Control Strategies for Microgrids

Ali Mehrizi-Sani
Assistant Professor
School of Electrical Engineering and Computer Science
Washington State University

(with thanks to my students: Chris Stone, Hooman Ghaffarzadeh, and Mehrdad Yazdanian)

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Outline

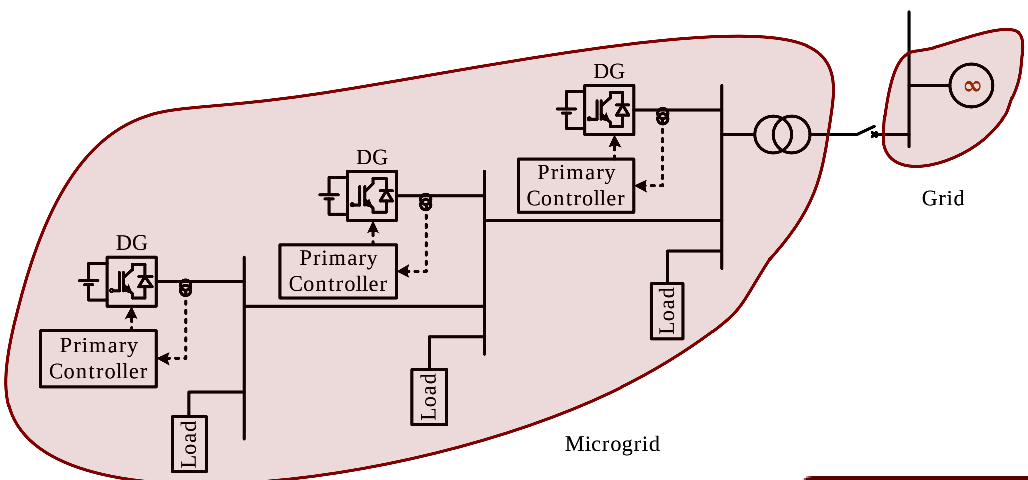
- **Problem**
  - Overview of control requirements and challenges
- **Proposed Strategy**
  - Online set point modulation
- **Results of Evaluation of the Strategy**
  - Offline simulation
  - Real-time implementation
  - Sensitivity to design parameters
- **Applications**

Problem

- **One of the grand energy challenges is to enable integration of large amounts of renewable energy resources at a competitive cost in the power grid (in the US, 80% by 2050 per NREL).**
- **What is missing is a flexible system that accommodates the unique characteristics of renewable resources:**
  - Intermittency
  - Lack of inertia
  - Susceptibility to violation of operational limits
- **Our work addresses the latter:**
  - How can we make sure our units are “tightly” controlled and do not violate their limits even when the host system changes significantly?

Microgrid Challenges (1/3)

- The future power system can be envisioned as a collection of microgrids as its building blocks.
- Microgrid is an aggregate of collocated resources (loads, generation units, and storage units) that are interfaced to the main grid at the distribution level and is capable of operating in the grid-connected mode, islanded mode, and the transition between these two modes.



Microgrid Challenges (2/3)

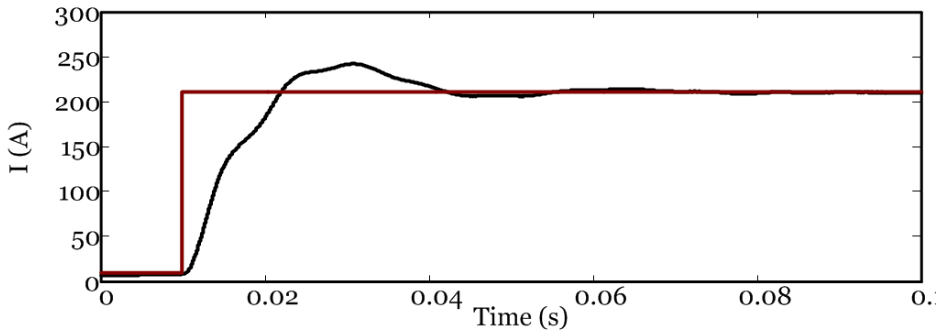
- **Microgrids offer many benefits, but they may experience**
  - Frequent changes in the topology;
  - Operation close to the limits to increase asset utilization; and
  - Limited total capacity.

- **This can have a detrimental effect on the performance of controllers.**
  - Controllers are designed for a prespecified configuration and their performance deteriorates when the host system varies significantly from what was used for the original design.
  - This can cause violation of the instituted limits, e.g., maximum power transfer and maximum current.

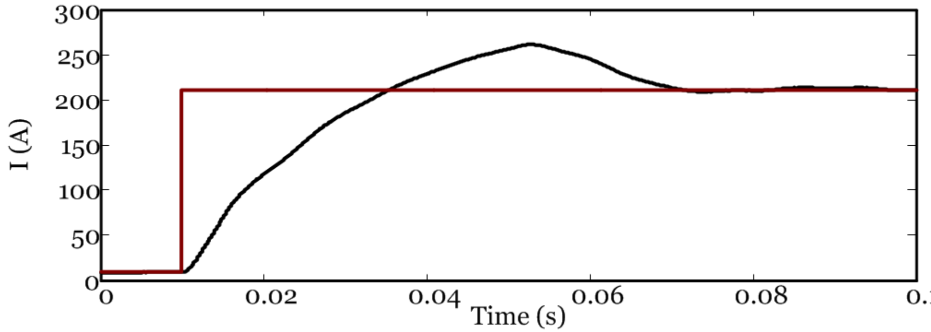
Microgrid Challenges (3/3)

- **Example**
  - Effect of large load change on controller performance.

Original System
Overshoot: 15%
Settling time: 32 ms



Load Disconnected
Overshoot: 26%
Settling time: 67 ms



Controller Design: Existing Approaches

- **Existing approaches to ensure dynamics of the system are handled design controllers based on**
  – Analytical formulation and model-based tuning (Astrom's work)
  – Optimization (Gole's work)

- **Why not just redesign?**
  – Need updated system models
  – Need a computational infrastructure to allow redesign
  – Need access to the internal parameters of the controller
  – New design will again have limited robustness to topology, operating point, and system parameters

State of the Art

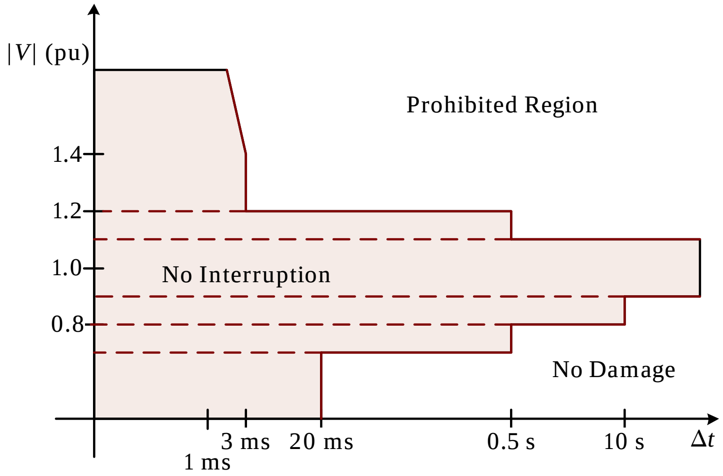
Approach	Model-Independent	Unintrusive	Parameter-Independent
PI scaling	√	√	X
Ramp	√	√	√
MPC	X	√	X
PID	X	√	X
ES/IFL	√	X	X
Posicast	X	√	√
SPAACE	√	√	√

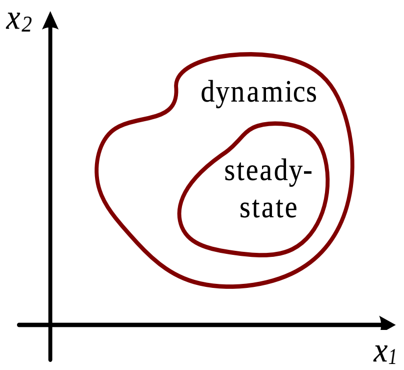
Desired Features for Controllers

- **Robust to topological and operational changes;**
- **Independent of the system model; and**
- **Require little information about the controlled unit.**

Shaping of the Response Trajectory

- **Consideration of Dynamic Limits of Devices**





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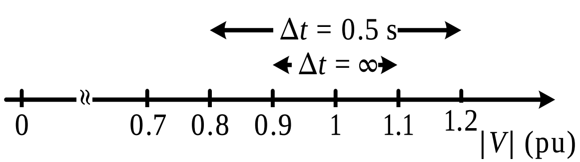
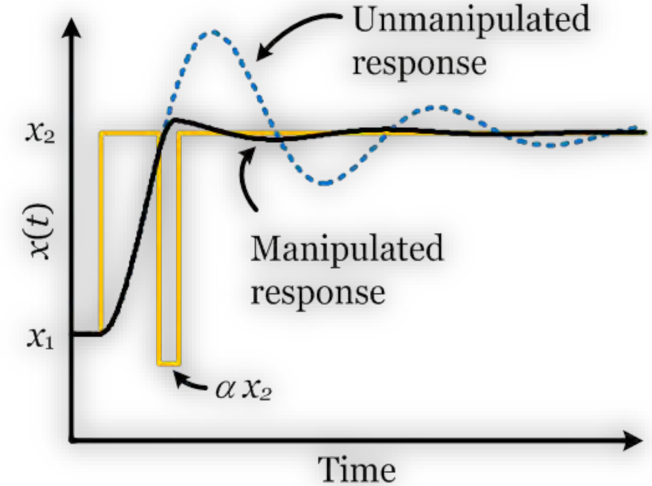


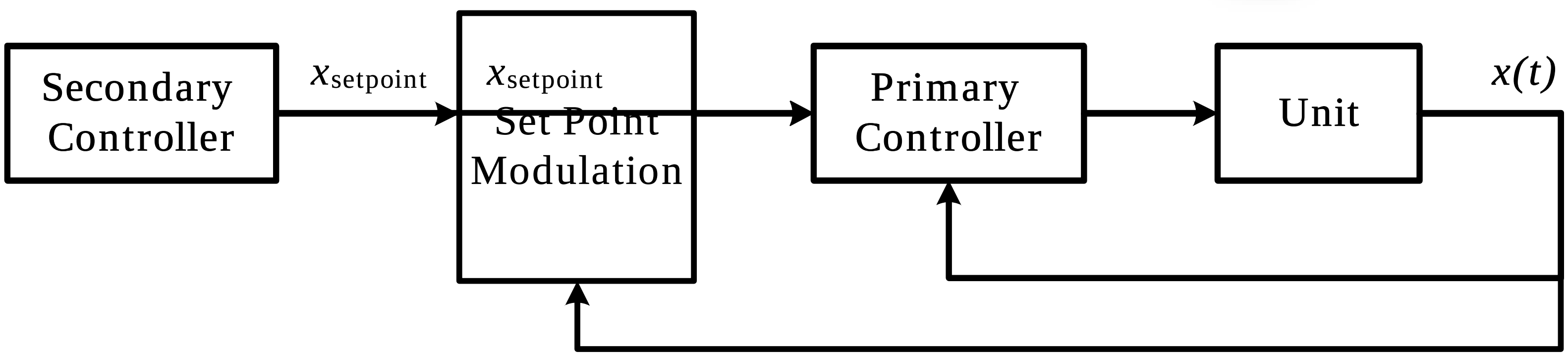
(b)

- **Challenges**
  - Avoid violating dynamic limits
    - With a small overshoot
  - Achieve a fast response
    - Without changing the existing controller

