Energy Systems Innovation Center
WASHINGTON STATE UNIVERSITY

Power Electronics for Integration of Renewables

Ali Mehrizi-Sani
Assistant Professor
LIPE • EECS • WSU

Based on the work of current and former graduate students: Mehrdad Yazdanian, Chris Stone, Younes Sangsefidi, Saleh Ziaeinejad, and Hooman Ghaffarzadeh

Microgrid Symposium • Niagara-on-the-Lake, ON • October 2016

WSU Power Engineering Program







Dave Bakken, Professor

Anjan Bose, Regents Professor

Anamika Dubey, Assistant Professor

Adam Hahn, Assistant Professor

Carl Hauser, Associate Professor

Tosh Kakar, Clinical Associate Professor

Chen-Ching Liu, Director of ESIC and Boeing Professor

Saeed Lotfifard, Assistant Professor

Ali Mehrizi-Sani, Assistant Professor

Robert Olsen, Professor

Noel Schulz, Professor and First Lady (June 2016)

Anurag Srivastava, Associate Professor

Mani Venkatasubramanian, Professor

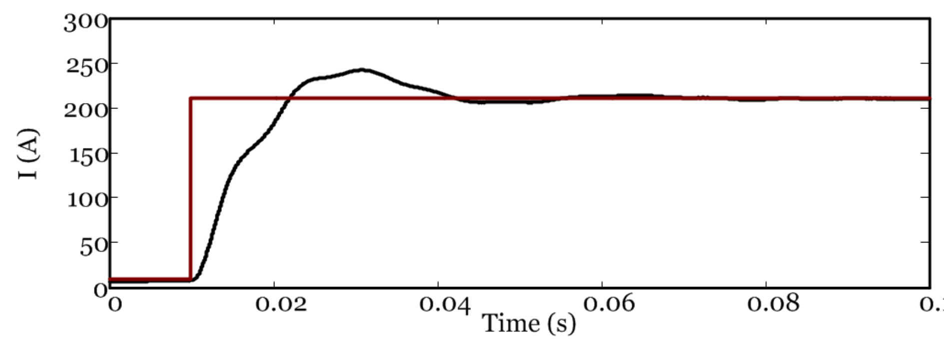




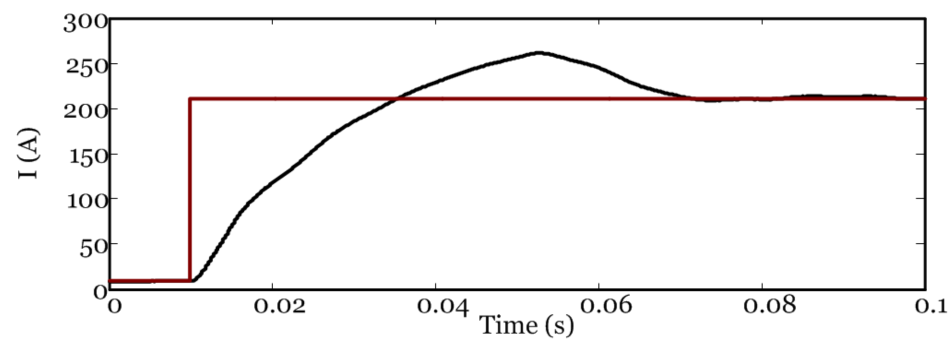
Challenge

- **Controllers are designed for a prespecified configuration and their performance deteriorates when the host system, which is also part of the plant, varies significantly from what was used for the original design.**

Original System
Overshoot: 15%
Settling time: 32 ms



Load Disconnected
Overshoot: 26%
Settling time: 67 ms



Background

- **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?

