Introduction to Power Grid Operation

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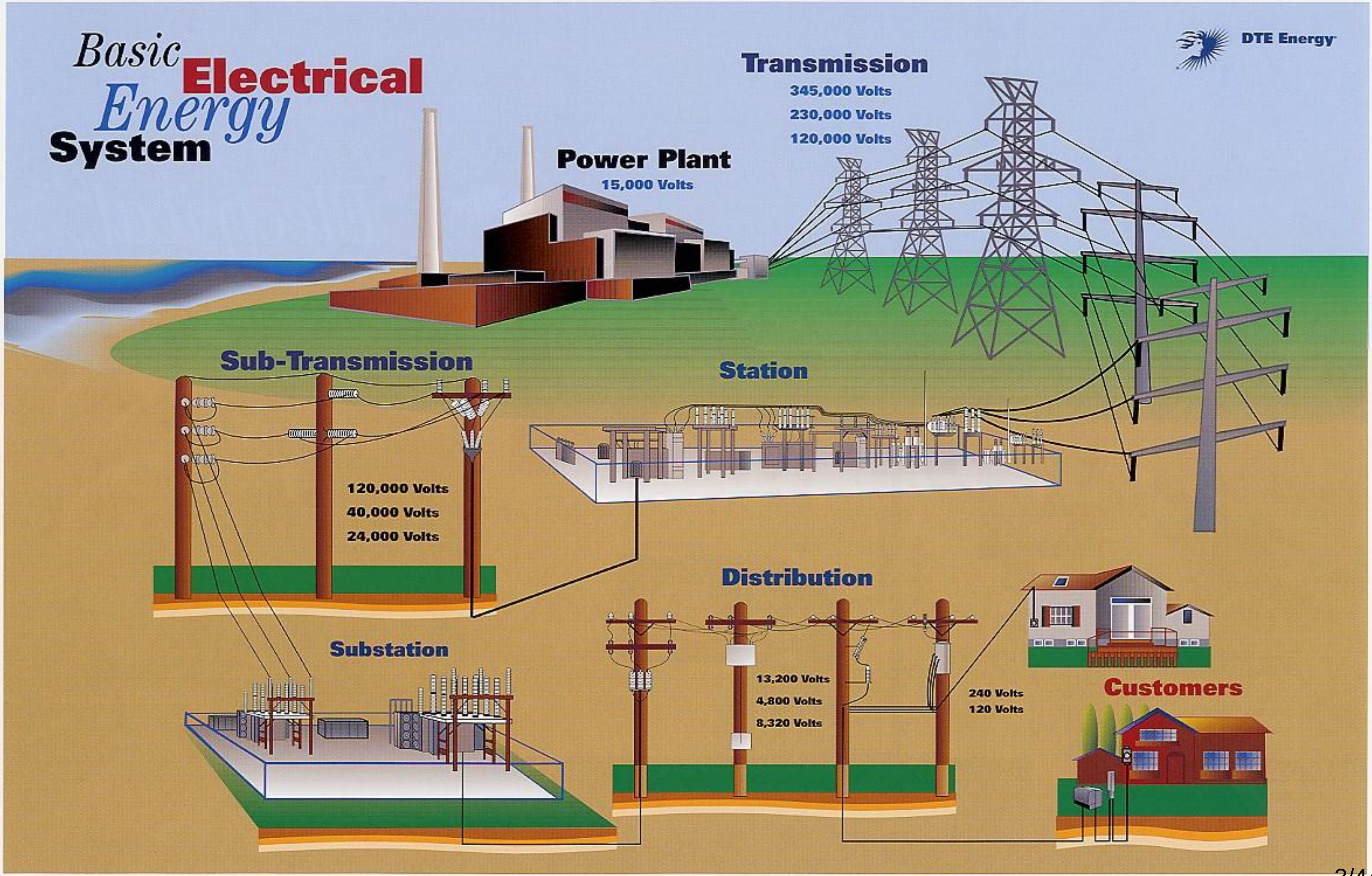
Tutorial on Ancillary Services from Flexible Loads
CDC'13, Florence, Italy

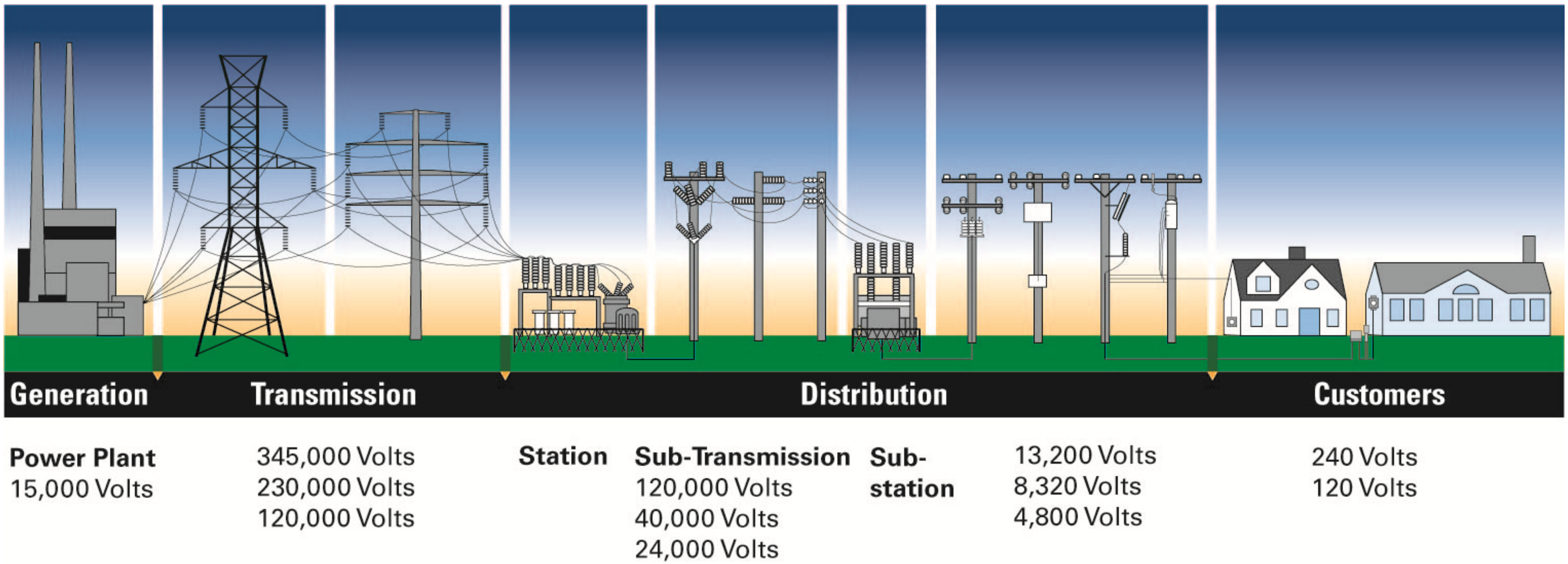
Outline

- Power system background.
- Fundamentals of power system angle and voltage stability.
- Generator controls.
- Frequency regulation.
- Corrective control versus preventative (N-1) strategies.

Power system overview



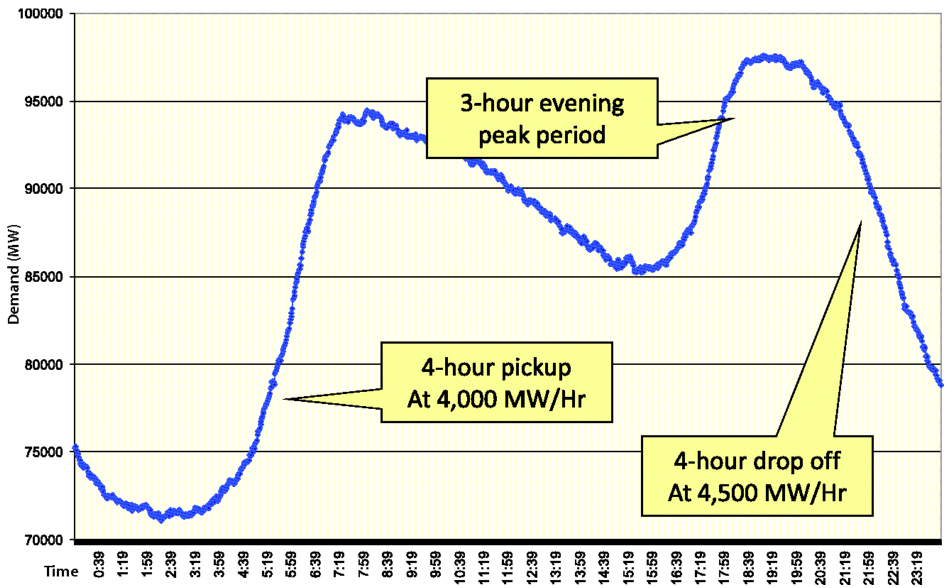
Another view of a power system



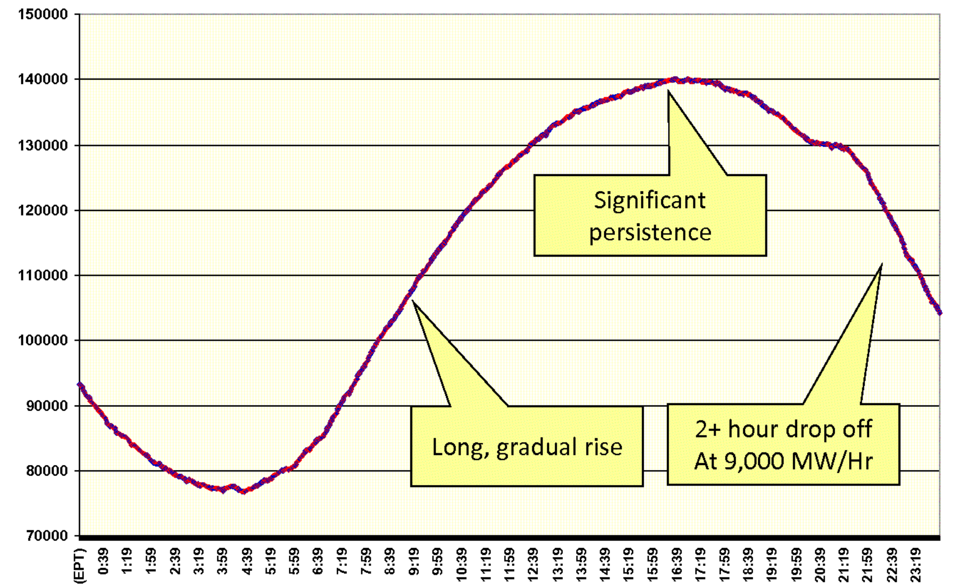
Daily load variation

- Loads follow a daily cycle.
- Traditional demand response seeks to flatten the load curves.
  - Open-loop schemes (for example water-heating and air-conditioning) have been in place for around 50 years.
- Example: PJM load profile.

Winter load



Summer load



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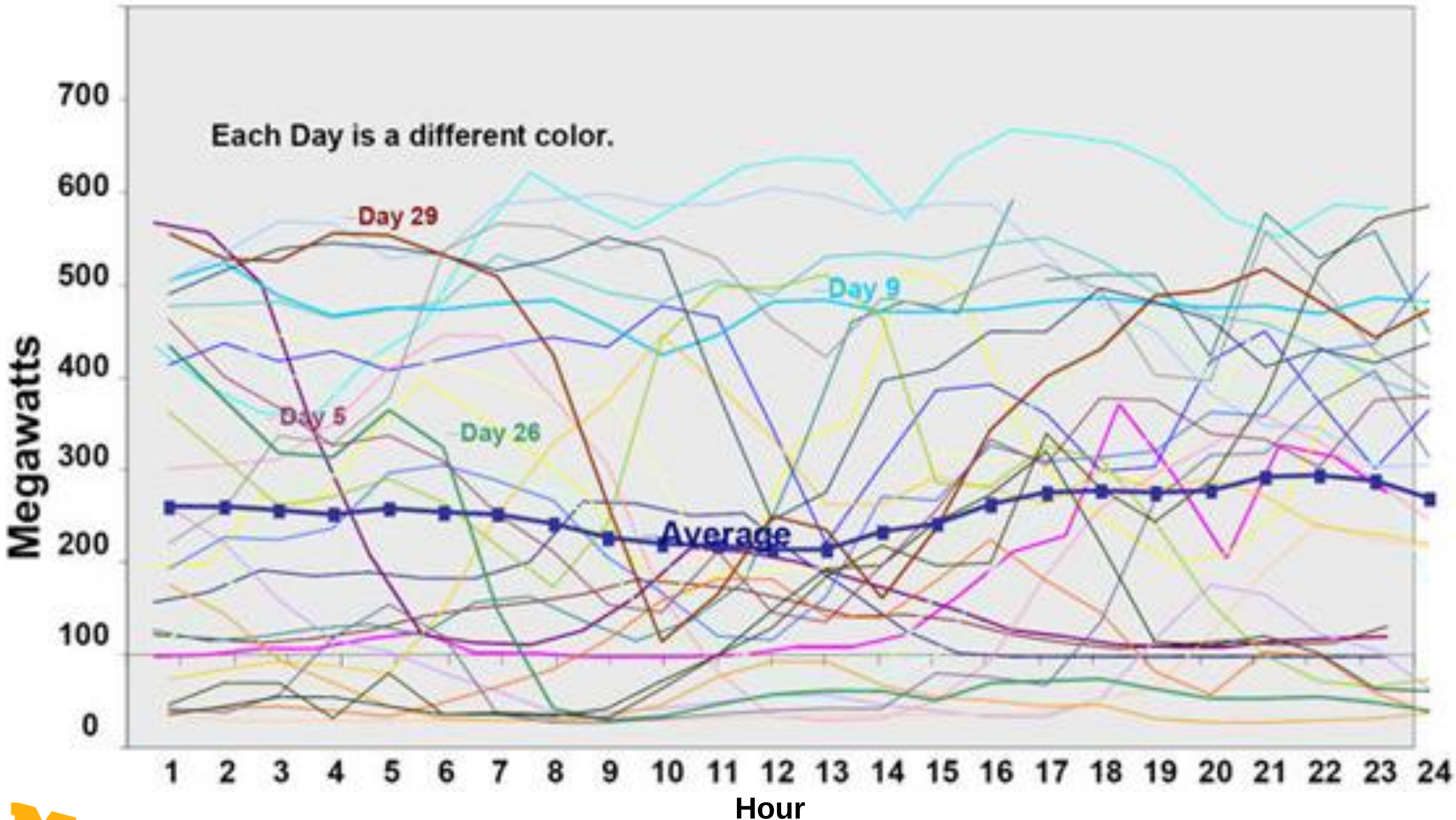
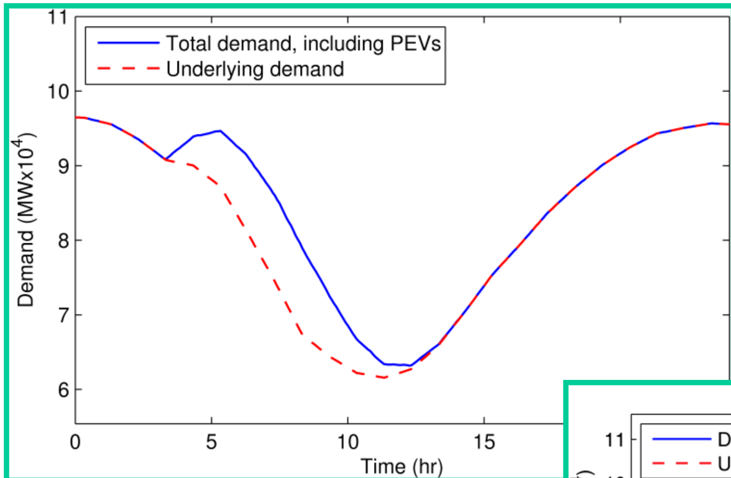
Wind power variation

- Hourly wind generation at Tehachapi, CA, in April 2005.