Proposed Solution

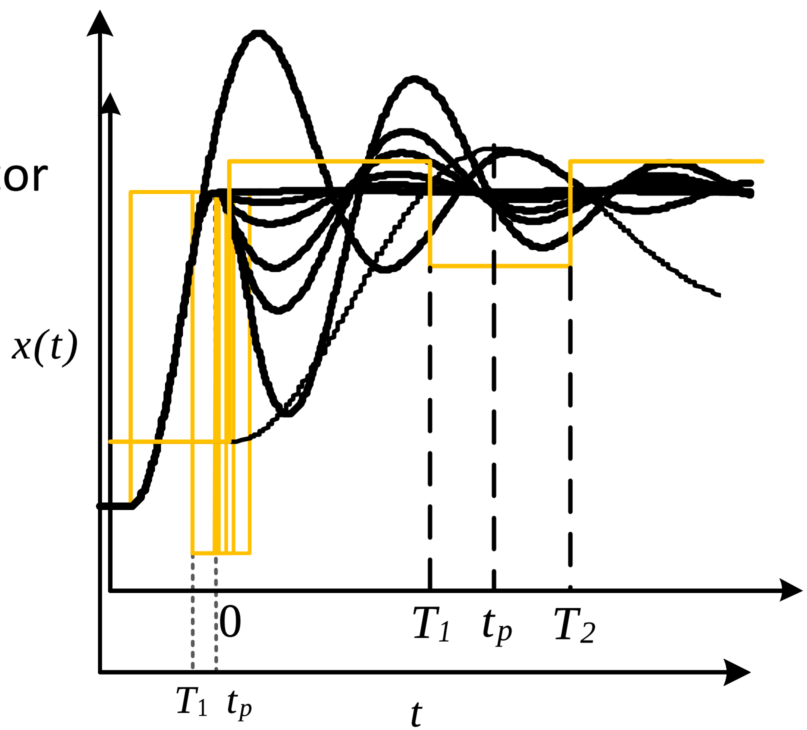
- **Improving the response by temporarily manipulating the set point**





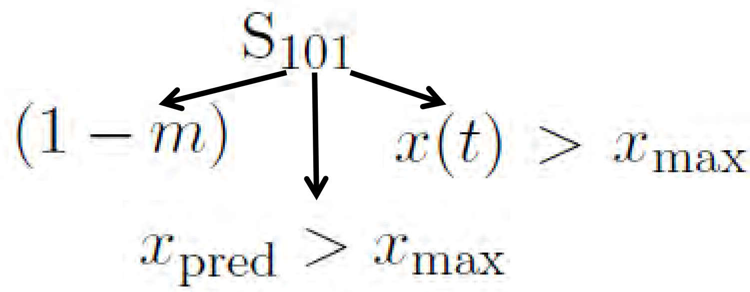
Set Point Modulation

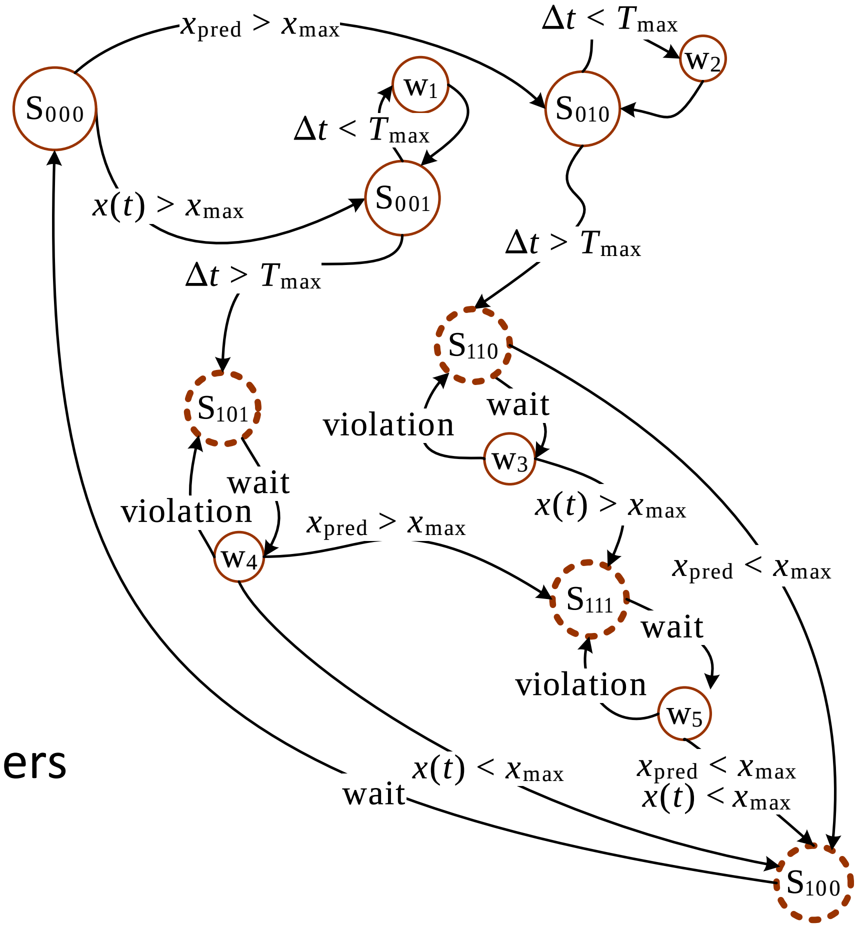
- **Best Strategy**
  - Choose T_1 so that the peak of the response equals the reference
  - Choose T_2 to be the time of this peak
- **Not Implementable**
  - Faster-than-real-time simulator
  - Closed-form solution
  - System parameters



Finite-State Machine

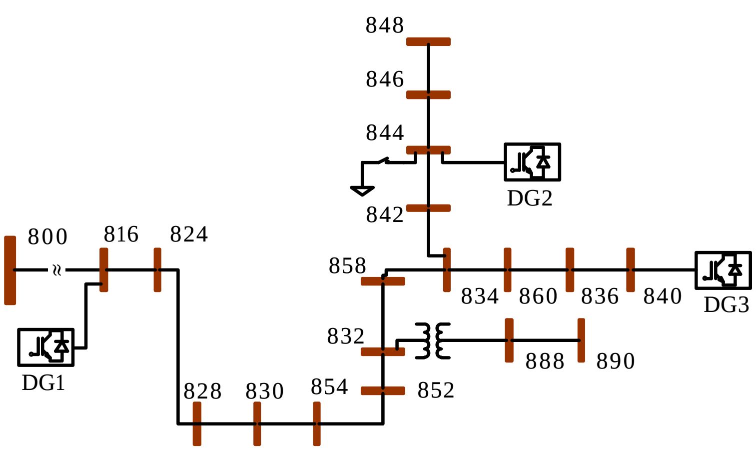
- **SPAACE /speɪs/: Set Point Automatic Adjustment with Correction Enabled**
- **State Numbering:**





- **Salient Features:**
  - Based on local signals
  - Independent of model
  - Robust to changes in parameters

