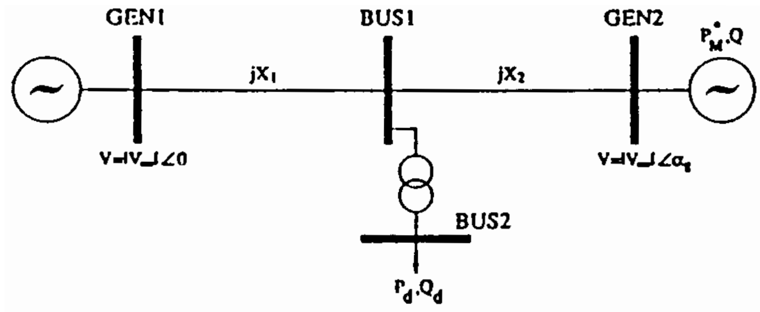
Transmission side voltage



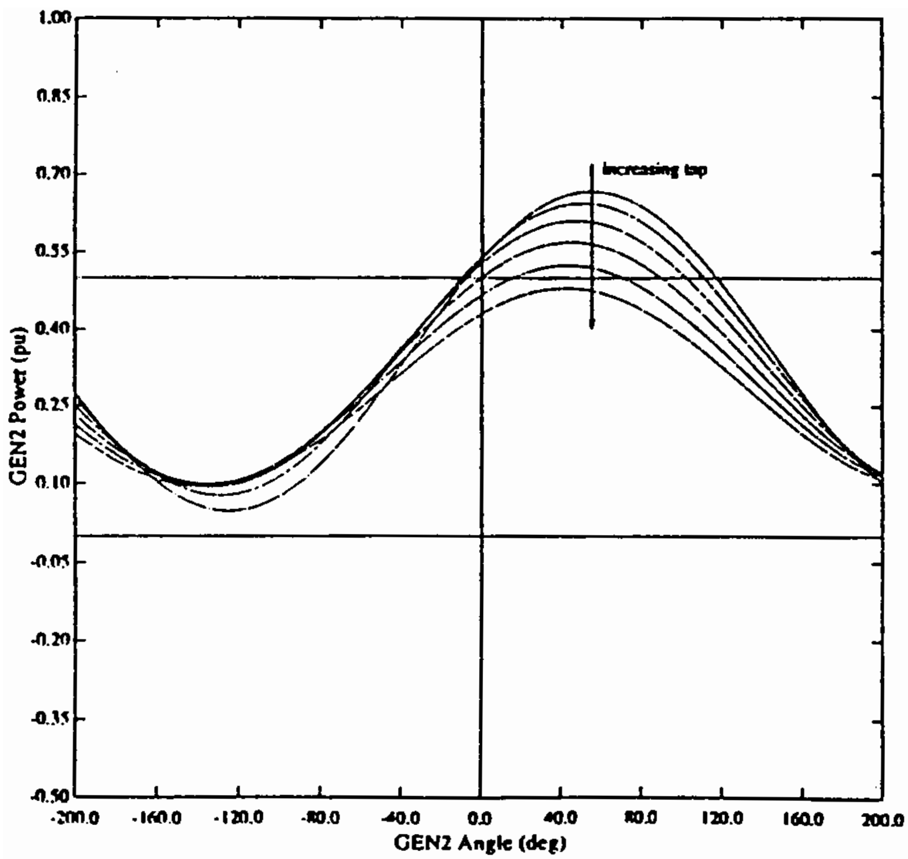
Generator field current

From Van Cutsem and Vournas, 1998.

- The following system provides an interesting illustration of the way in which tap changing can weaken the system.



  - Each time the transformer taps up to lift the voltage at BUS2, the transmission system is weakened a little more, until the generator loses synchronism.



2.10 Load modelling

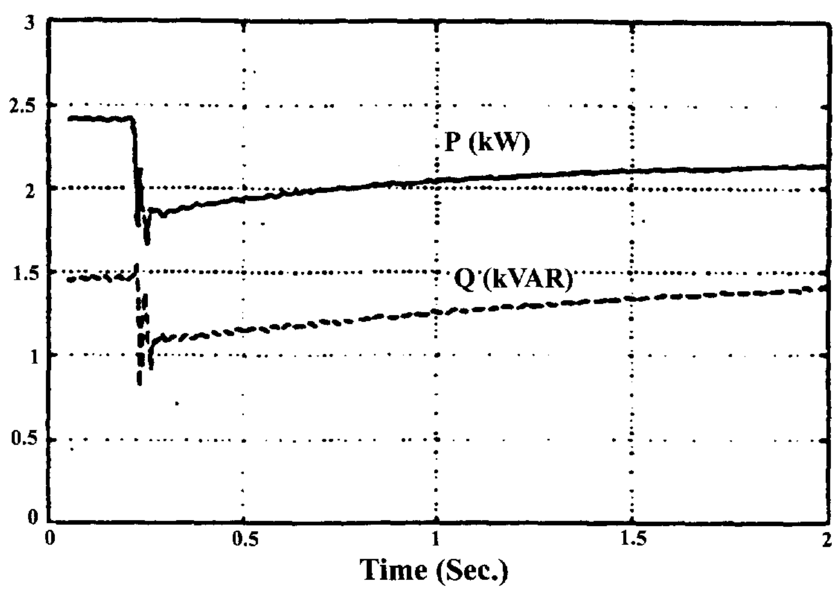
- Work is always on-going...
- Three philosophies:
  1. Very simple static load models of the form

$$P(V) = P^0\Big(\frac{V}{V^0}\Big)^{\alpha}, \qquad Q(V) = Q^0\Big(\frac{V}{V^0}\Big)^{\beta}.$$

     Such load models are generally appropriate for analysing transient angle stability, but do not capture the load recovery effects that are an important aspect of voltage stability.
  2. Use disturbance measurements to estimate parameters of generic load models that capture aggregate load behaviour.
  3. Undertake a detailed assessment of the load composition (amounts of various load categories) at load locations (distribution substations) that exert an important influence on system behaviour.
- Distributed generation further complicates load modelling.

Generic load recovery model

Load response to a voltage step typically consists of an initial step followed by a recovery phase.



From Lem and Alden, 1994.

- The transient and steady-state changes, and the rate of recovery, are load dependent.
  - For induction motors, the recovery is very fast.
  - For aggregated distribution loads that are dominated by tap-changing transformers, recovery is slow.

A commonly used generic dynamic load model has the form

$$\dot{x}_p = \frac{1}{T_p}(P_s(V) - P_d)$$
$$P_d = x_p + P_t(V)$$

where P_d is the active power drawn from the system, $P_t(V)$ describes the transient response of the load, and $P_s(V)$ gives the steady-state load response, with

$$P_s(V) = P_s^0\Big(\frac{V}{V_s^0}\Big)^{\alpha_s}$$
$$P_t(V) = P_t^0\Big(\frac{V}{V_t^0}\Big)^{\alpha_t}.$$

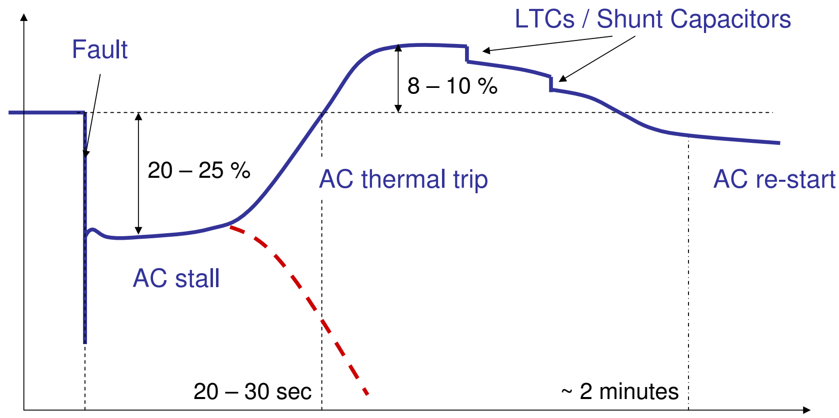
- When a disturbance (step change) in voltage occurs, the load state x_p cannot change instantaneously. Load demand P_d will vary instantaneously in response to the change in voltage V, according to $P_d = x_p + P_t(V)$.
- The load state x_p will evolve over time, driven by the mismatch $(P_s(V) - P_d)$, and with a rate of change dictated by the time constant T_p. This process will continue until steady-state is reached, when $P_d = P_s(V)$.
- Numerous other forms of generic load models have been proposed.

Reactive power load is handled in different ways.

- Constant power factor, or
- Reactive power has the same form of response, but $Q_s(V)$ and $Q_t(V)$ differ from $P_s(V)$ and $P_t(V)$.
- It is usual to assume the rate of recovery matches active power, $T_p = T_q$.

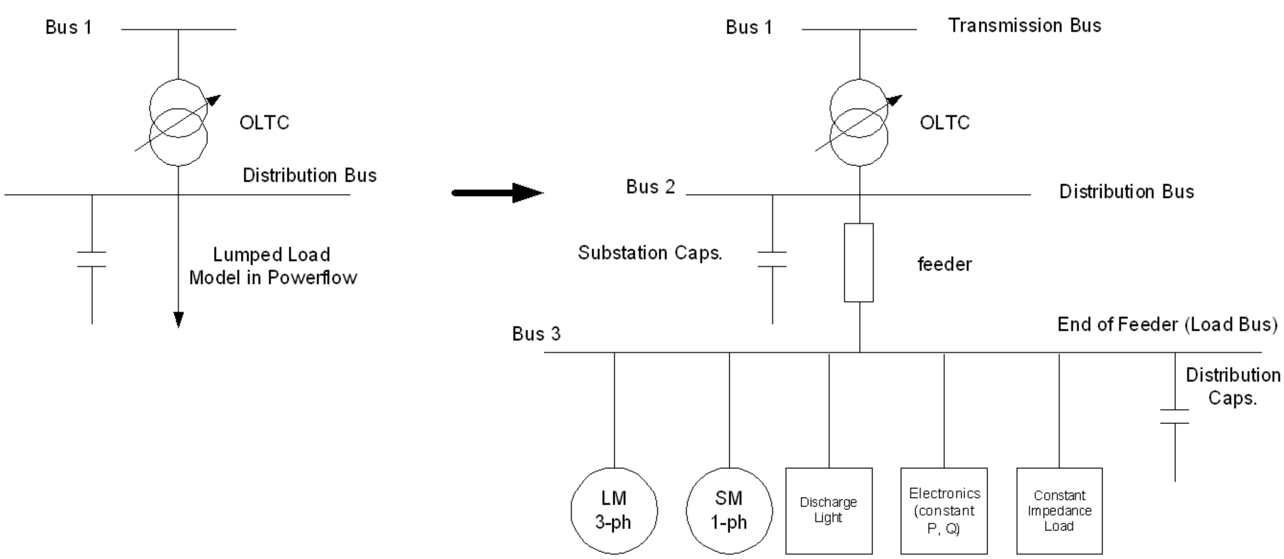
Detailed load modelling

Member utilities of the Western Electricity Coordinating Council (WECC) face difficulties with delayed voltage recovery.



From WECC Load Modeling Task Force.

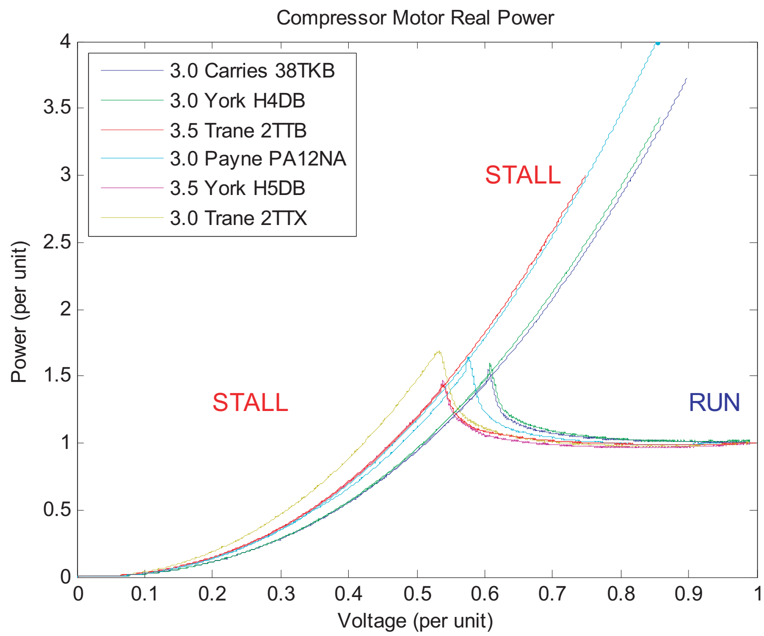
The WECC load model task force has proposed the following elaborate model.