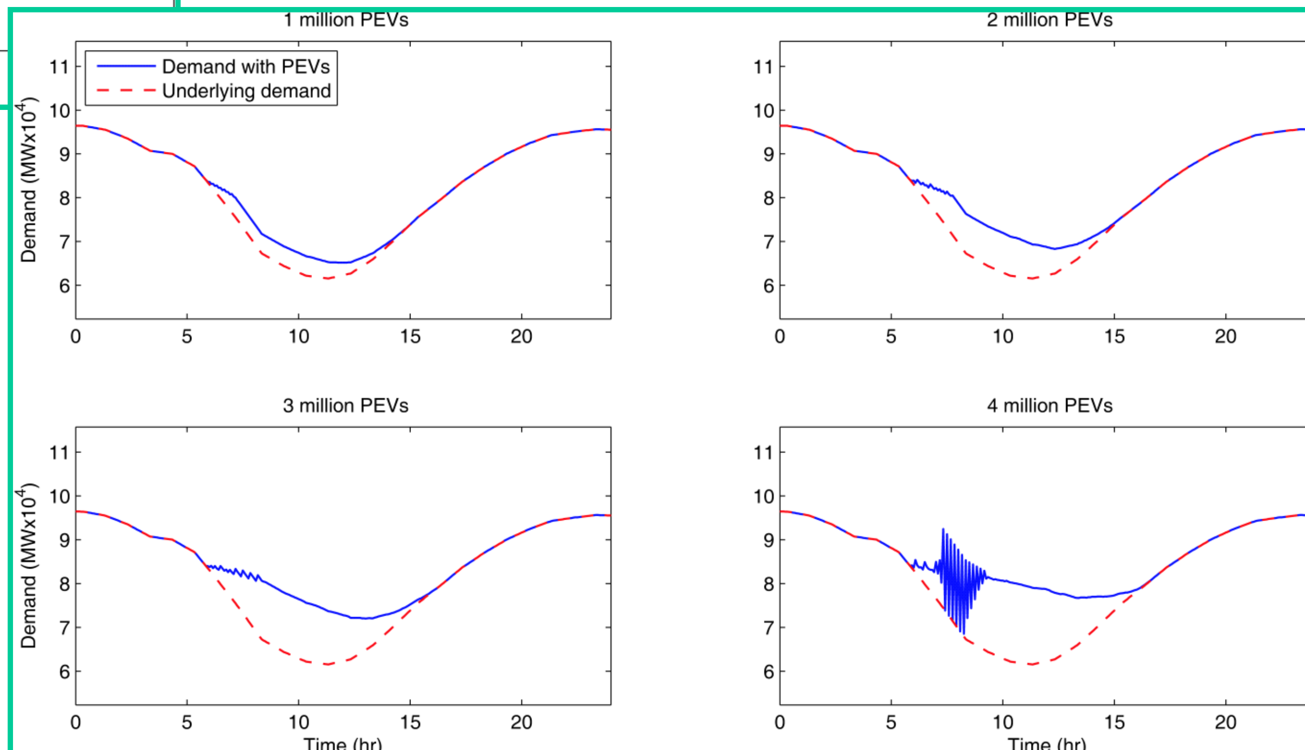


Charging plug-in electric vehicles



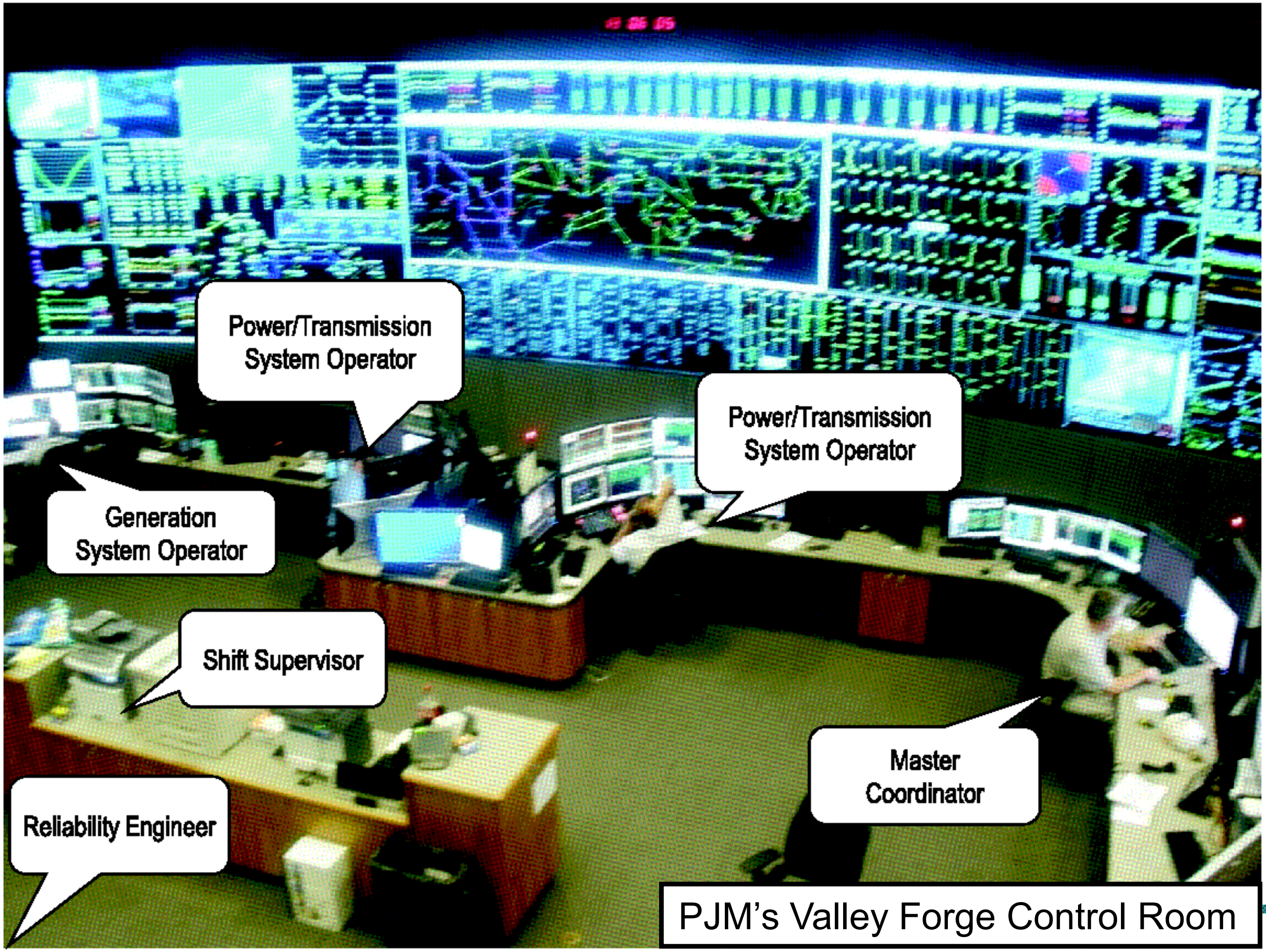
Time-based charging strategy

Price-based charging strategy



Power system operations

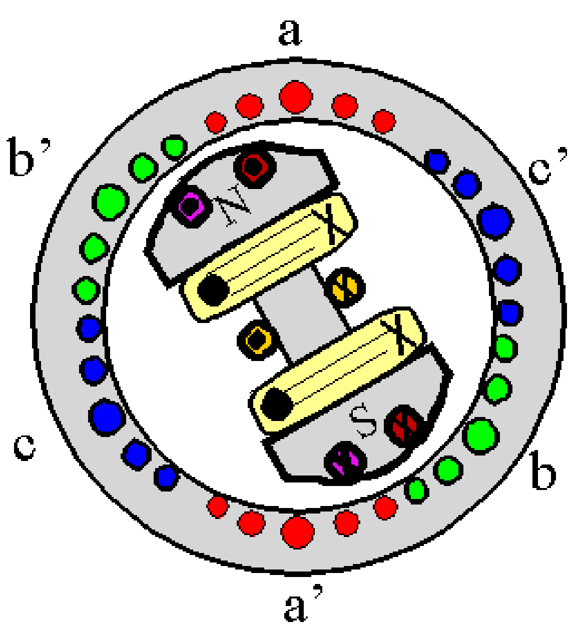
- Supervisory control and data acquisition (SCADA).
- Energy management system (EMS).



PJM's Valley Forge Control Room

Synchronous machines

- All large generators are synchronous machines.
  - Rotor spins at synchronous speed.
  - Field winding is on the rotor.
  - Stator windings deliver electrical power to the grid.



- Wind turbine generators are very different.
- Dynamic behaviour (as seen from the grid) is dominated by control loops not the physics of the machines.

Machine dynamics

- Dynamic models are well documented.
  - Electrical (flux) relationships are commonly modelled by a set of four differential equations.
  - Mechanical dynamics are modeled by the second-order differential equation:

$$J\frac{d^2\theta}{dt^2} = T_m - T_e$$

where

θ : angle (rad) of the rotor with respect to a stationary reference.

J : moment of inertia.

T_m : mechanical torque from the turbine.

T_e : electrical torque on the rotor.

Angle dynamics

- Through various approximations, the dynamic behaviour of a synchronous machine can be written as the *swing equation*:

$$M\frac{d\omega}{dt} + D\omega = P_m - P_e$$

where

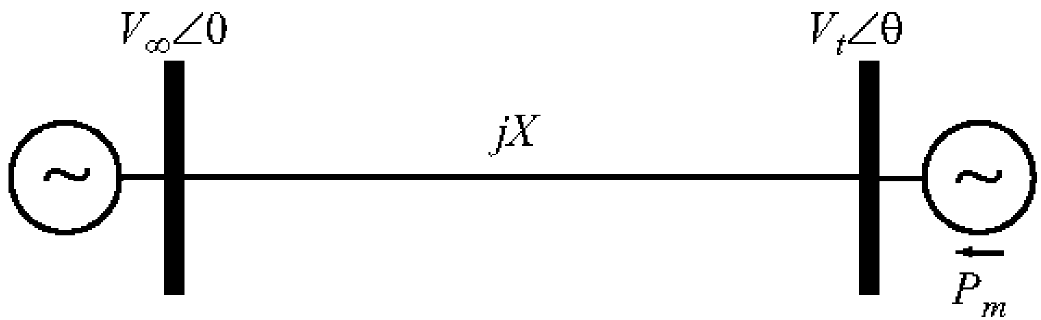
$\omega \equiv \frac{d\theta}{dt}$: deviation in angular velocity from nominal.

M : inertia constant.

D : damping constant, this is a fictitious term that may be added to represent a variety of damping sources, including control loops and loads.

P_m, P_e : mechanical and electrical power.

Single machine infinite bus system



- For a single machine infinite bus system, the swing equation becomes:

$$M\frac{d\omega}{dt} + D\omega = P_m - P_{max}\sin\theta, \qquad \frac{d\theta}{dt} = \omega$$

  where $P_{max} = \dfrac{V_\infty V_t}{X}$.
- Dynamics are similar to a nonlinear pendulum.
- Equilibrium conditions, $\omega = 0$ and $P_m = P_{max}\sin\theta$.

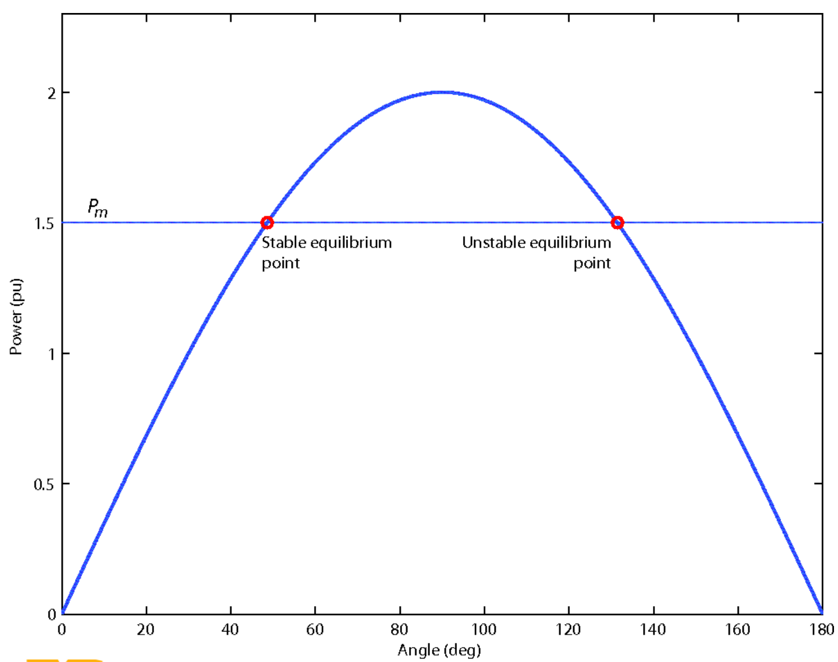
Region of attraction

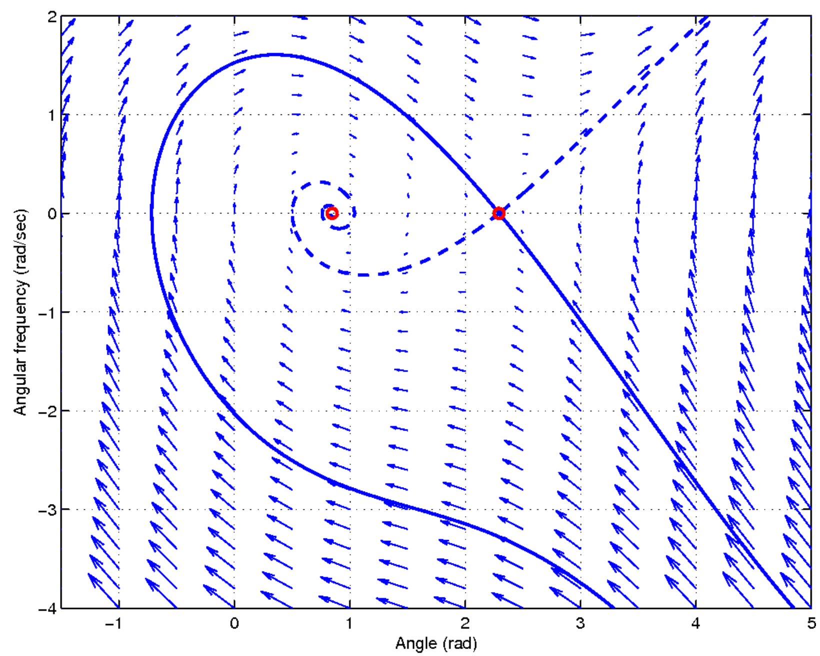
- The equilibrium equation has two solutions, θ_s and θ_u where

  θ_s : stable equilibrium point.

  θ_u : unstable equilibrium point.

