Control Strategies for Microgrids

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Outline

- **Current and Envisioned Status of the Power System**
  - Overview of control requirements
- **Proposed Control Strategy**
  - Online set point modulation
- **Results of Evaluation of the Strategy**
  - Offline simulation
  - Real-time implementation
  - Fine tuning the parameters of the strategy
- **Applications**

Motivation

- **One of the U.S. grand energy challenges is to enable integration of at least 80% renewable energy resources at a competitive cost in the power grid by 2050.**
- **While it is technically feasible to run the U.S. economy on renewable technologies available today, what is missing is a flexible power system that accommodates the unique characteristics of renewable resources:**
  - Intermittency
  - Lack of inertia
  - Susceptibility to violation of operational limits
- **This work addresses the latter—susceptibility to violation of limits.**

Global Need

- **The need to address this challenge is confirmed by**
  - Department of Energy 2012 microgrid workshop (and 2011/2010)
  - 2013 White House 21st century grid report (and 2012)
  - National Academy of Engineering (2013 grand challenges)
- **Our proposed strategy addresses this challenge:**
  - It empowers controllers to closely track their set points even when the host system changes significantly.
- **The existing work does not address this gap:**
  - The common designs assume the host system does not experience significant changes.
- **Significance of this work is that it reduces the need for overdesign and subsequently increases asset utilization.**

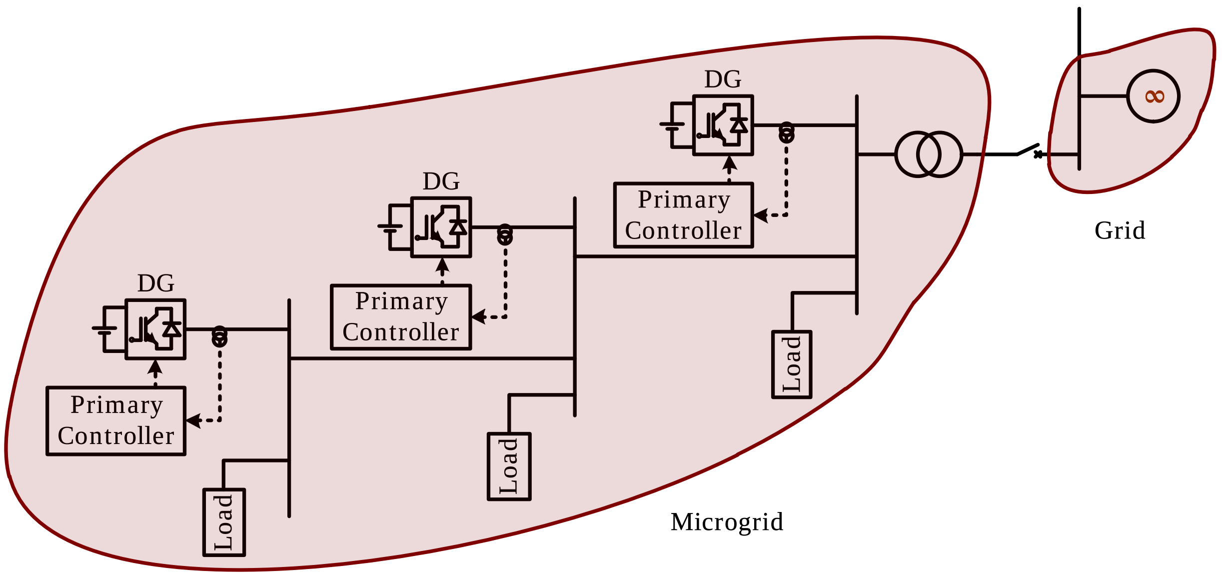
Goal

- **Our goal is to significantly improve the performance of controllers in a system that**
  - Is time varying
  - Has limited reserve

- **A prominent example of such systems is a microgrid.**
  - Enabling concept for the modern and smart power system as a building block.

Microgrids

- **Definition**
  - 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 (1/3)

- **Microgrids offer scalability, modularity, and security, but they may experience**
    - Frequent changes in the topology;
    - Units susceptible to overcurrents and overvoltages;
    - Operation close to the limits to increase asset utilization; and
    - Limited total capacity.
- **Therefore, changes in the microgrid may have a detrimental effect on the performance of controllers.**
    - Controllers are designed for a prespecified configuration.
- **It is imperative to ensure controllers retain their tracking capability under various operating conditions, including those very different from the original design.**

Microgrid Challenges (2/3)

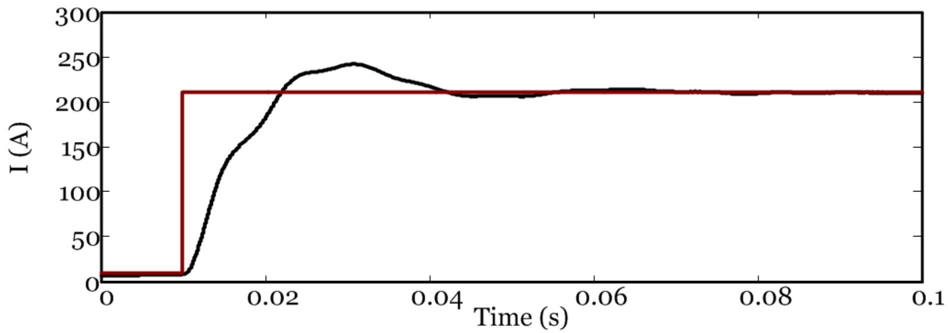
- **Existing control design approaches include**
  - Model-based automated tuning (Astrom's work)
  - Optimization-based (Gole's work)

- **However, these approaches**
  - Require access to updated system models;
  - Need availability of a computational infrastructure to allow redesign;
  - Have limited robustness to topology, operating point, and system parameters;
  - Are difficult to retune; or
  - Are intrusive.

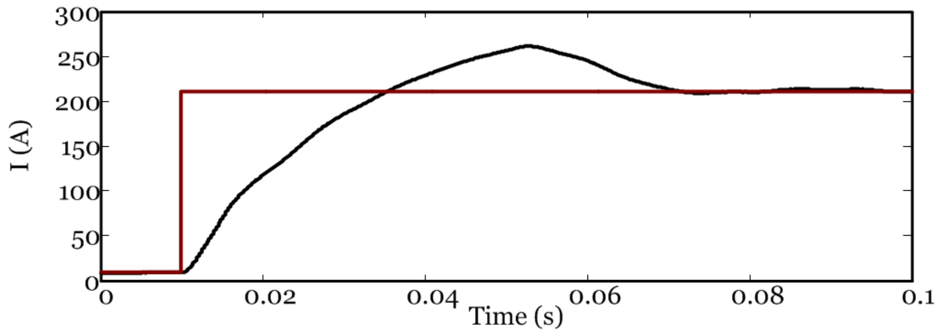
Microgrid Challenges (3/3)

- **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

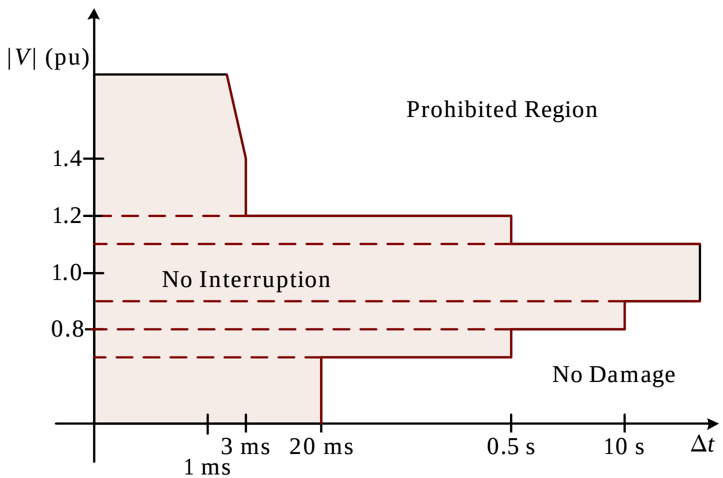


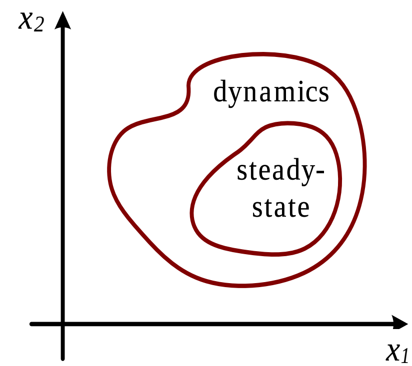
Objective

- **Our objective is to design stringent control strategies that offer close set point tracking while being**
  - Robust to topological and operational changes;
  - Independent of the system model; and
  - Operating with little information about the unit to which it is associated.

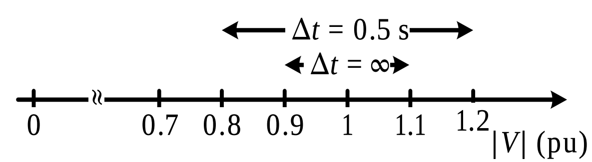
Shaping of the Response Trajectory

- **Consideration of Dynamic Limits of Devices**





(a)

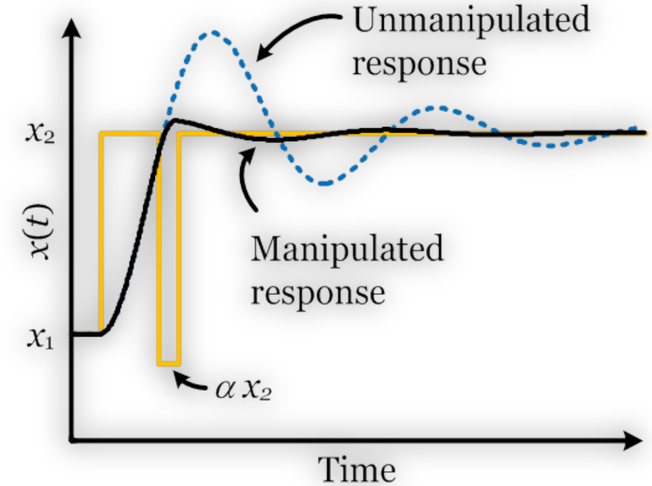


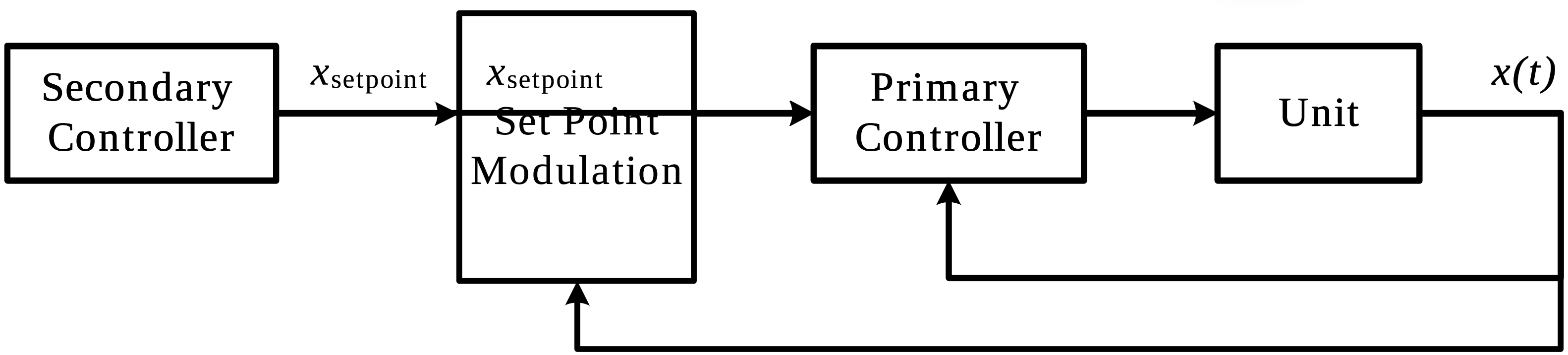
(b)