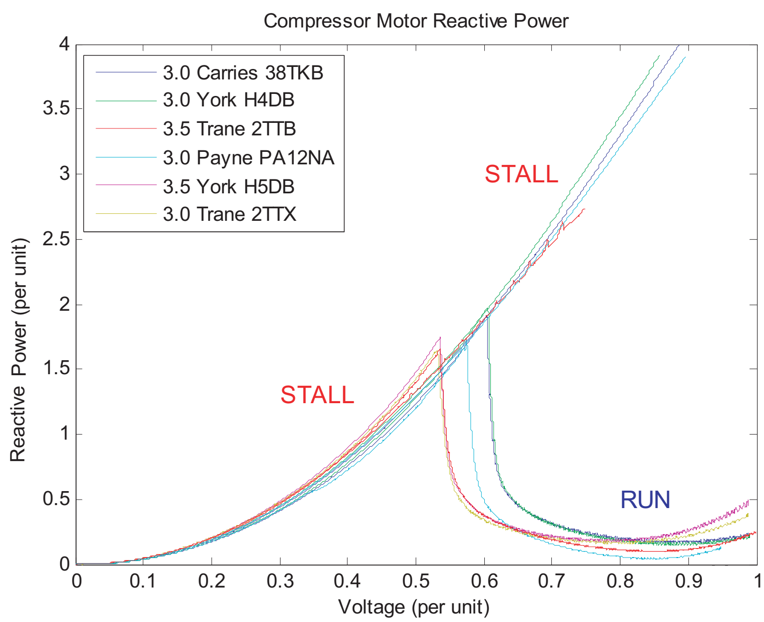


From WECC Load Modeling Task Force, 2007.

- Distribution system impedance.
  - As motor loads start to draw high current, the voltage seen by the loads will be lower than the supply point voltage.
- Distribution capacitors.
  - The reactive support drops with the square of the voltage seen down the distribution feeder. This response is different from most loads, so the capacitors should be included separately.

- Distributed generation can also be included on bus 3 of this model.
- Air conditioning motor load.
  - In summer, this can be a significant component of the total load.
  - Most residential air conditioners are single phase induction motors, which behave quite differently to three phase motors.
  - These motors stall in 3-5 cycles, and then draw significant current, eventually tripping on thermal protection.
  - The following plots were obtained by ramping voltage down to zero, and then ramping back up.





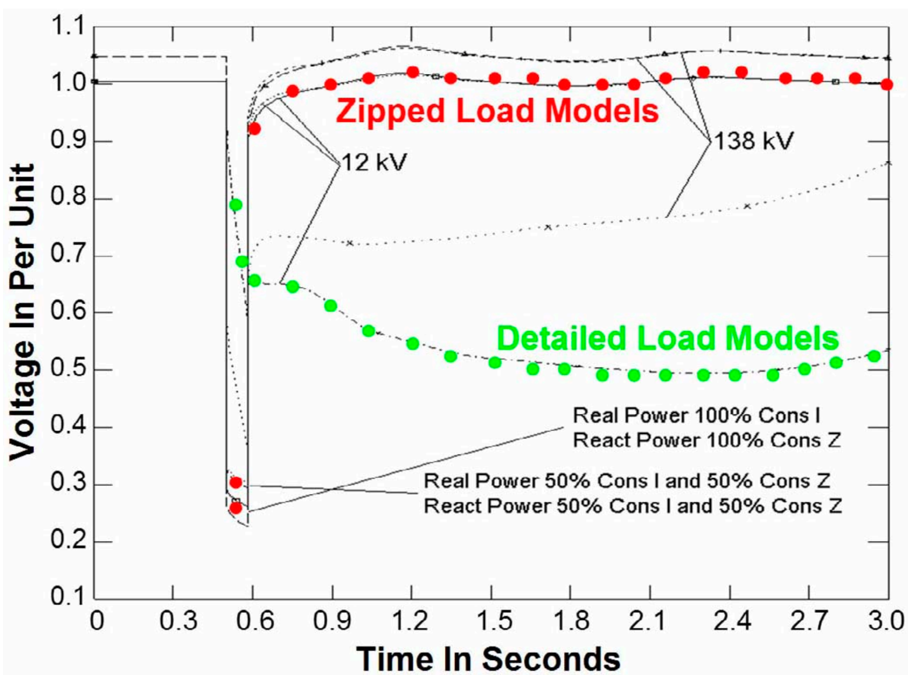
From WECC Load Modeling Task Force.

For a place like Wisconsin, the load contributions during a typical summer peak are given in the following table.

Percentage of: / Customer class:	Large Motor	Small Motor	Discharge Lighting	XFMR Saturation	Constant Power	Remaining
Residential	0	64.4	3.7	1.0	4.1	26.8
Agriculture	10.0	45.0	20.0	1.0	4.5	19.5
Commercial	0	46.7	41.5	1.0	4.5	6.3
Industrial	65.0	15.0	10.0	1.0	5.0	4.0
Power Factor	88.7%	82.0%	92.8%	0%	90.0%	Calculated

LOAD BREAKDOWN BASED UPON LITERATURE REVIEW AND HEURISTICS
From WPS/PTI

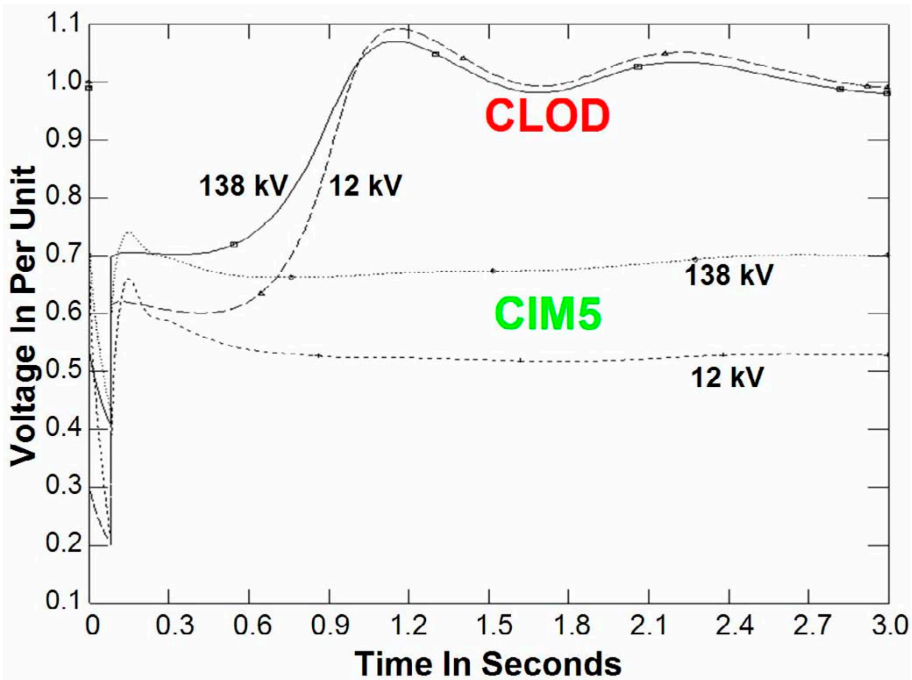
The ZIP (constant impedance plus constant current plus constant power) voltage-dependent load model and the detailed model behave quite differently.



From Diaz de Leon and Kehrli, 2006.

Different motor models may exhibit quite different responses.

- For example, the two motor models CLOD and CIM5 that are available within PSS/E behave very differently.



From Diaz de Leon and Kehrli, 2006.

2.11 Parameter estimation

Parameter estimation relies on a comparison of measurements with the corresponding simulated quantities.

- This comparison can be formulated as a nonlinear least squares problem, and solved using a Gauss-Newton procedure.
  - The error between a measurement and the corresponding simulation is given by

    $$e(p) = \mathbf{z}(p) - m$$

    where $\mathbf{z}$ is the simulation result, m is the measurement vector, and p is the vector of parameters that are to be estimated.
  - Minimize the nonlinear least-squares problem

    $$\breve{p} = \underset{p}{\operatorname{argmin}}\, \mathcal{C}(p)$$

    where

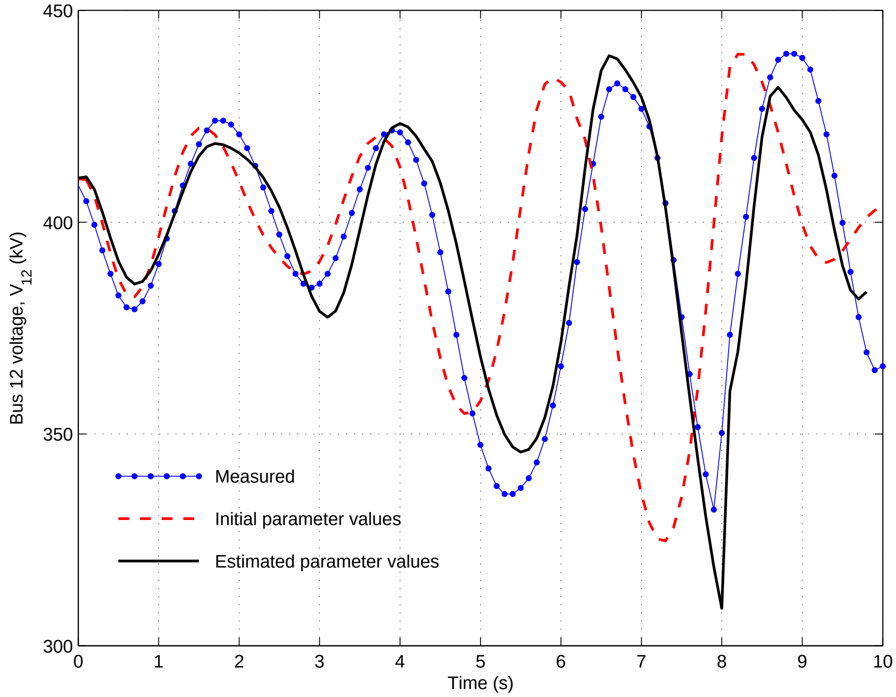
    $$\mathcal{C}(p) = \|e(p)\|_2^2 = \sum_{k=0}^{N} e_k(p)^2$$

    and the summation is over all measurement samples.
  - The minimum can be found using the Gauss-Newton process

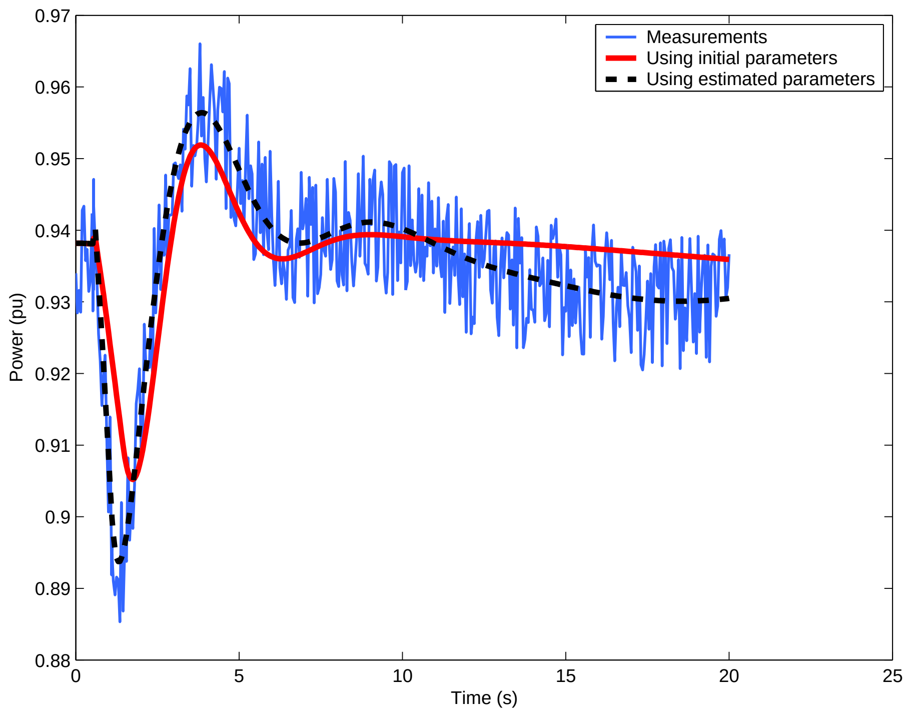
    $$\begin{aligned} \mathbf{S}(p^j)^T \mathbf{S}(p^j) \Delta p^{j+1} &= -\mathbf{S}(p^j)^T e(p^j) \\ p^{j+1} &= p^j + \alpha^{j+1} \Delta p^{j+1}. \end{aligned}$$

    where the Jacobian matrix $\mathbf{S}$ is built from trajectory sensitivities.
- Trajectory sensitivities describe the change in a trajectory that results from a small change in parameters.
  - As well as providing the gradient information required by the Gauss-Newton solution process, these sensitivities can be used to determine:
    - * Which loads have an important influence on large-disturbance behaviour.
    - * Which parameters are identifiable from particular measurement sets.

- Example: identifying parameters from a large disturbance in Sweden.



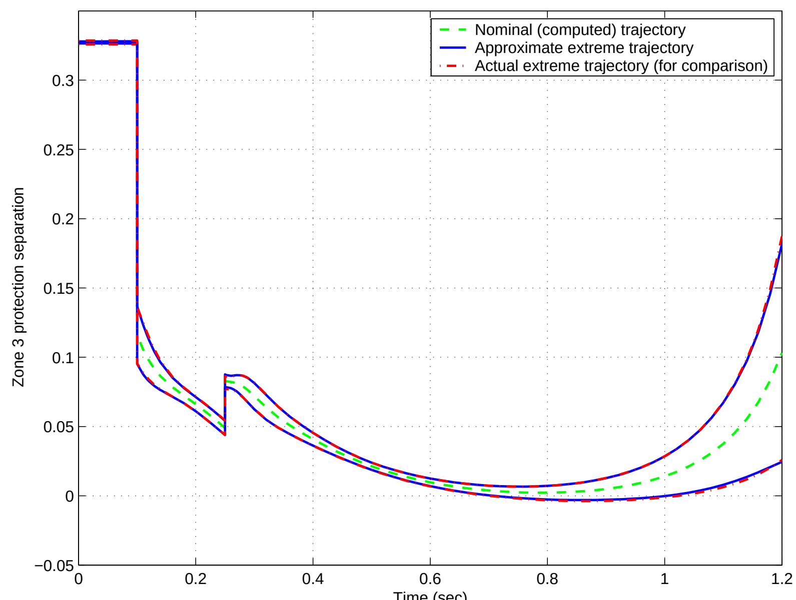
- Example: identifying parameters from measurements of a wind turbine.