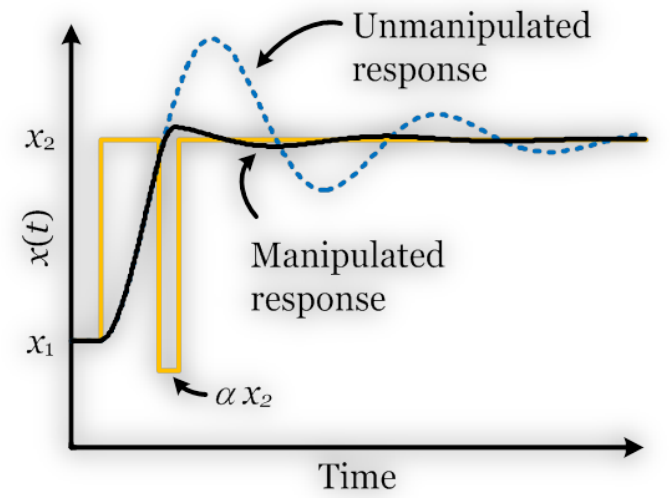
Controller Design: Existing Approaches

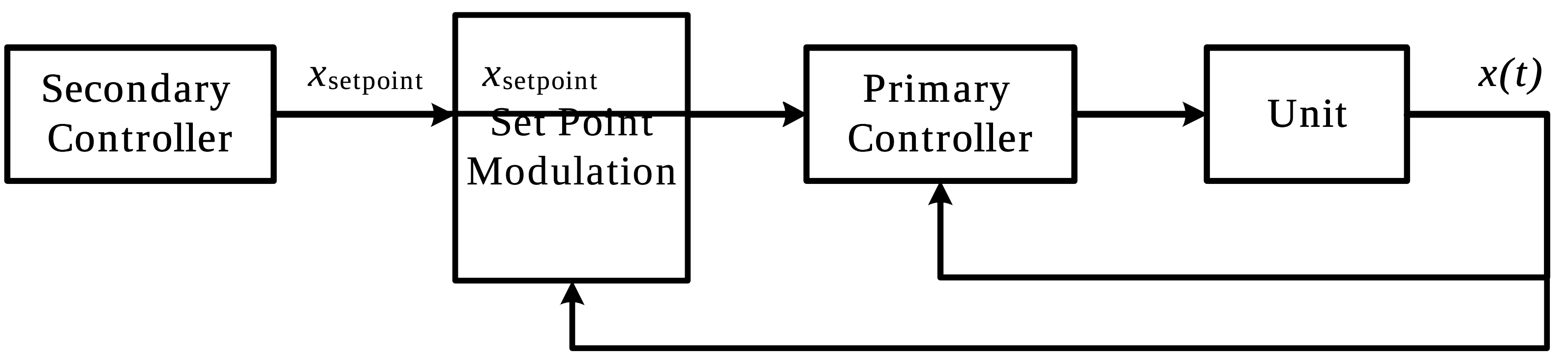
- **Existing approaches to ensure dynamics of the system are handled design controllers based on**
  - Analytical formulation and model-based tuning (Astrom's work)
  - Optimization (Gole's work)
- **Why not just redesign?**
  - Need updated system models
  - Need a computational infrastructure to allow redesign
  - Need access to the internal parameters of the controller
  - New design will again have limited robustness to topology, operating point, and system parameters

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

Proposed Solution

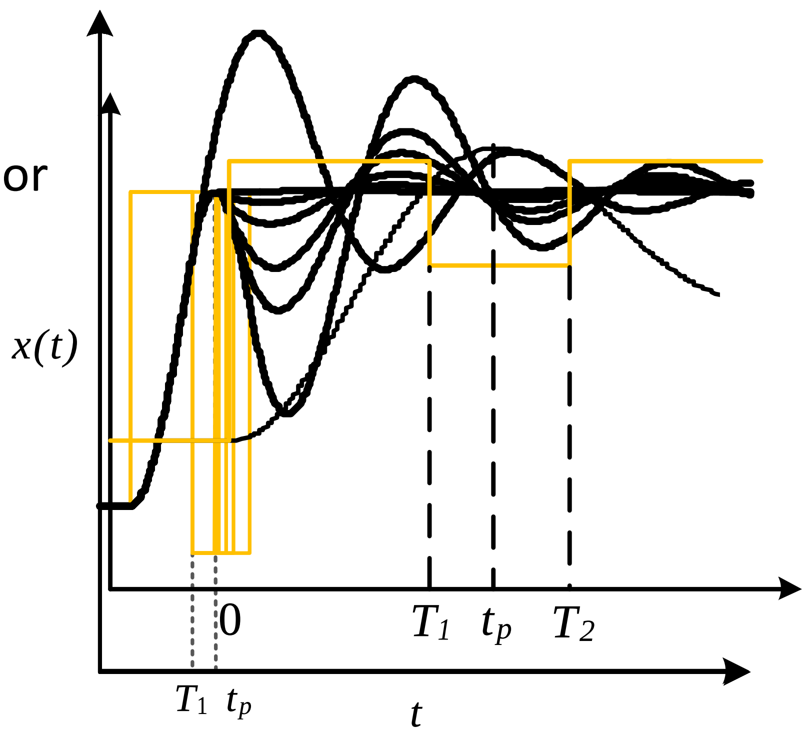
- **Improving the response by temporarily manipulating the set point without changing the original controller.**
- **Features:**
  - Robust to topological changes
  - Independent of the system model
  - Requires little information about unit