- **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**

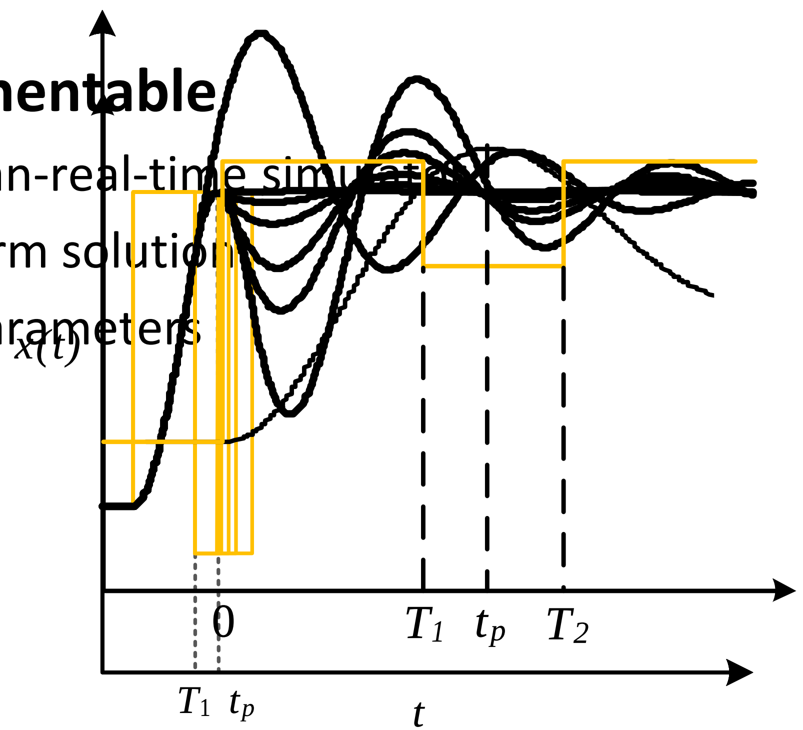




Set Point Modulation

- **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

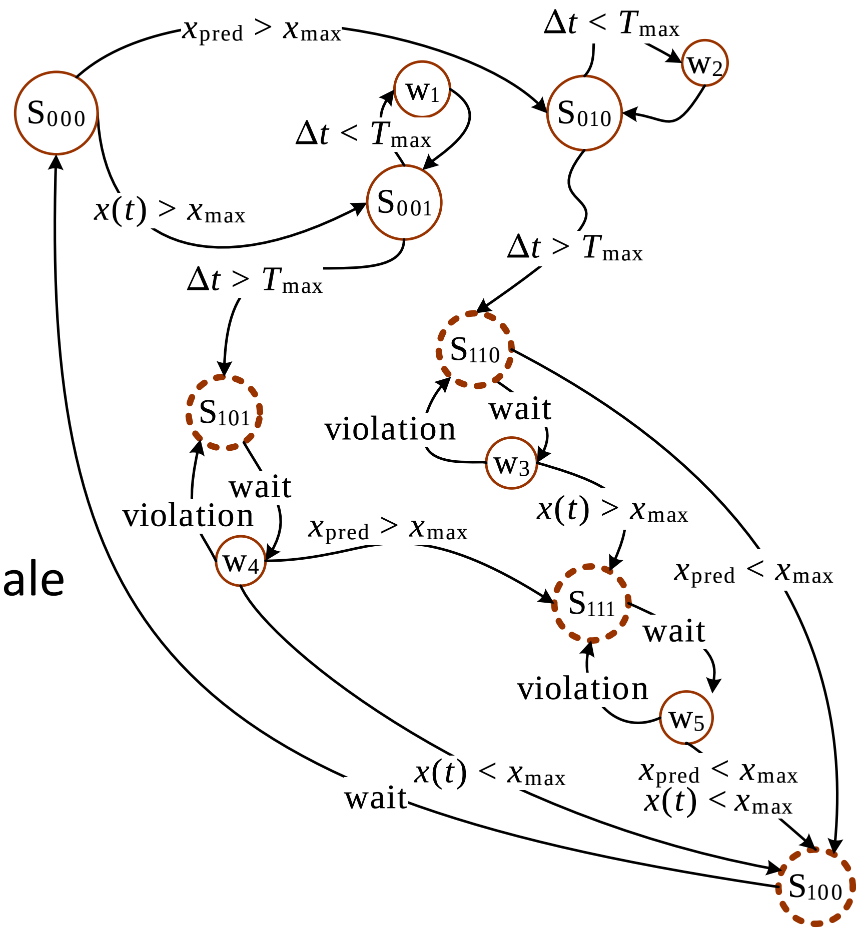
- **Not Implementable**
  - Faster-than-real-time simulator
  - Closed-form solution
  - System parameters



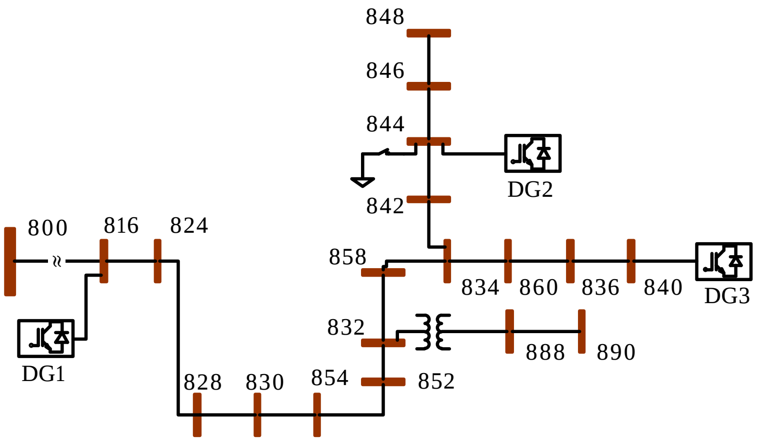
Finite-State Machine

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

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



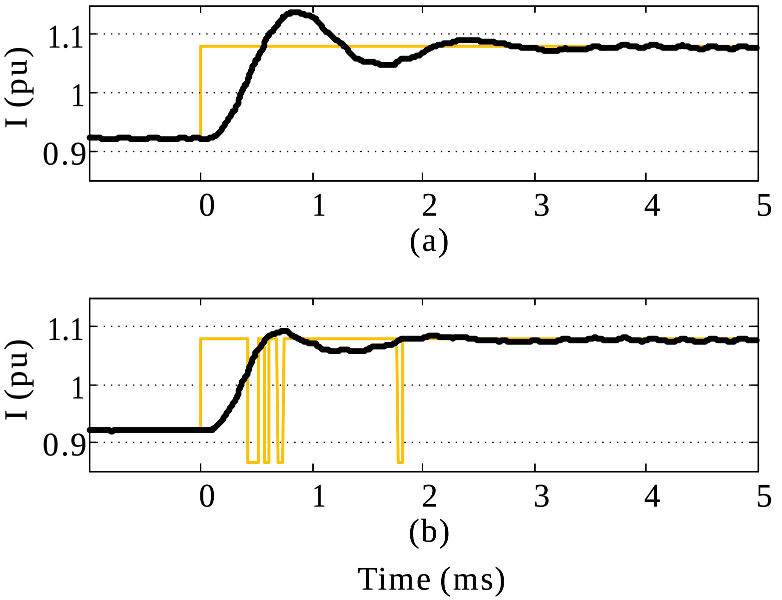
Case Study I: Set Point Change



IEEE 34-Bus System

Added 3 DG units and a load

Operates in grid-connected mode



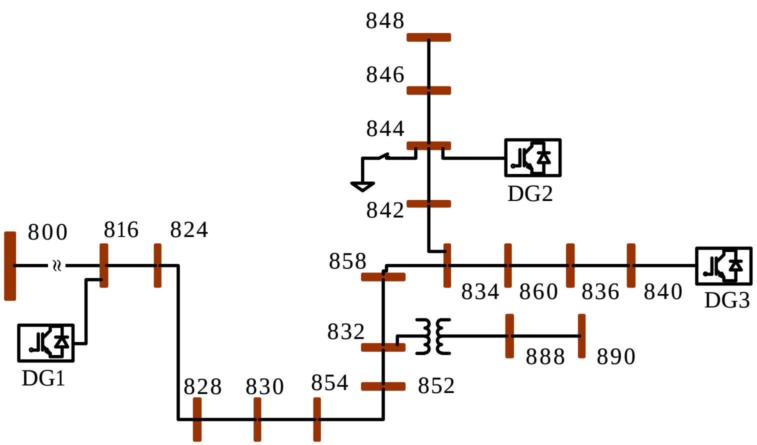
System Response

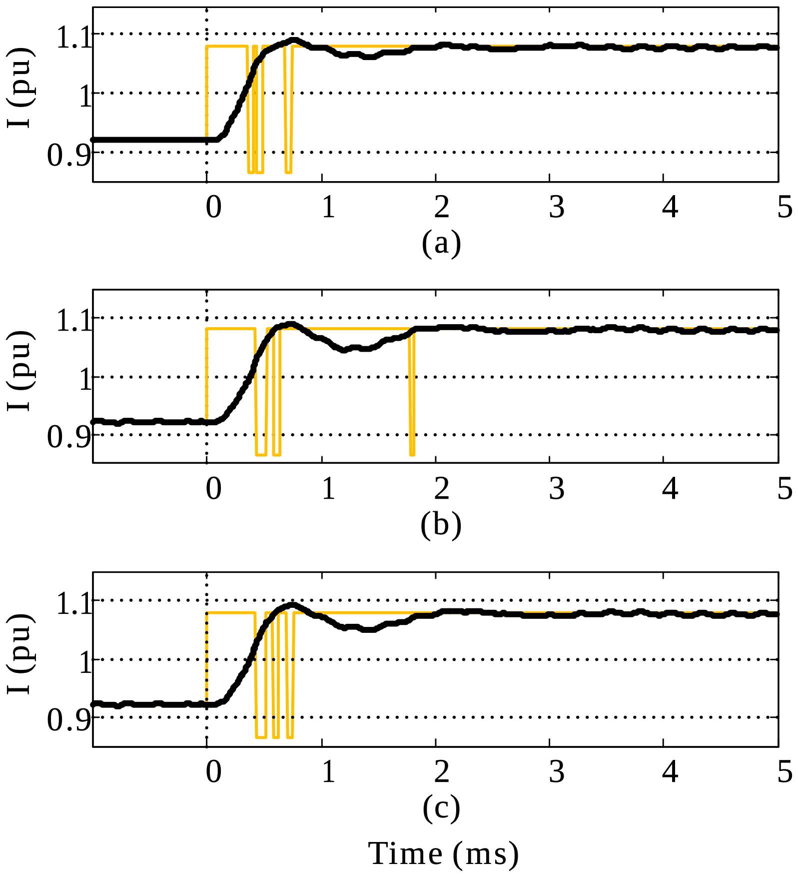
DG2 step change from 0.91 pu to 1.09 pu

DG1 and DG3 unchanged

(40% overshoot)