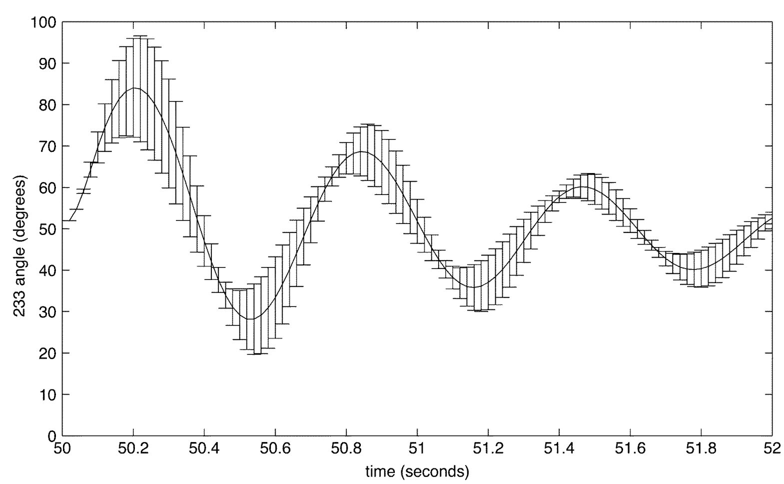
2.12 Parameter uncertainty

Load models are typically an aggregation of many, diverse loads.

- For example, the WECC load model involves around 90 parameters, very few of which are known with confidence.
- The composition of an aggregate load is continually varying, hence parameters have large uncertainty.
- Yet decisions must be made on the basis of those uncertain models.
- We have developed two computationally efficient methods for determining a confidence interval around the nominal trajectory.
  - Trajectory approximation, which uses trajectory sensitivities.
  - Probabilistic collocation method.



From Hiskens and Alseddiqui, 2006.



From Hockenberry and Lesieutre, 2004.

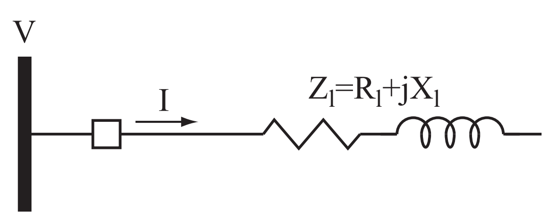
Protection

3.1 Protection in cascading failures

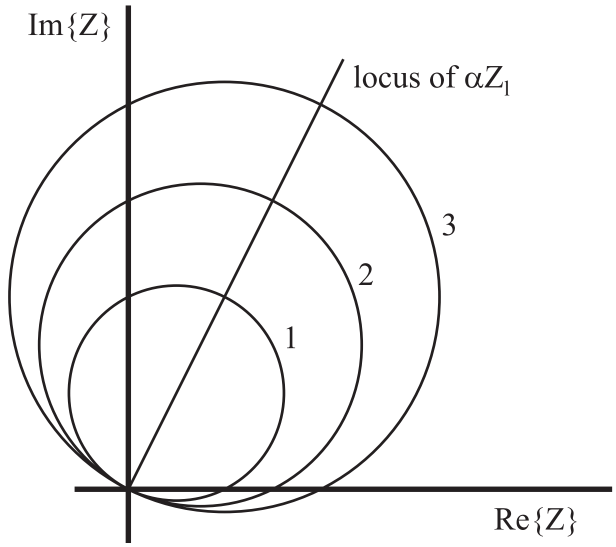
- Protection devices make decisions based on local measurements, and act to satisfy local objectives.
  - For example, when distance protection trips a transmission line, it doesn't care how the power flow is redistributed.
- Cascading failures grow from local decisions that are counter-productive on the global scale.
  - Various examples:
    * North-East United States and Canada in August 2003.
    * Italy in September 2003.

3.2 Distance protection

Distance protection monitors the apparent impedance $Z = V/I$ "seen" looking along a feeder.



- Traditional (mho) operating characteristics are circular, but more elaborate shapes are possible (and used) with digital protection.
- Distance protection typically has three zones:
  - Zone 1: Reaches 80% of the line length, $\alpha = 0.8$, instantaneous trip.
  - Zone 2: Reaches 120% of the line length, $\alpha = 1.2$, delayed trip.
  - Zone 3: Reaches $160 - 200\%$ of line length, $\alpha = 1.6 - 2.0$, delayed trip.
- Zones 2 and 3 provide backup protection, in case primary protection fails to operate.
- But zone 3 protection can interpret high-load situations, when voltages are low and currents are high, as remote faults.

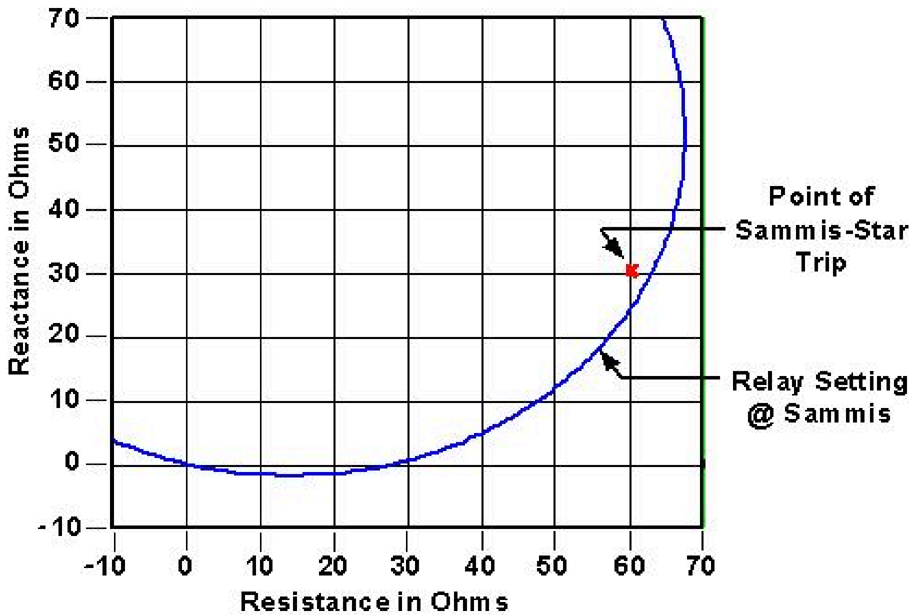


– Recall $Z_{app} = V/I$, so low V and high I gives small Z_{app}.

– These are exactly the conditions that prevail when reactive power is deficient.

- This was an important contributing factor to the North American blackout of August 2003.

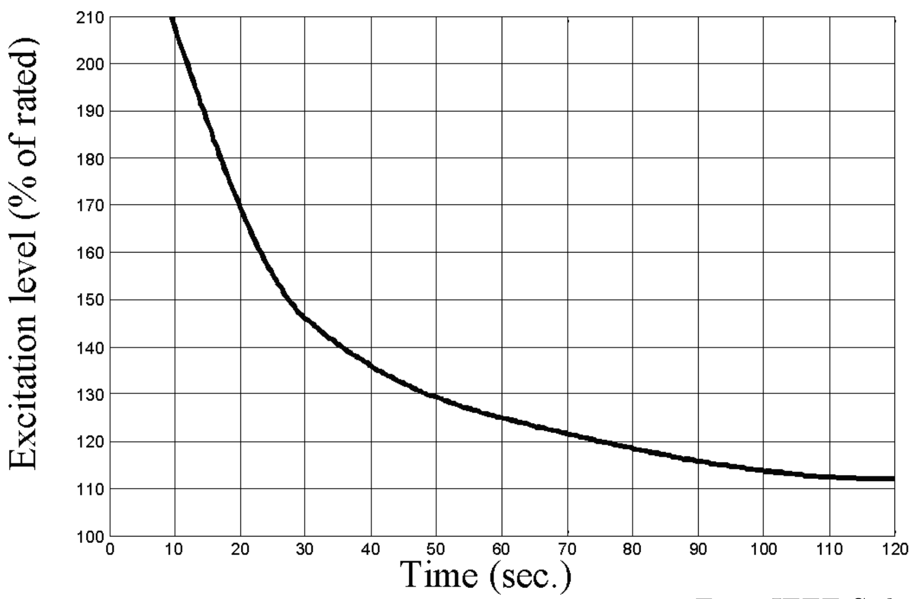
  – It was subsequently recommended that zone 3 be disabled, or at least carefully evaluated.



NERC blackout report 2004.

3.3 Generator over-excitation protection

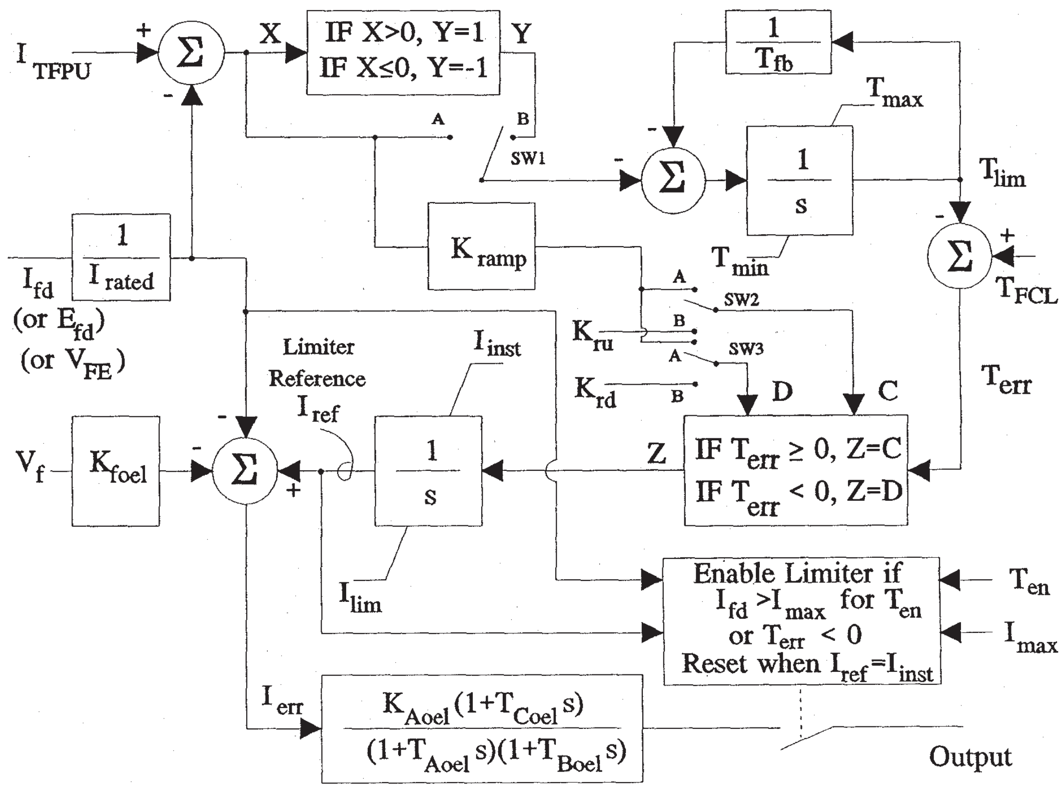
- Under heavy load conditions, generators often need to produce significant reactive power to maintain their scheduled terminal voltage.
- This over-excitation requires high exciter (field) current, which causes I^2R heating of the rotor windings.
- Excessive heating can be tolerated for a short period, but not indefinitely.
  - Generator designs specify a maximum temperature and heat dissipation rate.
- The over-excitation limiter (protection) ensures that temperature rises are not excessive.
  - Operates if field current stays high for too long.
  - Determined through an inverse time-current relay characteristic.
    * High current ⇒ short operating time.
    * Low current ⇒ long operating time.



From IEEE Std 421.5-2005.

- The over-excitation limiter (OXL) effectively reduces the terminal voltage setpoint.
  - Lower voltage implies less reactive power output.
  - But if the system is relying on that reactive support, then the action of the over-excitation protection may drive the system into voltage collapse.

- Over-excitation limiters have been around forever, but availability of appropriate models is still an issue.



From IEEE Task Force on Excitation Limiters, 1995.