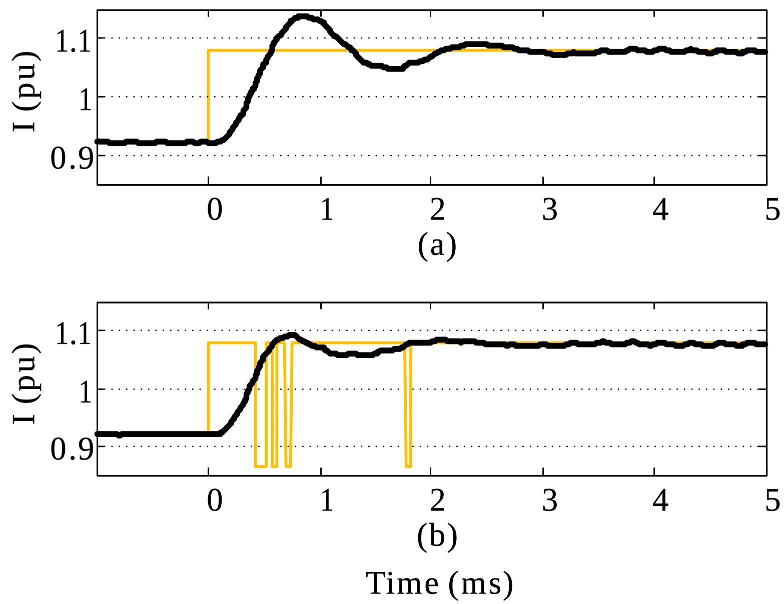
Case Study I: Set Point Change



IEEE 34-Bus System

Added 3 DG units and a load

Operates in grid-connected mode



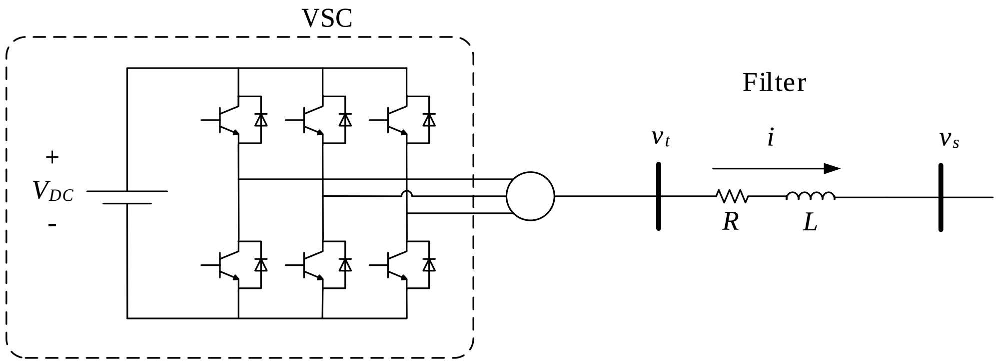
System Response

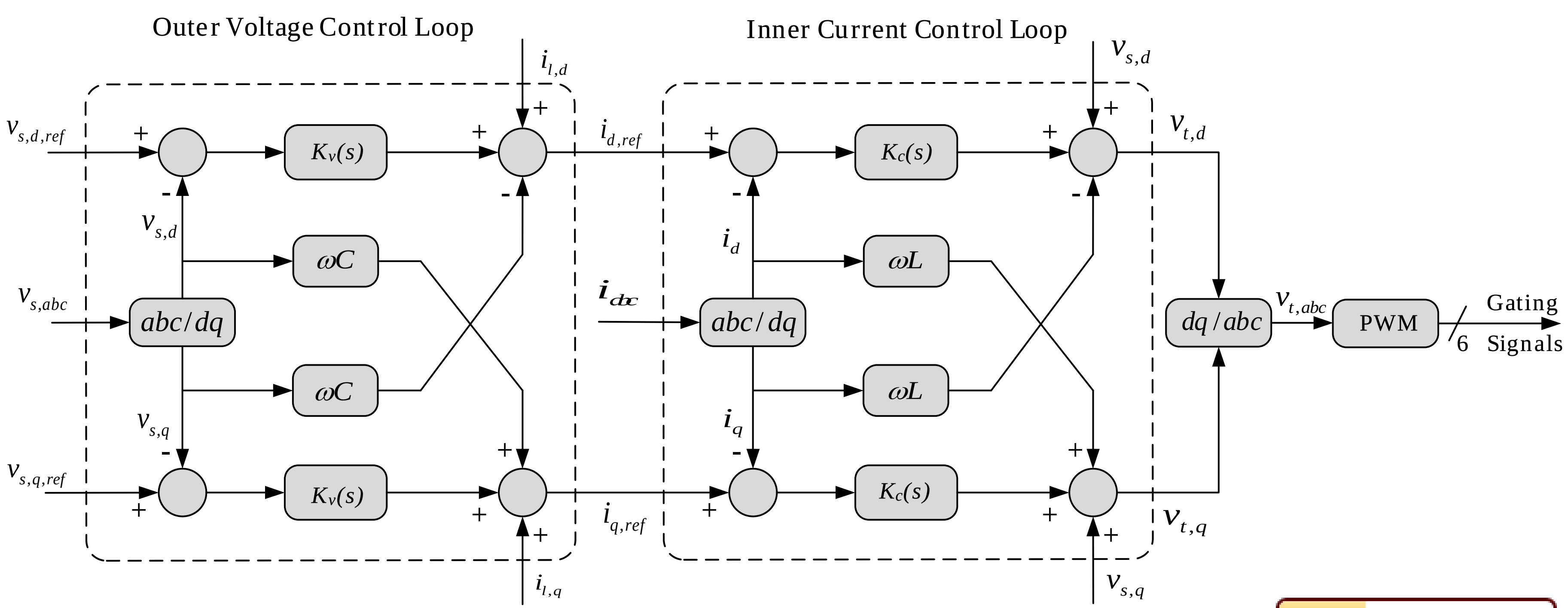
DG2 step change from 0.91 pu to 1.09 pu

DG1 and DG3 unchanged

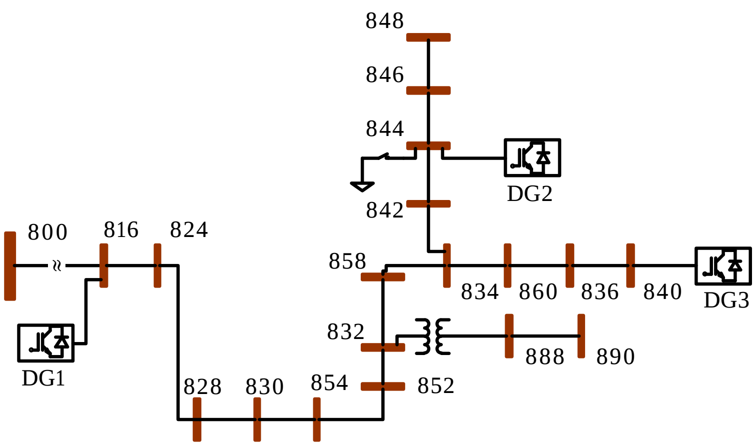
(40% overshoot)

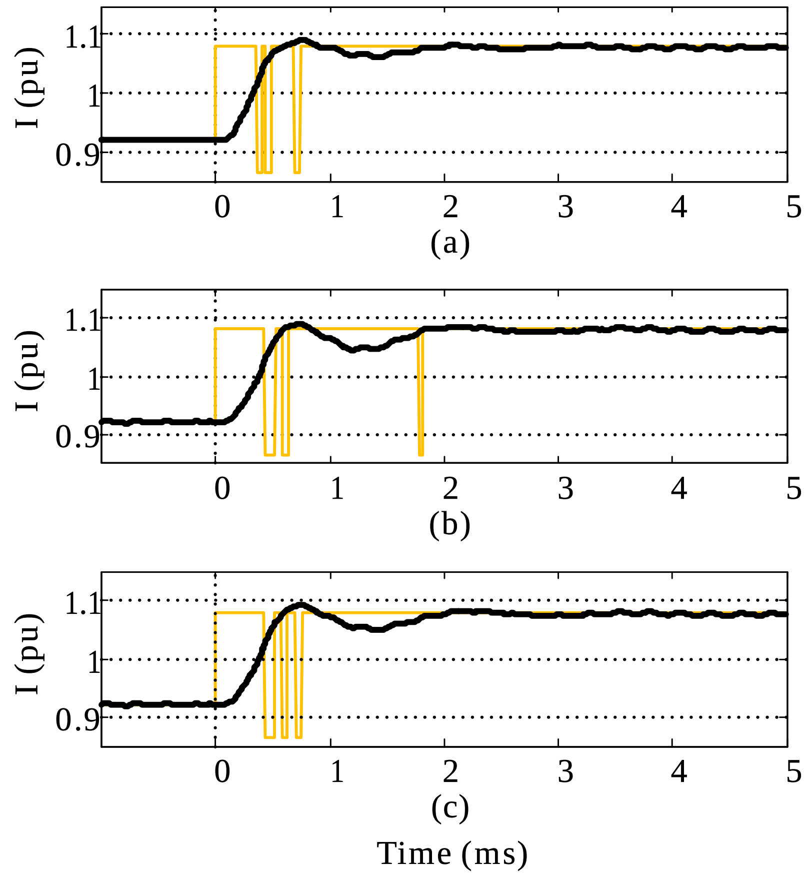
VSC Model and Control in Case Studies





Case Study II: Simultaneous Change

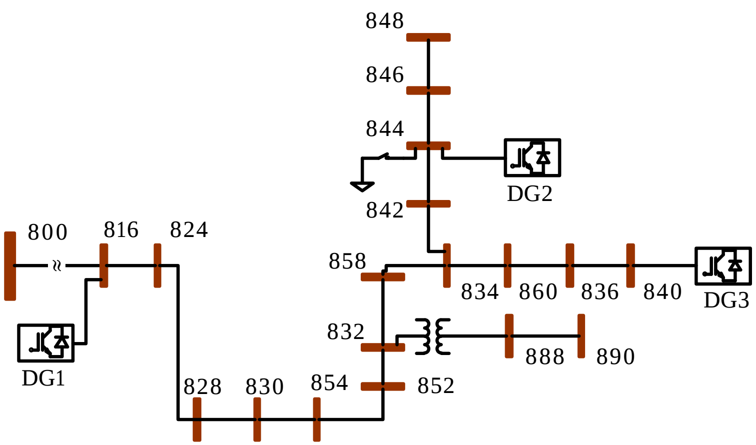


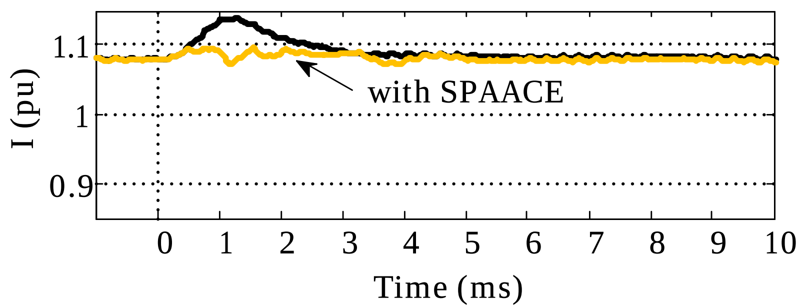


System Response

Simultaneous step change

Case Study III: Load Disconnection





IEEE 34-Bus System

Added 3 DG units and a load

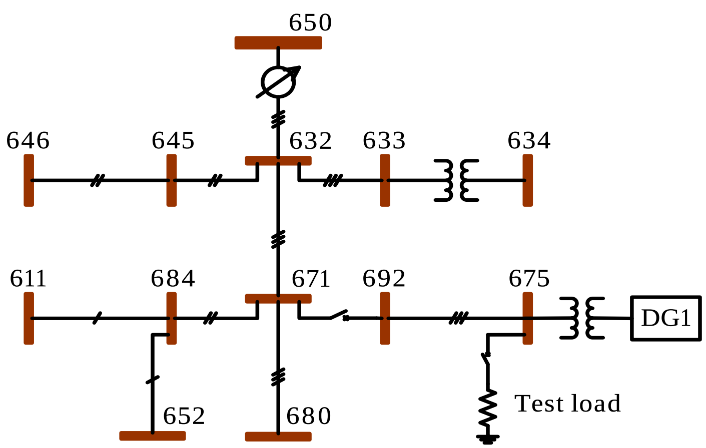
Operates in grid-connected mode

System Response

Resistive 0.5 pu load disconnected

(15% overshoot)