Case Study II: Simultaneous Change

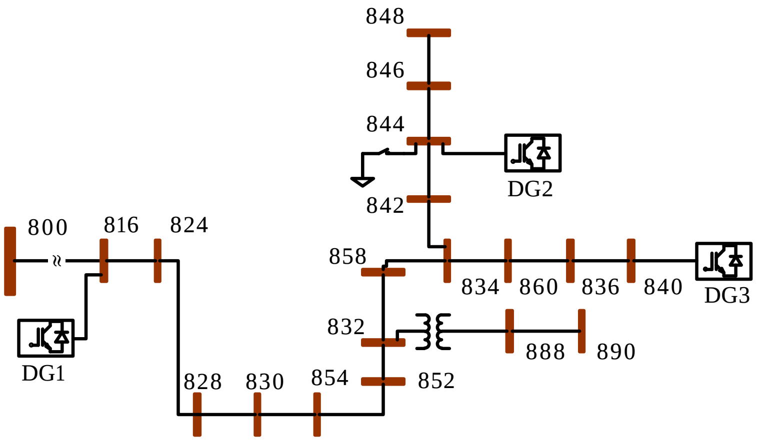


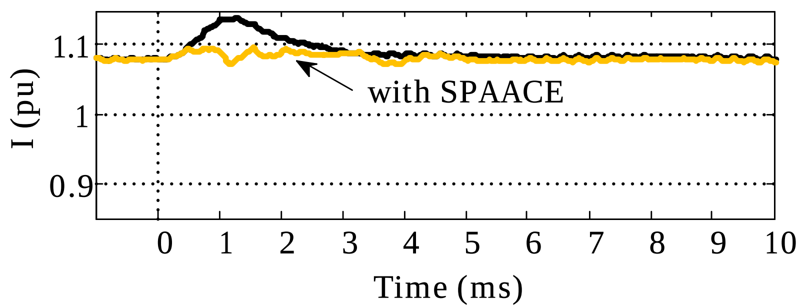


System Response

Simultaneous step change

Case Study III: Load Disconnection





IEEE 34-Bus System

Added 3 DG units and a load

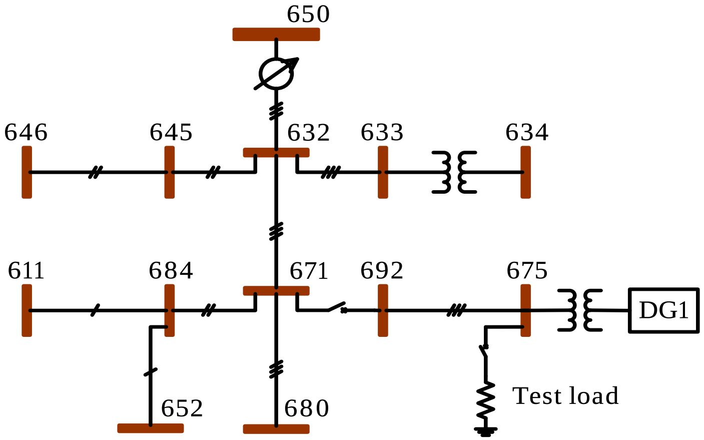
Operates in grid-connected mode

System Response

Resistive 0.5 pu load change

(15% overshoot)