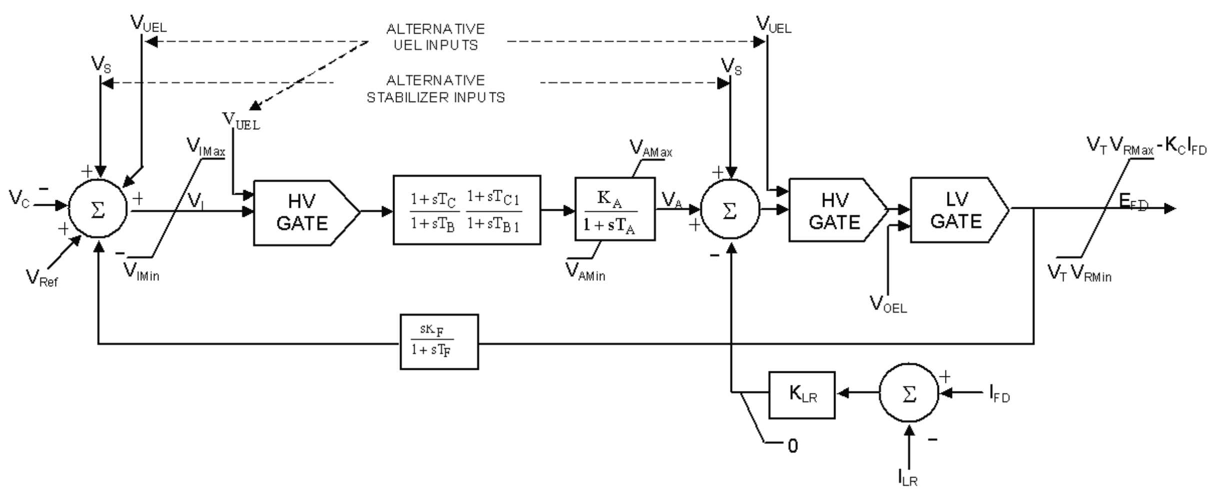
3.4 Under/over-voltage protection

- Many devices incorporate under/over-voltage protection.
- High voltages may cause insulation breakdown, component damage.
- Low voltages are responsible for:
  - Induction motors stalling.
  - Contactors dropping out.
  - Power electronics misfiring.
- Protection operating characteristics often take into account the magnitude and duration of a disturbance.
- Further discussion on under-voltage load shedding is provided later.

Voltage Control

4.1 Generator AVRs

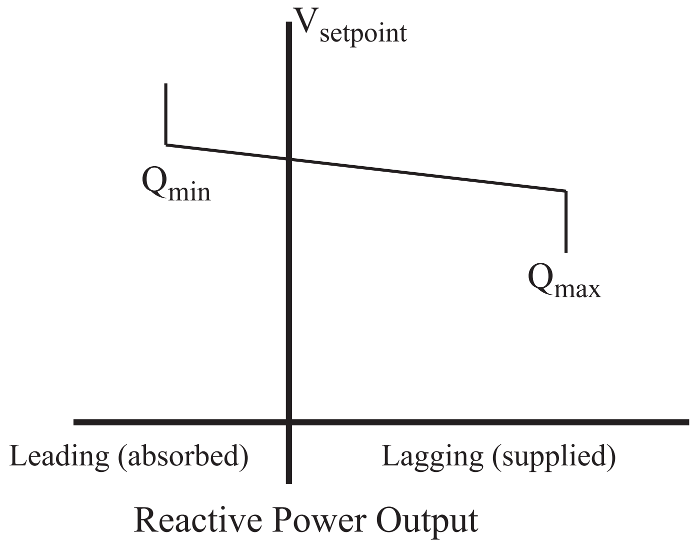
- Included for completeness, though there's nothing new.
- Measured voltage is compared with the setpoint. If the voltage is too low, field voltage is increased, resulting in an increase in reactive power production which lifts the voltage.
- The reverse occurs when the measured voltage is too high.
- A typical exciter model, in this case the IEEE standard model ST1A, is shown in the following figure.



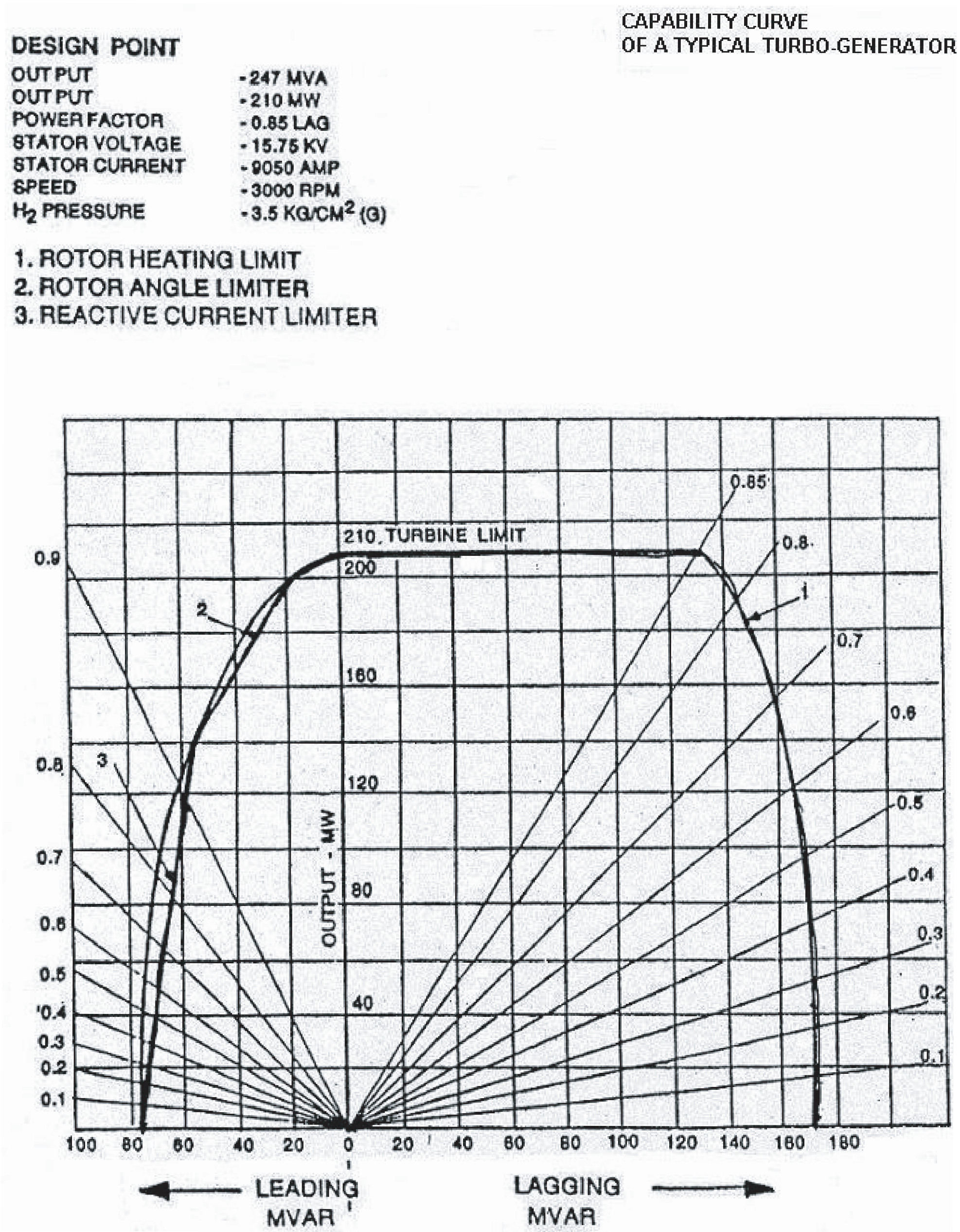
From IEEE Std 421.5-2005.

- The voltage may be measured at the generator terminal, or at a bus on the high side of the generator transformer.
  - In this latter case, it is important to ensure that the terminal bus voltage does not deviate greatly, particularly if it's the supply point for auxiliaries.

- Generators usually regulate to a fixed voltage setpoint, but may use a droop characteristic.

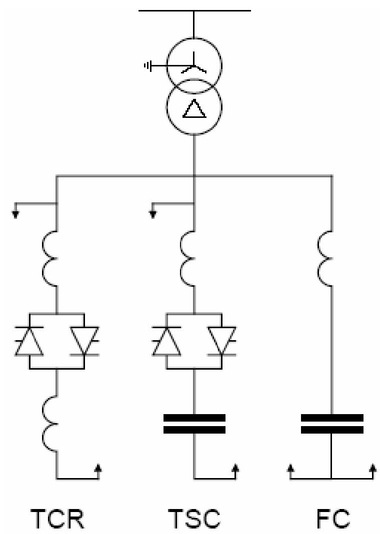


- Lagging refers to reactive power being supplied to the system, whereas leading refers to absorbed reactive power.
- The figure shows the steady-state characteristic.
  - As indicated before, generators may temporarily supply excess reactive power, but the over-excitation protection will prevent that situation from continuing indefinitely.
- The maximum reactive power Q_{max} is determined by the steady-state stator and rotor current limits.
  - The stator current limit creates a trade-off between active and reactive power production.
  - High active power production implies reduced reactive power output, and vice versa.
- Minimum reactive power Q_{min} is determined by generator stability considerations.
  - This limit may become binding during periods of light load, but is never a factor in voltage collapse.

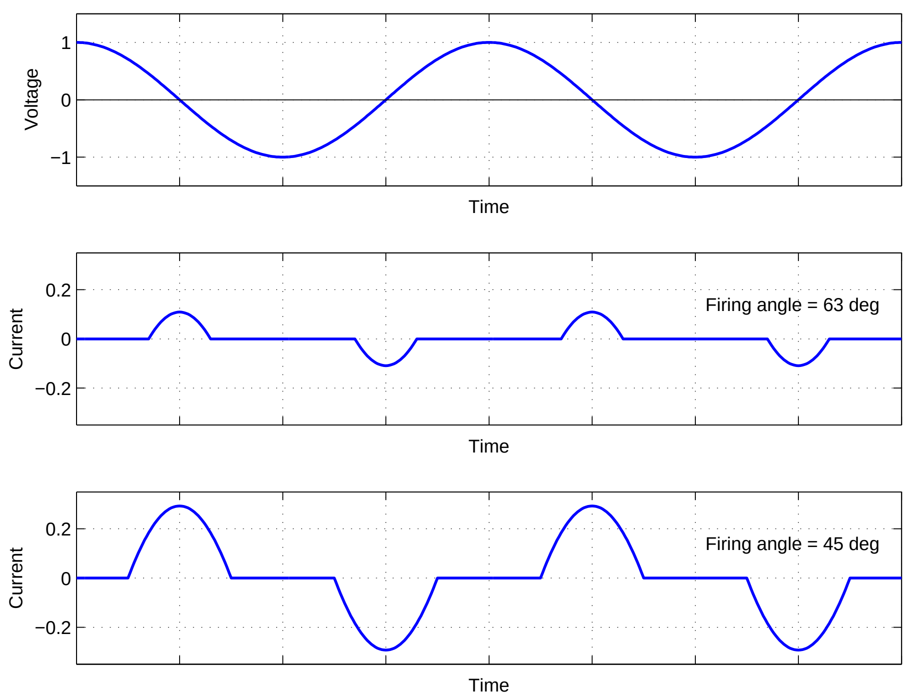


4.2 Static var compensators

- Static var compensators (SVCs) consist of a thyristor controlled reactor (TCR) in parallel with a fixed capacitor (FC) and possibly a switched capacitor (SC).
  - Switched capacitors may be thyristor switched capacitors (TSCs) or mechanically switched.
- Thyristors are self-commutated power electronic switches.
  - Turn-off occurs when the current through the thyristor drops to zero.



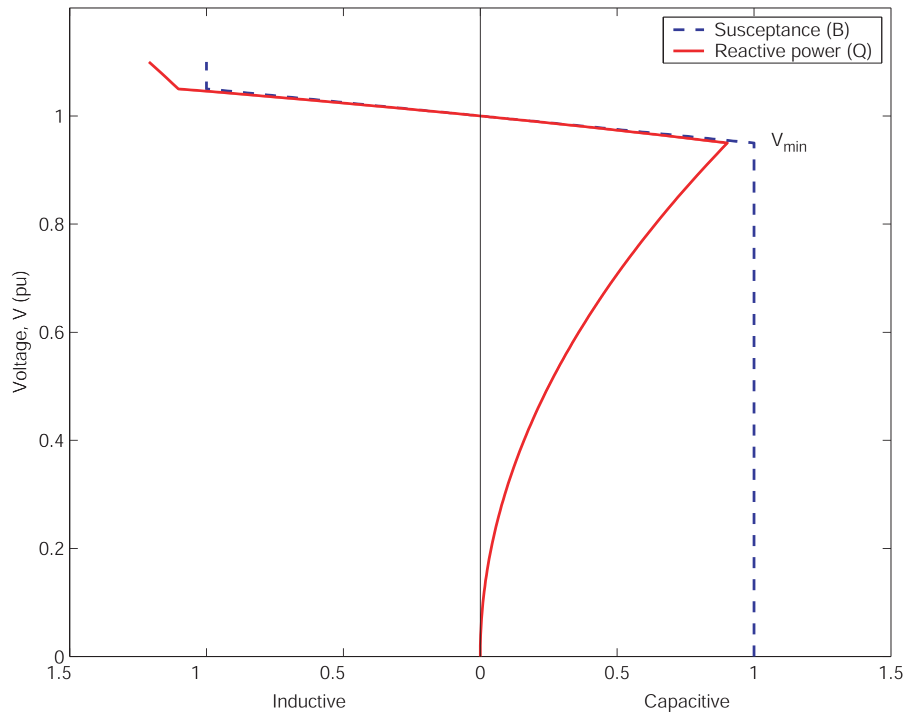
- The thyristor firing angle determines the current through the inductor, and hence the effective susceptance.
  - Blocked thyristors act like an open circuit.
  - Fully pulsed thyristors act like a short circuit.