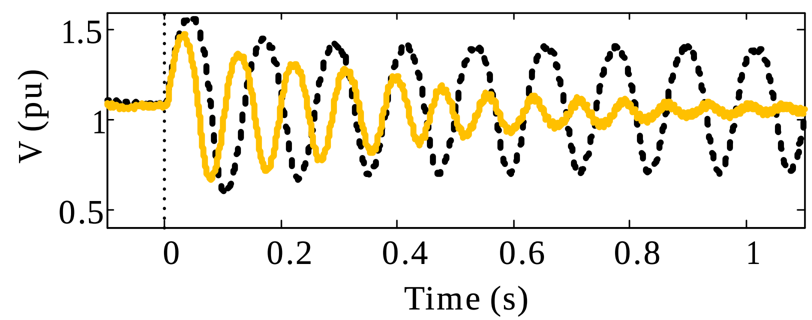
Case Study IV: Unbalanced System



IEEE 13-Bus Unbalanced System

Added a DG unit and a test load

Operates in islanded mode

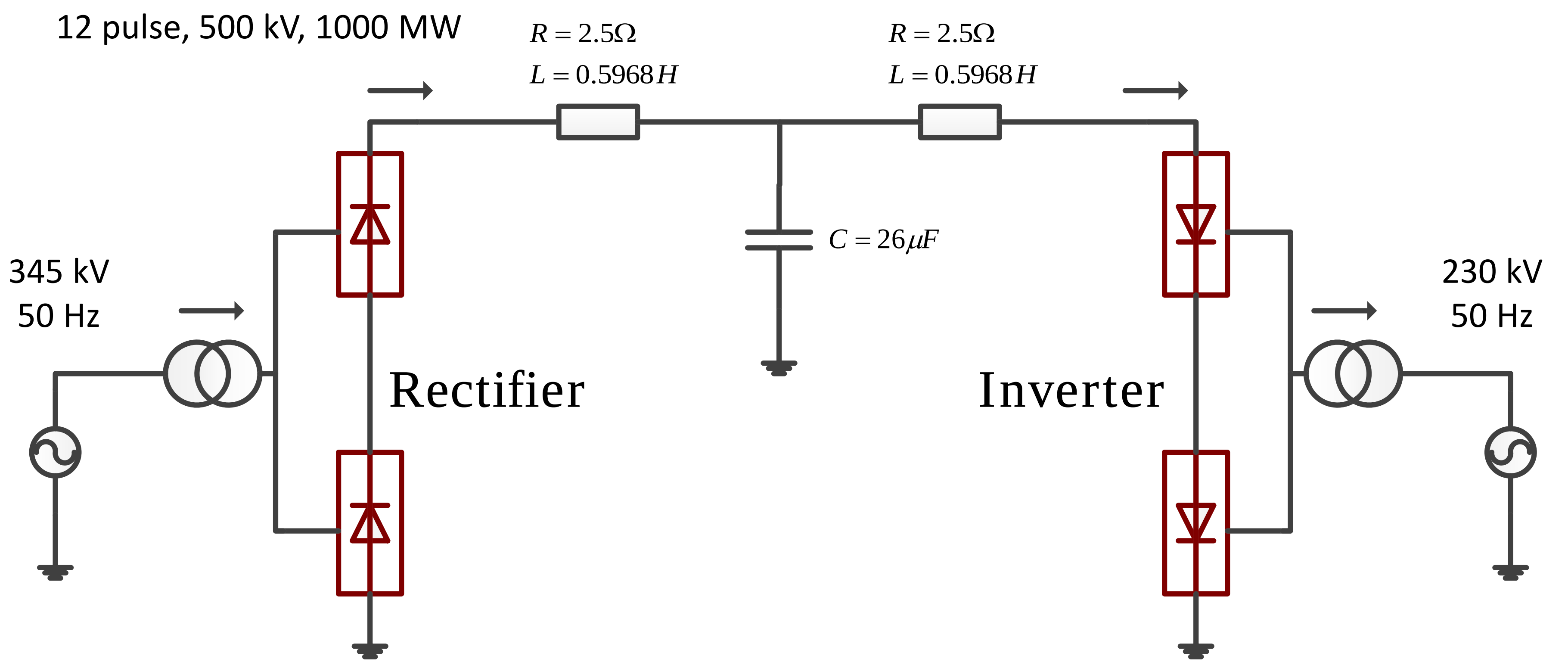


System Response

Resistive 1 pu load switched off

Unstable system to stable system

CIGRE HVDC Benchmark System

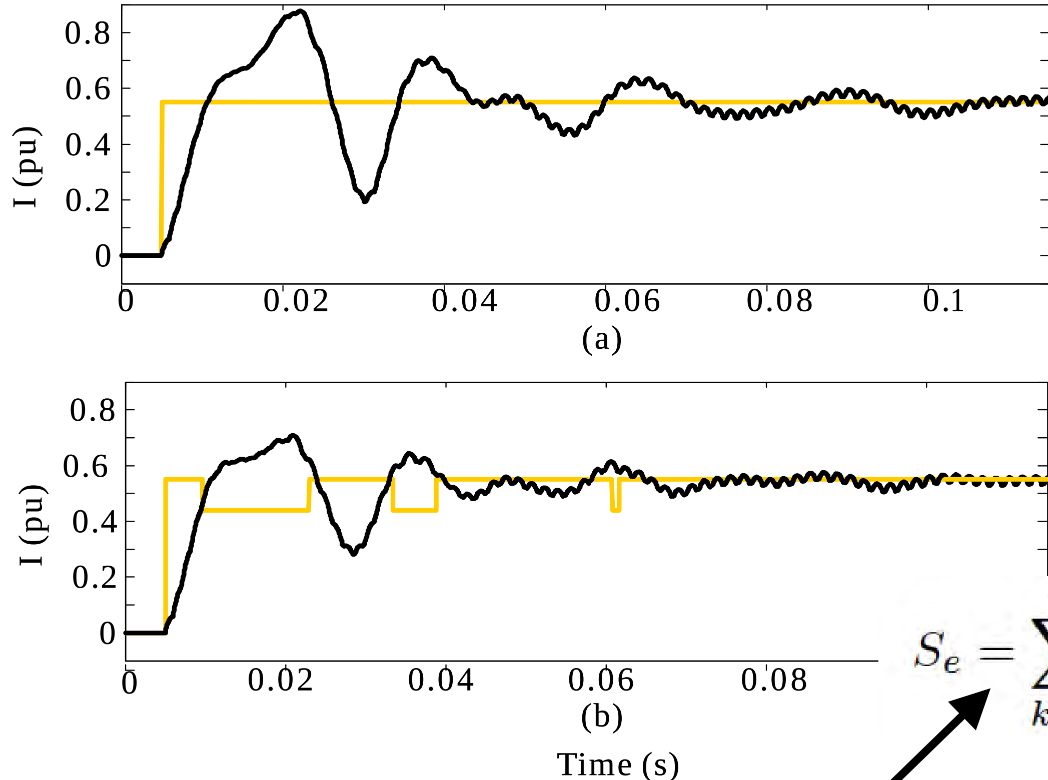


CIGRE HVDC Monopolar First Benchmark System

Rectifier is current controlled

Inverter is voltage controlled (by controlling gamma)

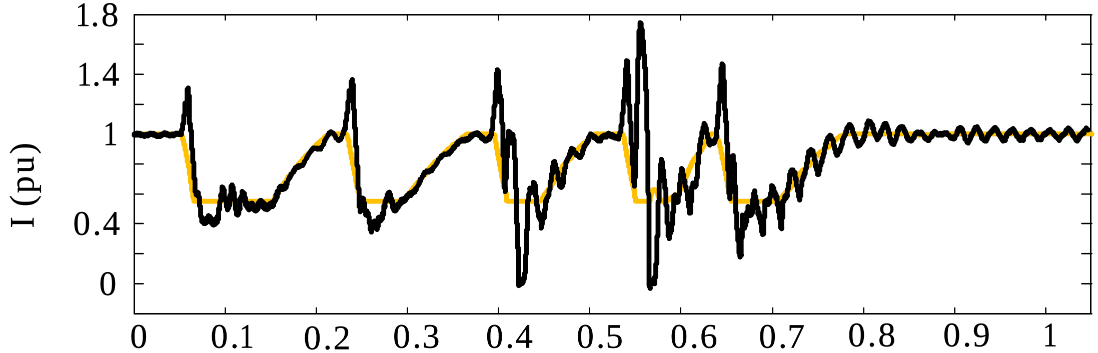
Case I: Rectifier Current Step (0 to 0.55 pu)



$$S_e = \sum_{k=0}^{N} \left(x_{\text{sp}}[k] - x[k] \right)^2$$

	Peak (pu)	Overshoot	Error (S_e)	Settling (ms)
No SPAACE	0.878	59.6%	1.0	95
With SPAACE	0.708	28.7%	0.56 (Δ=44%)	75 (Δ=26.3%)

Case II: Faulted (I-Side) DC Current, 50 ms



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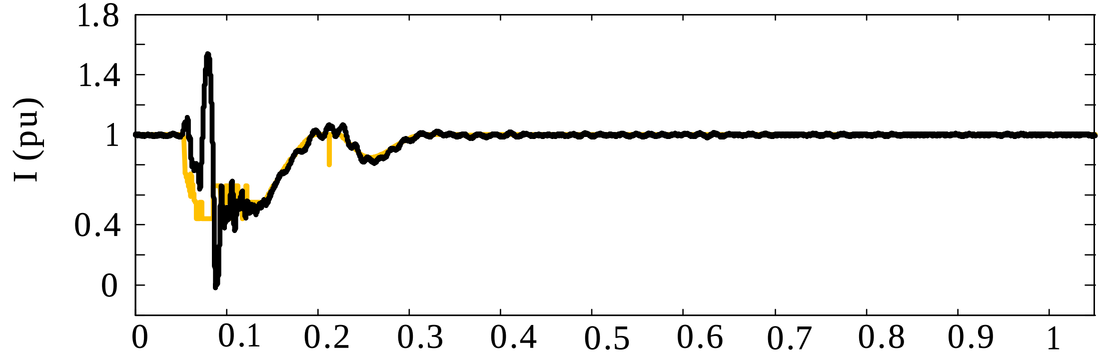
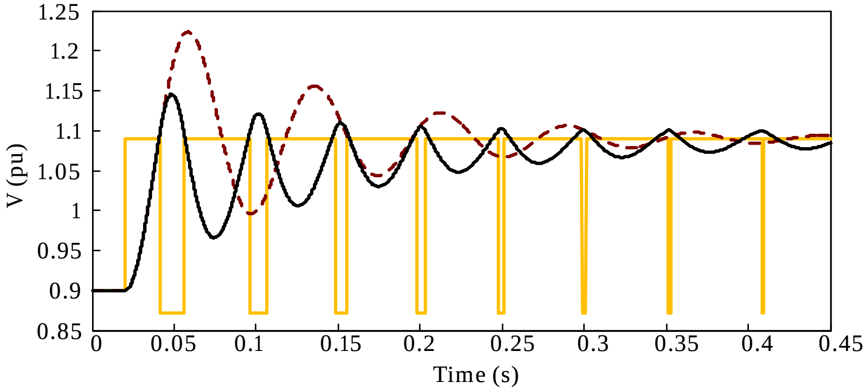


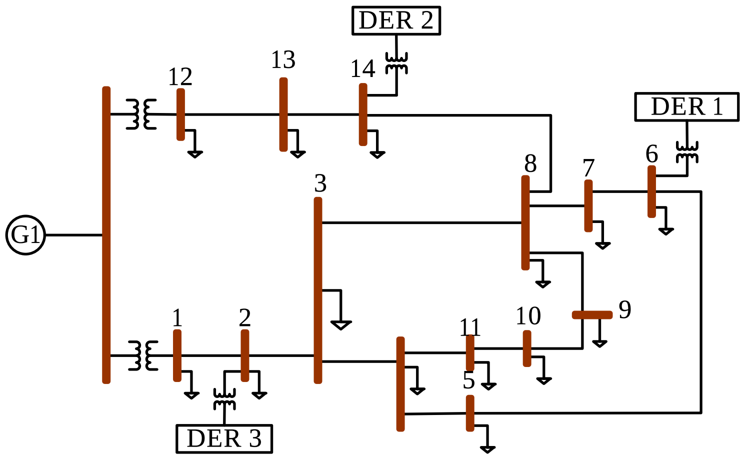
(b)

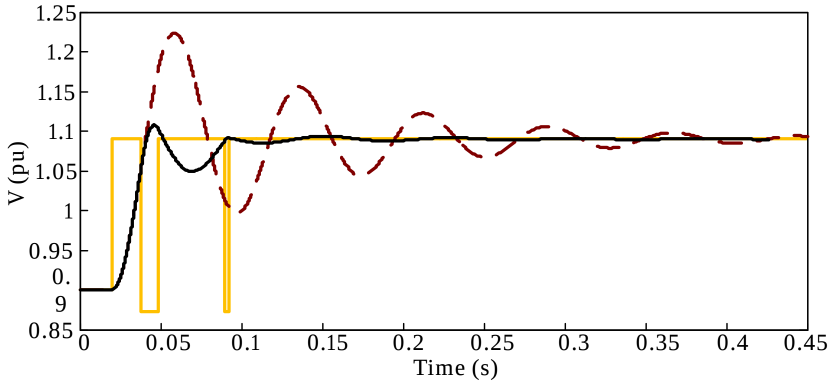
	Peak (pu)	Error (S_e)	Settling (ms)
No SPAACE	1.744	1.0	800
With SPAACE	1.540	0.45 (Δ=55%)	260 (Δ=67.5%)

Prediction Methods



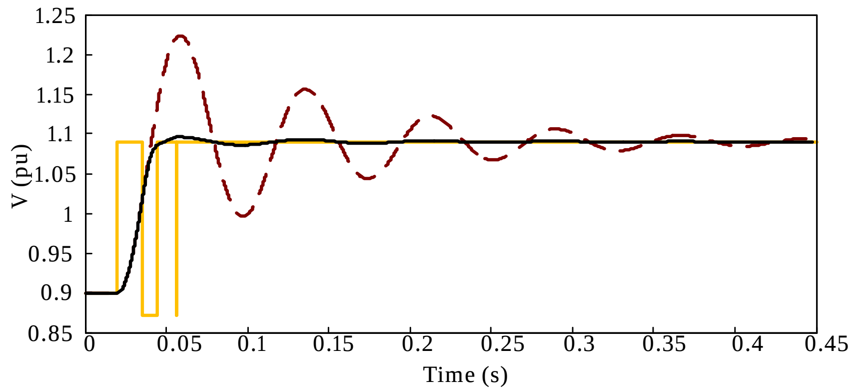
No Prediction





Linear Prediction

$$\hat{x}(t_0 + T_{\text{pred}}) = x(t_0) + r(t_0)T_{\text{pred}}$$

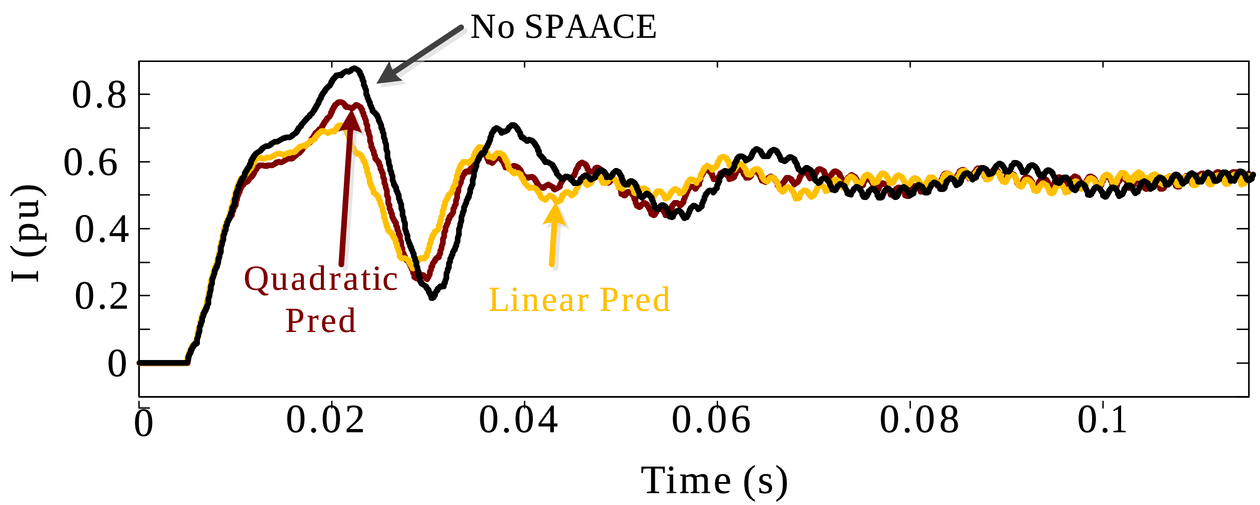


Quadratic Prediction

$$\hat{x}(t_0 + T_{\text{pred}}) = x(t_0) + r(t_0)T_{\text{pred}} + \frac{1}{2}q(t_0)T_{\text{pred}}^2$$