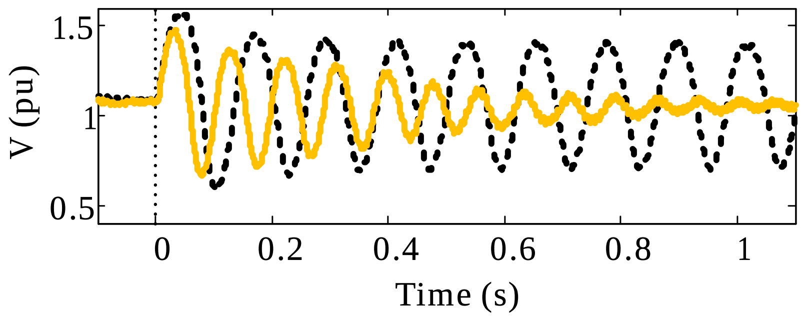
Case Study IV: Unbalanced System



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

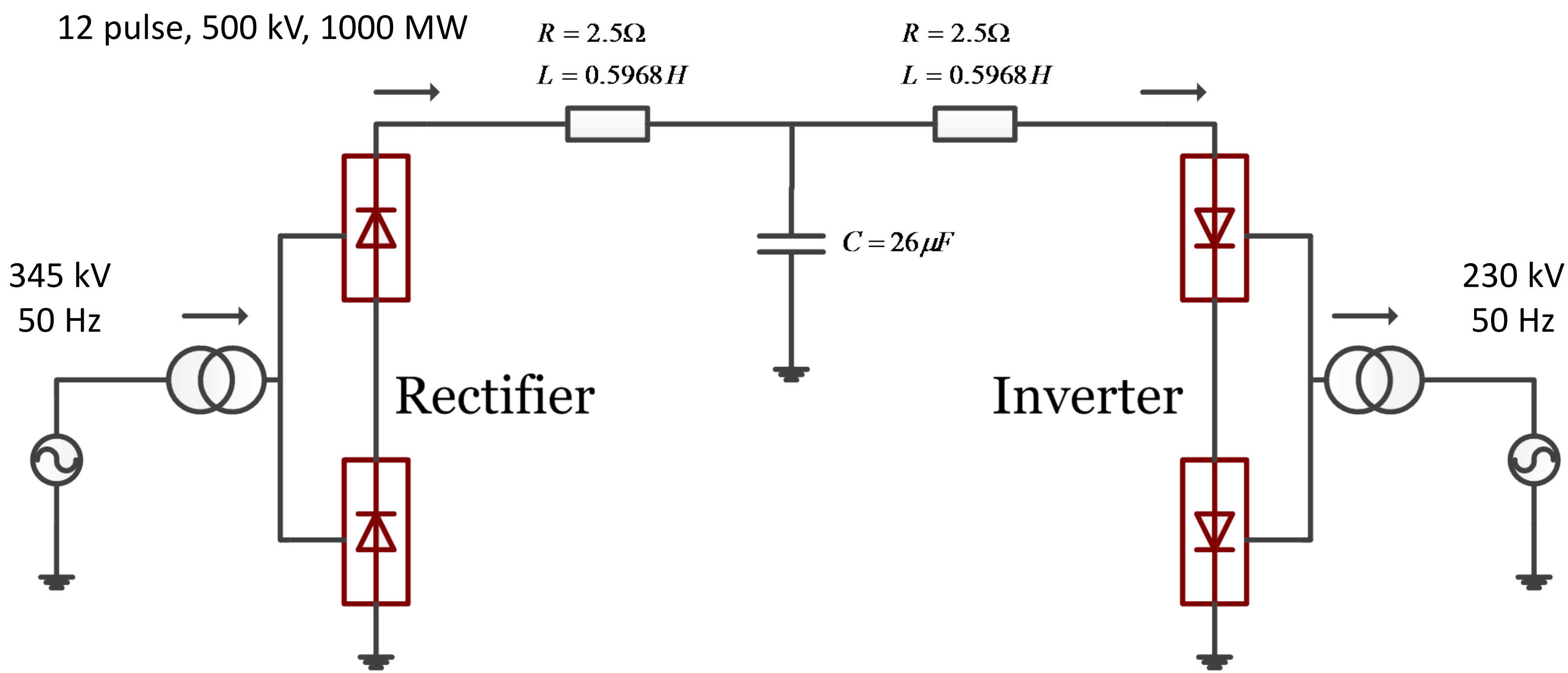
Unstable system to stable system

Metric

- **A Metric to Assess Improvement in Tracking**

$$\int_{t=t_0}^{t_f} \left(u(t) - x(t)\right)^2 dt$$

HVDC Study System

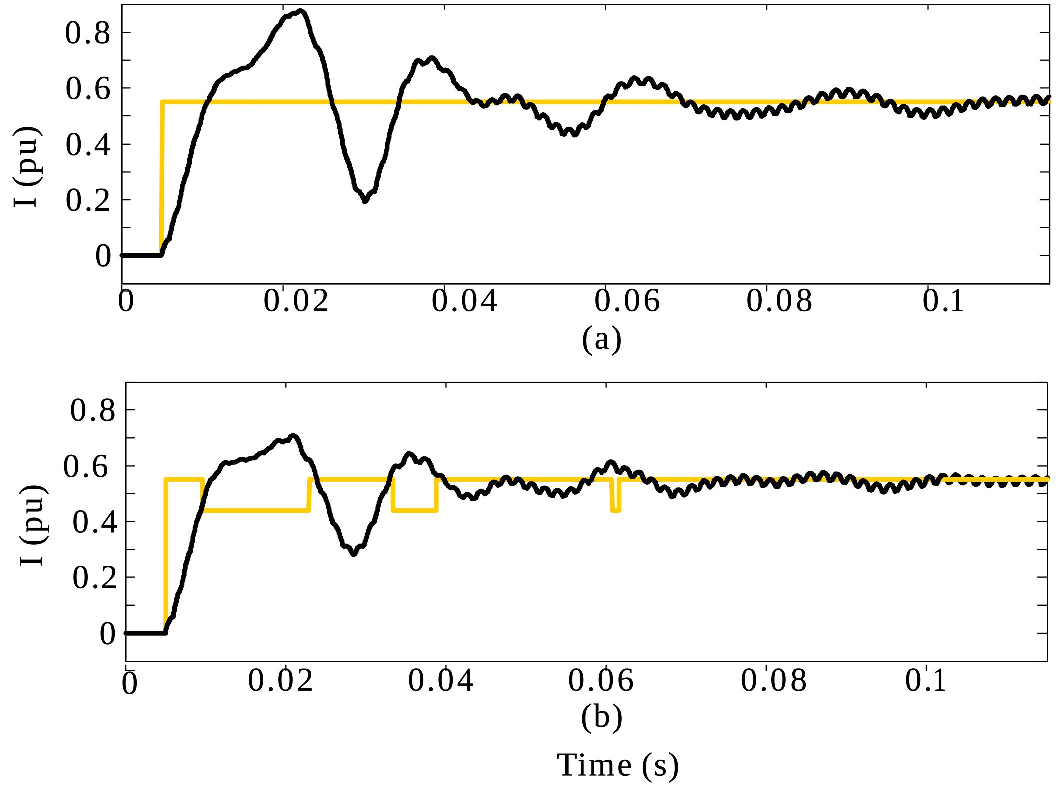


CIGRE HVDC Monopolar First Benchmark System

Rectifier is current controlled

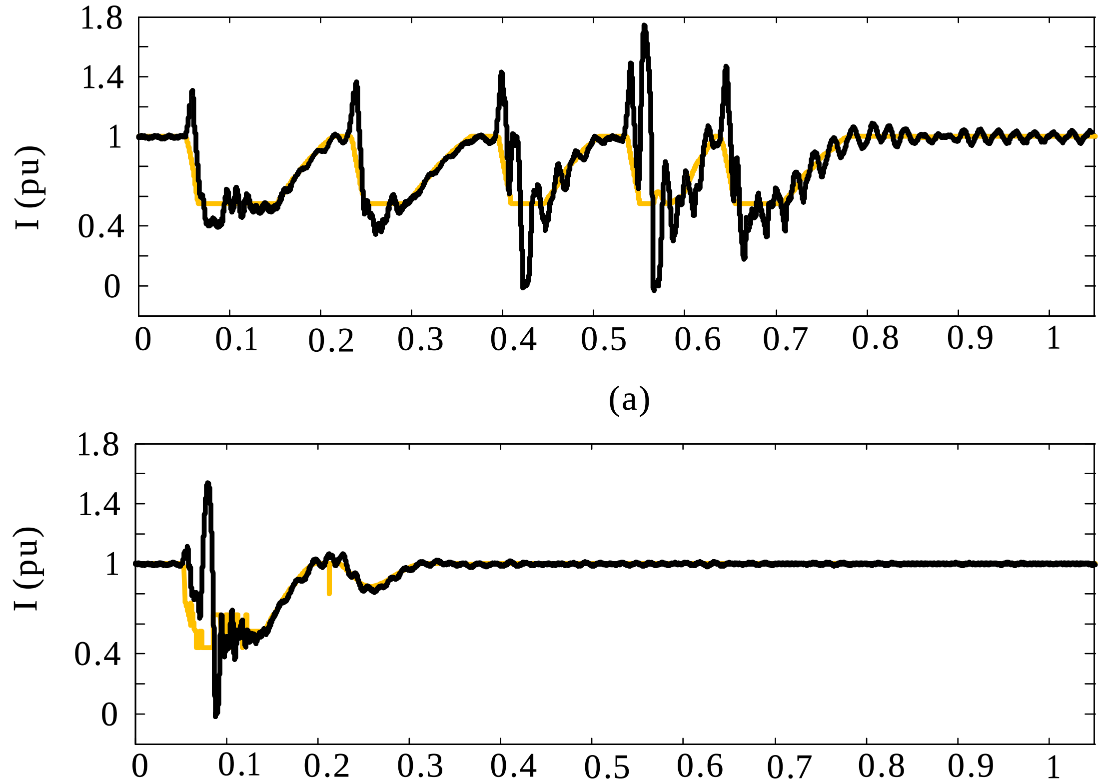
Inverter is gamma controlled

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



	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

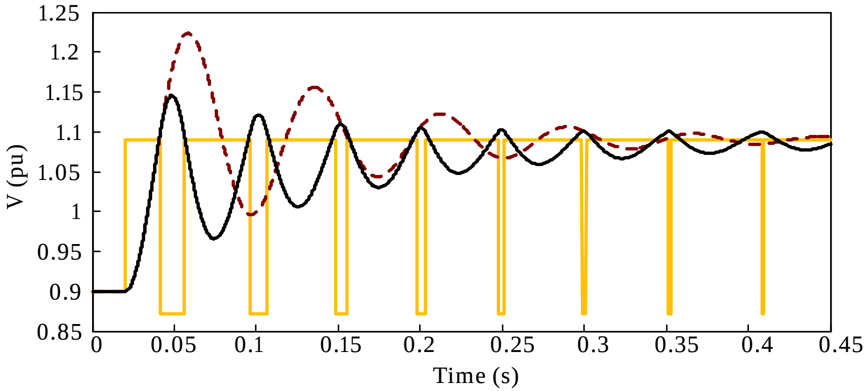


(a)

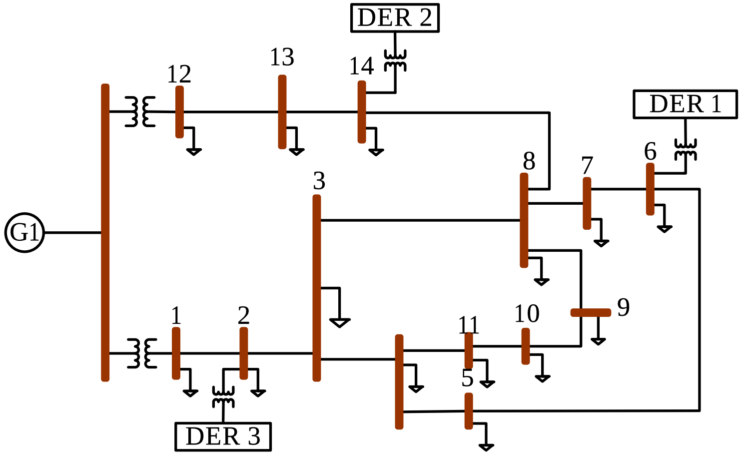
(b)

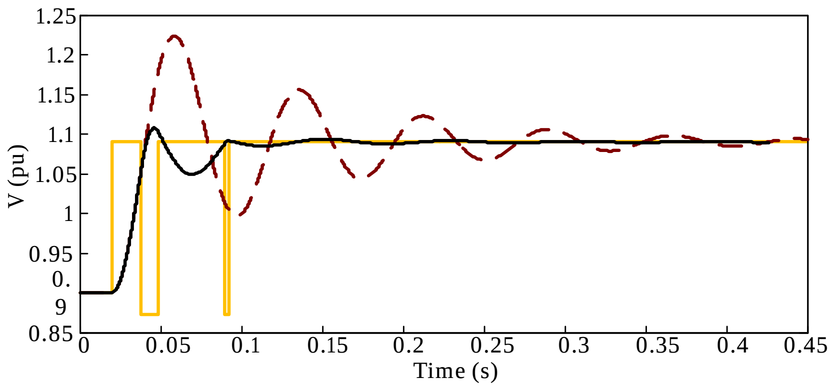
	Peak (pu)	Error (S_e)	Settling (ms)
No SPAACE	1.744	1.0	800
With SPAACE	1.540	0.45 (Δ=55%)	260 (Δ=67.5%)

Prediction Methods

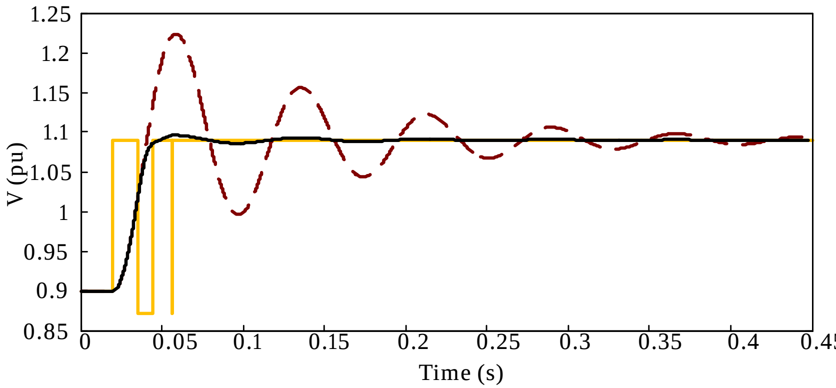


No Prediction





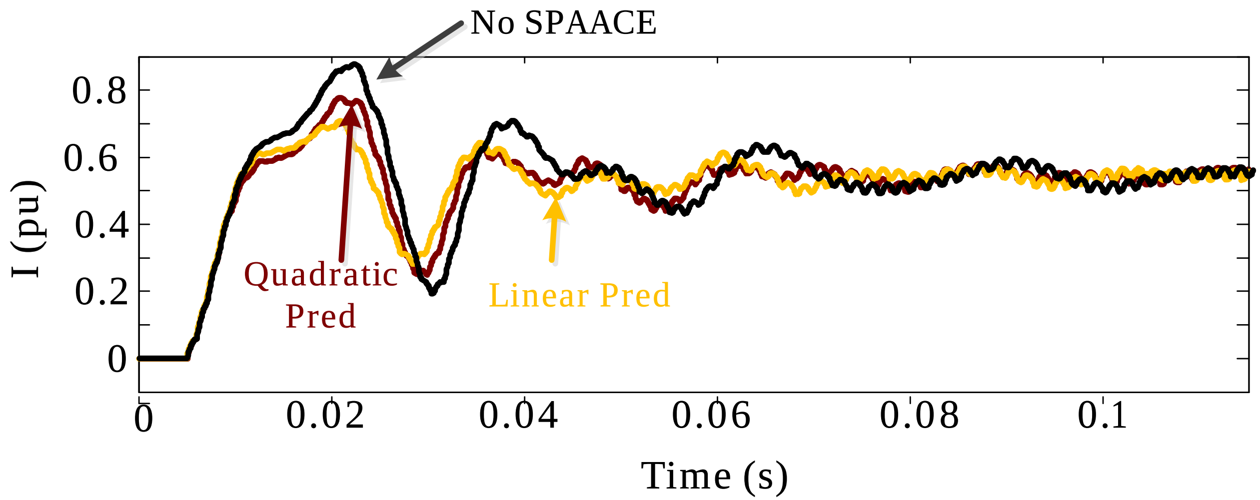
Linear Prediction



Quadratic Prediction

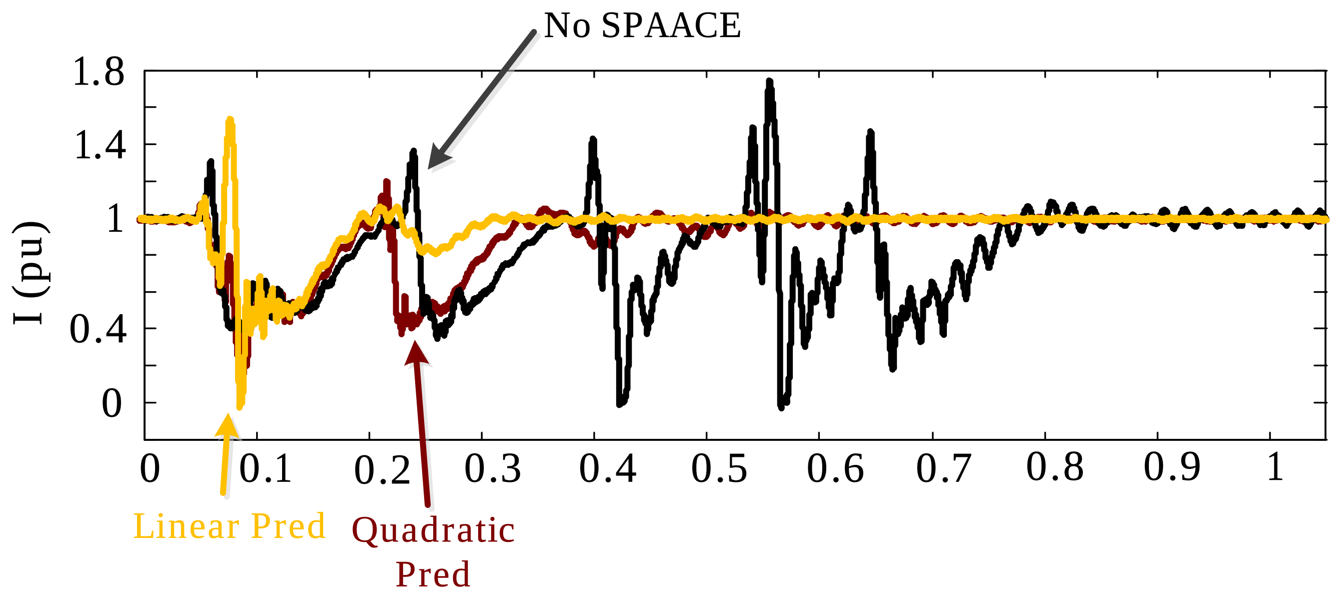
Prediction Algorithms: Step Change

- **Linear Prediction**
- **Quadratic Prediction**



	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%)