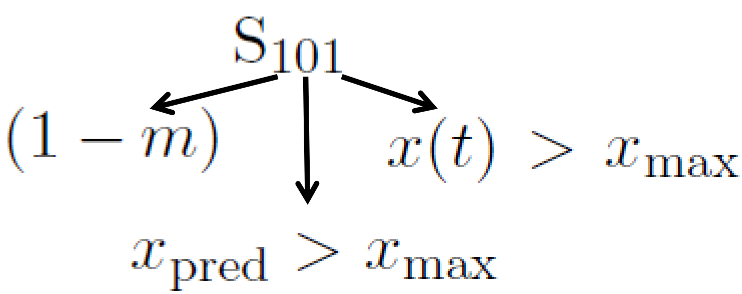
Set Point Modulation

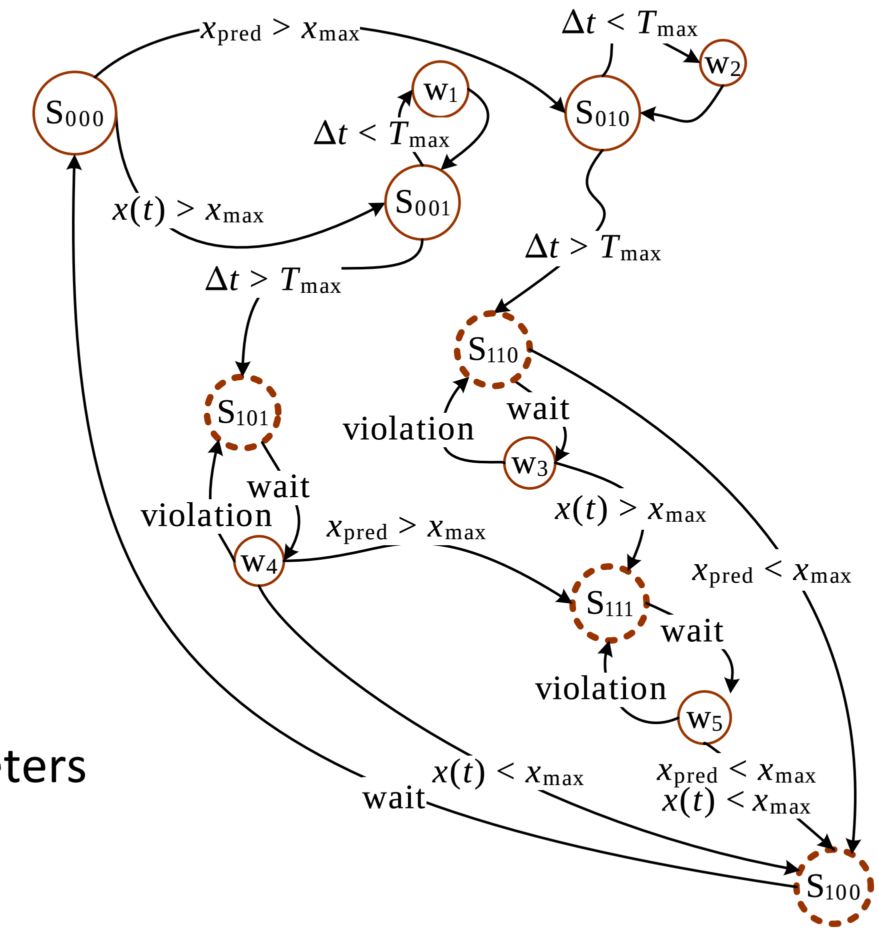
- **Initial Idea**
  - Choose T_1 so that the peak of the response equals the reference
  - Choose T_2 to be the time of this peak
- **Not Implementable**
  - Faster-than-real-time simulator
  - Closed-form solution
  - System parameters



Finite-State Machine

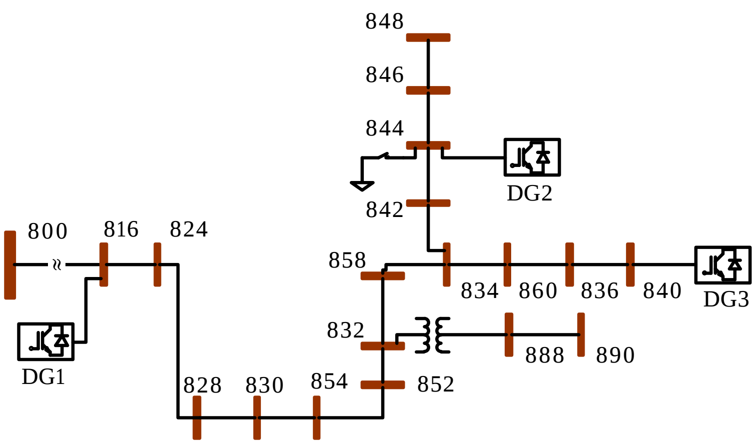
- **SPAACE /speɪs/: Set Point Automatic Adjustment with Correction Enabled**
- **State Numbering:**