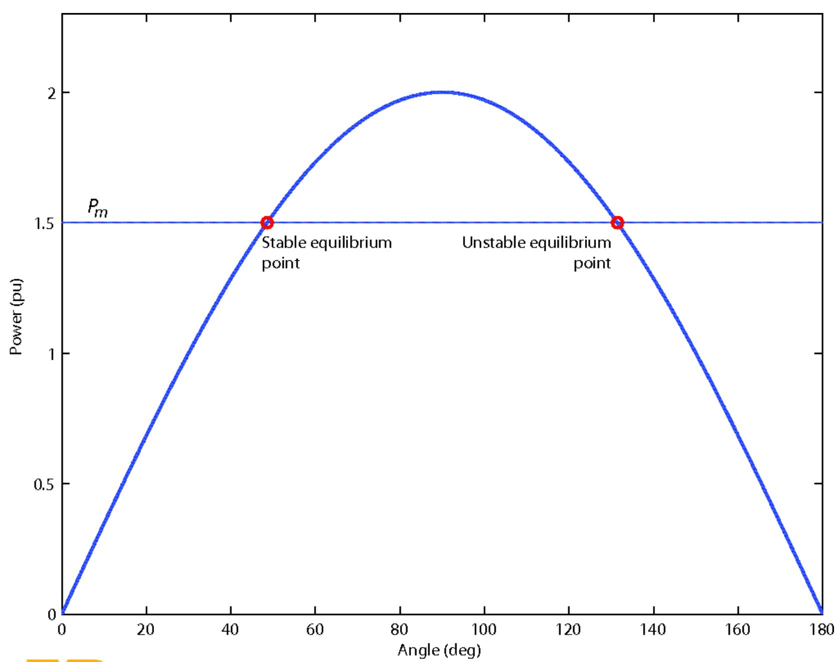
- Local stability properties are given by the eigenvalues of the linearized system at each equilibrium point.

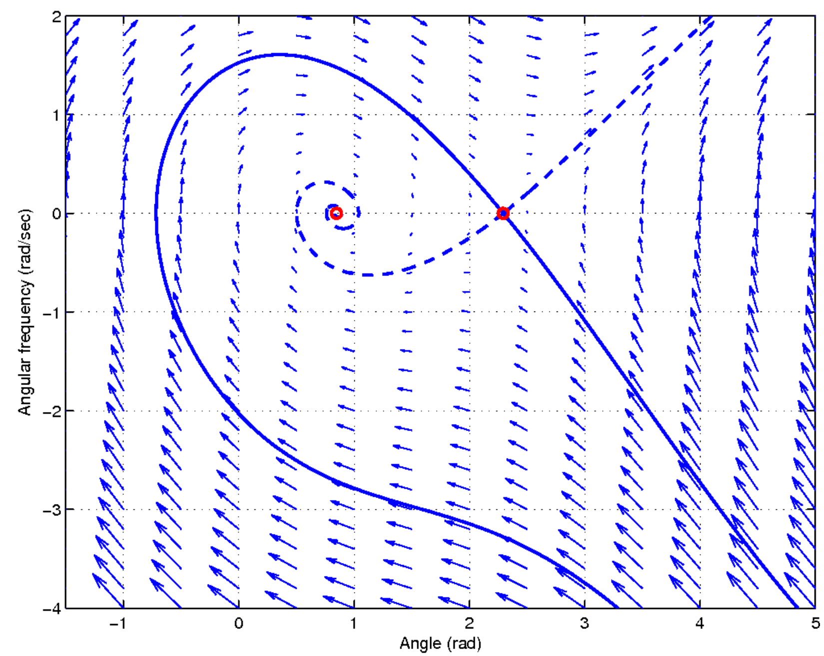




Region of attraction

- As P_m increases, the separation between equilibria diminishes.
  - The region of attraction decreases as the loading increases.
  - Solutions coalesce when $P_m = P_{max}$. A bifurcation occurs.





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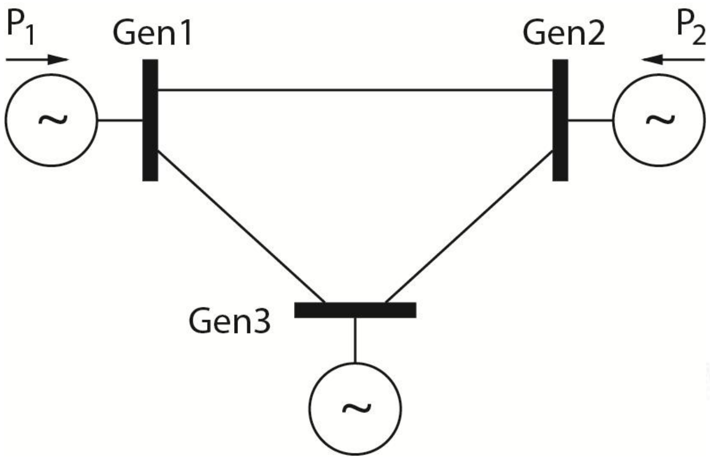
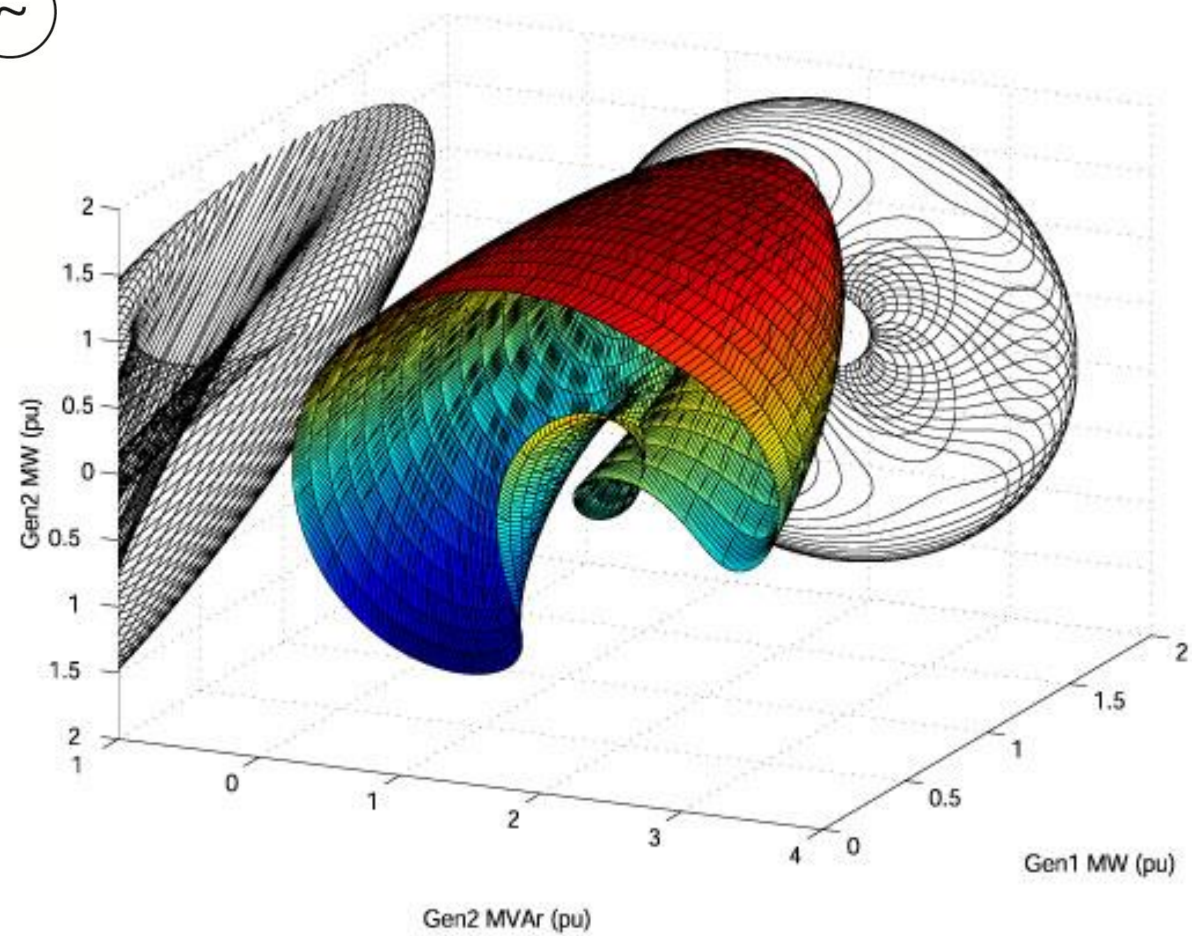
Multiple equilibria

- Real power systems typically have many equilibria.





Frequency excursions (1)

- Beyond the initial transient, the frequency of all interconnected generators will synchronize to a value that is (effectively) common across the entire system.
- The response of this common frequency is governed by

$$M_{tot}\frac{d\omega_{sys}}{dt} + D_{tot}\omega_{sys} = P_{m,tot} - P_{e,tot}$$

where

ω_{sys} : common system-wide frequency.

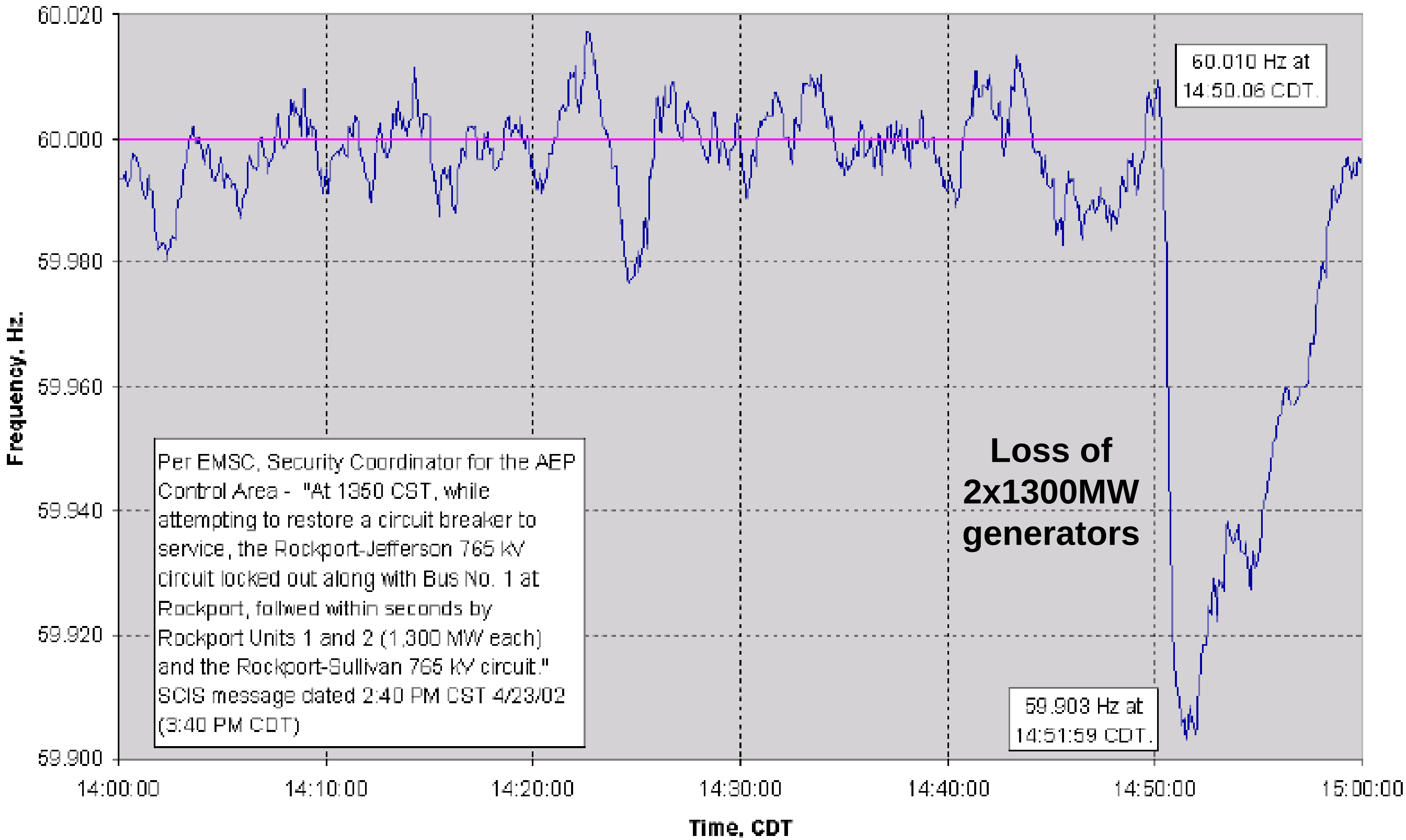
M_{tot} : effective inertia of the entire system.

D_{tot} : effective damping of the entire system.

$P_{m,tot}$: total power production across the system.

$P_{e,tot}$: total electrical power consumed across the system (demand plus losses).

Frequency excursions (2)



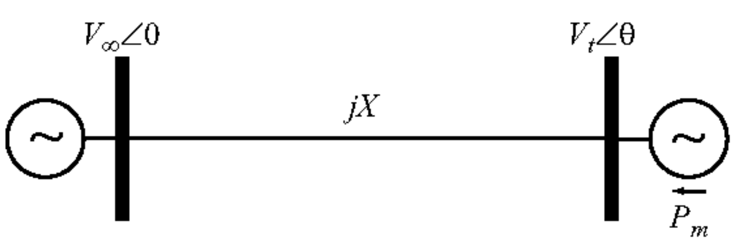
- Under-frequency load shedding occurs when the frequency dips to around 59.3 Hz.

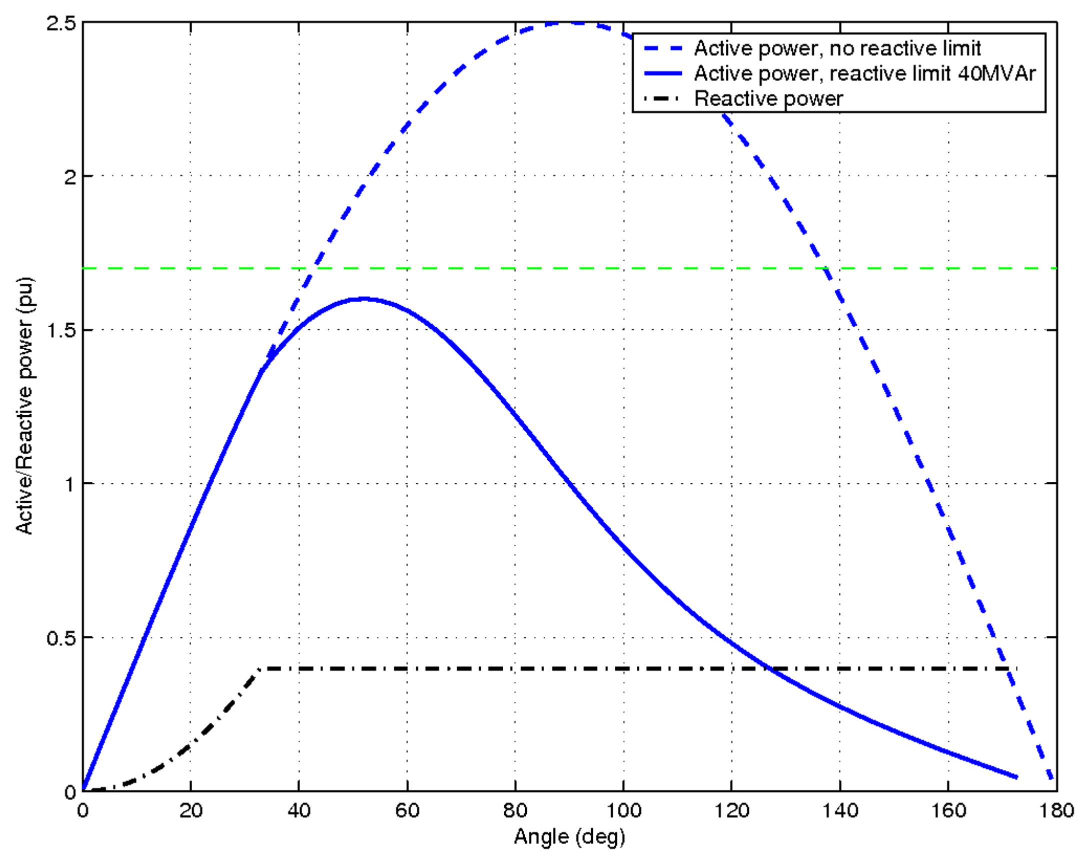
Frequency excursions (3)

- The two generators that tripped off in the previous slide:

Voltage reduction

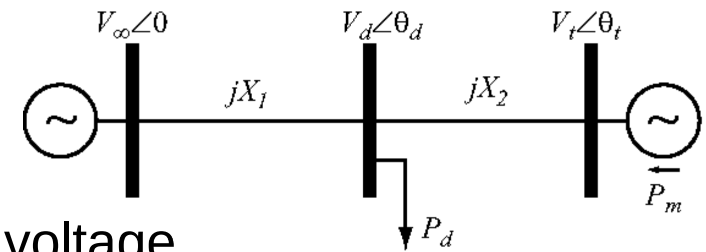
- The single machine infinite bus example assumes the generator will maintain a constant terminal voltage.
  - The reactive power required to support the voltage is limited.
  - Upon encountering this limit, the over-excitation limiter will act to reduce the terminal voltage.
  - This reduces the maximum power capability.



