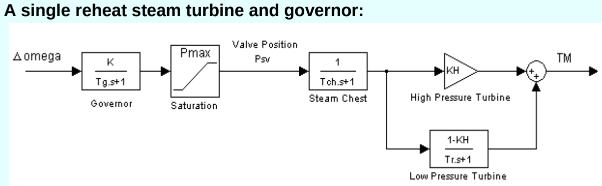
Saturation-Induced Instability in Electric Power Systems: The Case of Generator Speed Governor Control

Juhua Liu, Bruce H. Krogh and Marija D. Ilic, Carnegie Mellon University, Pittsburgh, PA

MOTIVATION

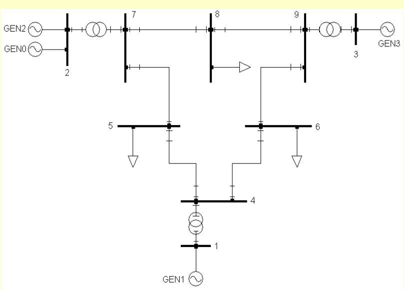
- Today's power systems are often operated near generation, transmission and control constraints
- These constraints compromise the dynamic responsiveness
- Governor saturation may lead to mid-term frequency instability

A single reheat steam turbine and governor:

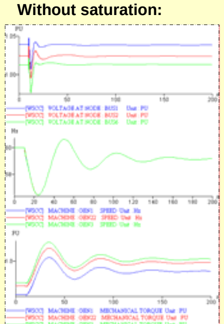


EXAMPLE

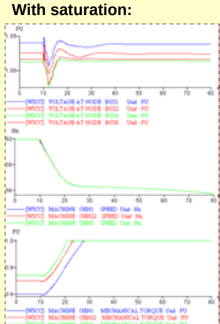
WSCC 9 Bus Test Case



Without saturation:



With saturation:

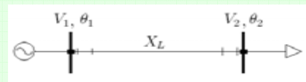


Scenario:

- GEN0 is tripped and causes a loss of 90 MW generation
- Total reserves of GEN1, GEN2 and GEN3 are 110MW
- Without considering the saturation, the system is stable
- Frequency instability occurs due to governor saturation. Low frequency would trigger protection relays and possibly lead to cascading failures

APPROACH

Generation-Transmission-Load Model:



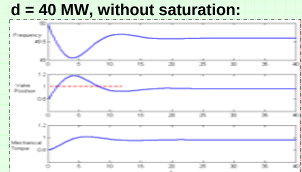
Scenario:

- Generator capacity: 250MW
- Initial load: 200MW/100MVar
- Event: Load increases to 240MW/100MVar

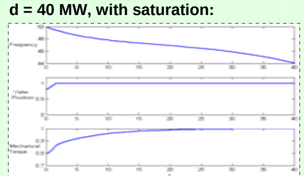
Would the system survive?

Static power flow analysis shows that the post-disturbance equilibrium point exists. The final load 240 MW is still within generator capacity. However, the system frequency is unstable due to the governor saturation effect.

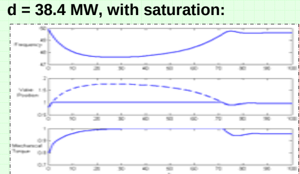
d = 40 MW, without saturation:



d = 40 MW, with saturation:



d = 38.4 MW, with saturation:



Linearized model with saturation represented:

DAE model:

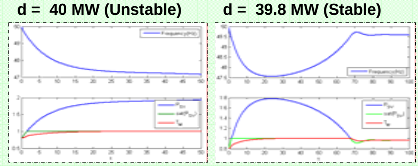
$$\dot{x} = f(x, y, u, d)$$
$$0 = g(x, y, u, d)$$

Linearized model:

$$\Delta\dot{x} = A\Delta x + B\cdot sat(\Delta u) + E\Delta d$$

where $u = k^T x$.

d = 40 MW (Unstable) **d = 39.8 MW (Stable)**



This model preserves the saturation-induced instability phenomenon.

Estimate the largest disturbance the system can tolerate:

- Transform to $\dot{\tilde{x}} = A\tilde{x} + B\cdot sat(k^T\tilde{x})$, where $\tilde{x} = \Delta x - x_e = \Delta x + (A + Bk^T)^{-1} E\Delta d$
- Find region of attraction (RoA) using LMI techniques:

Solve for a Lyapunov function matrix P to the following convex optimization problem

minimize $trace(P)$

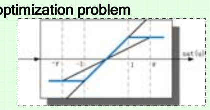
subject to $\begin{pmatrix} r^2 u_{\max}^2 & k^T \\ k & P \end{pmatrix} > 0$

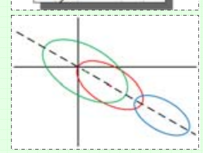
$$(A + Bk^T)^T P + P(A + Bk^T) < 0$$

$$(A + r^{-1}Bk^T)^T P + P(A + r^{-1}Bk^T) < 0$$

where $u_{\max} = P_{MAX} - P_{SV}(0) - k^T x_e = 0.2 + k^T (A + Bk^T)^{-1} E\Delta d$

guarantees that the ellipsoid $\{\tilde{x} \mid \tilde{x}^T P \tilde{x} \le 1\}$ is a RoA.





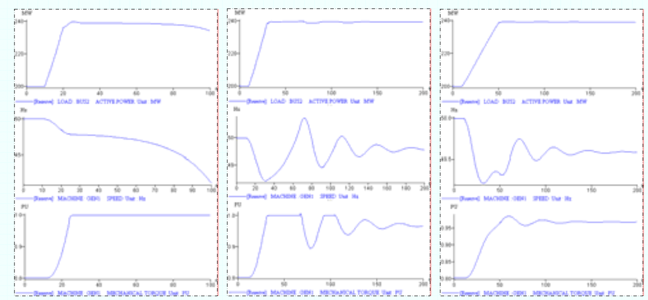
- Find the largest Δd that can make the origin inside RoA: d=22 MW.

LOAD CHANGE RATE

The interdependence of rate of change of load and control requirements:

Instead of abrupt load change, consider load increases 40MW linearly in 10s, 20s and 40s in the 2 bus system:

4 MW/sec: **2 MW/sec:** **1 MW/sec:**



The step load change can be considered as the worst case.

FUTURE WORK

- Reserve requirement / Responsiveness
- Study mid-term dynamics and Load following problem
- Develop controllers / strategies to avoid instability
- Coordination with frequency relay and load shedding

ACKNOWLEDGMENT

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REFERENCES

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