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

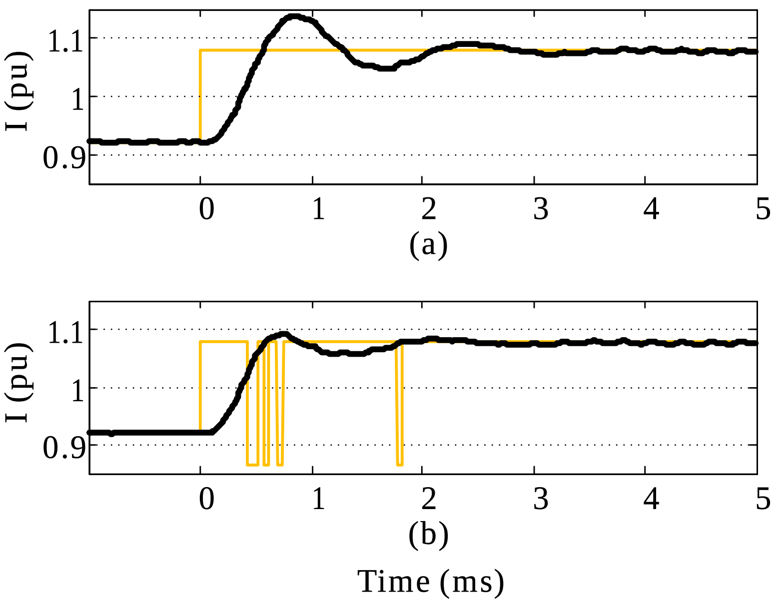
Case Study I: Set Point Change



IEEE 34-Bus System

Added 3 DG units and a load

Operates in grid-connected mode



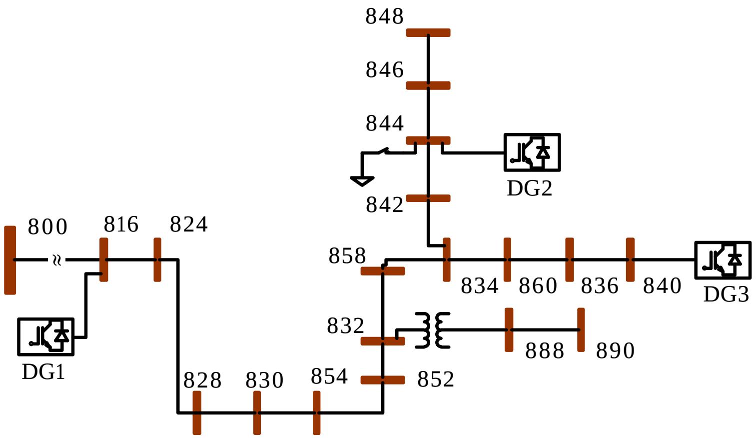
System Response

DG2 step change from 0.91 pu to 1.09 pu

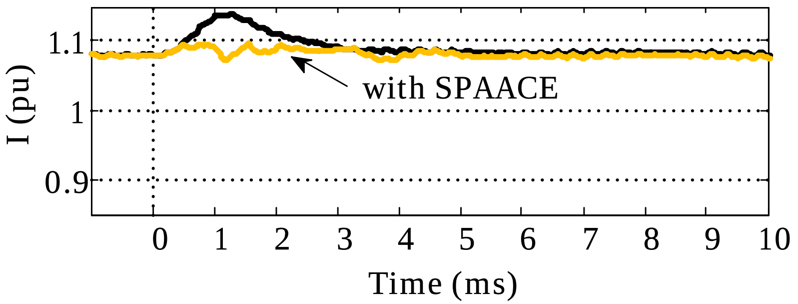
DG1 and DG3 unchanged

(40% overshoot)