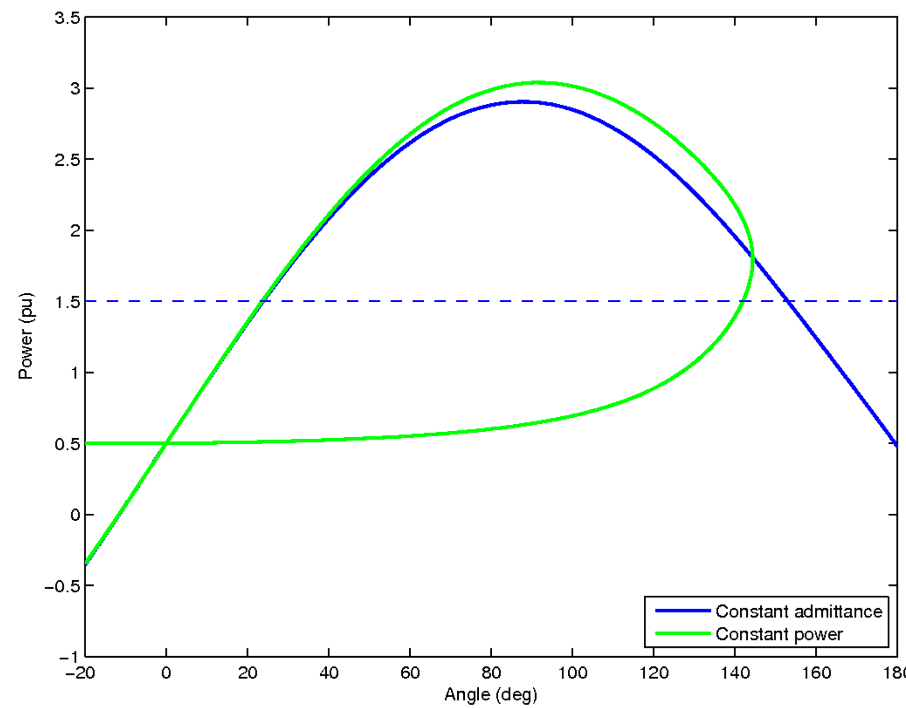


Effect of load

- Consider the effect of load behavior on stability.
- Two cases:
  - Constant admittance: $P_d = K_a V_d^2$
  - Constant power: $P_d = K_p$



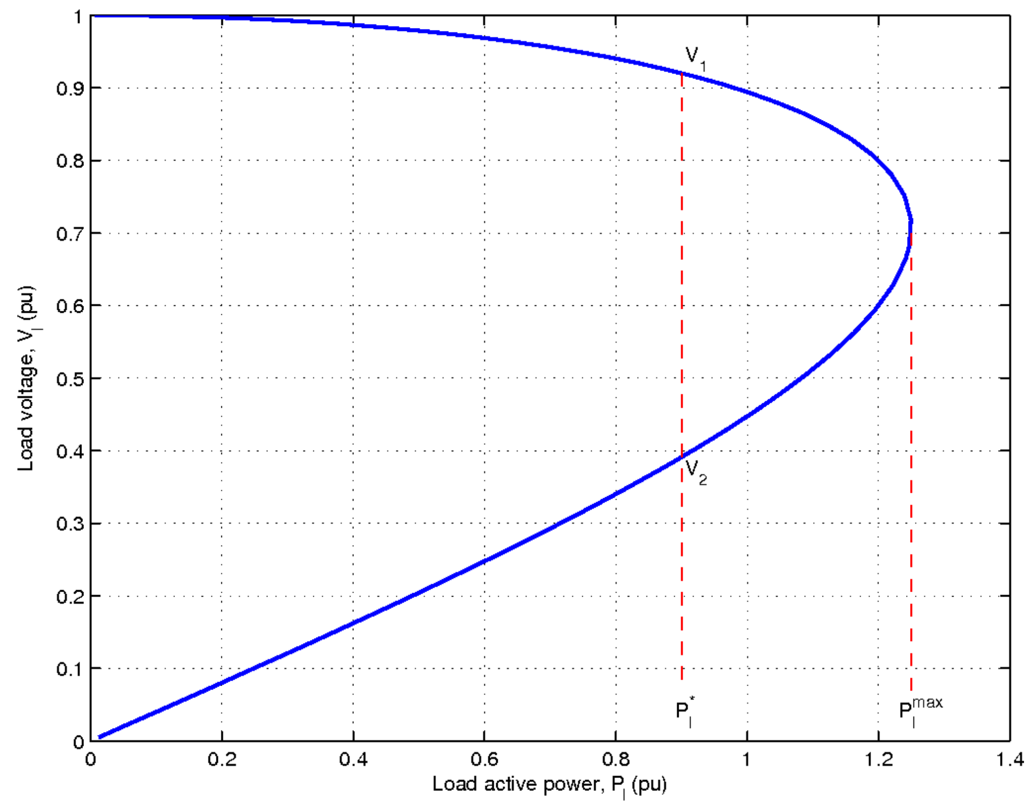
- Notice the loss of structural stability as the voltage index changes.



- Power electronic loads behave like constant power.
  - Bad for grid stability.
  - Examples: energy-efficient lighting, plug-in EVs.
  - Below a certain voltage, power electronics shut down.
  - This gives a fast transition from full power to zero.

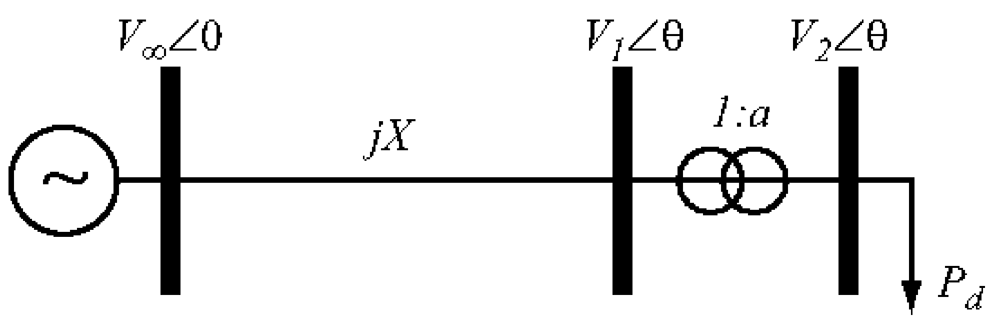
Voltage collapse

- Voltage collapse occurs when load-end dynamics attempt to restore power consumption beyond the capability of the supply system.
  - Power systems have a finite supply capability.
- For this example, two solutions exist for viable loads.
- Solutions coalesce at the load bifurcation point.
  - Known as the point of maximum loadability.

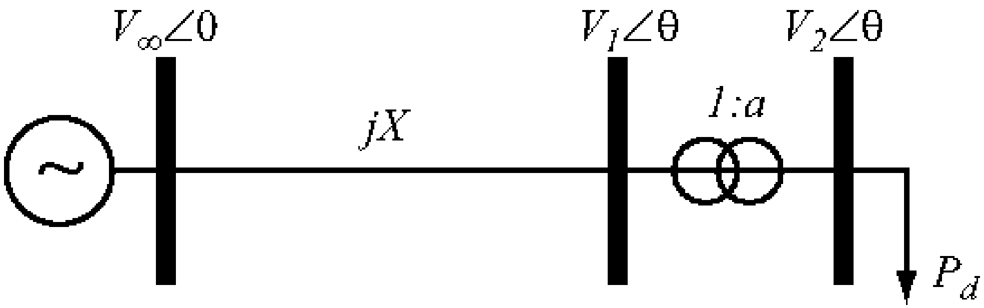


Load restoration dynamics (1)

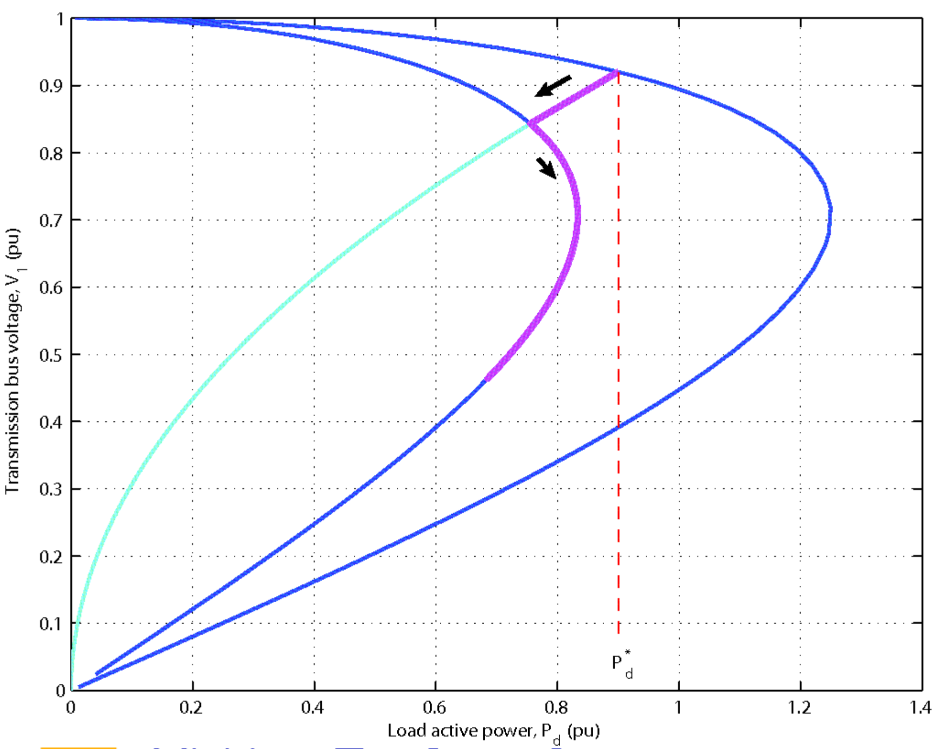
- Transformers are frequently used to regulate load-bus voltages.
- Sequence of events:
  - Line trips out, raising the network impedance.
  - Load-bus voltage V_2 drops, so transformer increases its tap ratio to try to restore the voltage.
  - Load is voltage dependent, so the voltage increase causes the load to increase.
  - The increasing load draws more current across the network, causing the voltage to drop further.

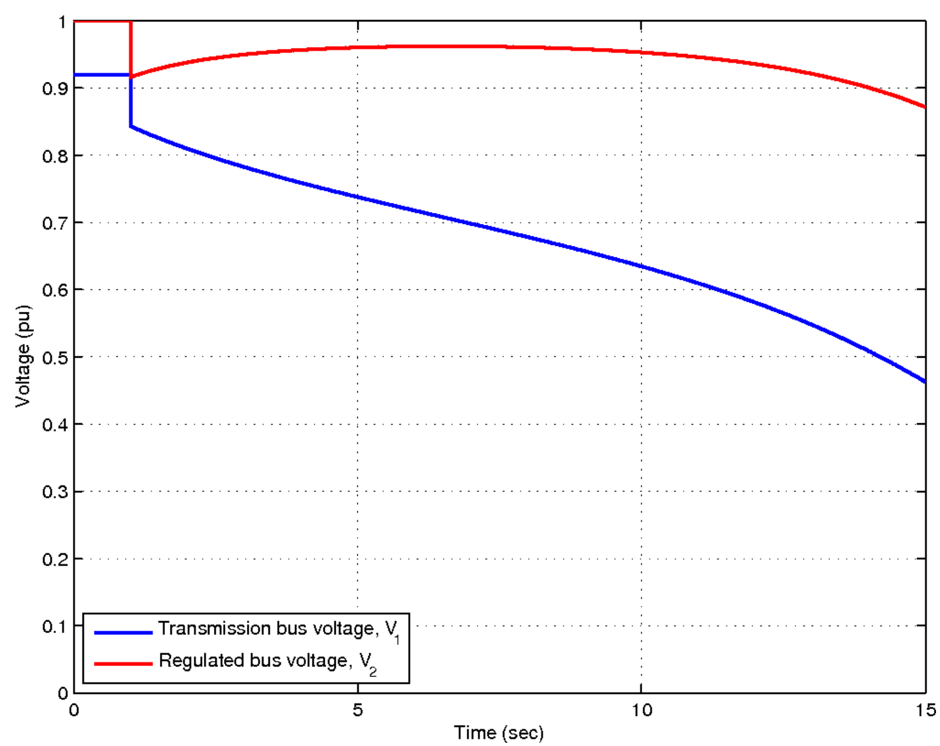


Load restoration dynamics (2)



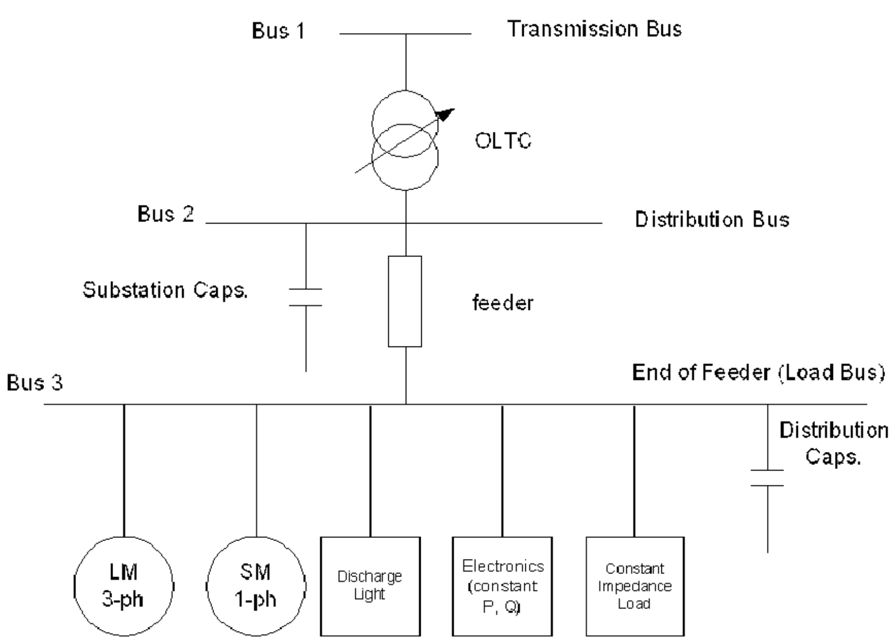
$$\frac{da}{dt} = \frac{1}{T}(V_{set} - V_2)$$
$$V_2 = aV_1$$
$$P_d = P_0 \left(\frac{V_2}{V_{set}}\right)^2$$