- Nebo (North Queensland) example: Dynamic range from 80 MVAr inductive (absorbing) to 260 MVAr capacitive (producing).
  - Achieved using a 170 MVAr TCR, a 90 MVAr FC, and a 170 MVAr TSC.

- The inductive limit is achieved with the TCR fully pulsed and the FC in service.
- The capacitive limit has the TCR fully blocked, the FC and the TSC in service.

- SVCs also often utilize a droop characteristic.



- Notice that as the voltage falls below V_{min}, when the SVC is on its capacitive limit, the reactive support drops off with the square of the voltage $Q = B_{max}V^2$.

- SVCs have been around a long time, have high reliability, and are relatively inexpensive.
  - But certainly more expensive than switched capacitors.

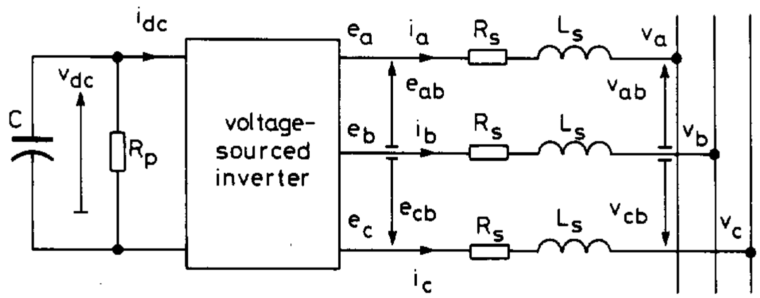
4.3 Statcoms

- Statcoms use power electronic switches that support forced commutation.
  - Their turn-off is controlled, making them quite different to thyristors.
  - This allows great flexibility in switching patterns, but incurs greater losses than SVCs.

- Most Statcoms use a voltage-sourced inverter. (The alternative is a current-sourced inverter.)

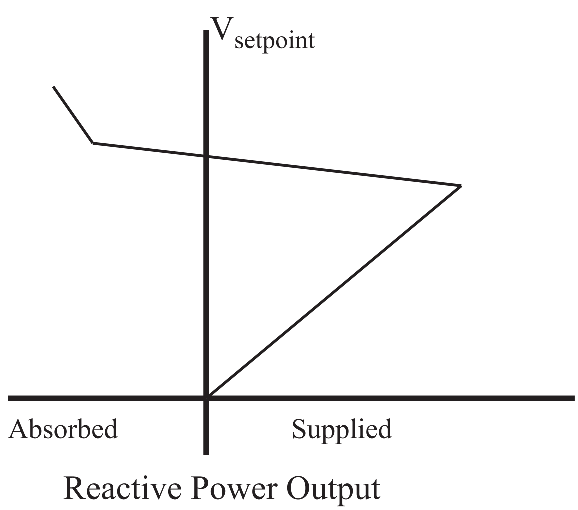
- The inverter switches the DC bus voltage in a pattern that creates balanced three phase AC voltage waveforms (plus some high harmonics.)

- A transformer is used to boost the synthesized AC voltages up to grid voltage levels.



From Schauder and Mehta, 1993.

- The capacitor does not provide energy storage (though it could conceptually do so).
  - Its role is to maintain a DC voltage.
  - It is therefore much smaller than the capacitance required for an SVC.
- The inverter has control over the magnitude and phase of the synthesized voltage.
- The control objectives are to regulate the AC bus voltage magnitude at the grid connection point, and maintain the DC bus voltage.
  - Forced commutation causes losses, which are drawn from the capacitor.
  - The controller must ensure that the capacitor energy is replenished, by drawing a small amount of active power from the grid.
- Statcom converters are conceptually similar to the technology used in a variety of applications that involve DC-AC conversion: VSC-HVDC, battery energy storage, grid connection of solar PV, type-3 and 4 wind turbine generators.
- The reactive power rating of a Statcom is primarily dependent on the current rating of the power electronic switches.
- Once a Statcom reaches its current rating, reactive power output falls linearly with the terminal voltage, $Q = VI_{rated}$.



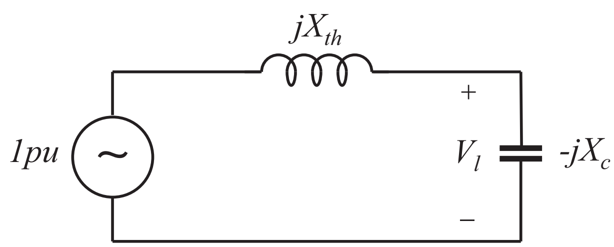
- Statcoms can continue to operate with quite low voltages, around 0.3 pu. Below that threshold, firing can no longer maintain synchronism with the grid.
- Many Statcoms are designed to operate beyond their rating for short periods.
  - They can temporarily withstand high I^2R losses.
- The control system performs a function similar to an inverse time-current relay.
  - Allows high overload for short time, smaller overload for longer time.
- Example: DVARs (manufactured by American Superconductor) are guaranteed to provide 2.67× rating for up to 2 seconds.

4.4 Comparison of SVCs and Statcoms

- Forced commutated devices are more expensive than thyristors, and have a lower rating.
- Statcoms are generally a better fit for applications requiring smaller rating, whereas SVCs are more suited to larger applications.
  - SVCs tend to be used at the transmission and sub-transmission levels, whereas Statcoms are used at the sub-transmission and distribution levels.
- Statcoms are modular. They come in their own housing, and are delivered to site on the back of a truck. SVCs require substation work to house capacitor banks and reactors (typically air cored, necessitating special earth mat requirements.)
- Forced-commutating devices (Statcoms) are more lossy than thyristors (SVCs), but SVCs incur losses in reactors and capacitor banks.
- Statcoms are often air cooled, whereas SVCs are water cooled.
- Small SVCs are generally not economic because of the substation and cooling requirements.
  - High cost for first MVAr, but lower incremental cost for subsequent MVArs.

4.5 Capacitor/reactor switching

- Time switched, voltage switched.
- Mechanical or thyristor switched.
  - Mechanical is cheaper, but doesn't allow rapid repeat switching.
- Need to size consistent with the fault level, so voltage steps are not too great.
  - Recall earlier per unit calculations.



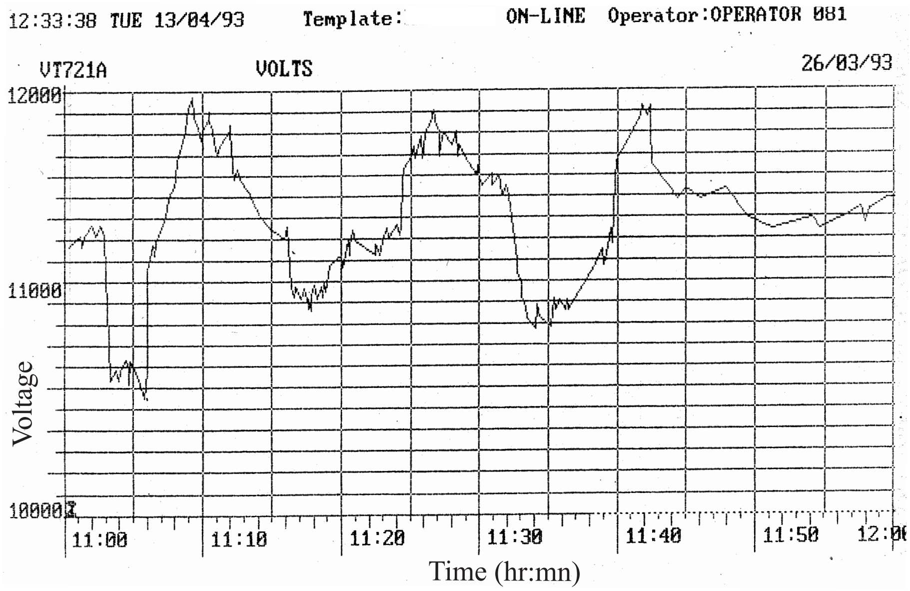
    * Fault level = $S_{fl} = 1/X_{th}$.
    * Capacitor rating = $B = 1/X_c$.
    * The load voltage is given by

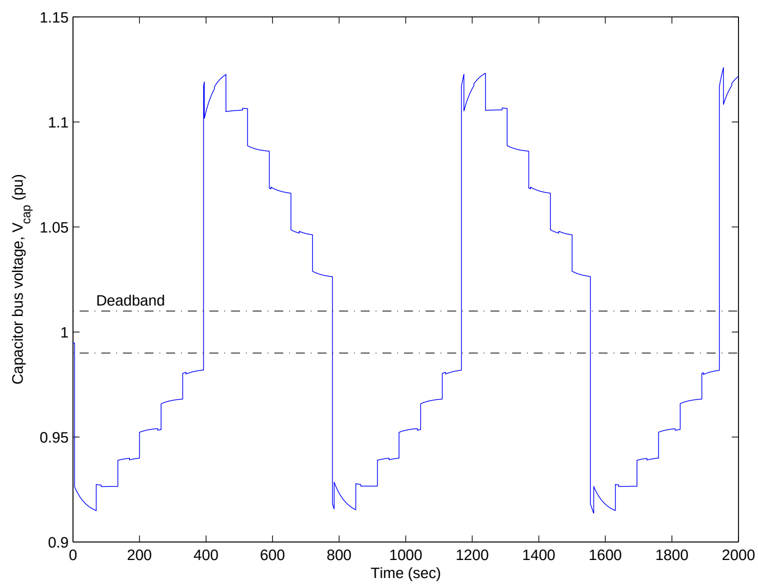
$$V_l = \frac{-jX_c}{jX_{th} - jX_c} = \frac{X_c}{X_c - X_{th}}.$$

      Substituting $X_c = 1/B$ and $X_{th} = 1/S_{fl}$, and rearranging, gives

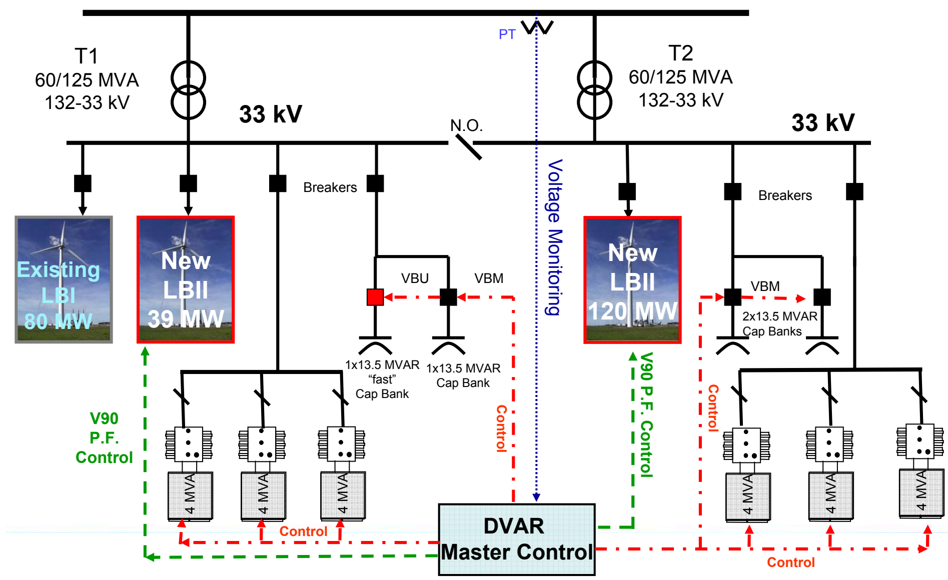
$$\frac{B}{S_{fl}} = \frac{V_l - 1}{V_l} \approx V_l - 1.$$

    * The voltage rise in per unit is given approximately by the ratio B/S_{fl}.
    * For a 5% change in load bus voltage V_l, the capacitor rating should be about 5% of the fault level.
  - Example of things going wrong: NSW mid-north coast
    * A planned outage followed by a forced outage left the Taree area supplied by a single 132 kV feeder.
    * With the reduced fault level, capacitor switching caused excessive voltage steps.
    * Transformer tapping responded, resulting in slow oscillations in the voltage on the distribution system.





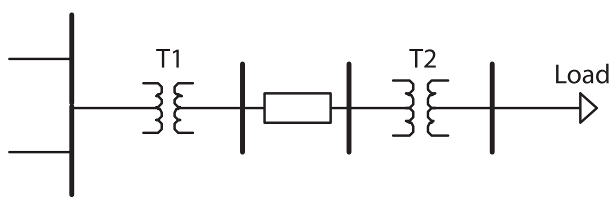
- A deadband is required so there's not continual switching in/out/in...
- Not uncommon to switch in conjunction with SVCs/Statcoms, to increase the dynamic range.
  - Nebo SVC example earlier incorporated a thyristor switched capacitor.
  - Statcom implementations often incorporate capacitor switching.
    - ∗ Example: Lake Bonney, South Australia.
    - ∗ Note the use of both fast and slow switched capacitors.



From American Superconductor.

4.6 On-load tap changing transformers

- Sense the local voltage and change taps to restore voltage to within a deadband.
- Various timer strategies are employed for initial and subsequent tap changes.
  - Equal time for each tap change, or alternatively a shorter wait for subsequent tap changes.
- Cascaded tap changing transformers should be coordinated to prevent oscillatory interactions.