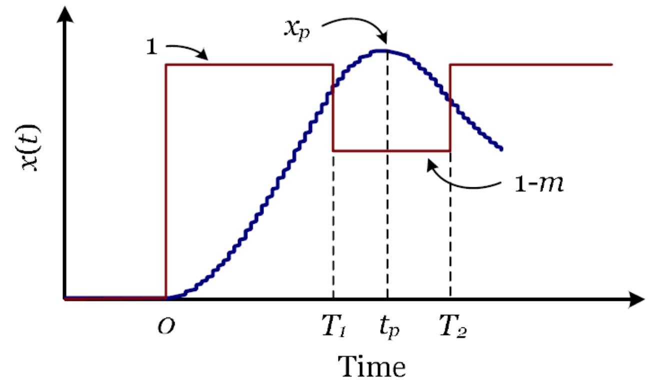
Prediction Algorithms: Step Change

- **Linear and Quadratic Prediction for the HVDC System**



	Peak (pu)	Overshoot	Error (S_e)	Settling (ms)
No SPAACE	0.878	59.6%	1.0	95
With SPAACE (L)	0.708	28.7%	0.560 (Δ=40%)	75 (Δ=26.3%)
With SPAACE (Q)	0.777	41.2%	0.668 (Δ=33%)	55 (Δ=42%)

Sketch of Proof of Existence of Response



- **We can show that with appropriate timing, the response settles at $T_2 = t_p$.**
  - Choose T_1 such that $x_p = 1$.
  - Choose T_2 to be t_p for $x(t)$.
- **We use the intermediate value theorem. For $f(t)$ continuous, if for some t_1 and t_2 $f(t_1)f(t_2) < 0$, IVT states that $f(t)$ has a root in (t_1, t_2).**

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

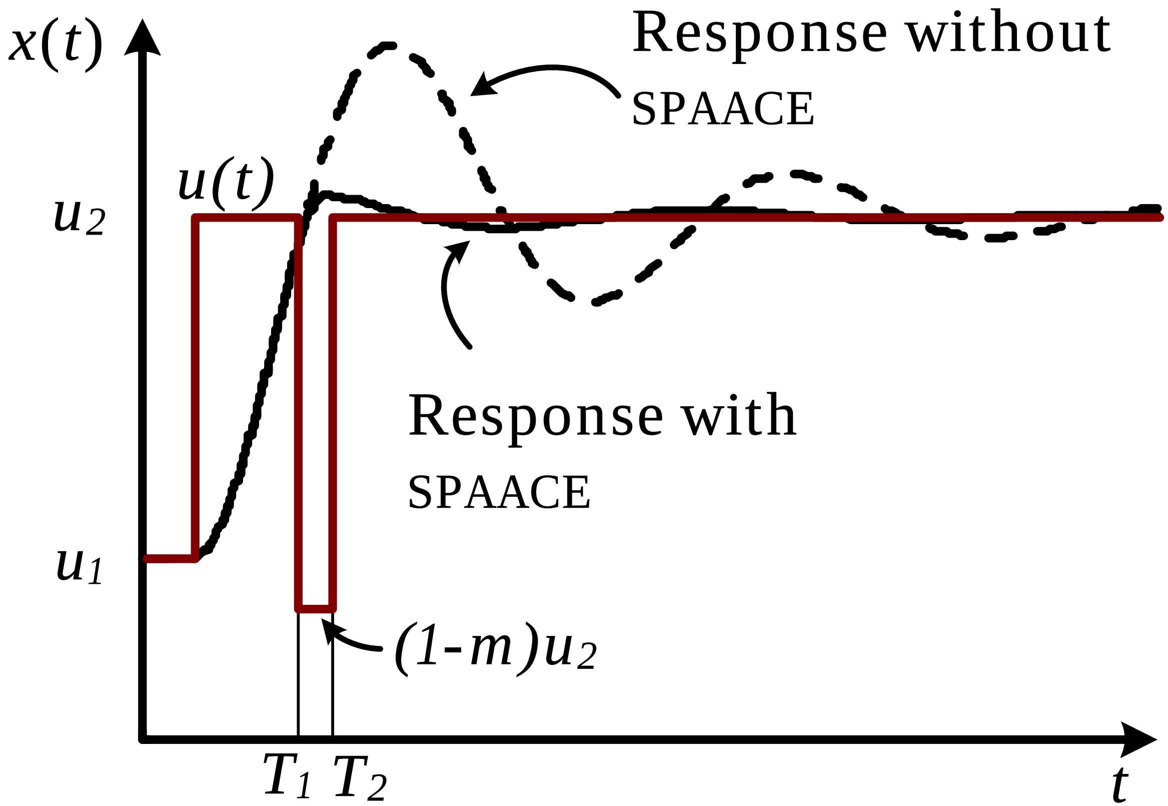
- **Choose $f(t) = x_p(t) - 1$. $t_1 = 0$, $t_2 = 5t_{\text{settling}}$.**

$$\hat{x}_p(T_1) = \frac{\sin(\psi)}{\omega_d} e^{-\psi\cot(\psi)} e^{\zeta\omega_n T_1} \times e^{-\gamma\cot(\psi)} \sqrt{(\hat{x}\omega_n)^2 + \dot{x}^2 + 2\hat{x}\dot{x}\omega_n\zeta}$$

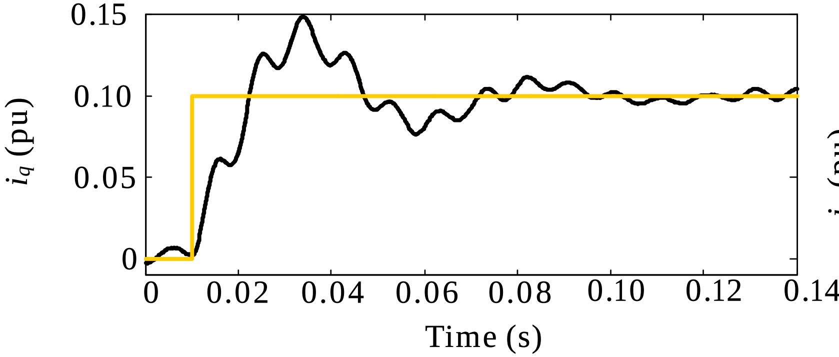
$$\begin{aligned} f(t_1) &= 1 - 2m > 0 \\ f(t_2) &= -m < 0 \end{aligned} \implies \exists t, f(t) = 0 \qquad \text{choose } T_1 = t$$