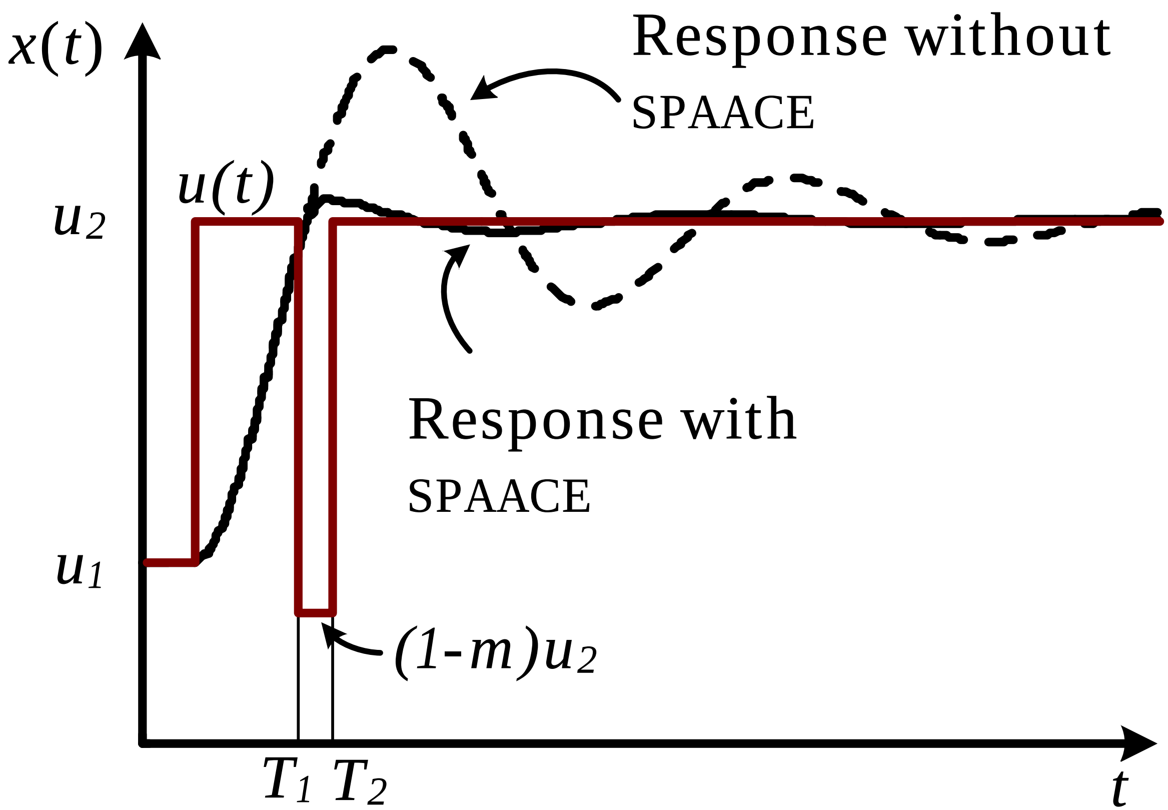
Prediction Algorithms: Fault



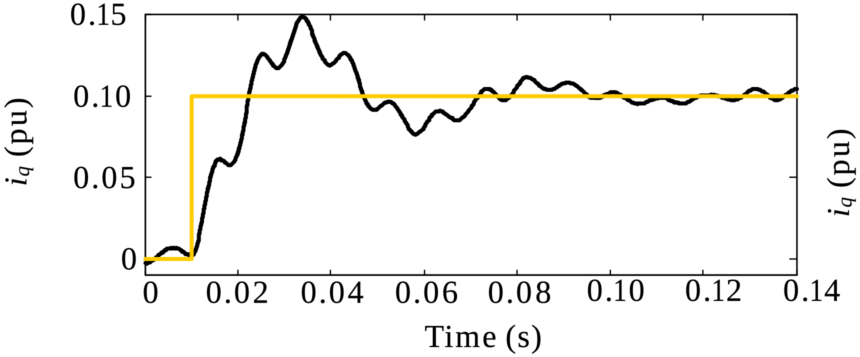
	Peak (pu)	Error (S_e)	Settling (ms)
No SPAACE	1.744	1.0	800
With SPAACE (L)	1.540	0.45 (Δ=55%)	260 (Δ=67.5%)
With SPAACE (Q)	1.206	0.21 (Δ=79%)	500 (Δ=37.5%)

Effect of Scaling Factor *m*

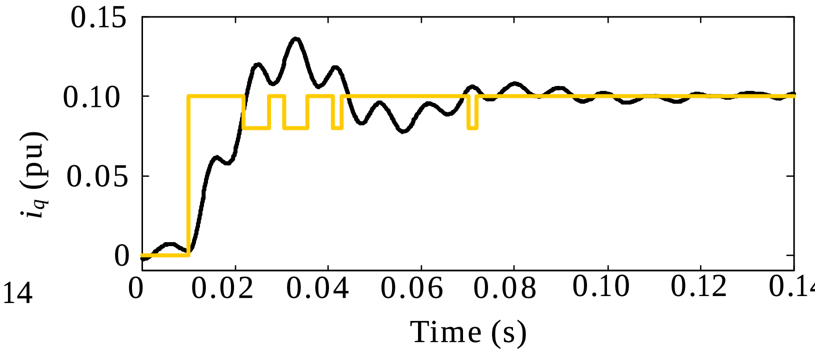
- **Adaptive Nature of SPAACE**



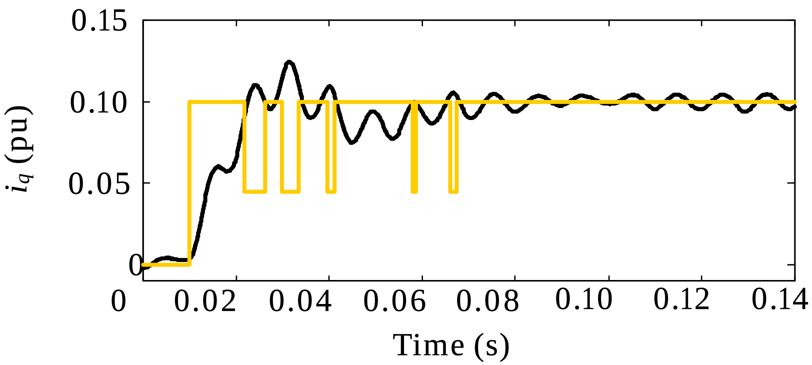
Scaling Factor *m*

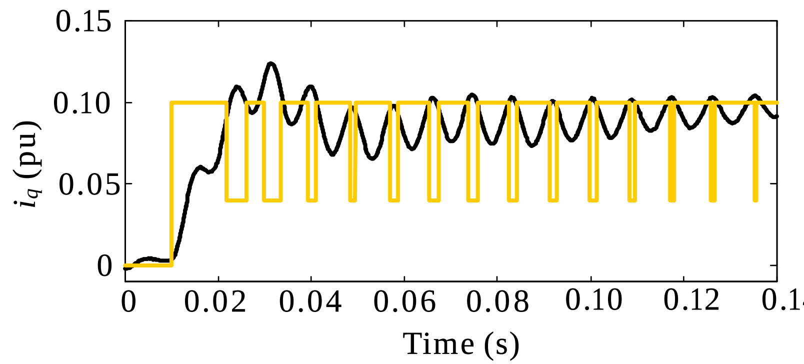


m=0.00



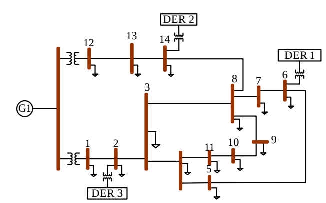
m=0.20





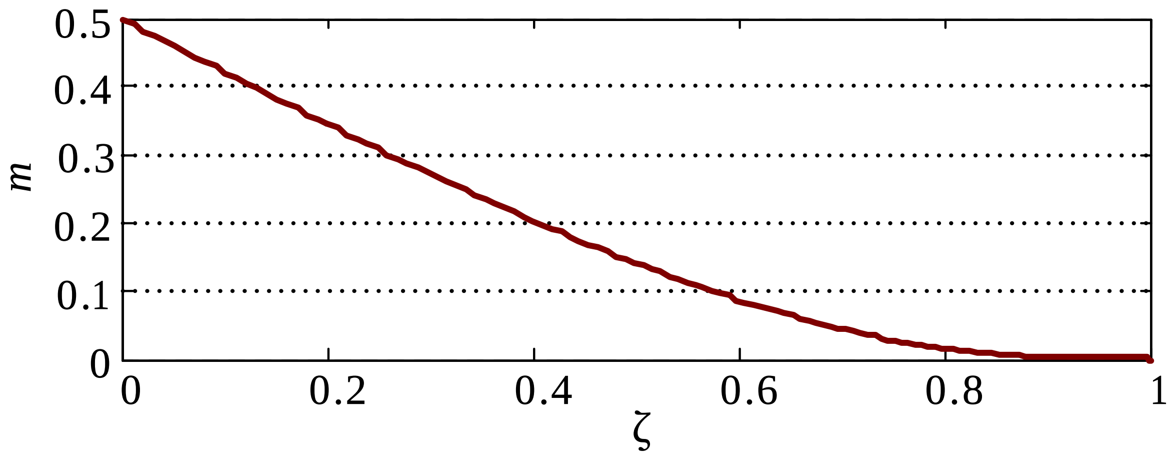
m=0.60

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



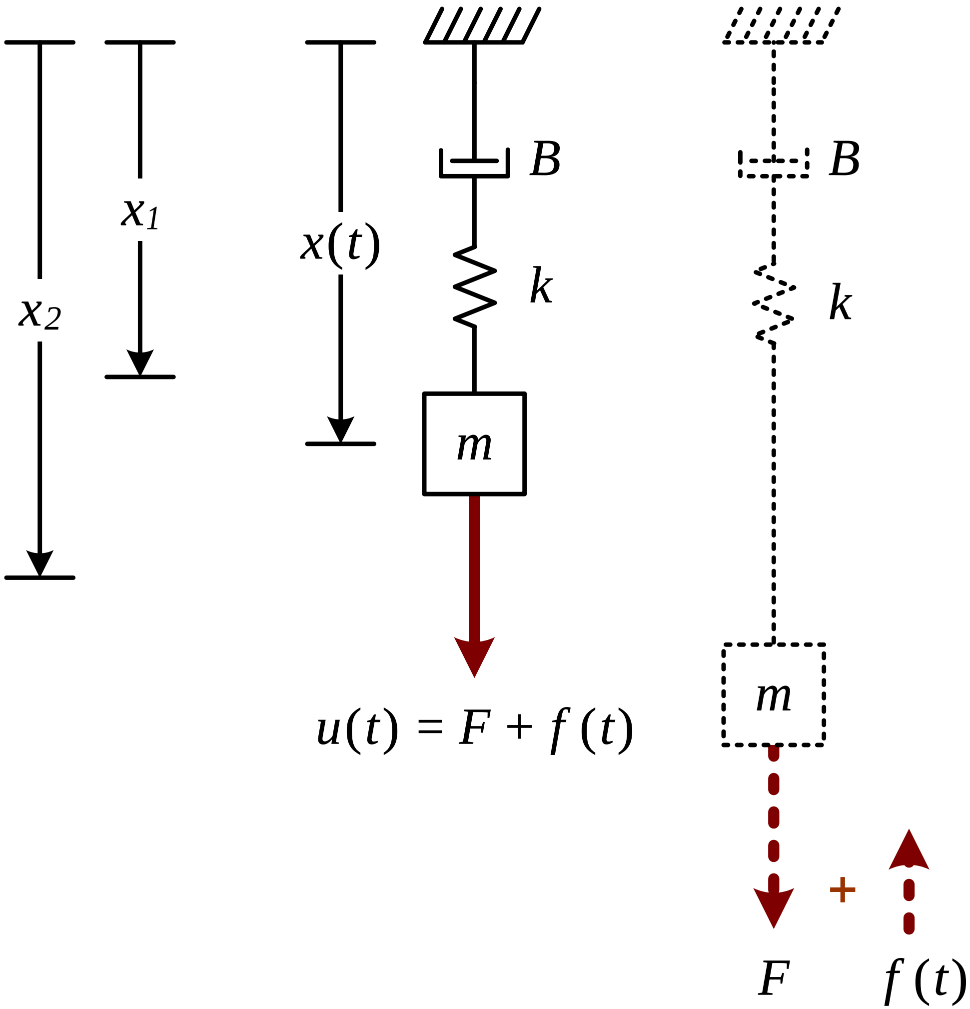
m	S_e
0.00	1.000
0.05	0.923
0.10	0.873
0.15	0.824
0.20	0.806
0.25	0.773
0.30	0.760
0.35	0.743
0.40	0.747
0.45	0.850
0.50	0.740
0.55	0.727
0.60	1.000
0.65	0.971
0.70	1.392
0.75	1.504
0.80	1.770
0.85	1.722
0.90	1.874
0.95	2.040
1.00	2.454