  - Assume the transformer at the lower voltage level (T2) taps faster than the higher-voltage transformer (T1).
  - In response to a wide-spread voltage drop, T2 will begin restoring the load voltage before T1 can respond.
  - Subsequently, when T1 finally taps, it will raise the load voltage. As a result of this voltage overshoot, T2 will have to tap down.
- Tap changers are a major contributing factor to voltage collapse.
  - As they restore the load voltage, voltage sensitive loads recover, placing greater stress on the transmission system.

  - With each tap up, the transformer consumes more reactive power itself.
  - In a voltage collapse scenario, as a transformer taps up to restore the load voltage, it actually pushes the transmission voltage down.
  - To minimize the risk of voltage collapse following a large disturbance, transformers that regulate transmission-level voltages should tap faster than distribution-level transformers.
    * This restores transmission system voltages before restoration of distribution voltages causes load recovery.
  - Various tap-blocking schemes have been proposed - more about this later.

4.7 Reactive power reserve

- When a contingency occurs, the loading on the remaining system invariably increases.
  - Demand for reactive power increases.
- The $n-1$ planning criterion implies that all voltages should remain within limits.
  - To achieve this, the intact system must maintain adequate reactive power reserve.
- Reserve is the difference between maximum available reactive power, and the reactive power that is actually being consumed.
- Short-term reserve: Reactive power that can be supplied immediately.
  - Provided by generators, SVCs, Statcoms, fast switched capacitors/reactors.
  - Includes short-term overload capability.
- Long-term reserve: Reactive power that is available to support load recovery.
  - Capacitors that switch in more slowly, reactors that switch out slowly.
  - Synchronous condensers that take time to start.
  - Cannot rely on short-term overload of generators and Statcoms.

4.8 Secondary and tertiary voltage control

Primary voltage control is provided by automatic voltage regulators (AVRs) on voltage regulating devices such as generators and tapping transformers.

Secondary voltage control replaces/augments manual adjustment of AVR setpoints by providing closed-loop control of those setpoints.

- Implemented in France and Italy since the early 1980s.
- Original scheme:
  - Power system divided into zones, with each zone consisting of buses whose voltages behave relatively coherently, and that are relatively unaffected by voltage deviations at buses in other zones.

  - Each zone has a pilot bus, and each participating generator is assigned to the control of a particular pilot bus.
  - Objectives:
    * Keep pilot bus voltages at specified setpoints.
    * Each generator's reactive power production should be proportional to its reactive power capability.
  - Implementation:
    * For each zone, the difference between the measured and setpoint values of the pilot bus voltage drives a PI (proportional-integral) controller to produce a signal N, that is sent to all generators in the zone.
    * For each generator in the zone, the AVR voltage reference is adjusted so that the generator reactive power production follows the setpoint NQ_{max} where Q_{max} is the generator reactive capability.
  - Response times are on the order of 3 minutes for the zone PI controllers, 20 seconds for the reactive power control loops, and 1 second for AVRs.
    * This time-scale separation ensures that interactions are avoided.

- Later scheme:
  - System partitioned into larger regions that include several pilot buses.
  - Closed-loop controller acts directly on the AVR voltage setpoints, with 10 second update period.
  - AVR setpoints are obtained from an optimization problem that minimizes the sum of squared pilot bus deviations and generator reactive power production, and takes into account interactions between generators.
  - Sensitivities of pilot bus voltages and reactive power outputs of generators are computed in real time.

- Secondary voltage control also switches shunt compensation to maximize reactive reserves.

Tertiary voltage control can be used to periodically reschedule the pilot bus setpoint voltages.

- The setpoints are the solution of a system-wide optimization.

- The objective may be to minimize losses and/or to maximize reactive reserve.

As load increases, secondary voltage control maintains a relatively flat voltage profile.

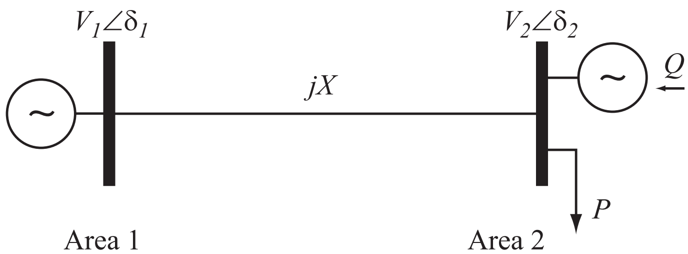
- Excessive load increases result in a sharp final voltage drop, as all generators tend to reach their reactive capabilities together.

- Network voltages tend to be poor indicators of system insecurity. Rather reactive power reserve should be monitored.

Reactive Power Compensation

5.1 Voltage collapse and reactive power deficiency

Consider a simple two bus power system.



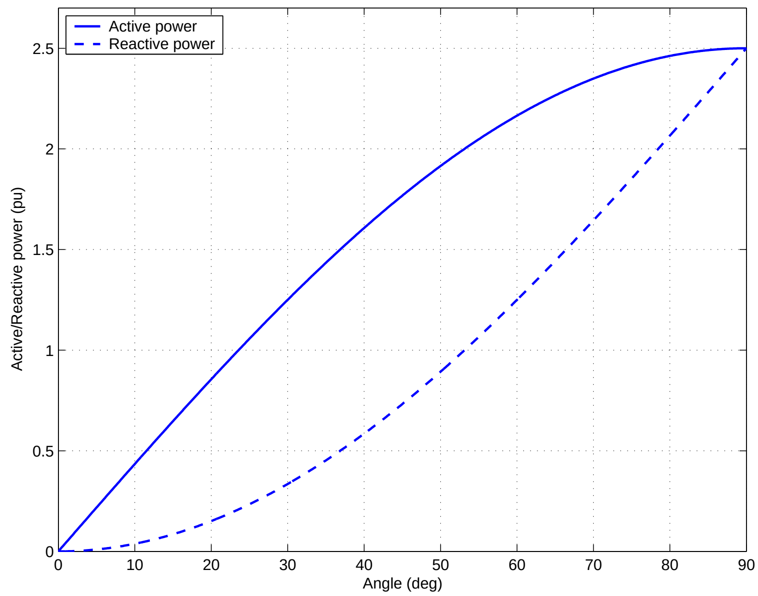
- Active power transfer is given by

$$P = \frac{V_1 V_2}{X}\sin(\delta_1 - \delta_2)$$

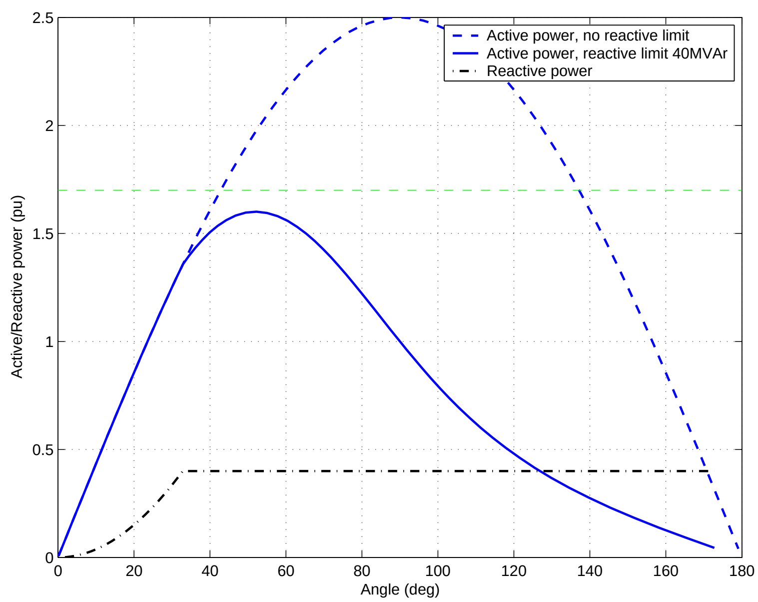
- While V_2 remains steady, the maximum power limit occurs when $\delta_1 - \delta_2 = 90^o$, giving $P_{max} = \frac{V_1 V_2}{X}$.
  - The system impedance X establishes the limit on the maximum active power that can be delivered.
- The reactive power required to support the delivery of active power is

$$Q = \frac{V_2^2}{X} - \frac{V_1 V_2}{X}\cos(\delta_1 - \delta_2)$$

- Reactive support becomes excessive for high active power demand.



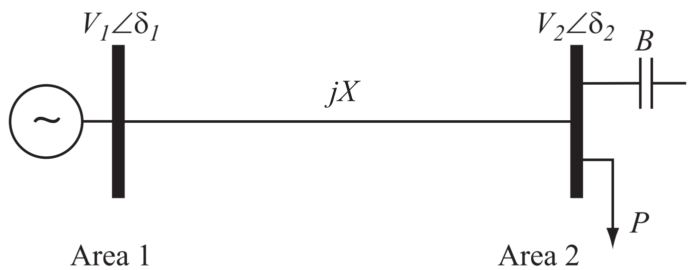
- If the reactive power support is limited, as is normally the case, the maximum active power transfer is reduced.
- When the reactive capability is exhausted, voltage V_2 falls.
  - Depressed voltages reduce the maximum active power transfer.



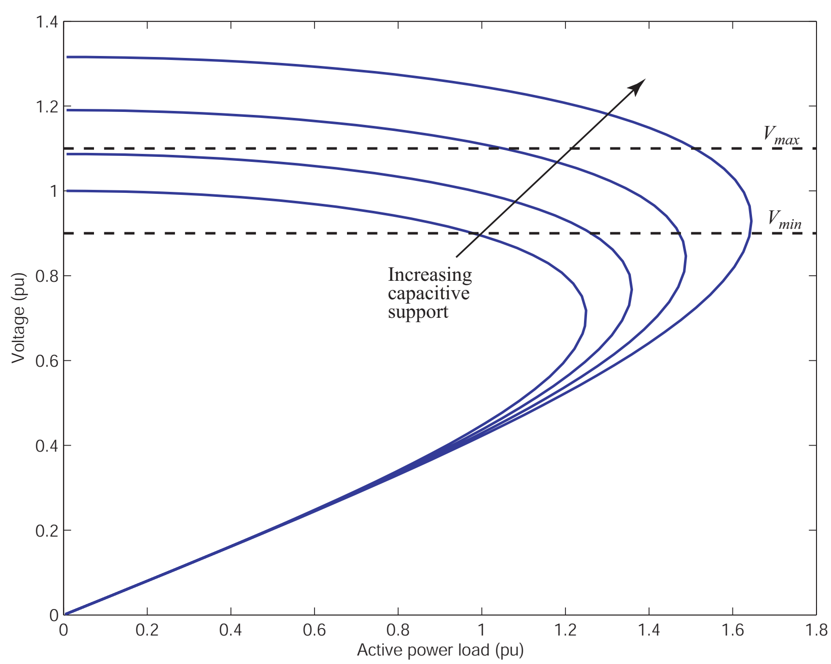
- Note that this figure illustrates a voltage collapse mechanism akin to that induced by OXL action.
  - Prior to OXL action, the receiving-end voltage is held constant.
  - The OXL acts to restrict reactive support, causing the receiving-end voltage to fall, with a consequent reduction in the active power that can be delivered.

– This may lead to angle instability if active power demand exceeds supply capability.

Reactive power support can be provided by static capacitors, rather than a dynamic source as in the previous illustration.



- Reactive power varies with the square of the voltage.
  - If voltage is high, capacitors produce extra reactive power, pushing the voltage even higher.
  - If voltage is low, reactive support is diminished just when it is needed most.

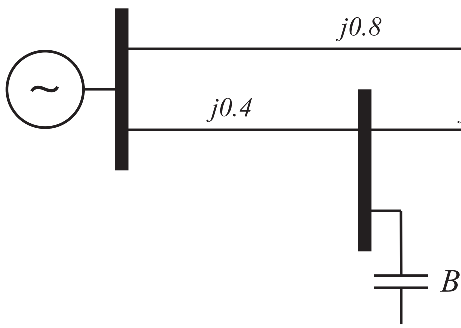


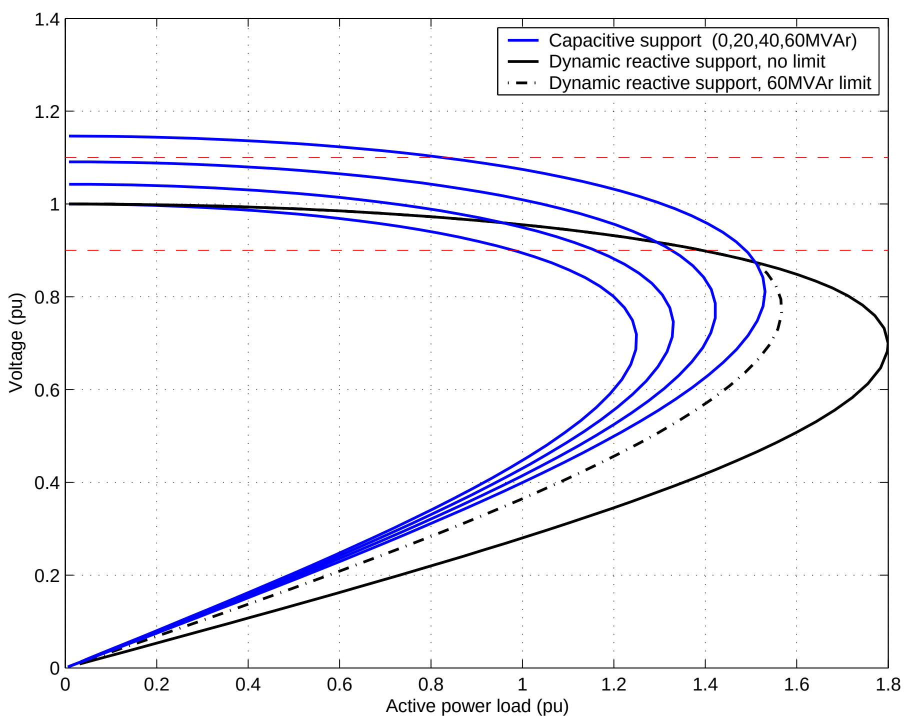
- As capacitive support increases, P can increase while ensuring $V_2 \geq V_{min}$.
  - But notice that the turning point voltage increases, eventually rising above V_{min}.
  - Maximum loadability occurs at "normal" voltage levels.
    - ∗ Voltages no longer provide an indication of proximity to voltage collapse.
- With a high level of capacitive support, a small change in load causes a large change in voltage.