Effect of Scaling Factor m

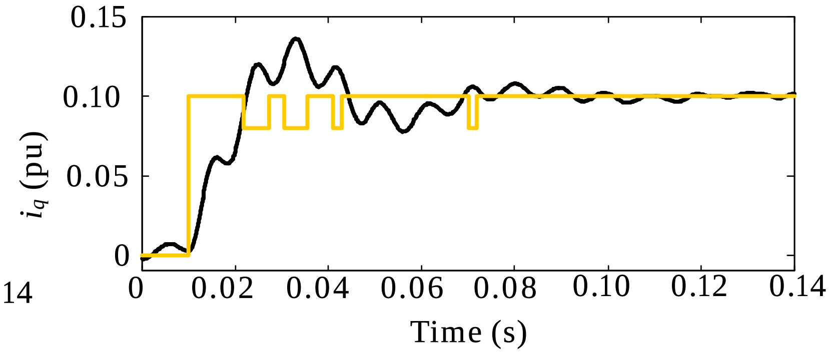
- **Adaptive Nature of SPAACE**



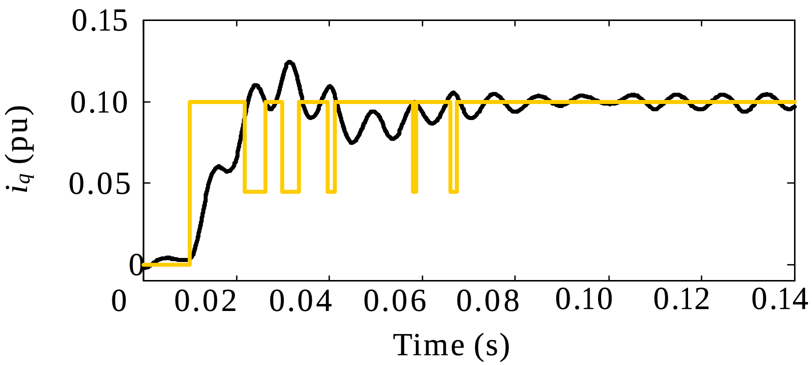
Scaling Factor *m*



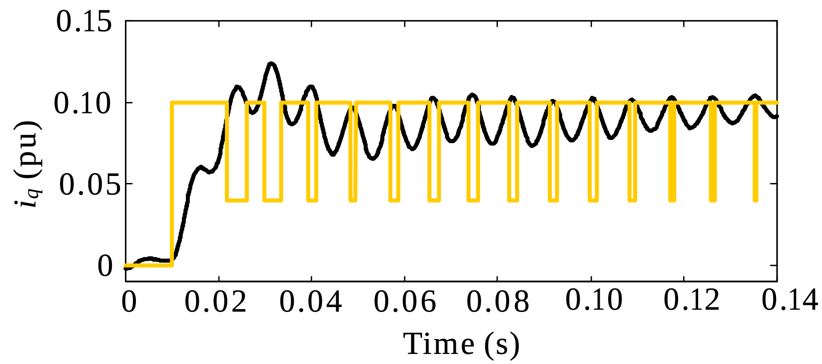
m=0.00



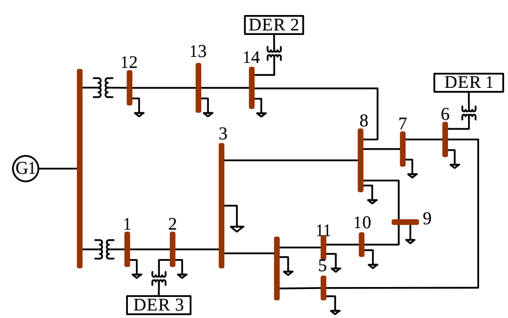
m=0.20



m=0.40

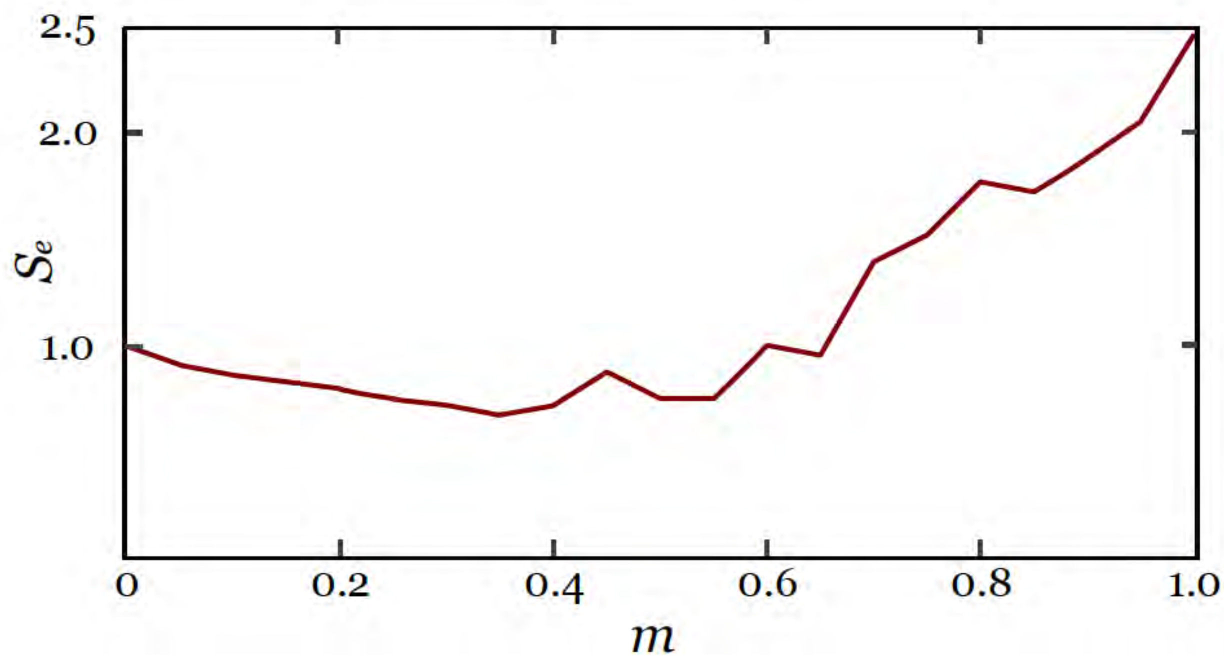


m=0.60

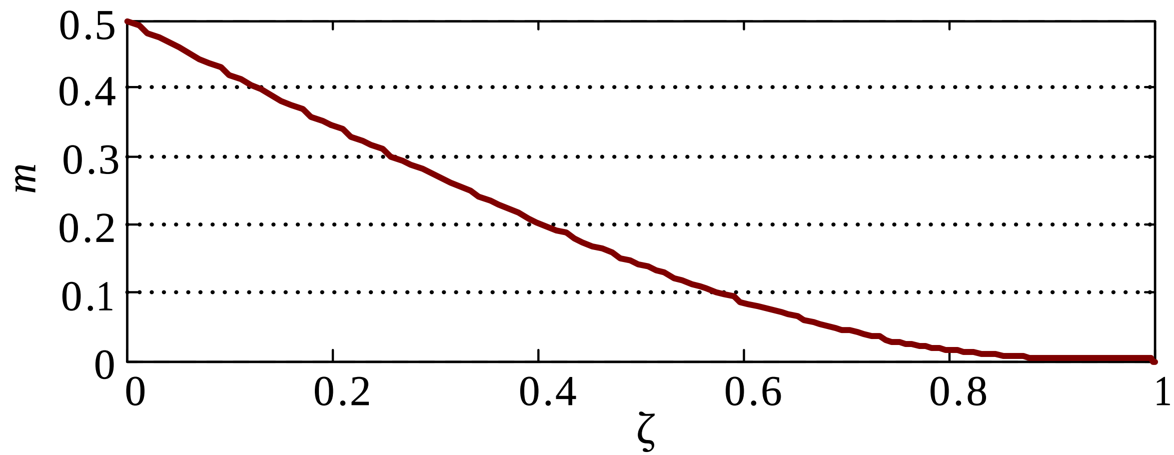


Effect of m

m	Peak (A)	Error (S_e)	Settling (ms)
0	0.149	1.0	80
0.20	0.136	0.806	60
0.55	0.125	0.727	55



Upper Bound of *m*



$$m < \frac{e^{-\pi \cot(\psi)}}{1 + e^{-\pi \cot(\psi)}}$$

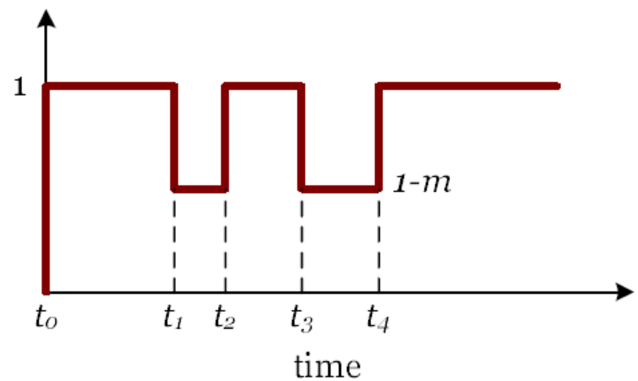
- **Proof is using the conditions of IVT. That is, to ensure $f(t_1=0) > 0$.**

Effect on Stability

- **SPAACE does not make a stable system unstable (but may make an unstable system stable).**
- **Sketch of proof (finite number of set point changes):**

$$r(t) = u(t - t_0) + \sum^{2n} (-1)^i m u(t - t_i)$$

$$R(s) = \frac{1}{s} + m \sum_{i=1}^{2n} (-1)^i \frac{e^{-t_i s}}{s}$$



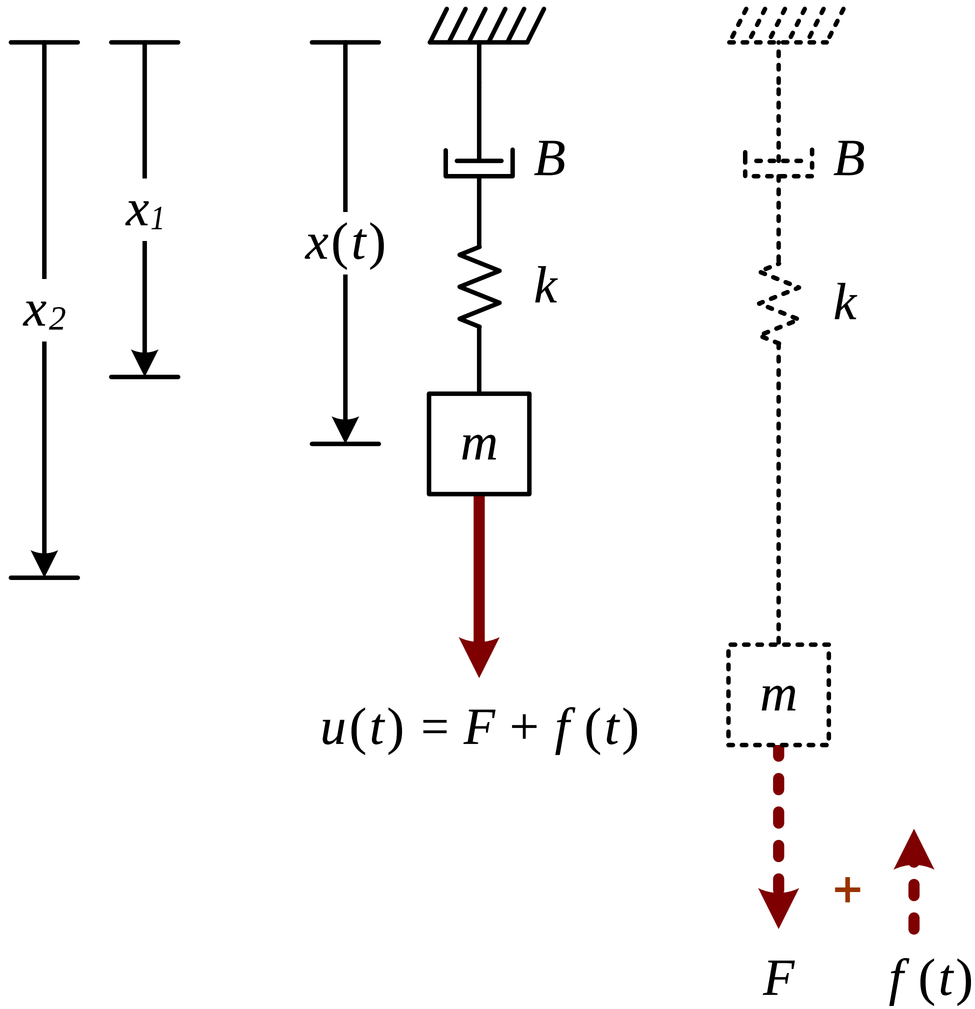
- **The response, from the final value theorem, is**

$$X(s) = H(s)R(s)$$

$$= H(s)\left(\frac{1}{s} + m \sum_{i=1}^{2n} (-1)^i \frac{e^{-t_i s}}{s}\right)$$

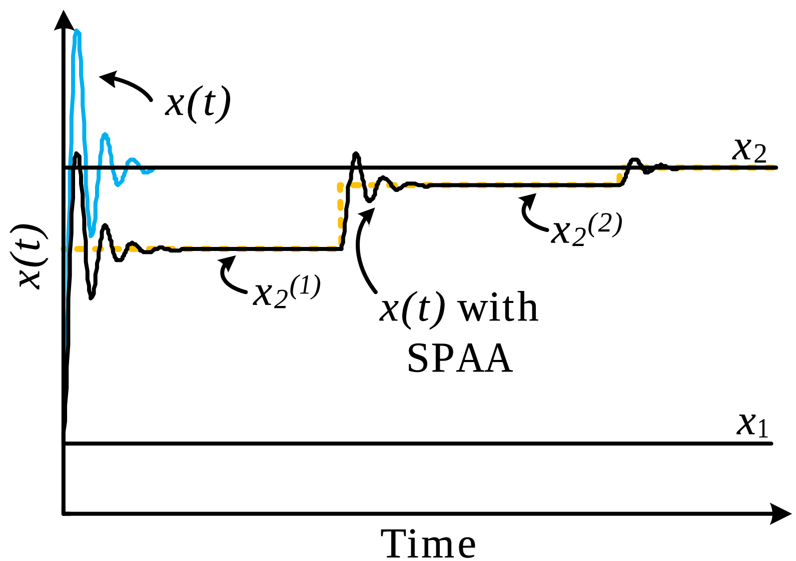
$$\Rightarrow \quad \lim_{t\to\infty} x(t) = \lim_{s\to 0} sX(s) = 1$$

Physical Analogy



SPAA

- **If *a priori* knowledge of overshoot is available**
  - SPAA /spɑː/: Set point automatic adjustment

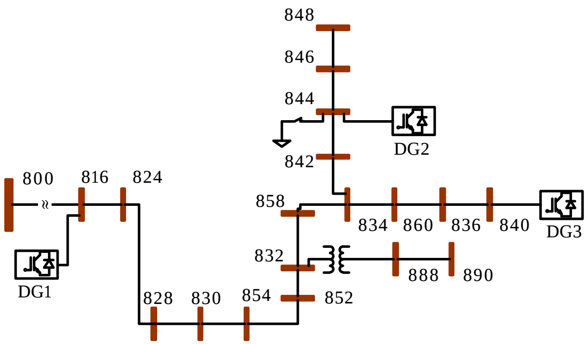


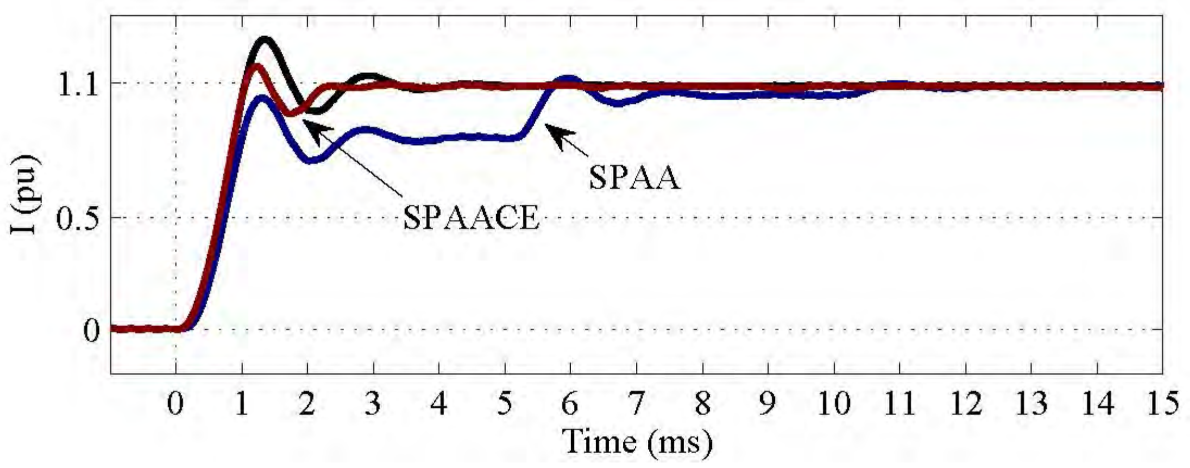
$$x_2^{(i)} = \frac{x_{\text{upper-limit}} + M_p x_2^{(i-1)}}{1 + M_p}$$