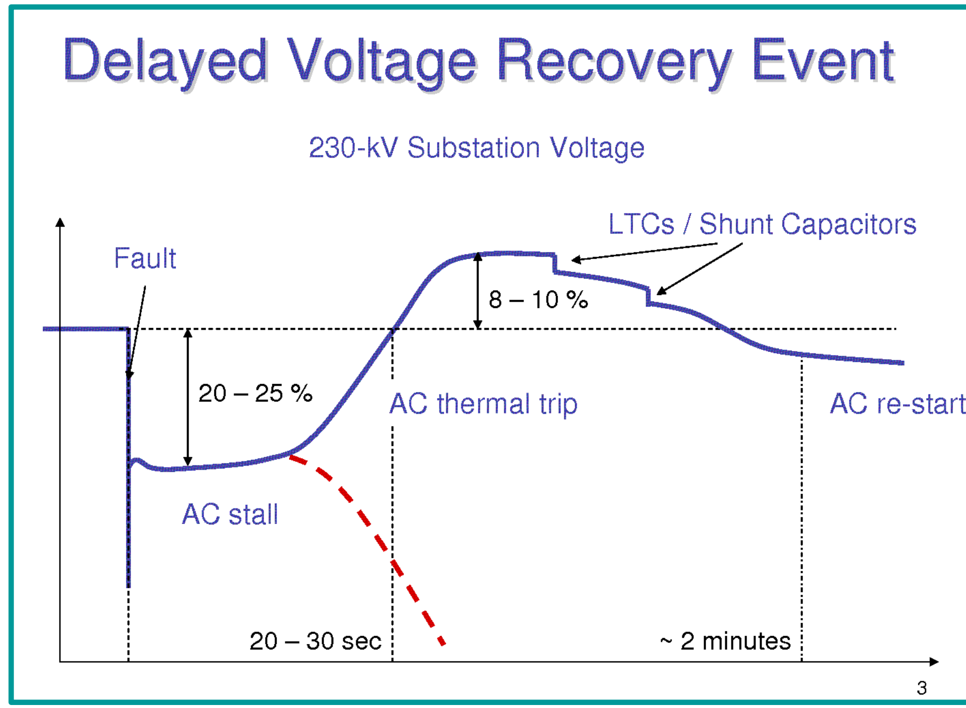




Load synchronizing events

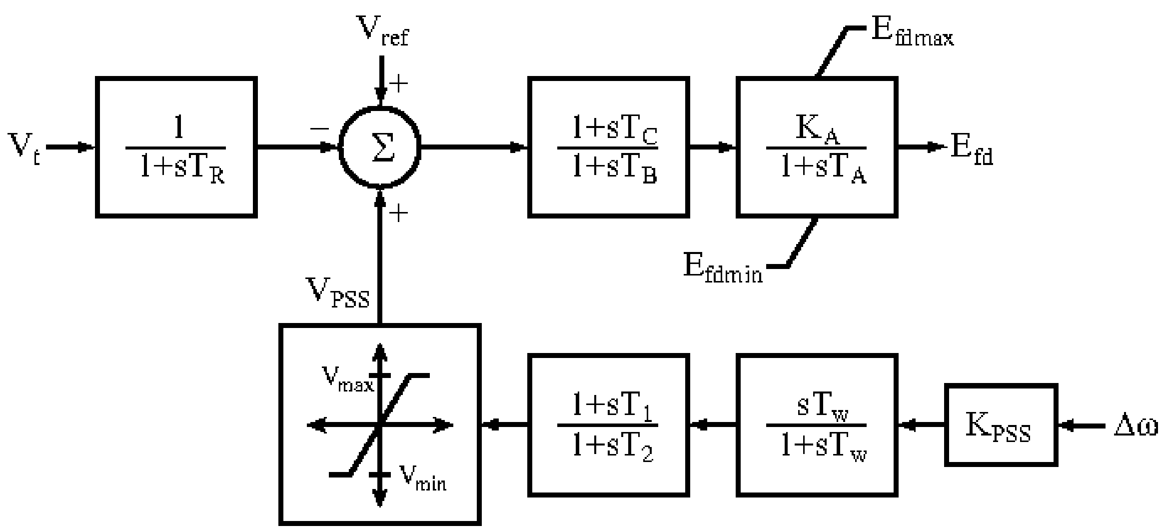
- “Fault induced delayed voltage recovery” (FIDVR) has occurred when a temporary voltage dip causes large numbers of air-conditioners to stall.
- WECC load model:





Generator voltage control

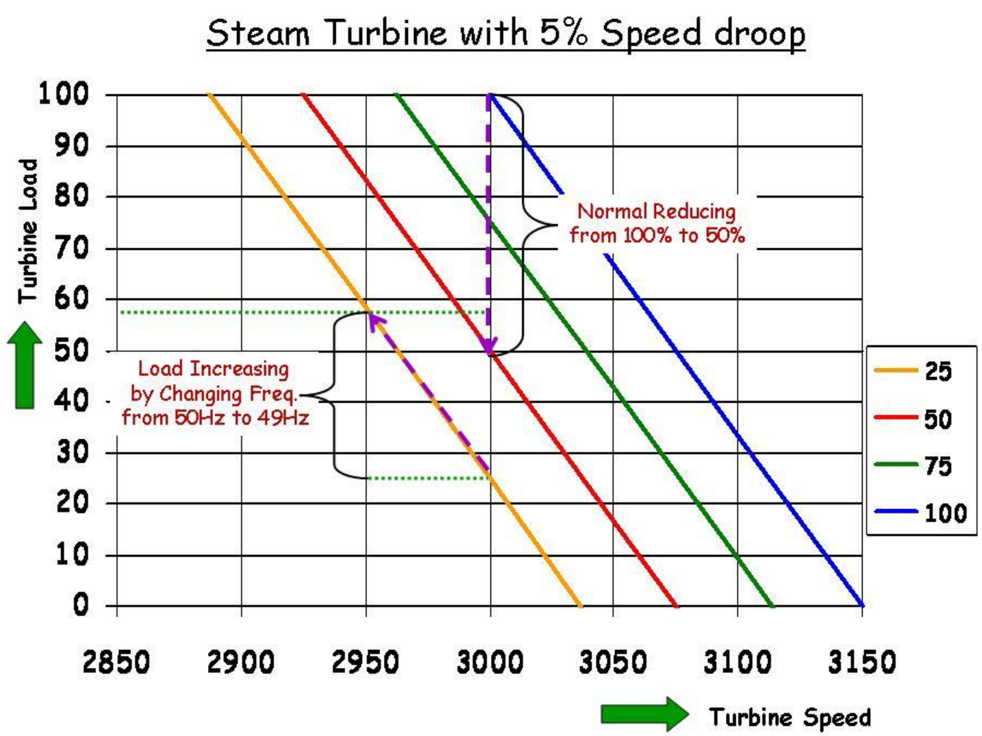
- Voltage control is achieved by an “automatic voltage regulator” (AVR) which adjusts the generator field voltage.
- An increase in the field voltage will result in an increase in the reactive power produced by the generator, and hence in the terminal voltage.
- If field current becomes excessive, an over-excitation limiter will operate to reduce the field voltage. The terminal voltage will subsequently fall.
- High-gain voltage control can destabilize angle dynamics.



Typical model for static AVR/PSS

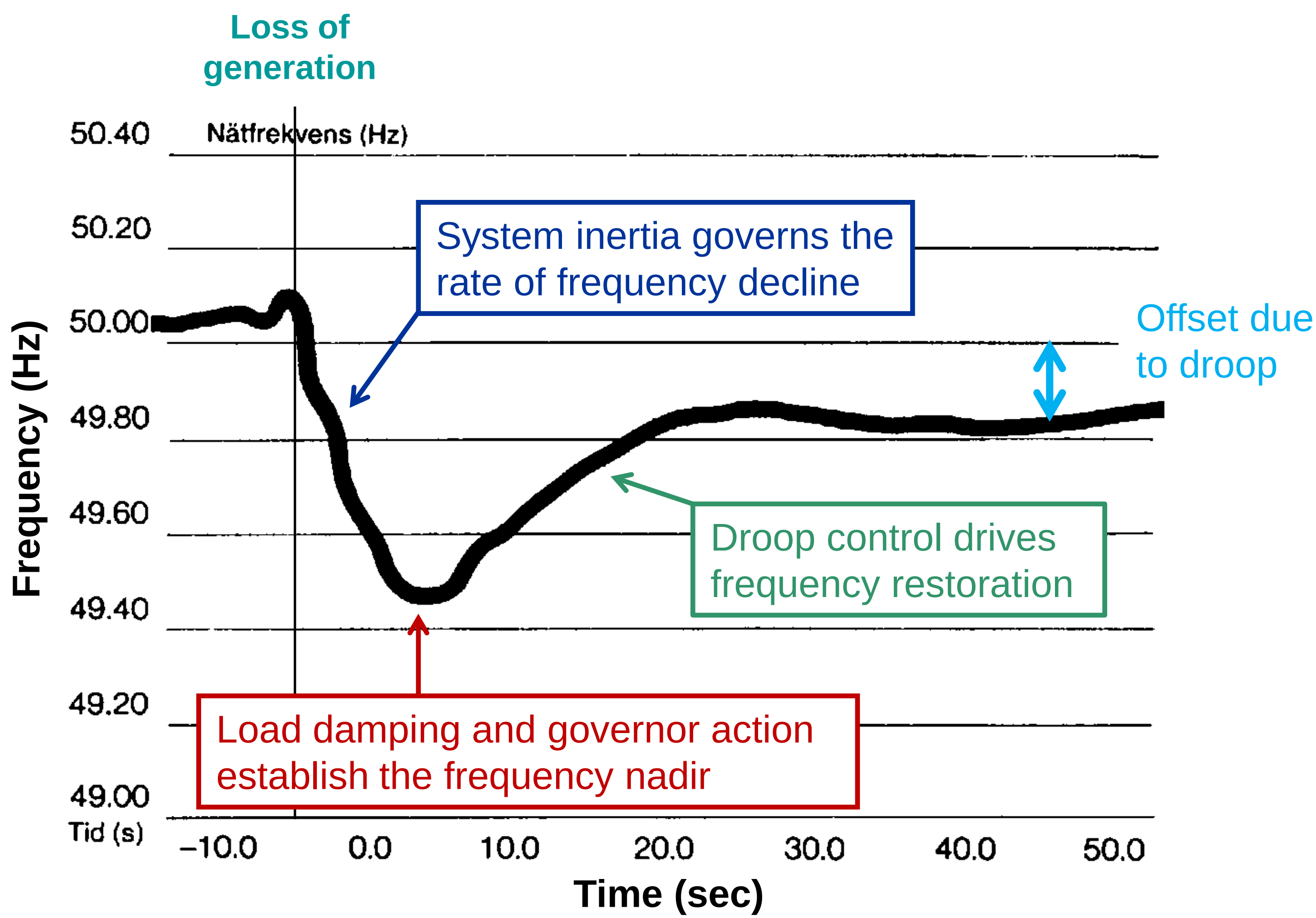
Generator governor (droop) control

- Active power (primary) regulation is achieved by a governor.
  - If frequency is less than desired, increase mechanical torque.
  - Decrease mechanical torque if frequency is high.
- For a steam plant, torque is controlled by adjusting the steam value, for a hydro unit control vanes regulate the flow of water delivered by the penstock.
  - Governed by ramp-rate limits.
- If all generators were to regulate frequency to a nominal set-point, hunting would result.
  - This is overcome through the use of a droop characteristic.
- Primary regulation typically operates within 10-30 sec.



Primary frequency response

- Transient frequency response of the Nordic system after loss of 1000 MW generating unit, November 1983.



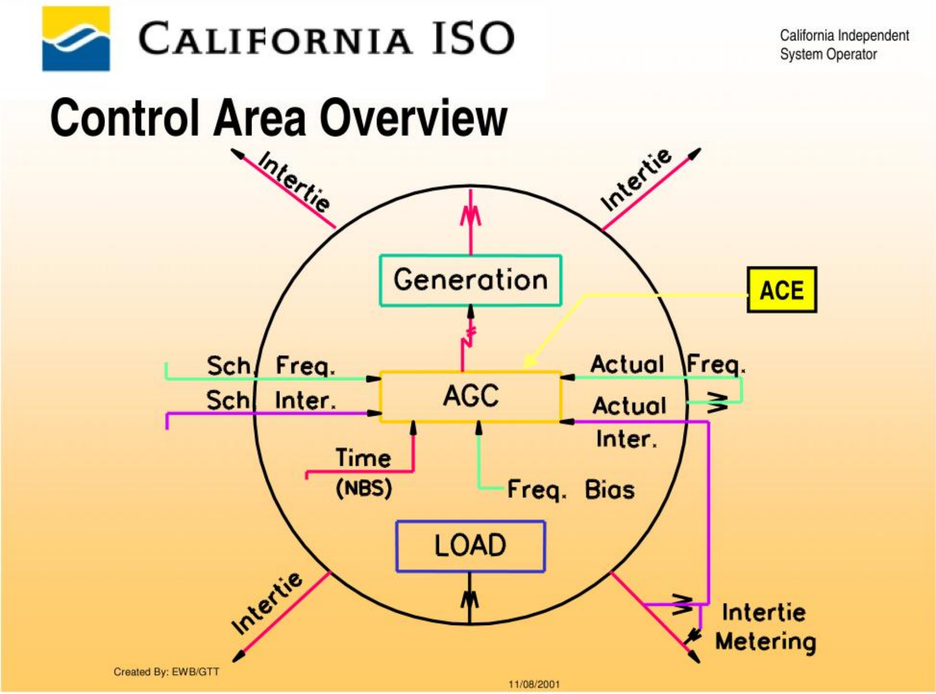
Automatic generation control (AGC)

- Based on decomposing the inter-connected network into "balancing authorities".
- Each balancing authority generates an "area control error" (ACE) signal,

$$ACE = -\Delta P_{tie} - B\Delta f$$

where B is the frequency bias factor.