Upper Bound of *m*



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

Physical Analogy

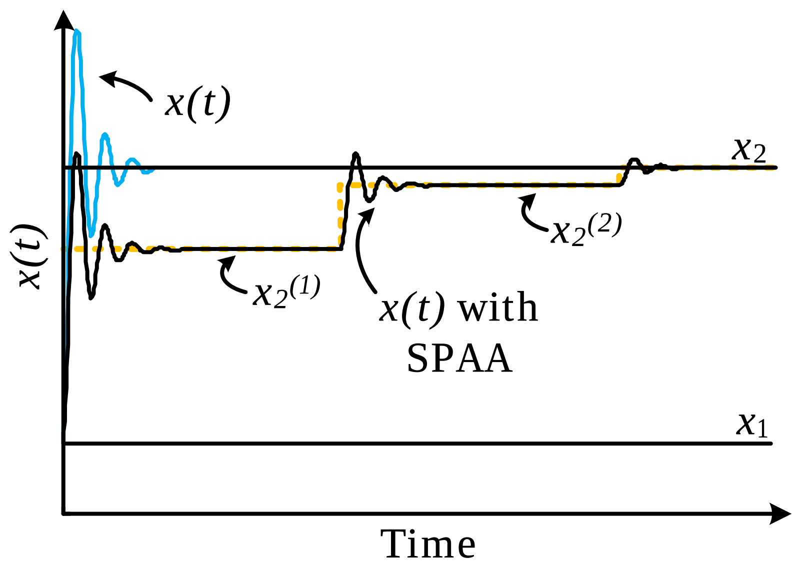


Alternative Methods to SPAACE

	Model-Free	Non-Intrusive	No Access to Controller	Comments
SCALING PI	✔	✔	X	Limited to performance of the original design
RAMP	✔	✔	✔	Unnecessary intervention, DC tracking
MPC	X	✔	X	Computationally intensive
PID	X	✔	X	D as linear extrapolation
ES / IFL	✔	X	X	Sinusoidal perturbation o input
POSICAST	X	✔	✔	Essentially open-loop, 2nd-order
SPAACE	✔	✔	✔	

SPAA

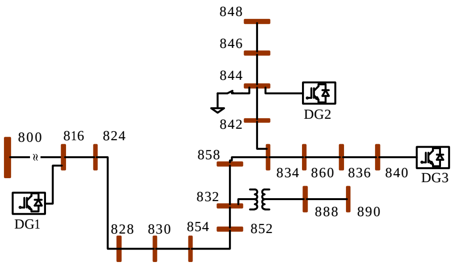
- **If *a priori* knowledge of overshoot is available**
  - SPAA /spɑː/: Set point automatic adjustment

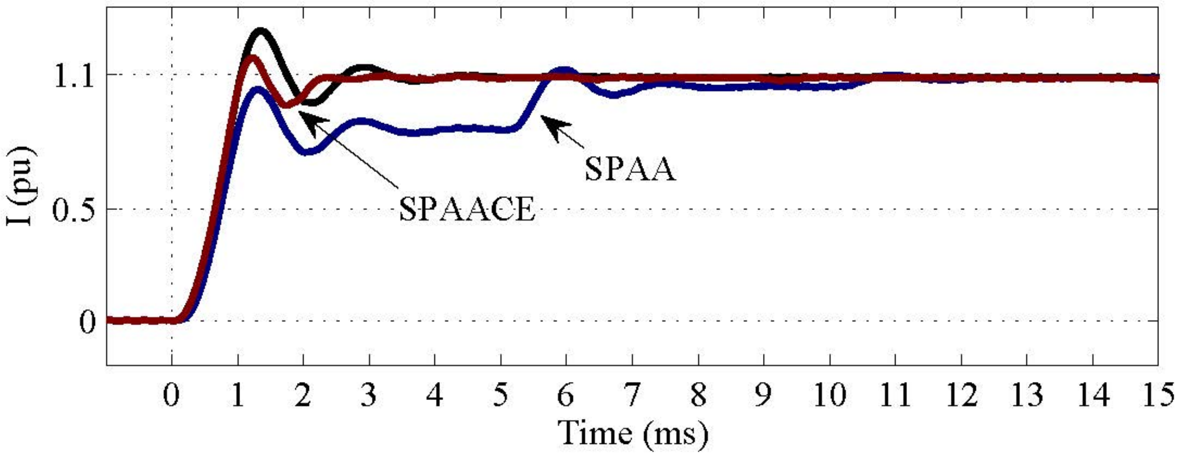


$$x_2^{(i)} = \frac{x_{\text{upper-limit}} + M_p x_2^{(i-1)}}{1 + M_p}$$

SPAA Case Study

- **Start-Up Current Control**
  - IEEE 34-bus system with 3 DERs
  - DER1 and 3: i_d = 1.0 pu, i_q = 0
  - DER2: off to i_d = 1.08 pu
  - SPAA assumes ζ=0.361 and ω=8450 rad/s