SPAA Case Study

Start-Up Current Control

- IEEE 34-bus system with 3 DERs
- DG1 and 3: i_d = 1.0 pu, i_q = 0
- DG2: off to i_d = 1.08 pu
- SPAA assumes ζ=0.361 and ω=8450 rad/s

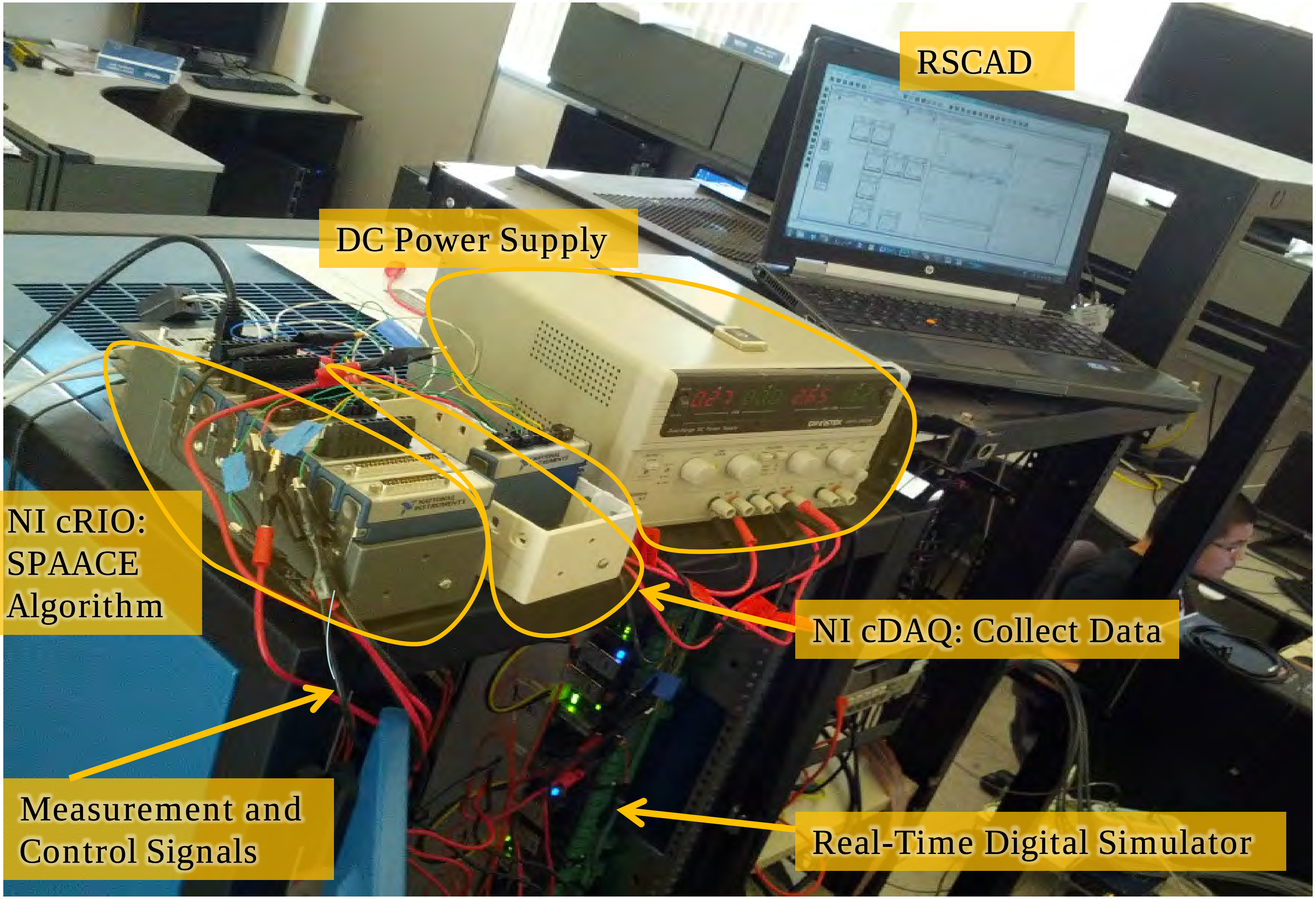




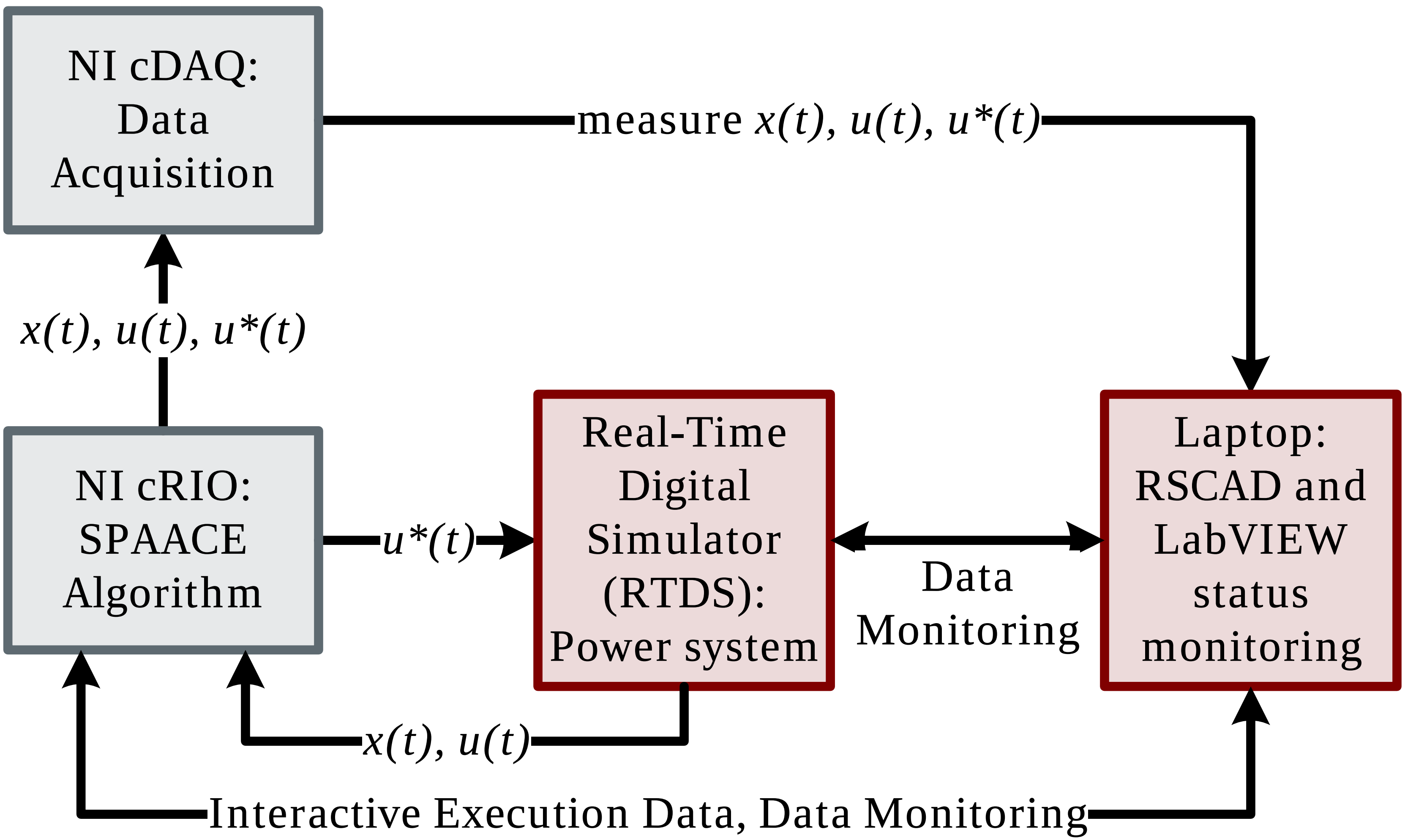
SPAA vs. SPAACE

	SPAA	SPAACE
Rate of Update	After steady state	Continuously
Need to model	Yes (approximate)	No
Effectiveness	Large changes	Moderate changes
Approach	Open loop	Closed loop
Responsiveness	Set point change	Any difference in the set point and response (set point change, load switching, faults)

Experimental Implementation

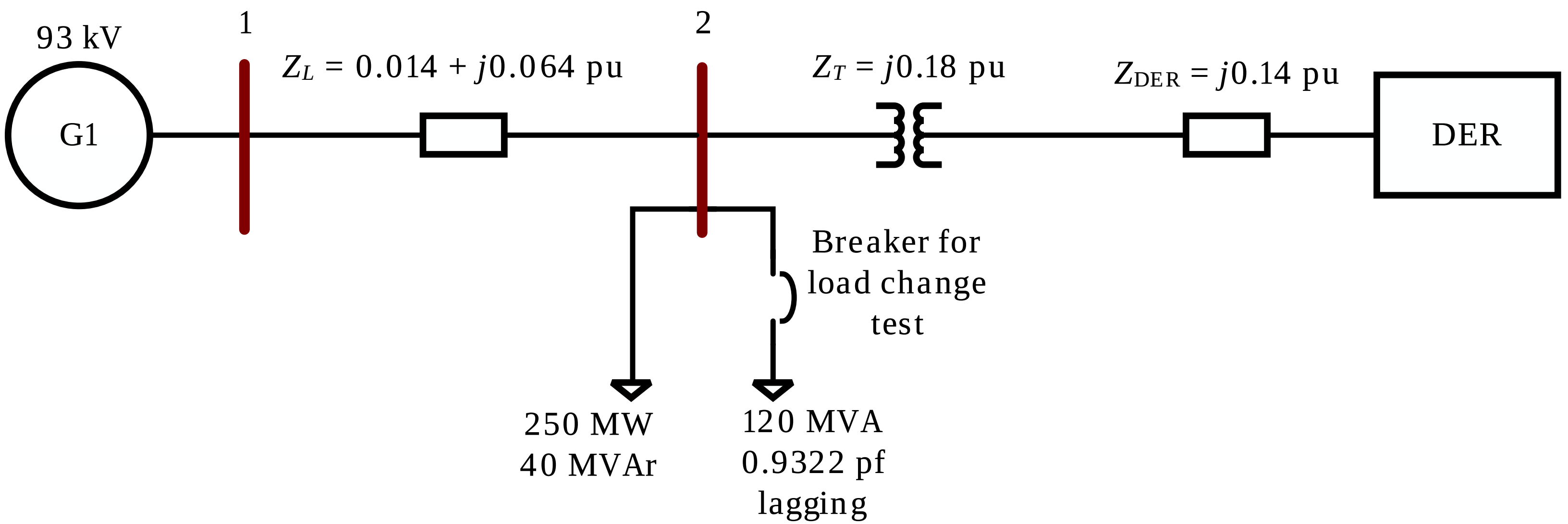


Experimental Implementation



$x(t)$: output signal, $u(t)$: set point, $u^*(t)$: adjusted set point.