Case Study II: Load Disconnection

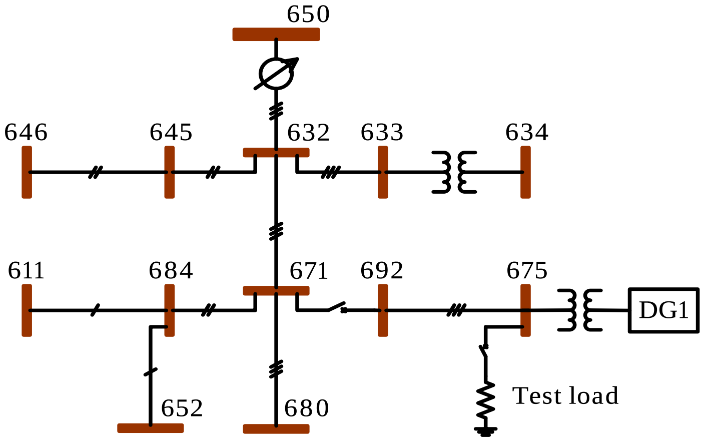


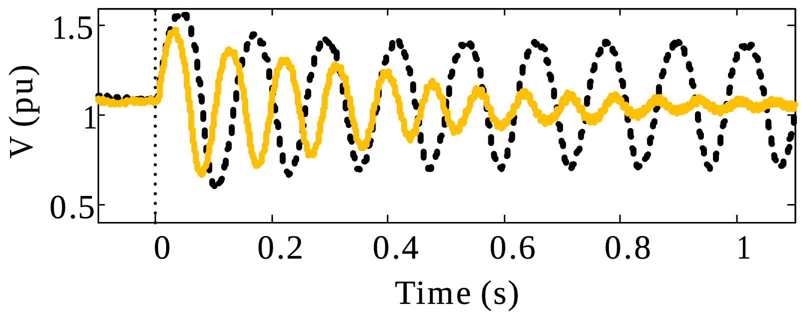
IEEE 34-Bus System
Added 3 DG units and a load
Operates in grid-connected mode



System Response
Resistive 0.5 pu load disconnected
(15% overshoot)