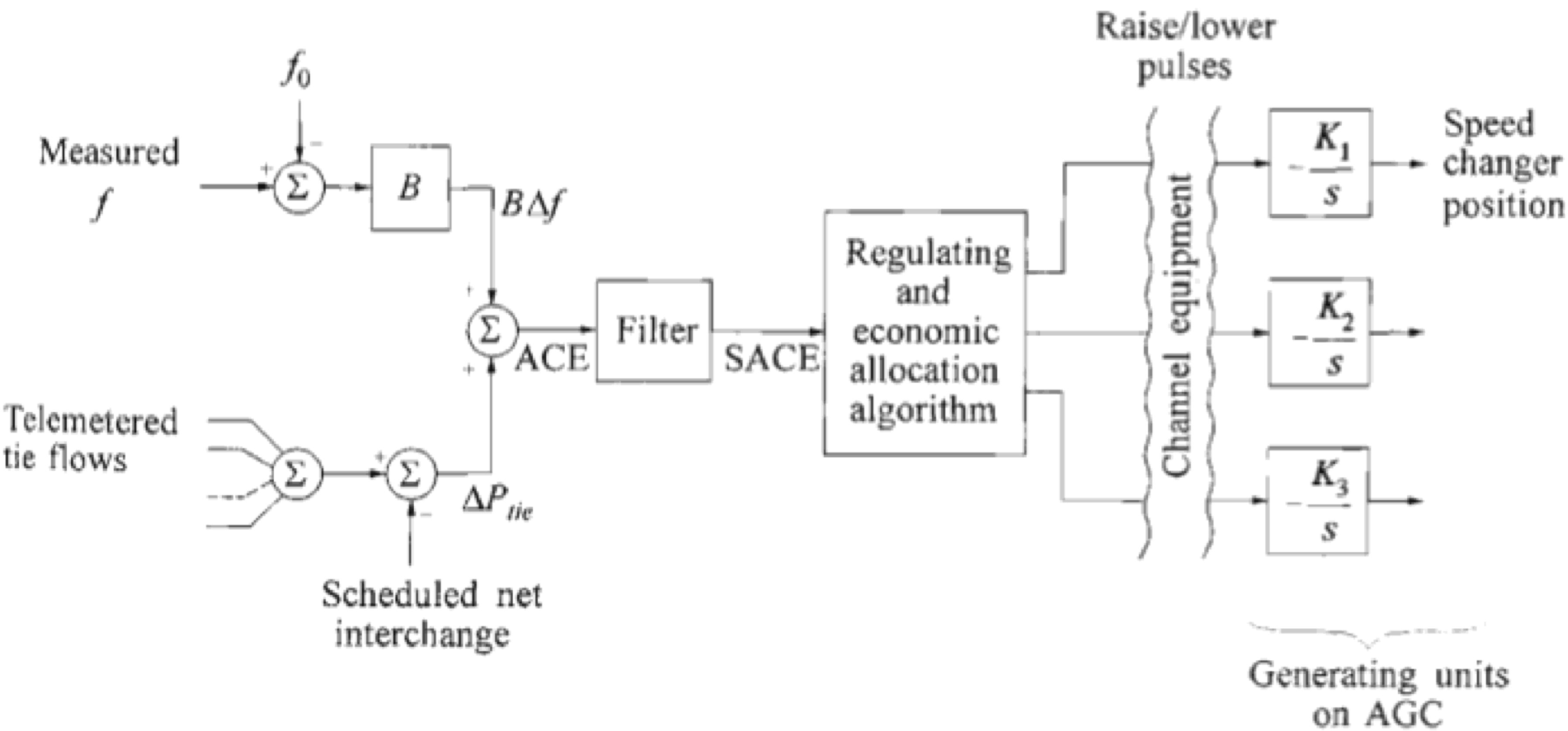
- The ACE signal provides the input to a PI controller that adjusts governor set-points at participating generators.



  - Raise/lower pulses are sent every 2-4 seconds.
  - Referred to as the *regulation signal*.
  - This restores frequency and tie-line flows to their scheduled values.
- Economic dispatch operates on a slower timescale to re-establish the most economic generation schedule.

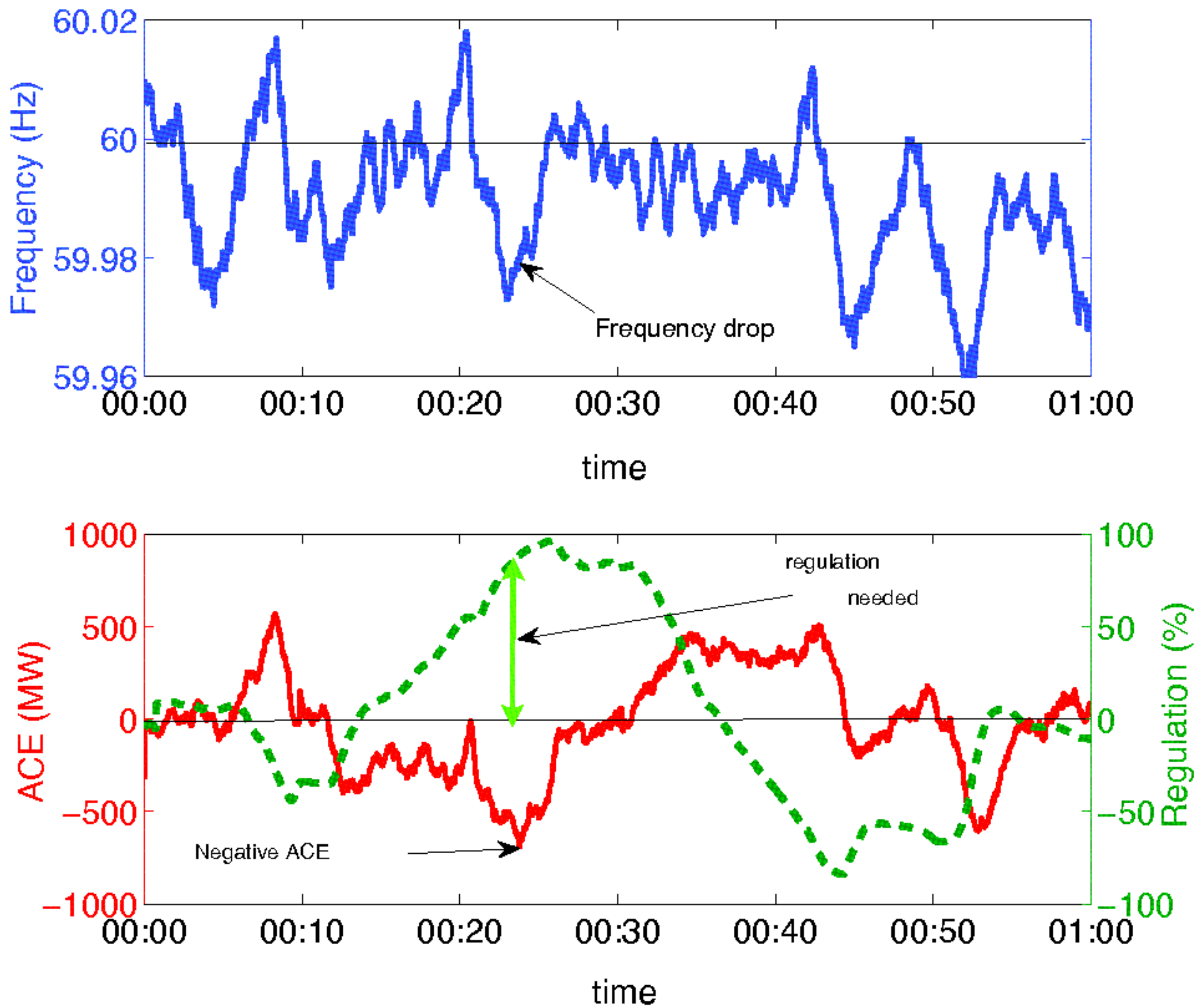
See: Jaleeli, Ewart, Fink, VanSlyck and Hoffmann, "Understanding Automatic Generation Control", *IEEE Trans. Power Systems*, Vol. 7, No. 3, August 1992.

AGC implementation



Typical regulation signal

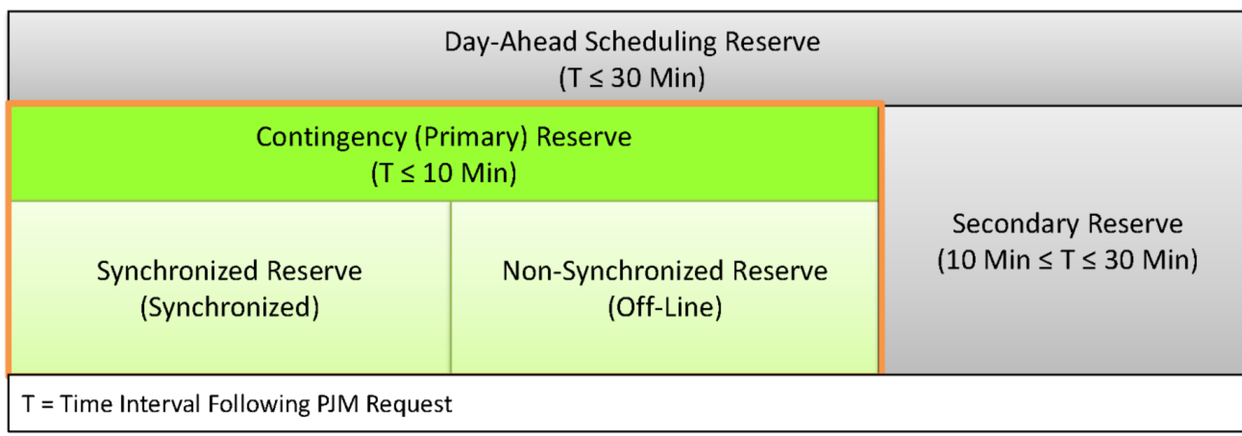
- Example from PJM:



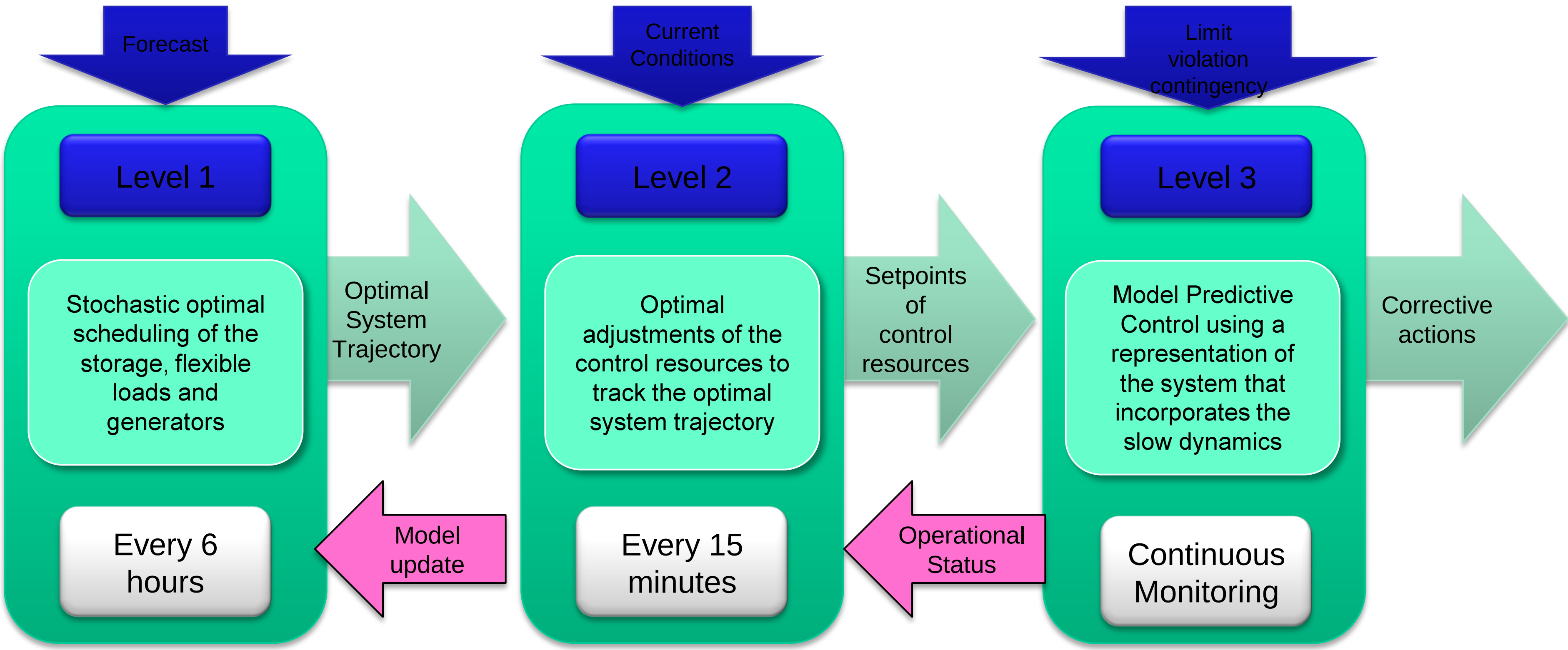
Operating reserves

- Multiple levels of frequency control.
  - Primary frequency control is performed by generator governors.
  - Secondary frequency control is performed by AGC.
- Spinning reserve is the generating capacity that is on-line, and that is in excess of the load demand.
  - Should be sufficient to cover the loss of the largest generating unit, or loss of the largest interconnecting tie-line, plus a safety margin.
  - The variability of wind power necessitates a higher safety margin.
  - Spinning reserve should be distributed over numerous generators.
    - Generators have limits on the rate at which they can increase output.
- Reserves also include:
  - Interruptible loads.
  - Quick-start generation: gas turbines (simple cycle), diesel units, hydro units.

PJM reserve categories



Corrective control using MPC



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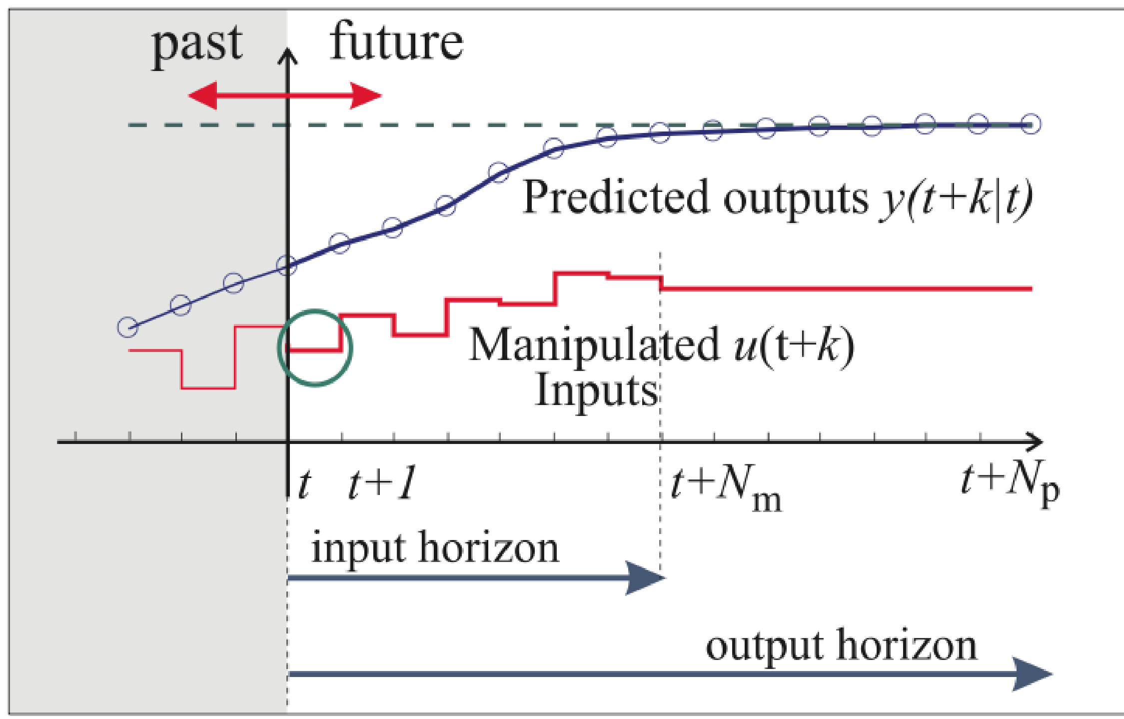
Role of Level 2 and 3

- Level 2 is an optimal power flow that provides set-points for Level 3.
- Level 3 provides corrective control.
  - Realized using receding horizon model predictive controller (MPC).
  - Requires a simple but sufficient system model.
  - Exploits the thermal inertia of conductors to allow temporary transmission line overloads.