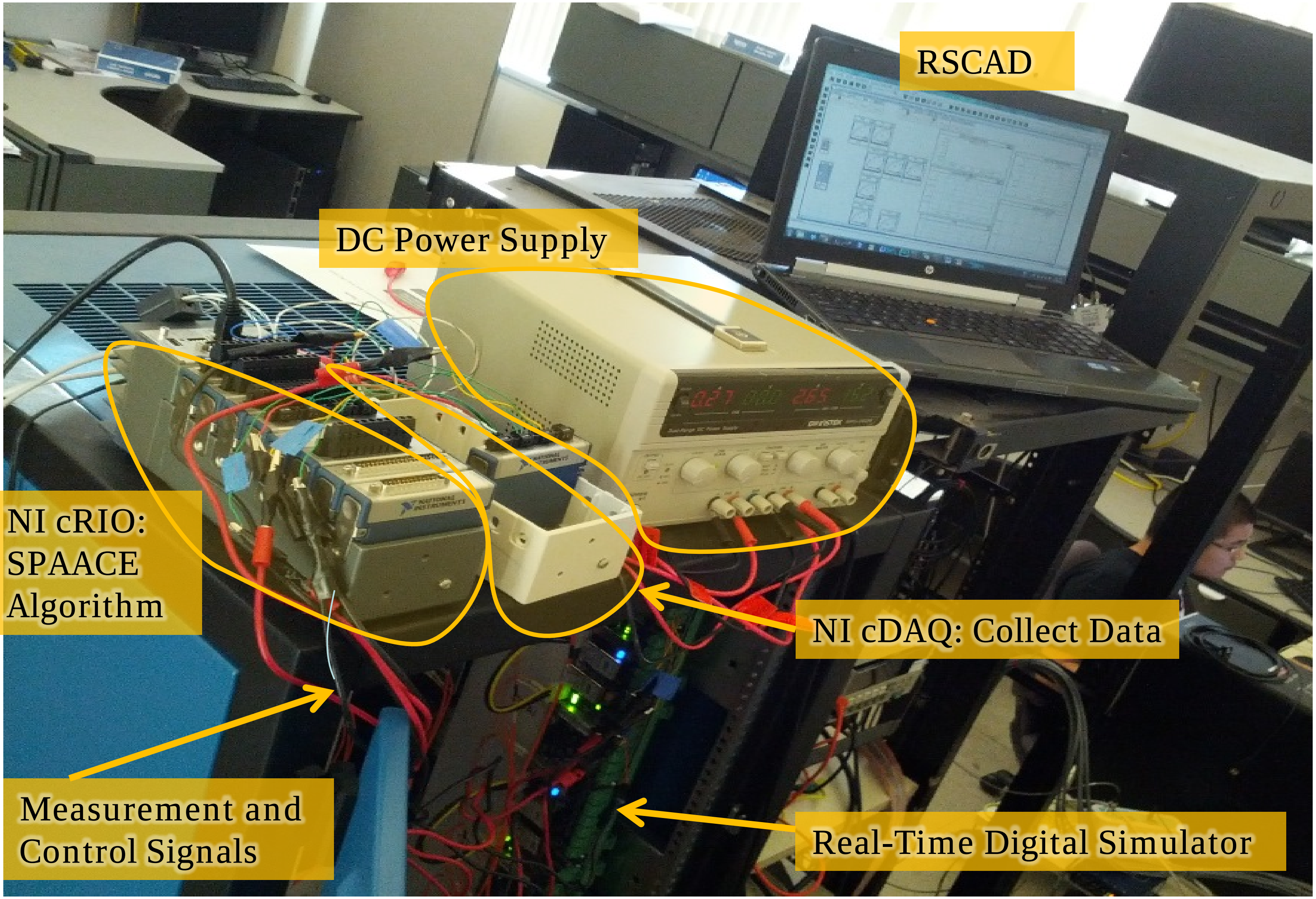




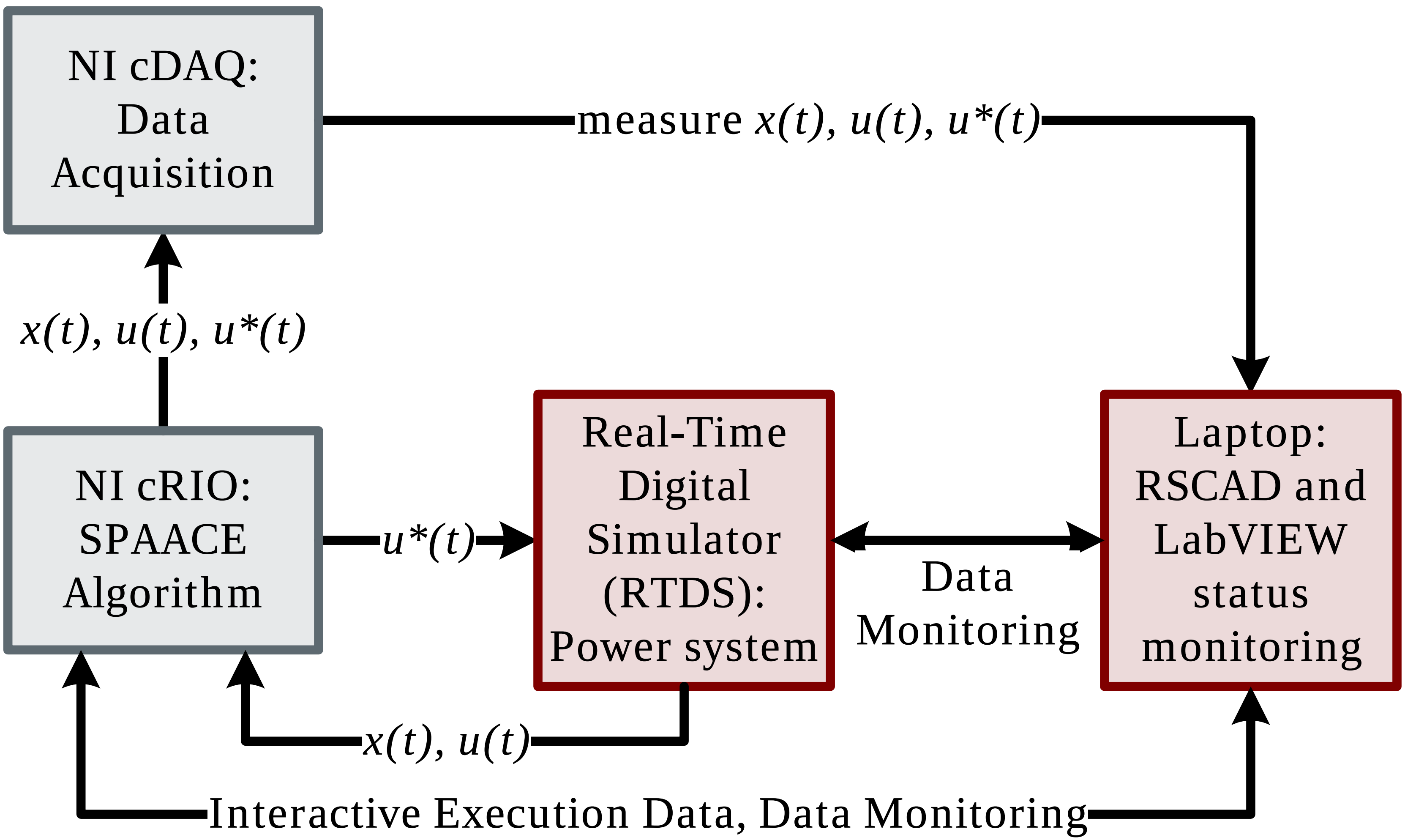
SPAA vs. SPAACE

	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)

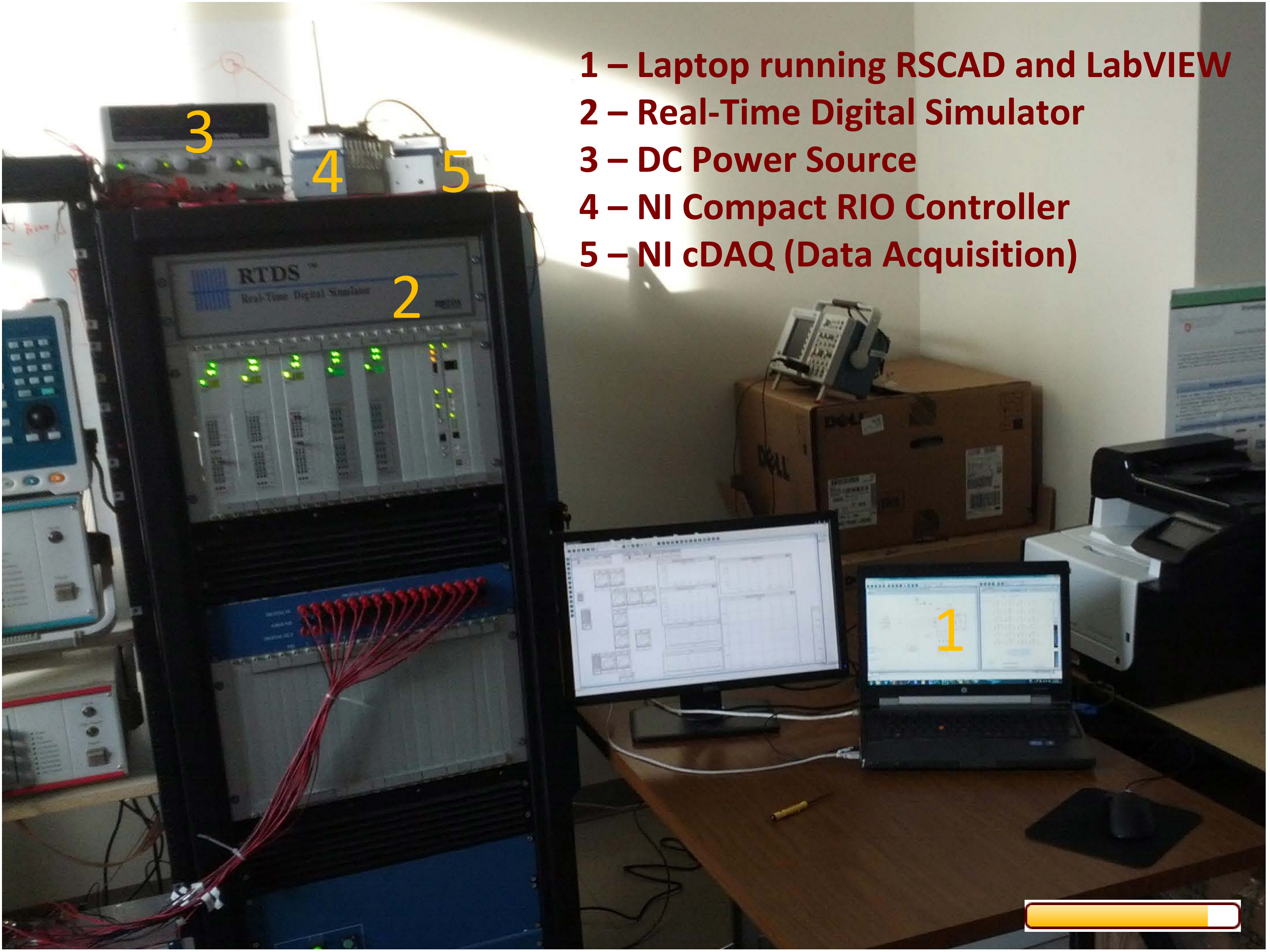
Experimental Implementation



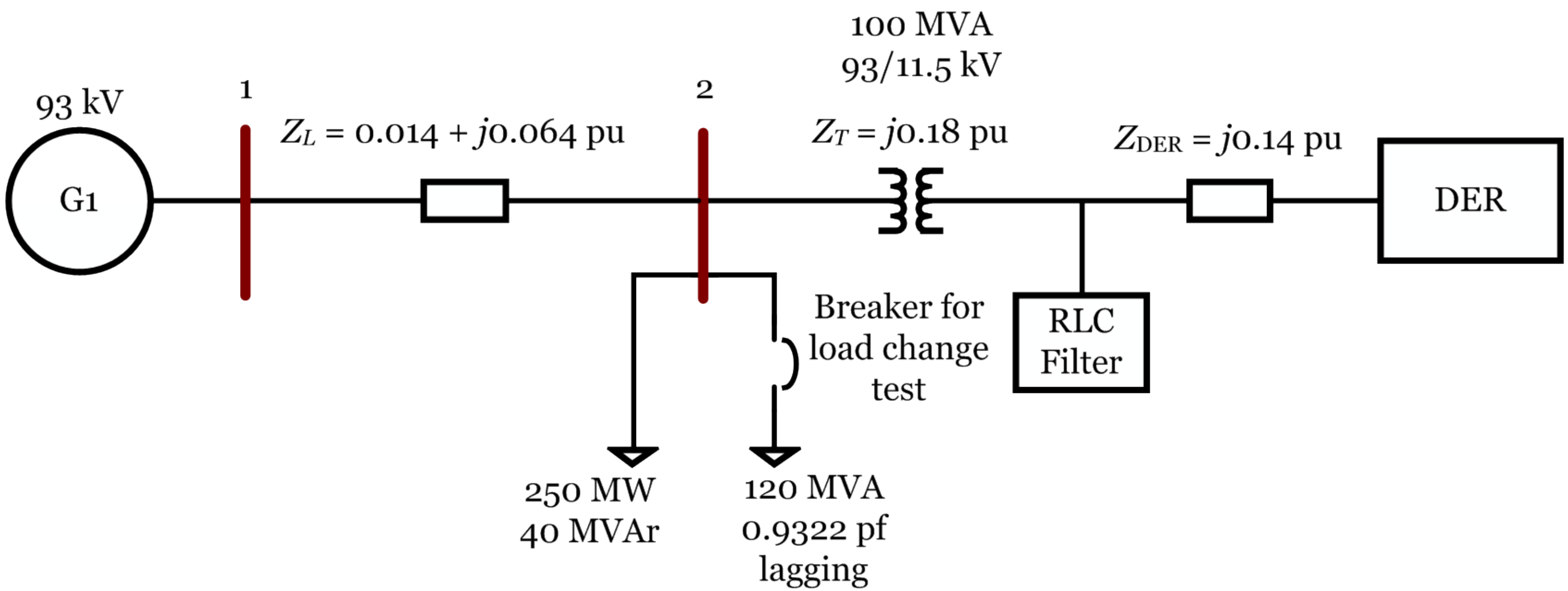
Experimental Implementation



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

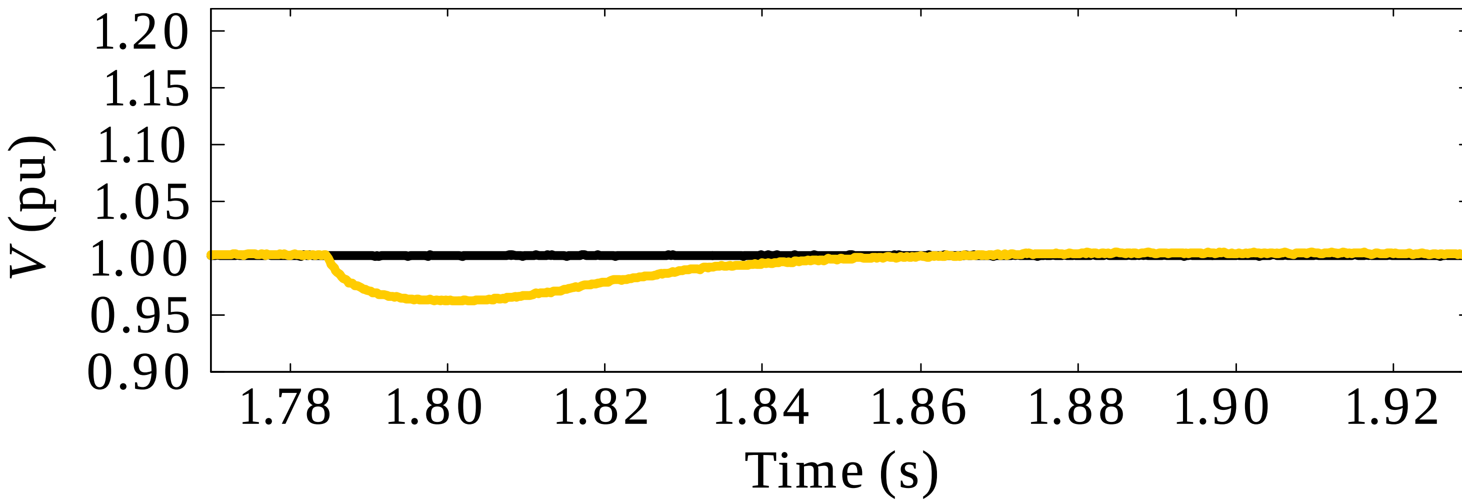

1 – Laptop running RSCAD and LabVIEW
2 – Real-Time Digital Simulator
3 – DC Power Source
4 – NI Compact RIO Controller
5 – NI cDAQ (Data Acquisition)
RTDS
3
4
5
2
1