- System voltages are very sensitive to loading changes.
- A reliable indicator of proximity to voltage collapse.

- The vertical distance between curves describes the voltage step upon capacitor switching.
  - At low loads, the step is acceptable. At high loads the step is unacceptably large.

Consider reactive support in the transmission system rather than at the load.





- This configuration gives better (flatter) $P - V$ relationships, but doesn't increase the maximum active power transfer by as much.
  - The voltage step (at the load bus) upon capacitor switching is more acceptable.
- Turning point voltages are a bit lower.

- Dynamic reactive support is shown for comparison.
  - The $P - V$ characteristic is much flatter.
- For unlimited reactive support, the maximum active power transfer is increased quite considerably.
- For limited reactive support, the maximum active power is close to that achieved with a capacitor of the same rating (but the $P - V$ curve is flatter).
- Note that just prior to encountering the reactive power limit, the $P - V$ sensitivity gives no indication of proximity to voltage collapse, but as soon as the reactive resources are exhausted, voltage falls rapidly.
  - Hence the importance of monitoring the reactive reserve.

5.2 Dynamic reactive support

Dynamic reactive support is particularly important for mitigation of transient voltage collapse, where fast post-disturbance response is required.

- The response of SVCs and Statcoms is dependent on their controller tuning, but is generally fast.
- Synchronous condensers are rotating machines.
  - They impose a voltage on the system through their internal flux leakage, so transiently the machine will deliver reactive current to the system roughly in proportion to the change in system voltage.
  - As the flux decays, reactive support is dictated by the field current.
  - The excitation system may be fast, but the field time constant generally slows the response time.
  - Response is therefore slower than SVCs and Statcoms.
  - Synchronous condensers can deliver considerable short-term overload capability.
- When an SVC reaches its capacitive limit, it acts just like a capacitor, so reactive support drops with the square of the voltage.
- A Statcom is limited by the current carrying capability of the power electronic switches, and their ability to dissipate I^2R heating.
  - Reactive support therefore drops linearly with the voltage.
  - Generally have a short-term overload capability built into the power electronics. (Example: DVARs allow 2.67 overload for 2 seconds.)
- SVCs and synchronous condensers can be arbitrarily large.
  - Nebo SVC has a 340 MVAr dynamic range.
  - Zion nuclear plant, near Chicago, was converted to a synchronous condenser.

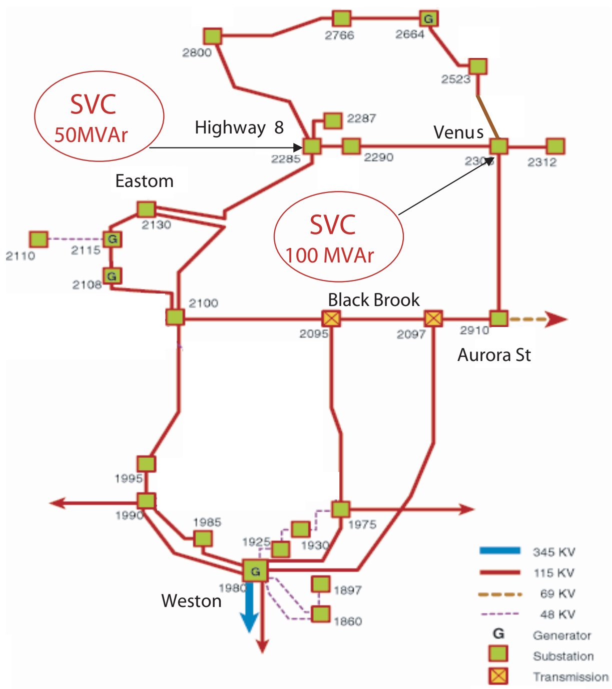
        * Each unit rated at around 600 MVA.
        * Now decommissioned and replaced by an SVC.

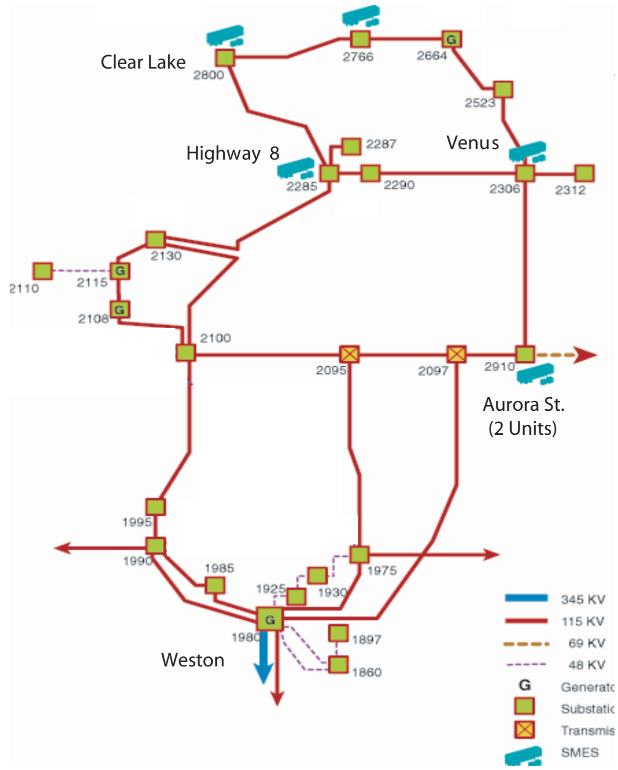
As mentioned earlier, it is fairly common for SVCs and Statcoms to be used in conjunction with switched capacitors/reactors.

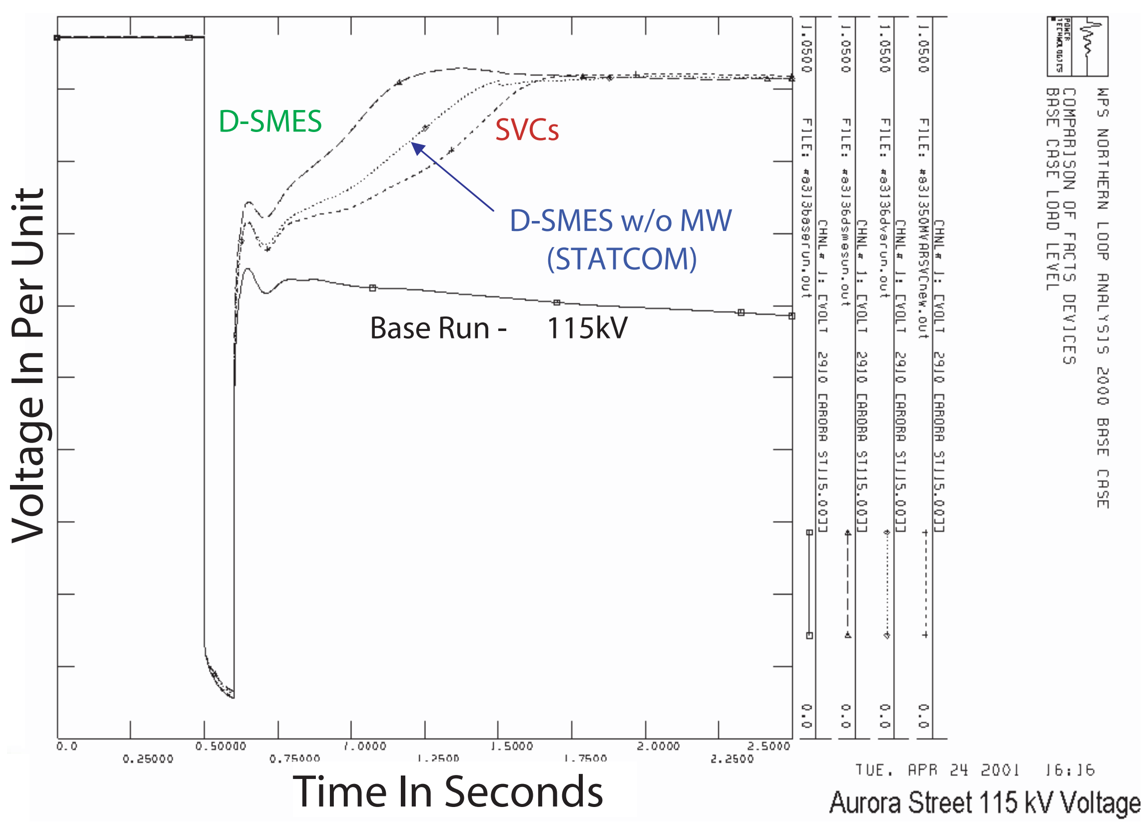
- Switching strategies typically ensure that the maximum capability of the dynamic device is available for fast response, but excessive switching of the static compensation should be avoided.
    - Further discussion is provided later, in conjunction with wind generation.

Reactive compensation tends to be most effective when applied close to where it is consumed.

- This is particularly so when loads include a large amount of induction motors. The voltage support at the distribution level helps prevent motor deceleration, and provides the extra reactive power needed during re-acceleration.
- This tends to favour the use of smaller, distributed reactive compensation, rather than larger centralized compensation.
- However, the centralized approach tends to be less expensive.
- Generally, as systems become more heavily stressed and highly compensated, the distributed approach becomes necessary for mitigation of voltage collapse.
    - The reactive power from centralized sources cannot "flow" to where it is most needed.
- Example: American Superconductor investigation of Wisconsin Public Service Corporation's northern loop.
    - Loop consists on 115 kV transmission grid, supplying 230 MW total load. The network is highly compensated with capacitors.
    - Load:
        * Industrial - paper mills.
        * Residential - vacation area.
    - Trade-off between two SVCs and six Statcoms (D-SMES).
        * Each D-SMES configured as a Statcom can deliver up to 3 MVAr continuously, and up to 6.9 MVAr transiently.


SVC
50MVAr
Highway 8
SVC
100 MVAr
Eastom
Venus
Black Brook
Aurora St
Weston
2800
2766
2664
2523
2287
2285
2290
2306
2312
2130
2110
2115
2108
2100
2095
2097
2910
1995
1990
1985
1925
1930
1975
1980
1897
1860
345 KV
115 KV
69 KV
48 KV
Generator
Substation
Transmission

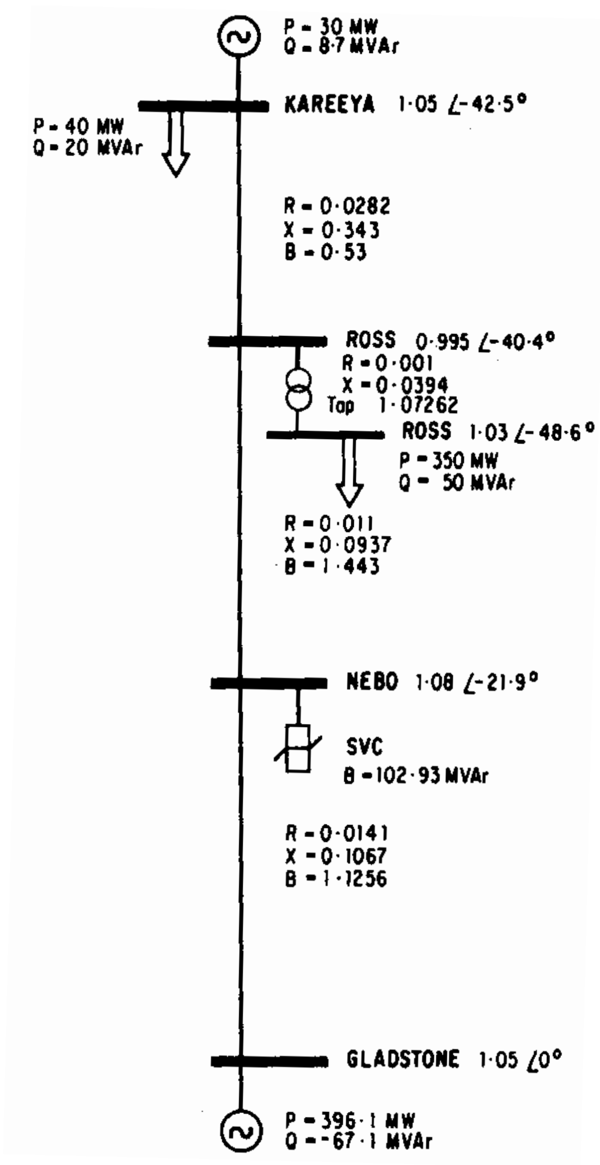

Clear Lake
Highway 8
Venus
Aurora St.
(2 Units)
Weston
2800
2766
2664
2523
2287
2285
2290
2306
2312
2130
2110
2115
2108
2100
2095
2097
2910
1995
1990
1985
1925
1930
1975
1980
1897
1860
345 KV
115 KV
69 KV
48 KV
SMES


Voltage In Per Unit
Time In Seconds
D-SMES
SVCs
D-SMES w/o MW
(STATCOM)
Base Run - 115kV
0.0
0.25000
0.50000
0.75000
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
1.0500
WPS NORTHERN LOOP ANALYSIS 2000 BASE CASE
COMPARISON OF FACTS DEVICES
BASE CASE LOAD LEVEL
TUE. APR 24 2001 16:16
Aurora Street 115 kV Voltage

5.3 SVC behaviour on the lower side of the QV curve

Investigation reported in Hiskens and McLean, 1992.