Level 3 MPC description (1)

- Level 3 employs:
  - DC power flow model for active power.
  - Piecewise linear relaxation of active line losses.
  - Linearized temperature dynamics of transmission lines.
  - Standard linear model of energy storage (integrator dynamics).

Cost function objective is to minimize the following:

$p_p \theta_{ij}^{\text{PST}}[k]^2$	- control penalty for PST shift	$\forall ij \in \mathcal{P}_{\text{PST}}$
$p_w f_{G_i}^{\text{spill}}[k]^2$	- control penalty for wind-spill	$\forall G_{i,\text{wind}} \in \mathcal{C}$
$p_p \Delta f_{G_i}[k]^2$	- control penalty for generator ramping	$\forall G_i \in \mathcal{C}$
$p_p Q_h[k]^2$	- control penalty on storage utilization	$\forall h \in \mathcal{H}$
$p_s f_{D_i}^{\text{shed}}[k]^2$	- control penalty for load shed	$\forall D_i \in \mathcal{D}$
$p_g (f_{G_i}[k] - f_{G_i}^{\text{ref}}[k])^2$	- state penalty for generator deviation	$\forall G_i \in \mathcal{C}$
$p_o \max\{0, \Delta T_{ij}[k]\}^2$	- state penalty for risky line temperature	$\forall (i,j) \in \mathcal{A}$
$p_e (E_h[k] - E_h^{\text{ref}}[k])^2$	- state terminal penalty on storage deviation	$\forall h \in \mathcal{H}$

To prioritize objectives, set $p_s > p_o > p_e > p_g > p_w > p_p$

Level 3 MPC description (2)

Controllable inputs are as follows:

$$
\begin{array}{rll}
\theta_{ij}^{\mathrm{PST}}[k] & \text{- PST phase shift} & \forall (i,j) \in \mathcal{T} \\
Q_i^h[k] & \text{- storage device flow} & \forall i \in \mathcal{E}_h \\
\Delta f_{G_i}[k] & \text{- generator changes} & \forall G_i \in \mathcal{C} \\
f_{G_i,\mathrm{wind}}^{\mathrm{spill}}[k] & \text{- wind spilled} & \forall G_{i,\mathrm{wind}} \in \mathcal{C} \\
f_{D_i}^{\mathrm{shed}}[k] & \text{- load shed} & \forall D_i \in \mathcal{D}
\end{array}
$$

Uncontrollable inputs/disturbances are as follows:

$$
\begin{array}{rll}
f_{G_i,\mathrm{wind}}^{\mathrm{nom}}[k] & \text{- expected nominal wind} & \forall G_{i,\mathrm{wind}} \in \mathcal{C} \\
f_{D_i}^{\mathrm{nom}}[k] & \text{- expected nominal demand} & \forall D_i \in \mathcal{D} \\
d_{ij}[k] & \text{- expected exogenous thermal effects} & \forall (i,j) \in \mathcal{A}
\end{array}
$$

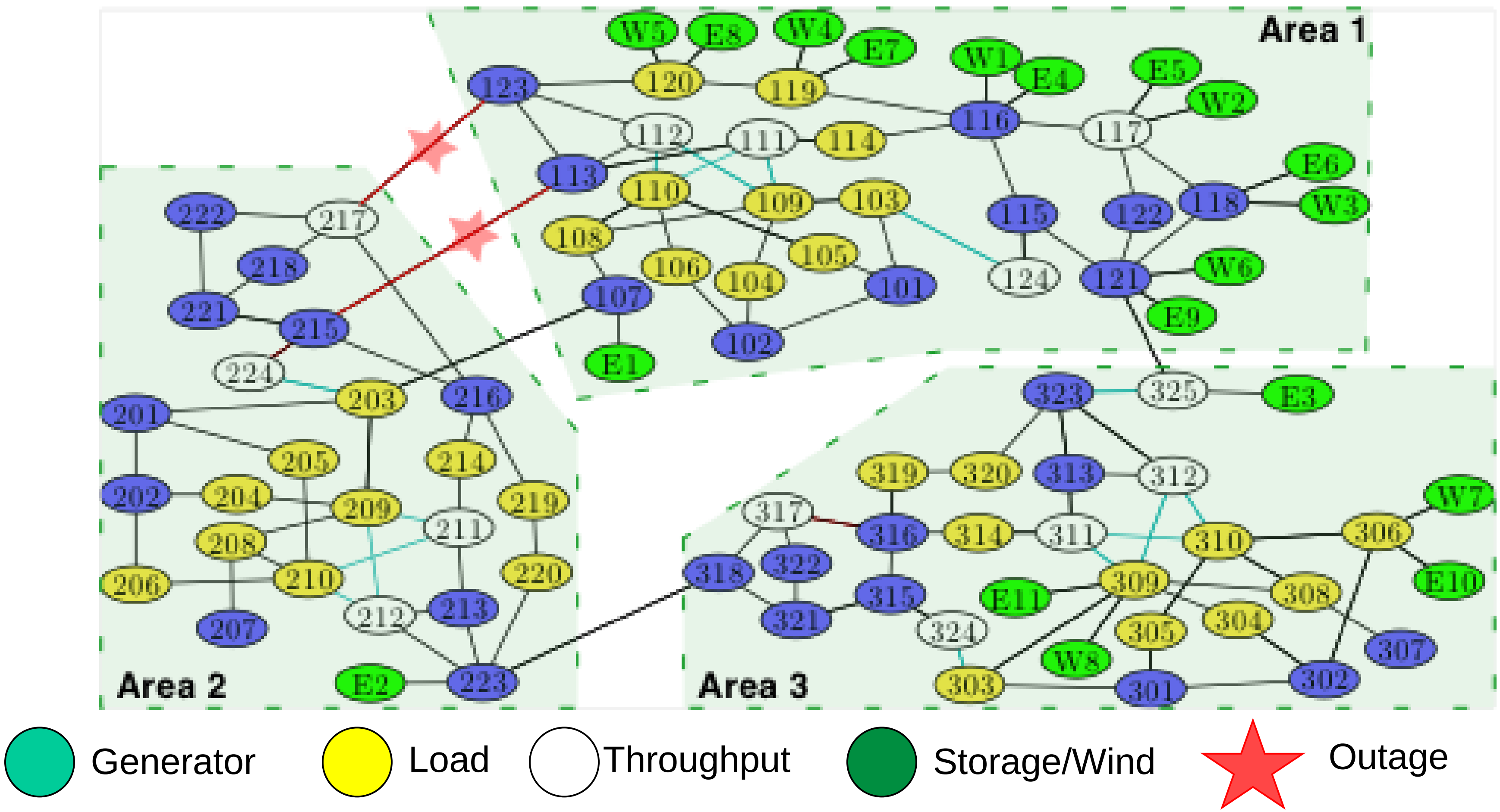
Dynamic state variables are the following:

$$
\begin{array}{rll}
E_i^h[k] & \text{- hub storage device state-of-charge} & \forall i \in \mathcal{E}_h \\
\Delta T_{ij}[k] & \text{- line temperature deviation from limit} & \forall (i,j) \in \mathcal{A} \\
f_{G_i}[k] & \text{- generator output level} & \forall G_i \in \mathcal{C}
\end{array}
$$

Coupling of inputs and dynamic states is achieved through ***algebraic states*** that arise from power balance

Example

- Standard RTS-96 test case.

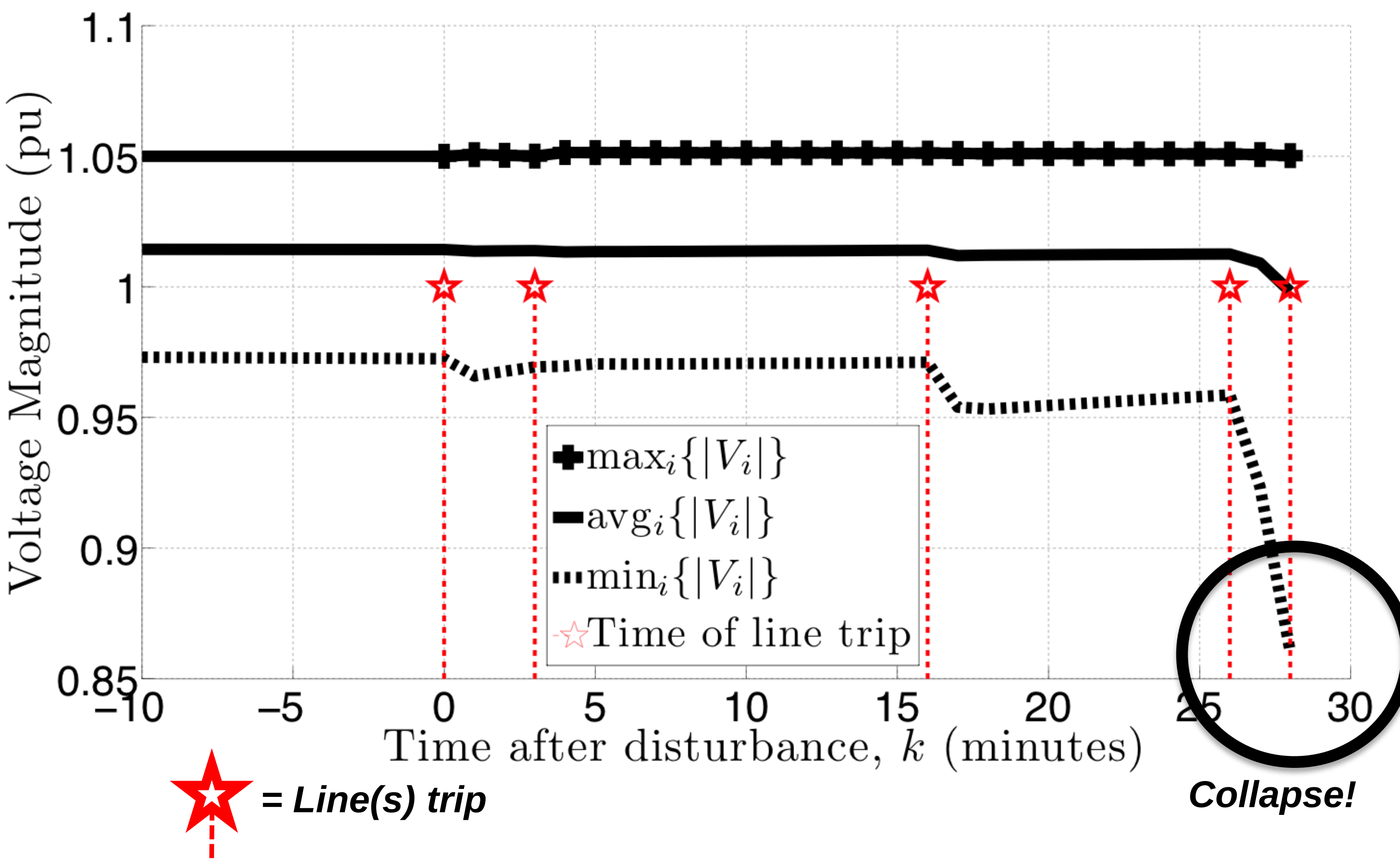


Results

- Base-case undergoes cascading failure (5 more lines trip), and voltage collapse occurs around 29 minutes.
- Level 3 MPC alleviates temperature overloads, so no further lines trip.
  - Employs storage to manage overloads.
  - Curtails wind at the appropriate times.
  - Brings system to economic set-points.
  - Rejects errors due to model approximation.
- Larger horizons → less expensive control, higher line temperatures.

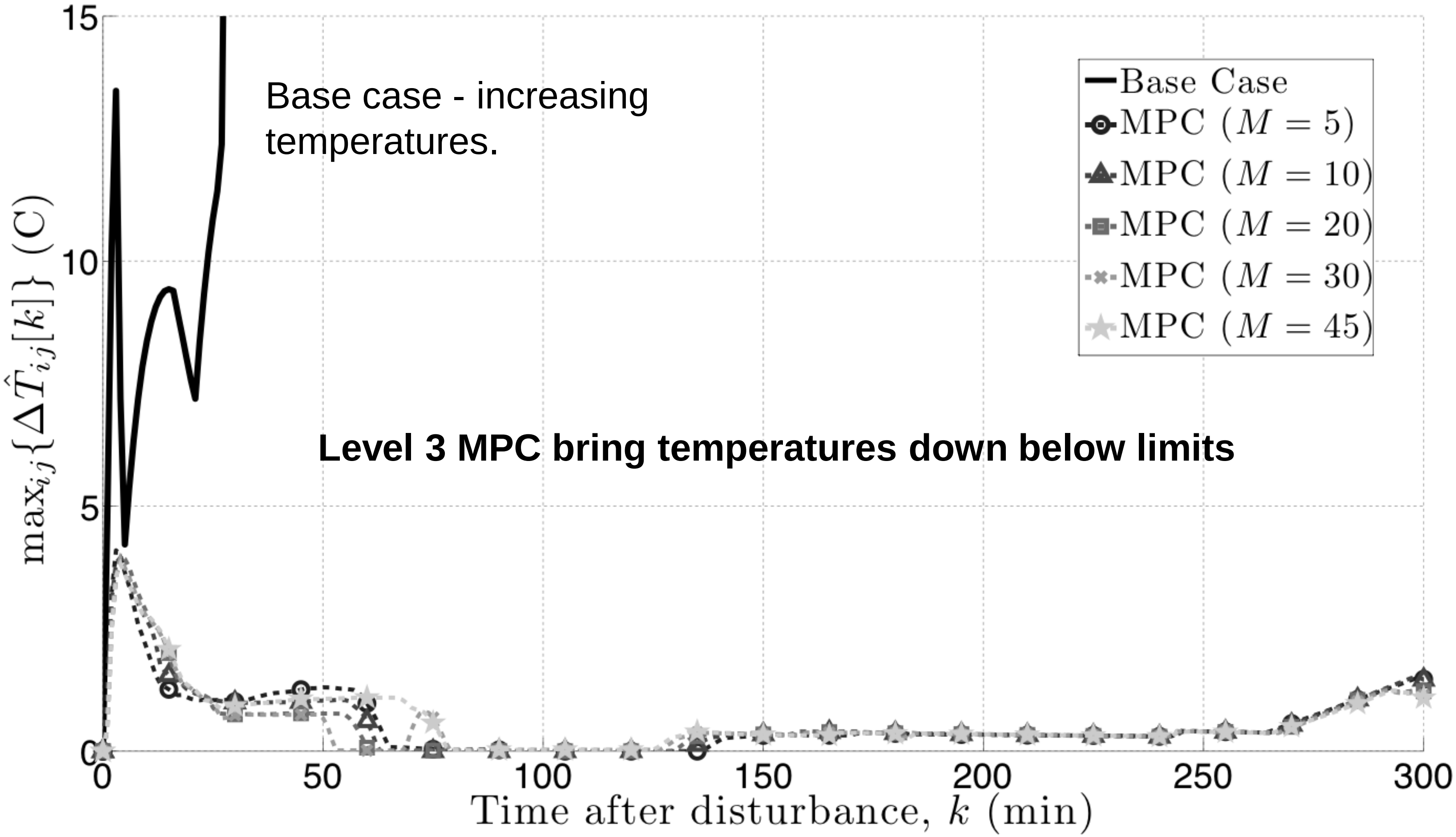
Base case

- Five lines trip, leading to voltage collapse.