Test System

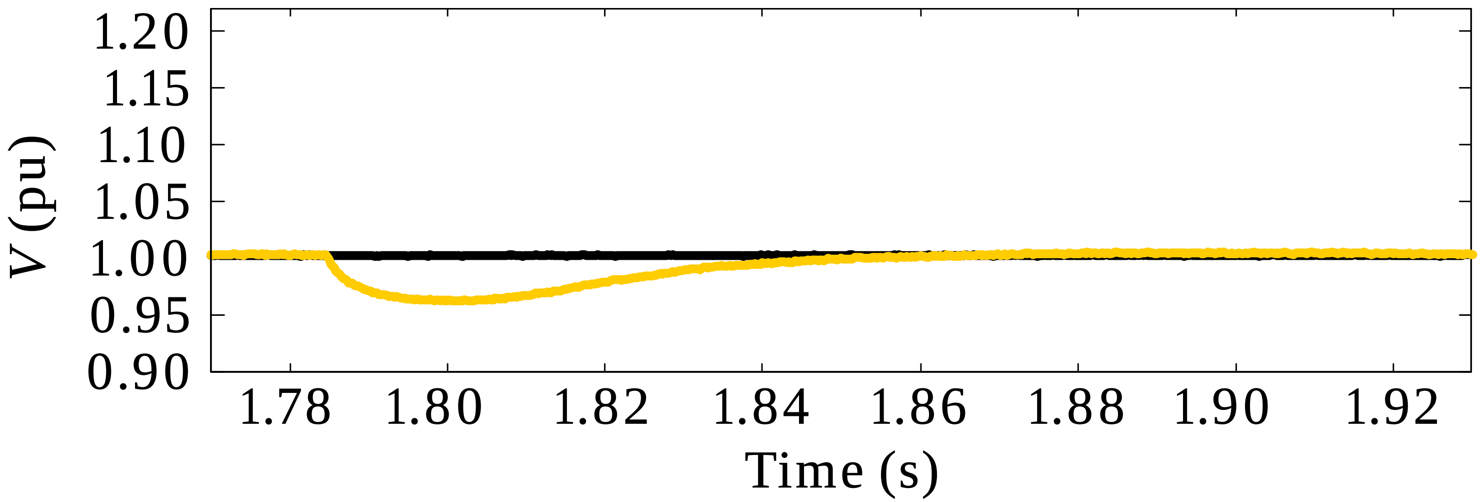


93 kV
G1
1
Z_L = 0.014 + j0.064 pu
2
Z_T = j0.18 pu
Z_{DER} = j0.14 pu
DER
Breaker for load change test
250 MW
40 MVAr
120 MVA
0.9322 pf
lagging

Case I: Load Energization (1.2 pu)

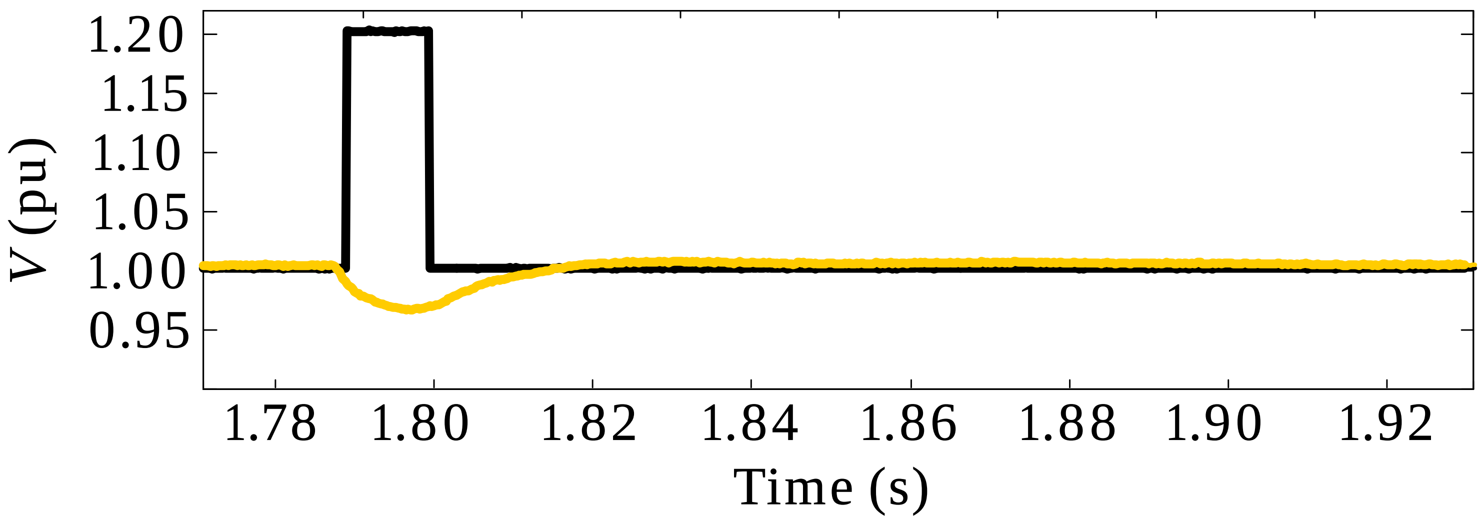
Without SPAACE

M_p: 5%
$t_{settling}$: 60 ms



With SPAACE

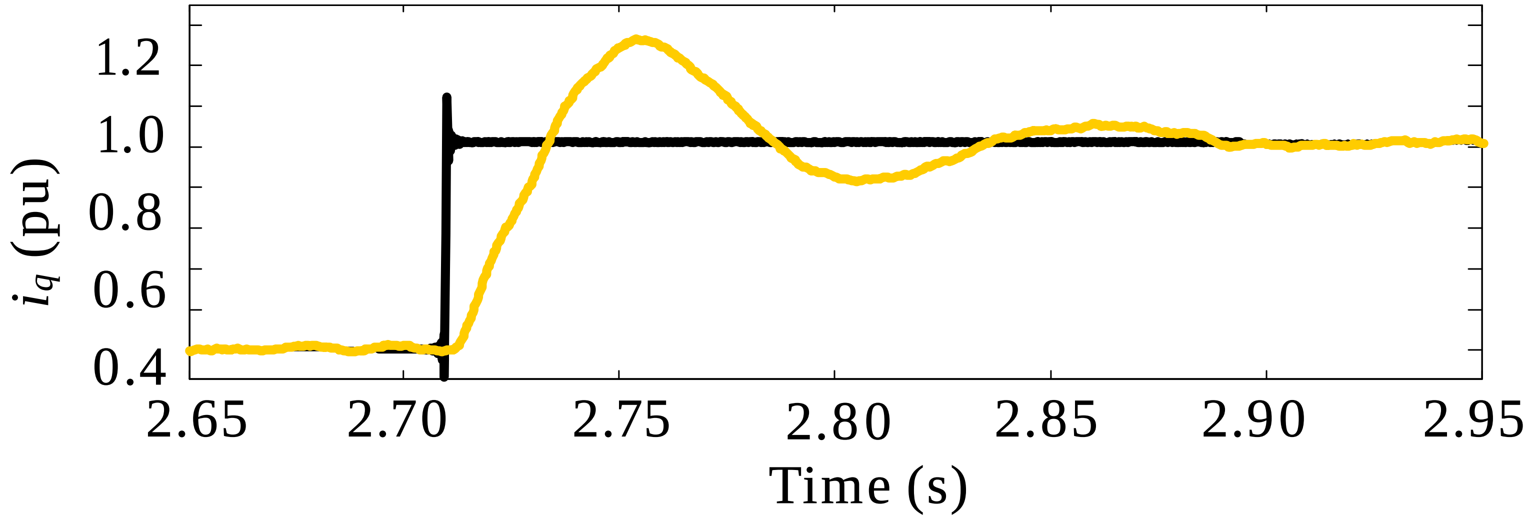
M_p: 4%
$t_{settling}$: 30 ms



Case II: Step Change in i_q

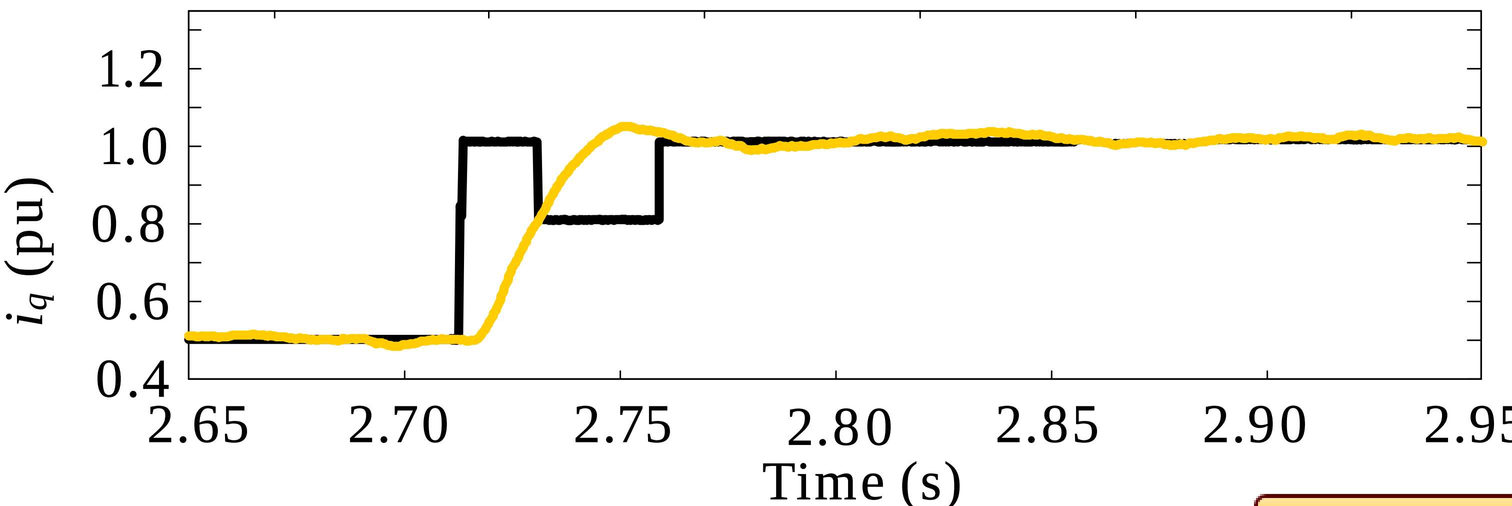
Without SPAACE

M_p: 30%
$t_{settling}$: 150 ms



With SPAACE

M_p: 0%
$t_{settling}$: 50 ms



Conclusions

- **By appropriately designing the trajectory to reduce overshoots, it is possible and safe for a system to operate closer to its limits.**
- **Offline (PSCAD) and real-time (RTDS) simulation studies show that SPAACE is effective in mitigating transients:**
  - Step change: Mitigating overshoots
  - Fault: Closer set point following
  - Load energization: Eliminating a peaks
  - Load disconnection in a unbalanced system: Stabilizing oscillatory behavior of voltage
- **The significance of this work is that it can reduce the need for overdesign and subsequently increase asset utilization.**

Applications

Electric Drives Systems
Control of Speed and Torque Electric Machines
(TU Graz)

Applications

La
Segme

ems
Systems

ns
:tric Machines

Thank You

Control Strategies for Microgrids

Ali Mehrizi-Sani

mehrizi@eecs.wsu.edu

http://eecs.wsu.edu/~mehrizi