- Based on the QEC (now Powerlink) system.



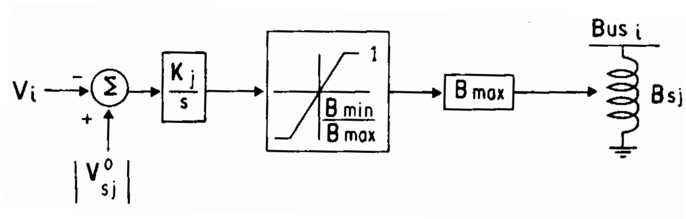
Simple modelling:

- Load model:

$$P_d = P^0\Big(\frac{V}{V^0}\Big)^\alpha, \qquad Q_d = Q^0\Big(\frac{V}{V^0}\Big)^\beta$$

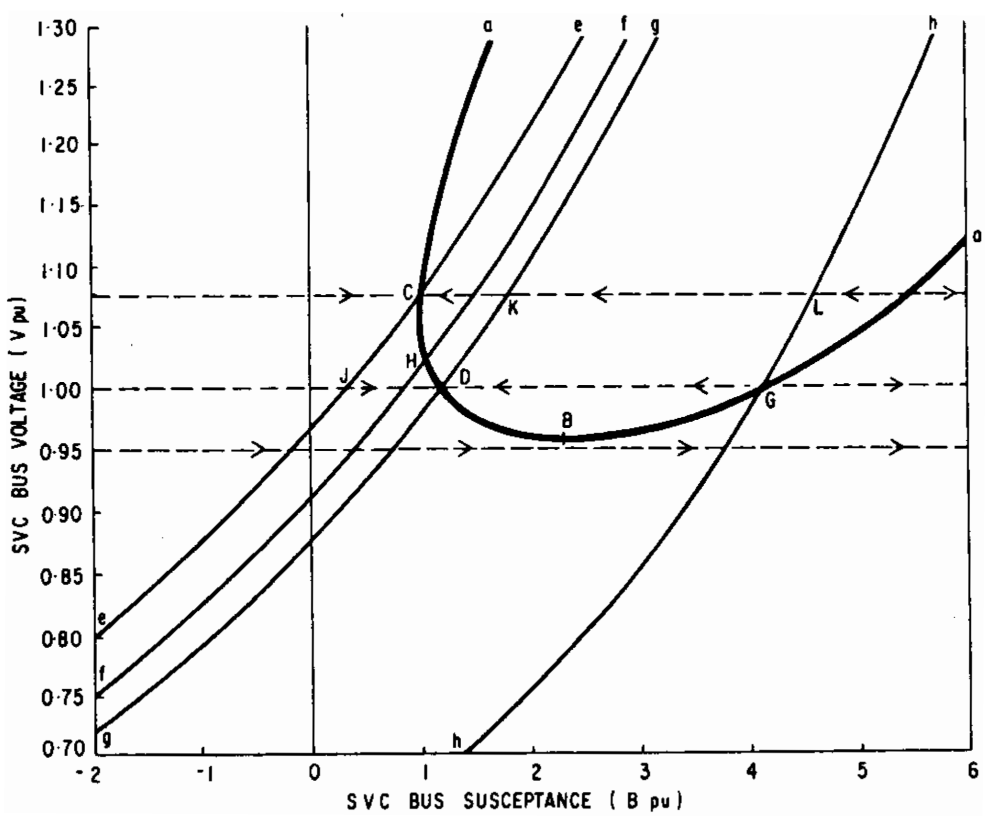
where P_d, Q_d are the active and reactive powers demanded by the loads.

- SVC model:



- Tap changing transformer model:
  - Taps change at a constant rate whenever the controlled bus voltage deviates outside the setpoint deadband.
  - Tap position is a continuous variable in this simple model.

Instantaneous and long-term characteristics.



- Instantaneous:
  - All dynamic states, for example generator angles and transformer taps, are locked at their current values.
  - Network states, for example voltage magnitudes and angles, are free to vary.
  - In the figure, curves e-e, f-f, etc are instantaneous characteristics.

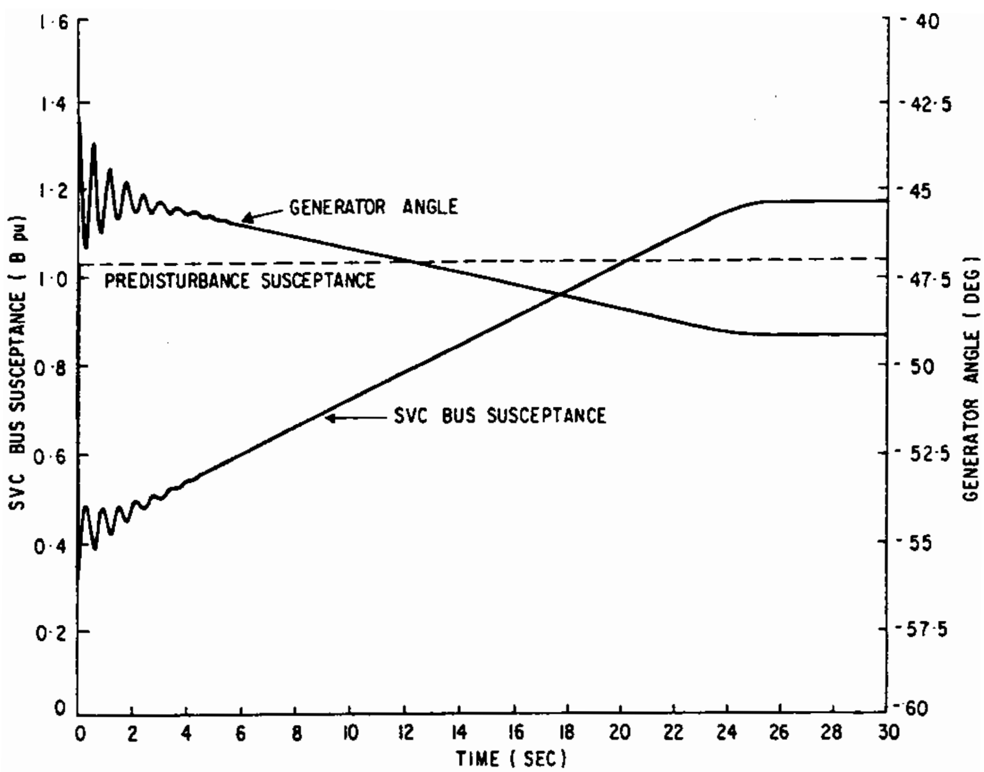
- Long term:
  - All dynamic and network states vary to achieve steady-state conditions.
  - In the figure, curve a-a is the long-term characteristic.

If SVCs respond quickly (relative to other dynamic devices), their behaviour will initially follow an instantaneous characteristic.

- Referring to the figure, if the SVC is initially operating at point C, and its voltage setpoint is reduced from 1.07pu to 1.00pu, susceptance will alter along the curve e-e to point J.

The system will adjust to this new setpoint.

- Generators will respond and taps will change.
- Susceptance will move along the path $J - D$.



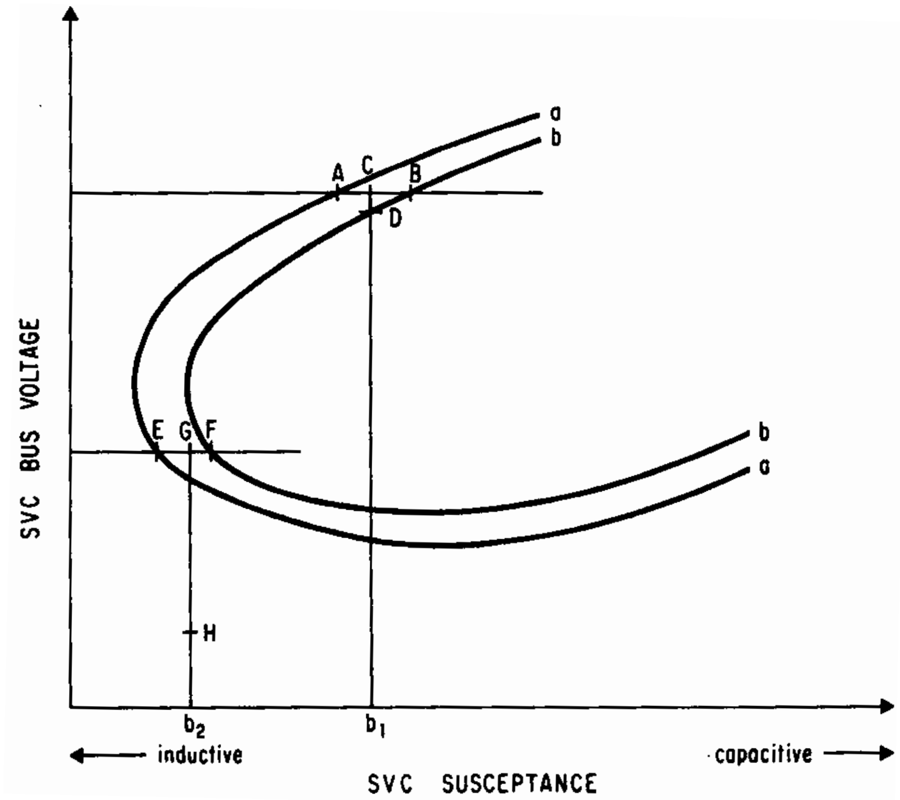
Restoring the SVC voltage setpoint will result in the path $D - K - C$.

Prior analysis assumed SVC response was faster than other dynamic effects.

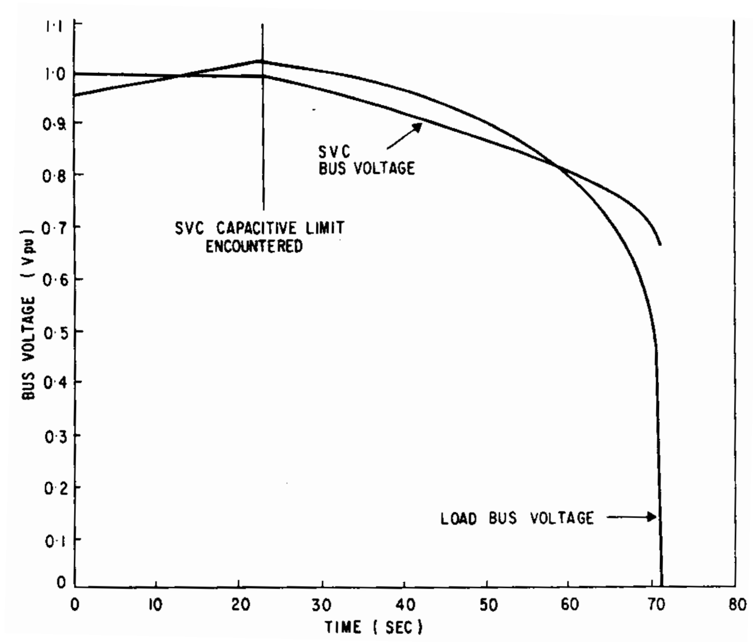
- This is not true when the SVC is on its capacitive limit.

SVC limits.

- Consider a system disturbance (for example a line outage) that moved the long-term characteristic from a-a to b-b in the following figure.



- If the system is initially operating at point A, susceptance will vary along the path $A - B$.
  - If the SVC capacitive limit is b_1, the system will move along the path $A - C$, then the voltage will fall to point D.
- If the system is initially operating at point E, and the SVC capacitive limit is b_2, then the system will follow the path $E - G - H \rightarrow$, and voltage will steadily decline.
- This behaviour is illustrated in the following figure.



5.4 SVC behaviour when the system is weak

It is common practice to reduce the gain of an SVC when the system is weakened, for example by line outages.

- Because of the reduced fault level under such conditions, variations in SVC susceptance have a magnified effect on the system voltage.

5.5 Series capacitor compensation

Series compensation reduces the effective impedance of the transmission line, allowing higher transfer of active power.

- Recall $P = \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2)$.
- Series compensation reduces X.

The reactive power produced by a series capacitor increases quadratically with the load current.

- This contrasts with shunt capacitors where reactive support drops quadratically with the voltage.
- Under heavy load conditions, series capacitors provide more assistance whereas shunt capacitors provide less.
- At light load, the reactive power produced by series capacitors tends to reduce (because current flows are lower) whereas production from shunt capacitors tends to increase (because voltages are higher.)

- Series compensation is therefore “self regulating”.

Series compensation is not widely used though.

- At the transmission level, series compensation can instigate subsynchronous resonance problems.
- At lower voltage levels, concerns include high voltages under high load conditions, and harmonic resonance.