Test System

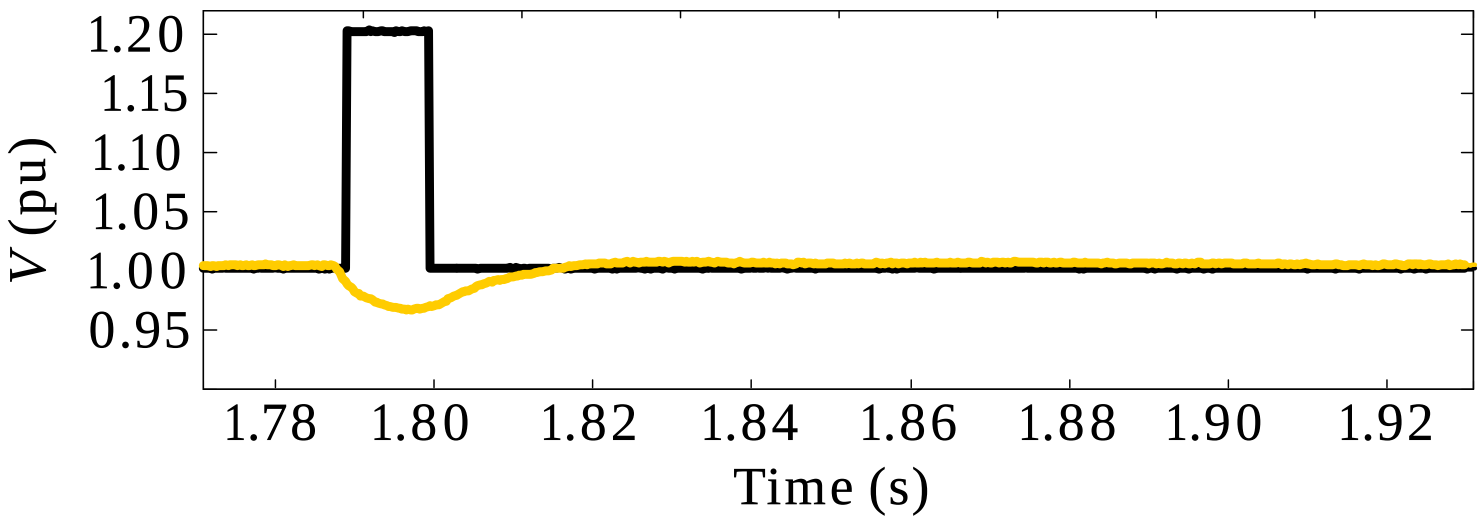

100 MVA
93/11.5 kV
93 kV
1
2
Z_L = 0.014 + j0.064 pu
Z_T = j0.18 pu
Z_{DER} = j0.14 pu
G1
DER
Breaker for load change test
RLC Filter
250 MW
40 MVAr
120 MVA
0.9322 pf
lagging

Case I: Load Energization (1.2 pu)

Without SPAACE

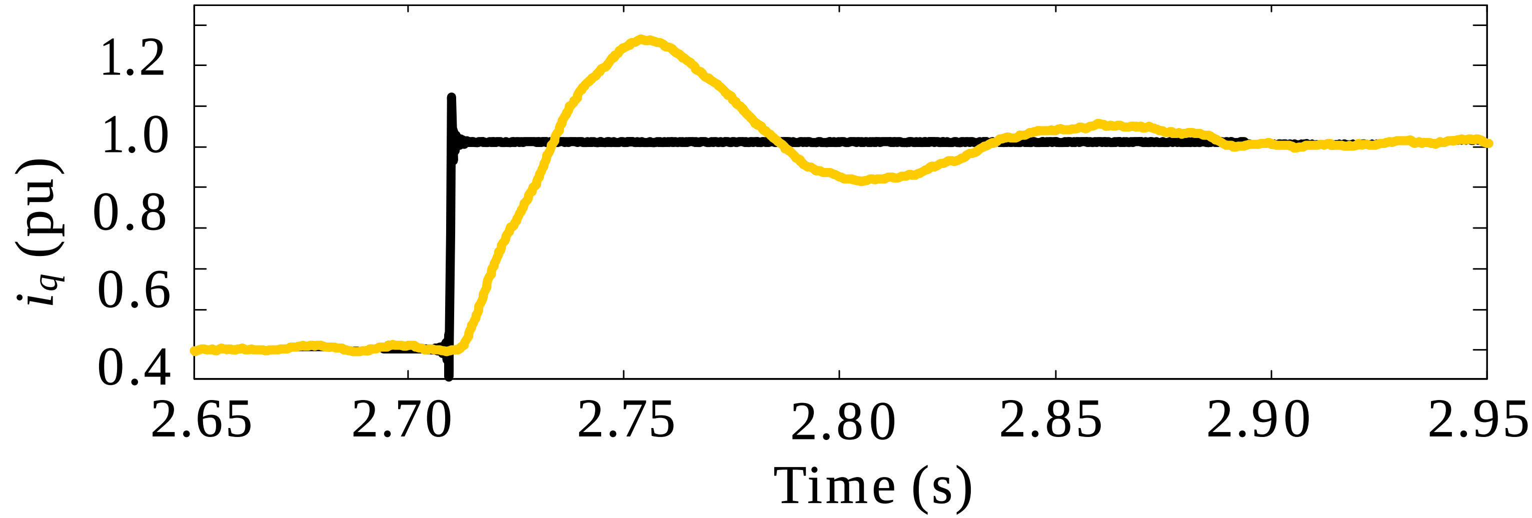


With SPAACE

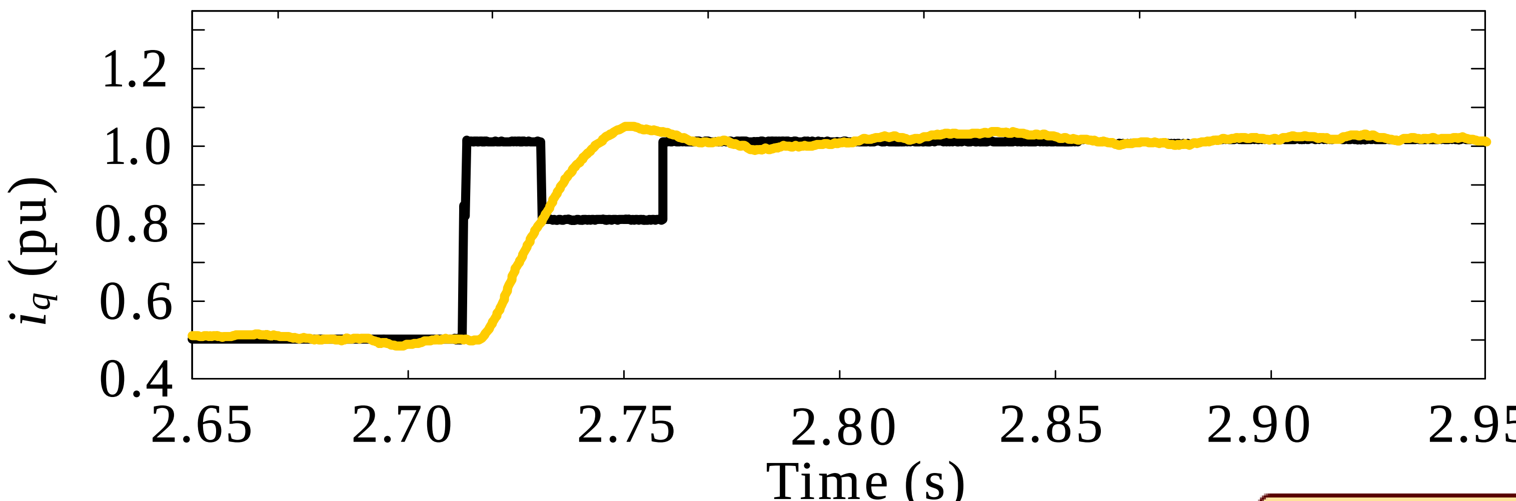


Case II: Step Change in i_q

Without SPAACE



With SPAACE



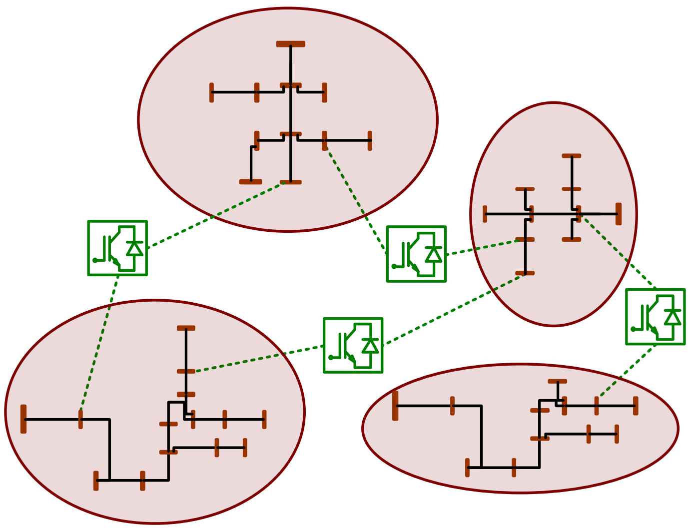
Conclusions

- **By appropriately designing the trajectory to reduce overshoots, it is possible and safe for a system to operate closer to its limits.**

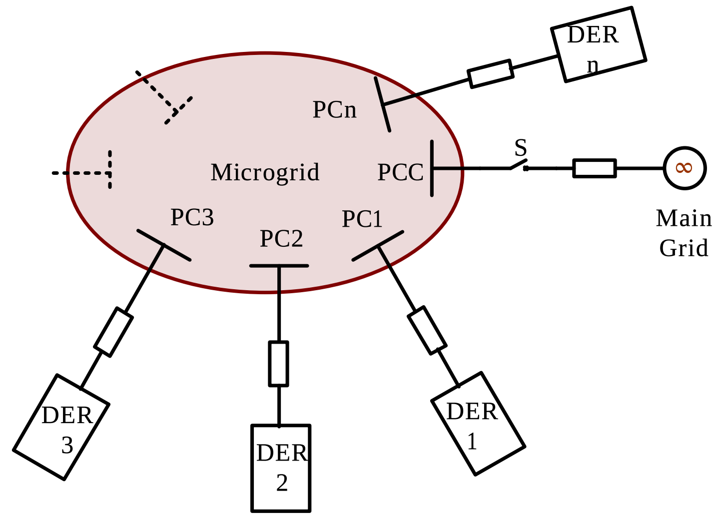
- **Offline (PSCAD) and real-time (RTDS) simulation studies show that SPAACE is effective in mitigating transients:**
  - Step change: Mitigating overshoots (37%)
  - Fault: Closer set point following
  - Load energization: Eliminating a peak of 1.15 pu
  - Load disconnection in a unbalanced system: Stabilizing oscillatory behavior of voltage

Applications

- **Systems with Limited Resources**
  - Transients may exceed the capacity of the system



Large AC/DC Systems
Segmented Power Systems



Emerging Small AC Systems
All-Electric Ships and Military Systems

- **Emerging Application: HSIL transmission lines**

Thank You

Control Strategies for Microgrids

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