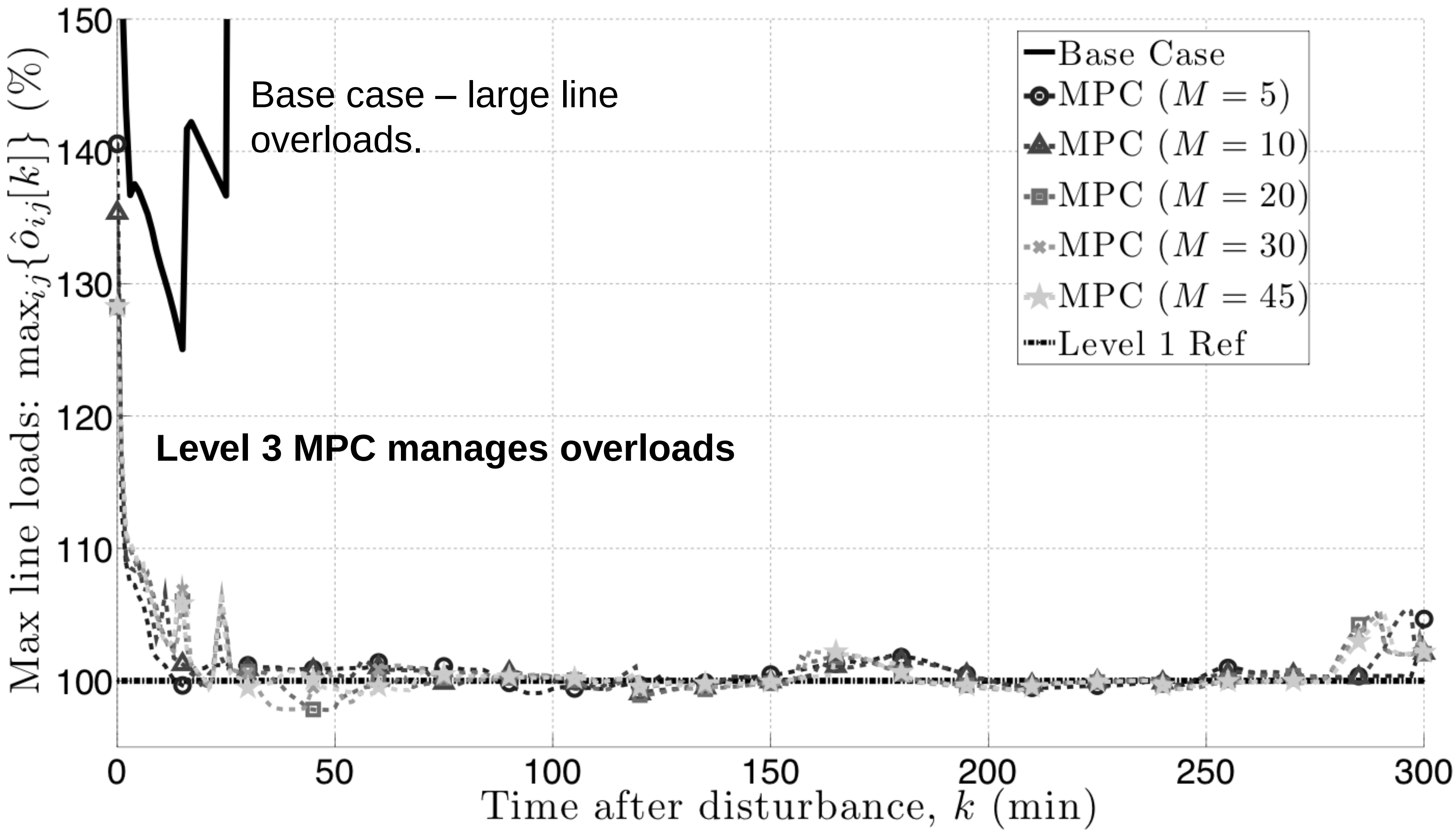
MPC response (1)

- Maximum line temperatures.



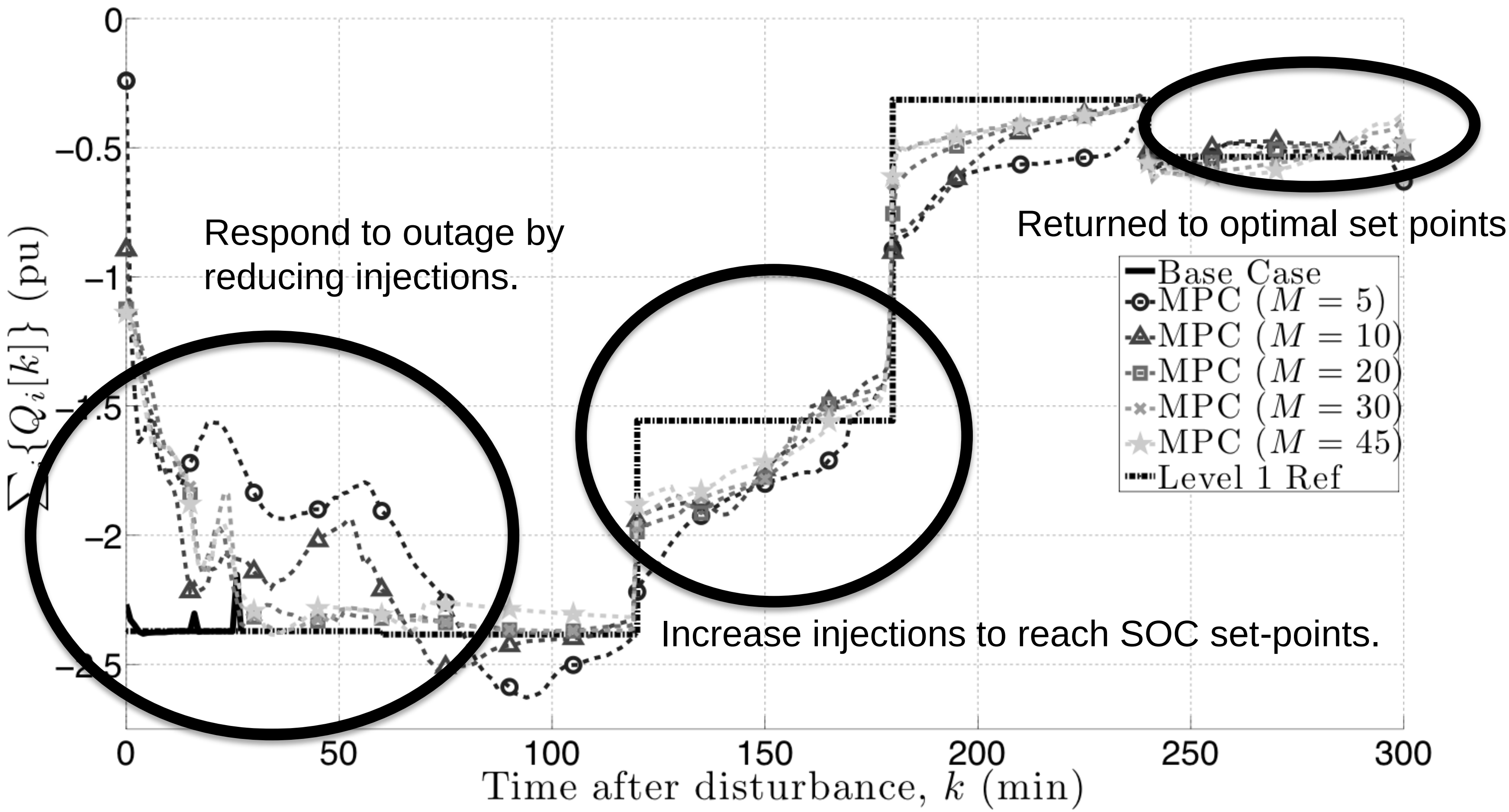
MPC response (2)

- Maximum line flows.



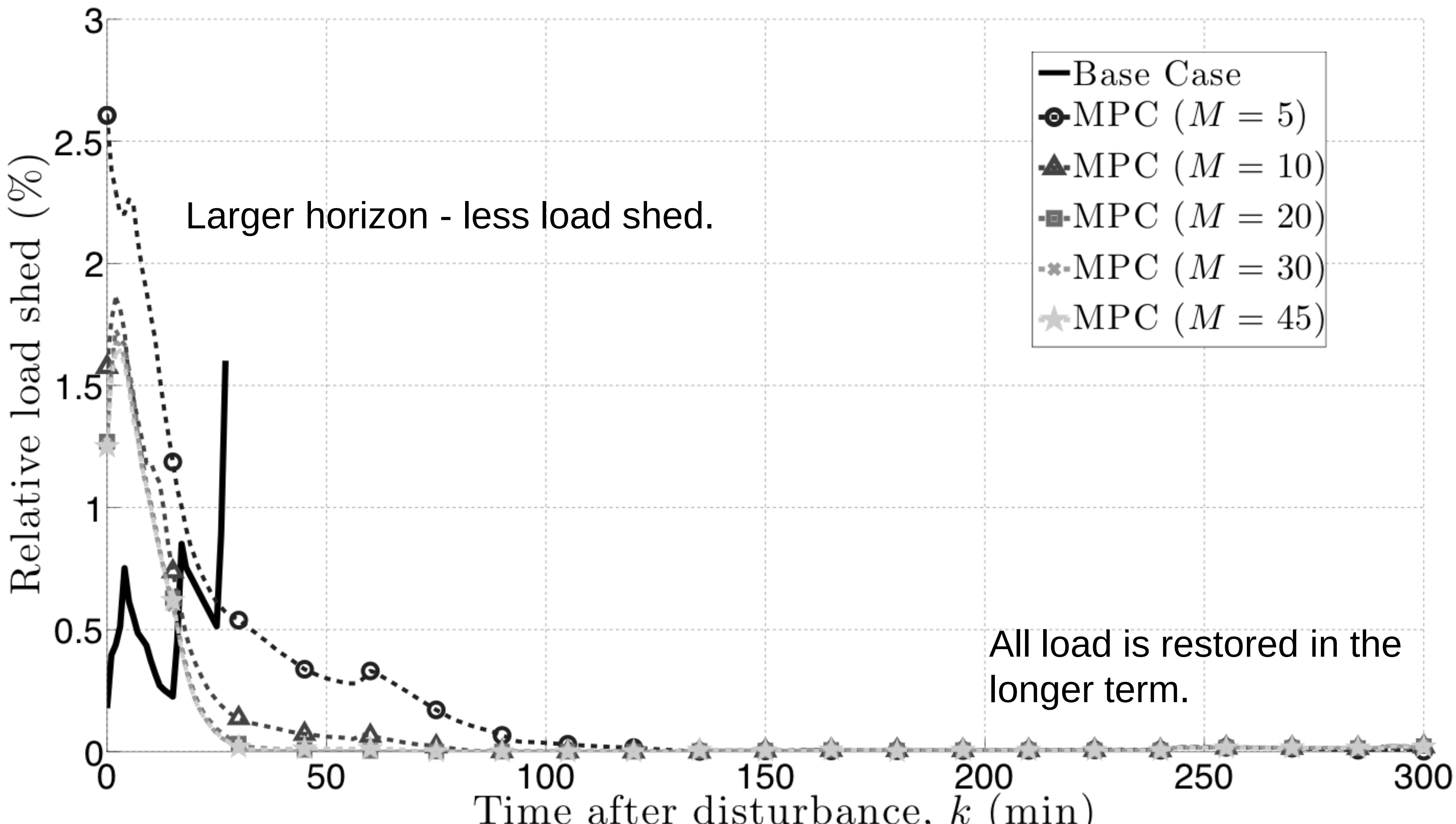
MPC response (3)

- Aggregate storage injections.



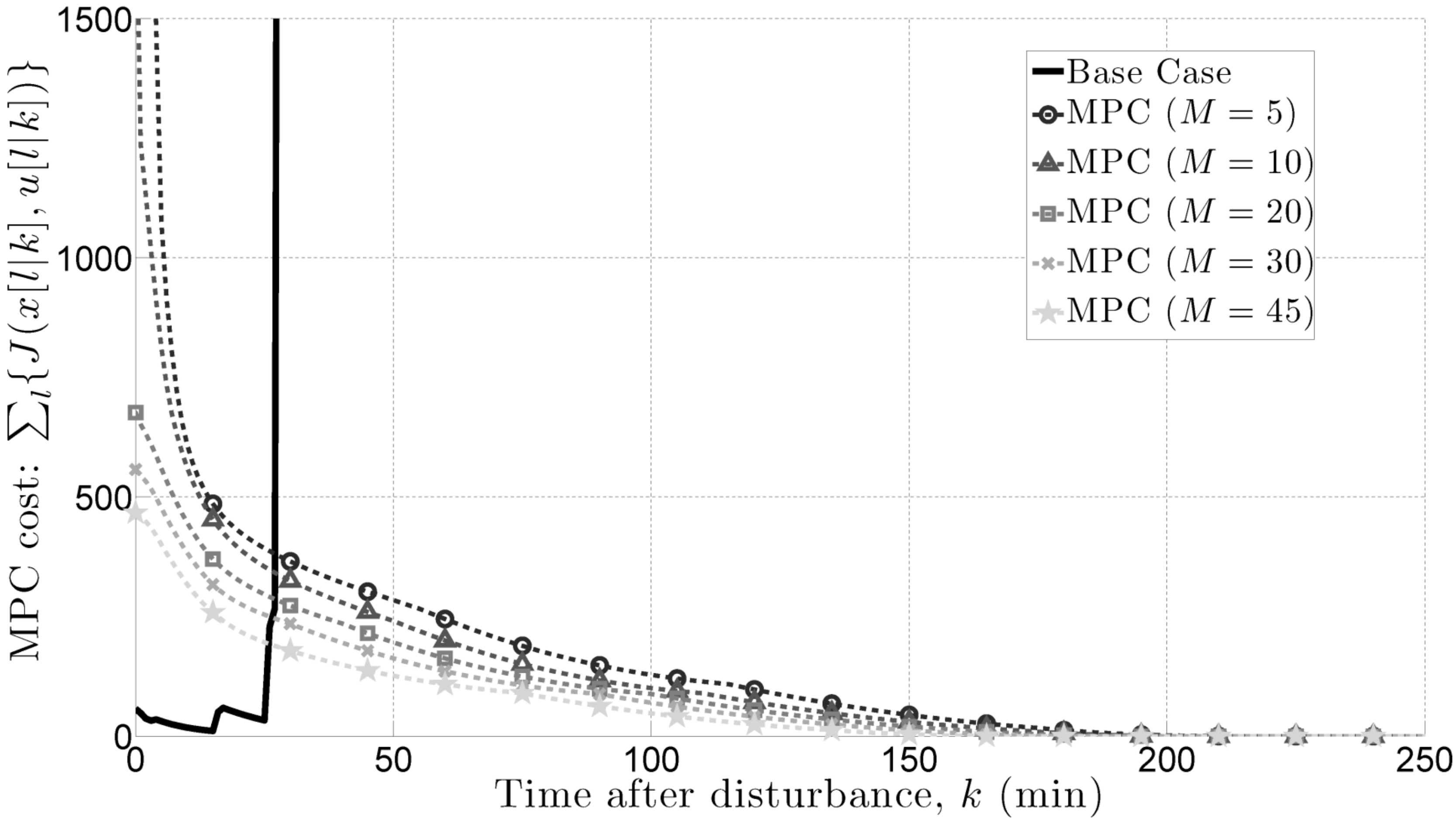
MPC response (4)

- Aggregate load curtailment.



MPC response (5)

- MPC objective function value.



Conclusions

- Power systems are nonlinear, non-smooth, differential-algebraic systems.
  - Hybrid dynamical systems.
- A variety of controls, from local to wide-area, are used to ensure reliable, robust behaviour.
- Future directions:
  - Corrective control reduces reliance on conservative N-1 preventative strategies.
  - The variability inherent in renewable generation will challenge existing control structures.
  - There are enormous opportunities for exploiting responsive, non-disruptive load control.