Case Study III: Unbalanced System





IEEE 13-Bus Unbalanced System

Added a DG unit and a test load

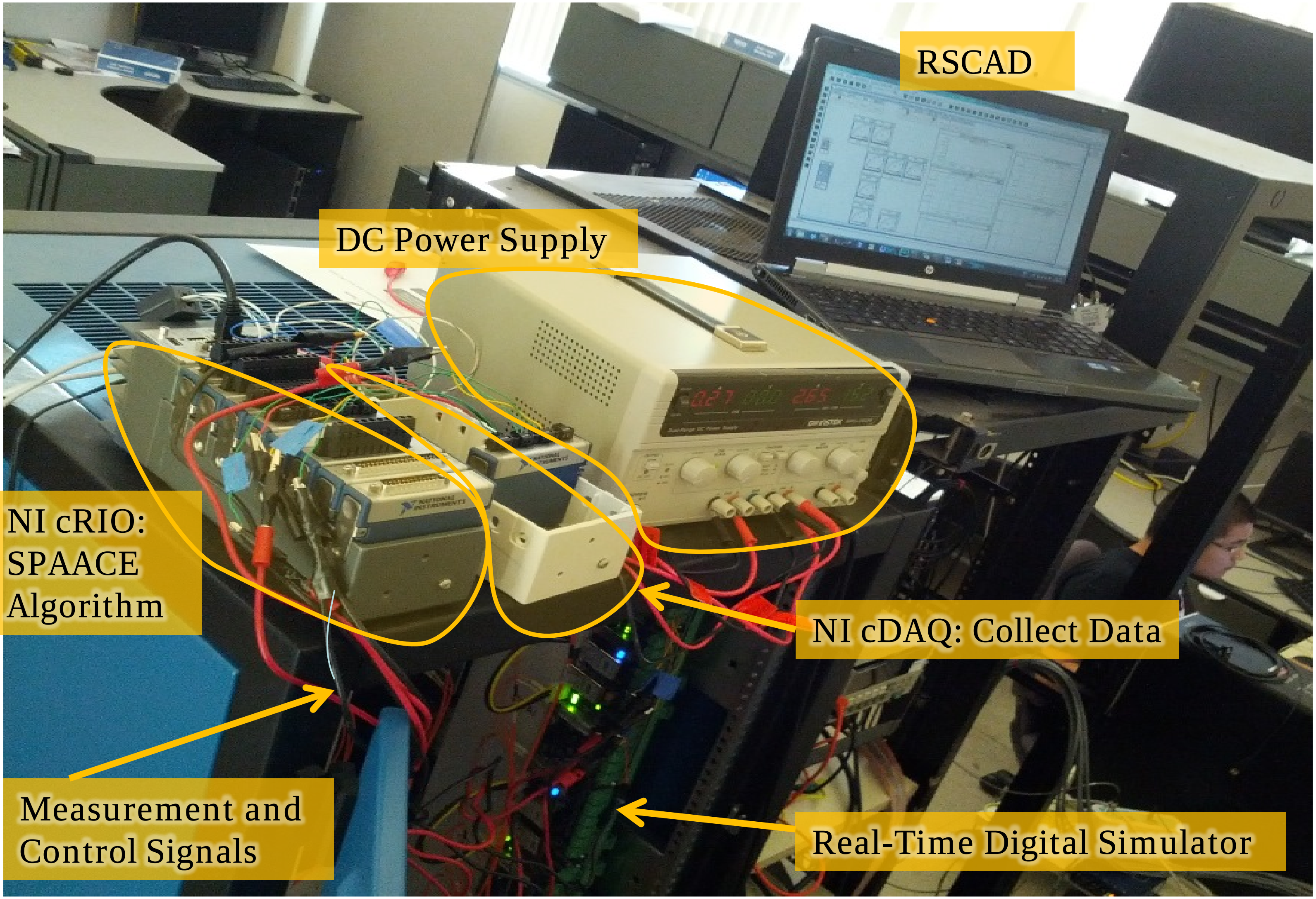
Operates in islanded mode

System Response

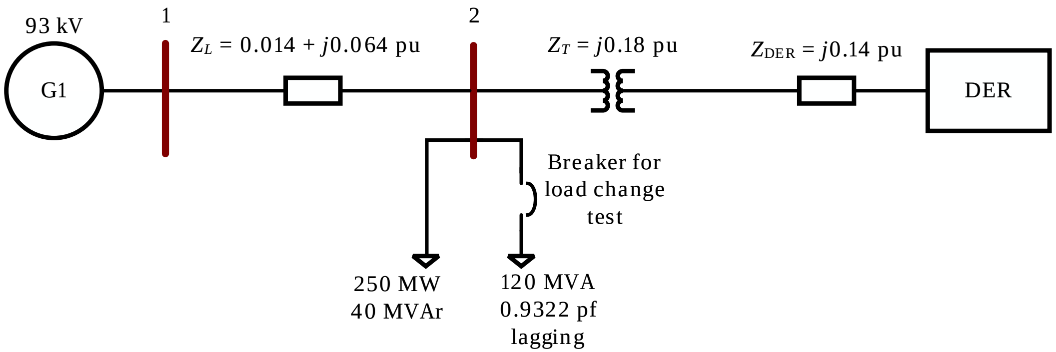
Resistive 1 pu load switched off

Unstable system to stable system

Experimental Implementation

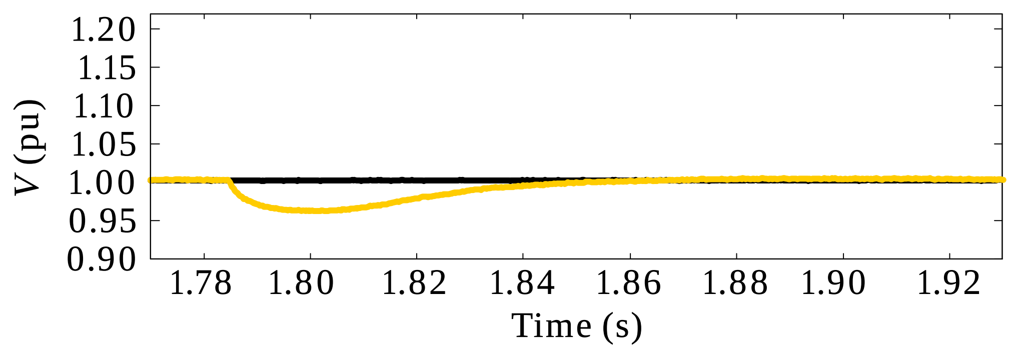


Case I: Load Energization (1.2 pu)



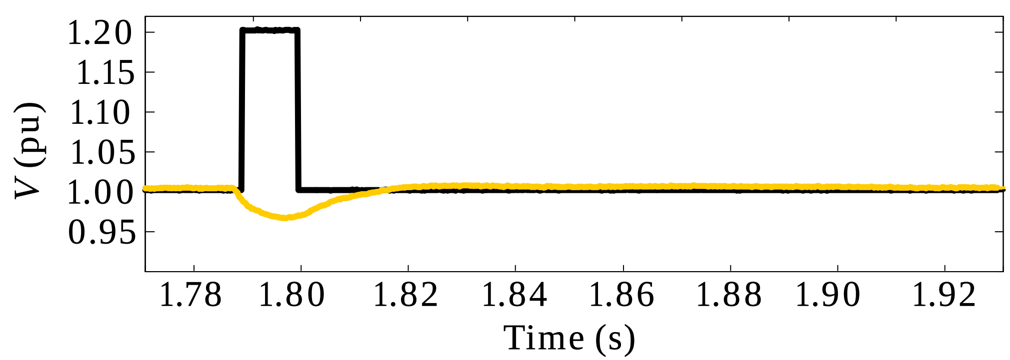
Without SPAACE

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



With SPAACE

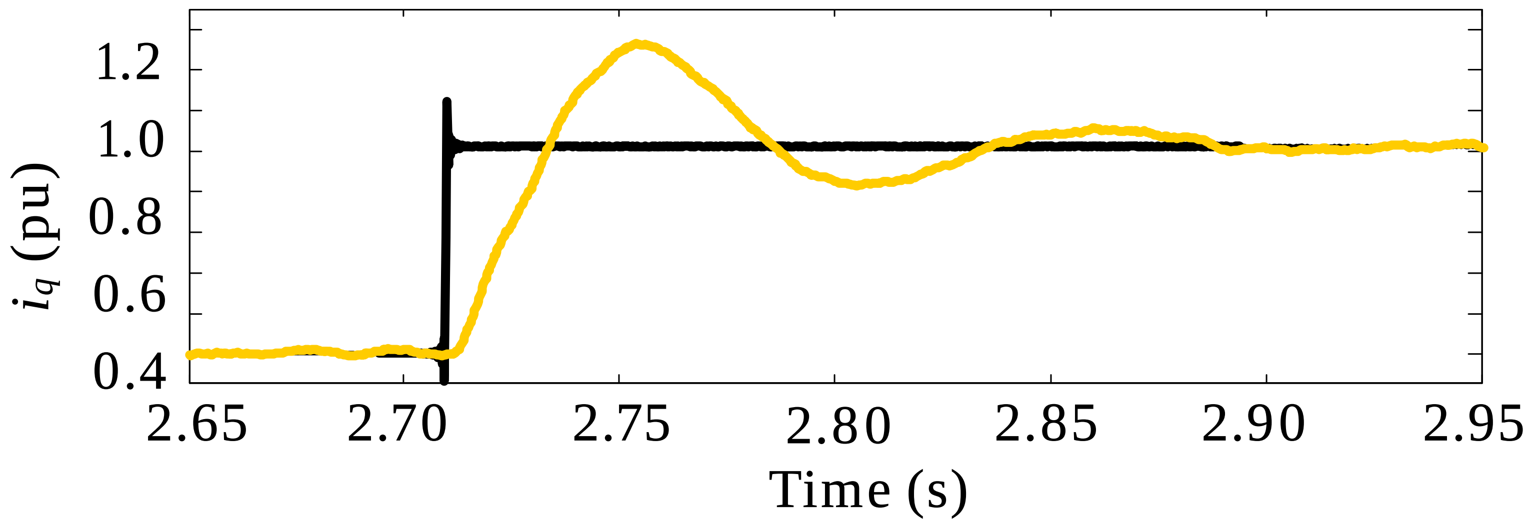
M_p: 4%
$t_{settling}$: 30 ms



Case II: Step Change in i_q

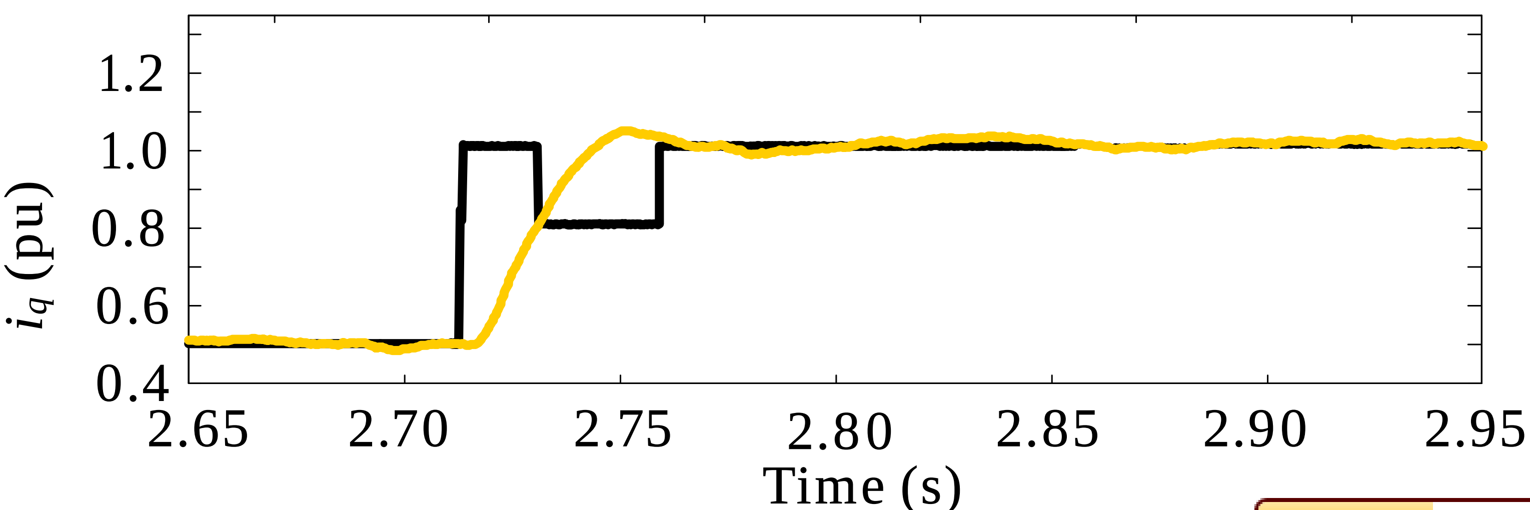
Without SPAACE

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



With SPAACE

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



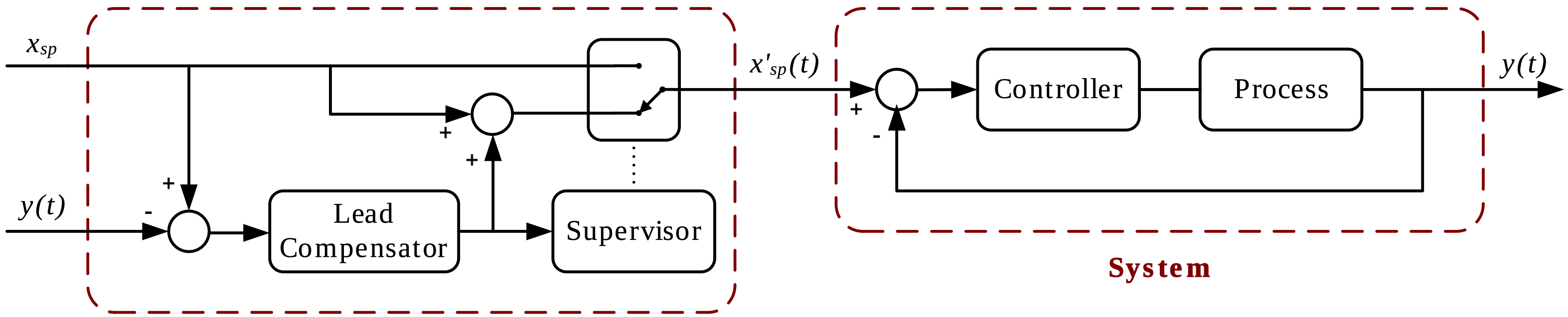
Variant: Smooth SPAACE

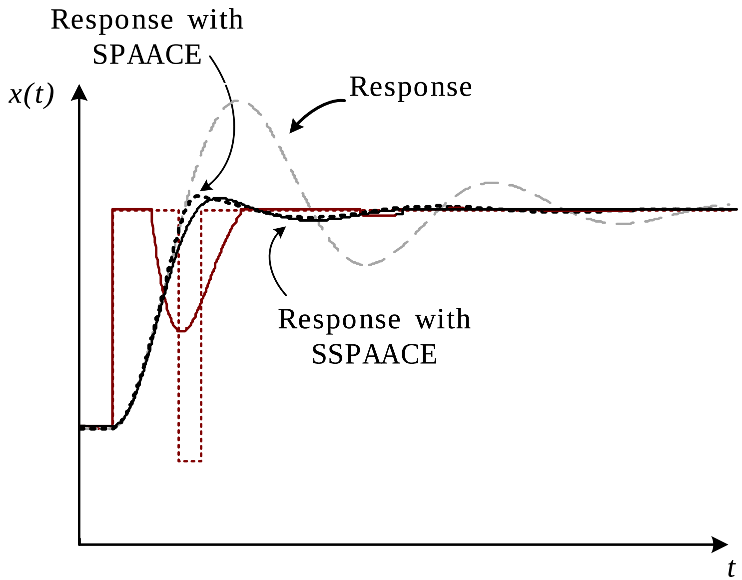
- **SPAACE is not directly applicable to applications such as drive systems because the step changes introduced in the set point may cause torque pulsation, mechanical fatigue, and stress.**

- **A “smooth” variant of SPAACE (SSPAACE) is proposed to modify the set point more gracefully than SPAACE; that is, it introduces a smooth change as opposed to a step change.**

SSPAACE with a Hybrid Structure

- **SSPAACE utilizes a supervisory switching scheme based on observing the set point and the predicted error.**





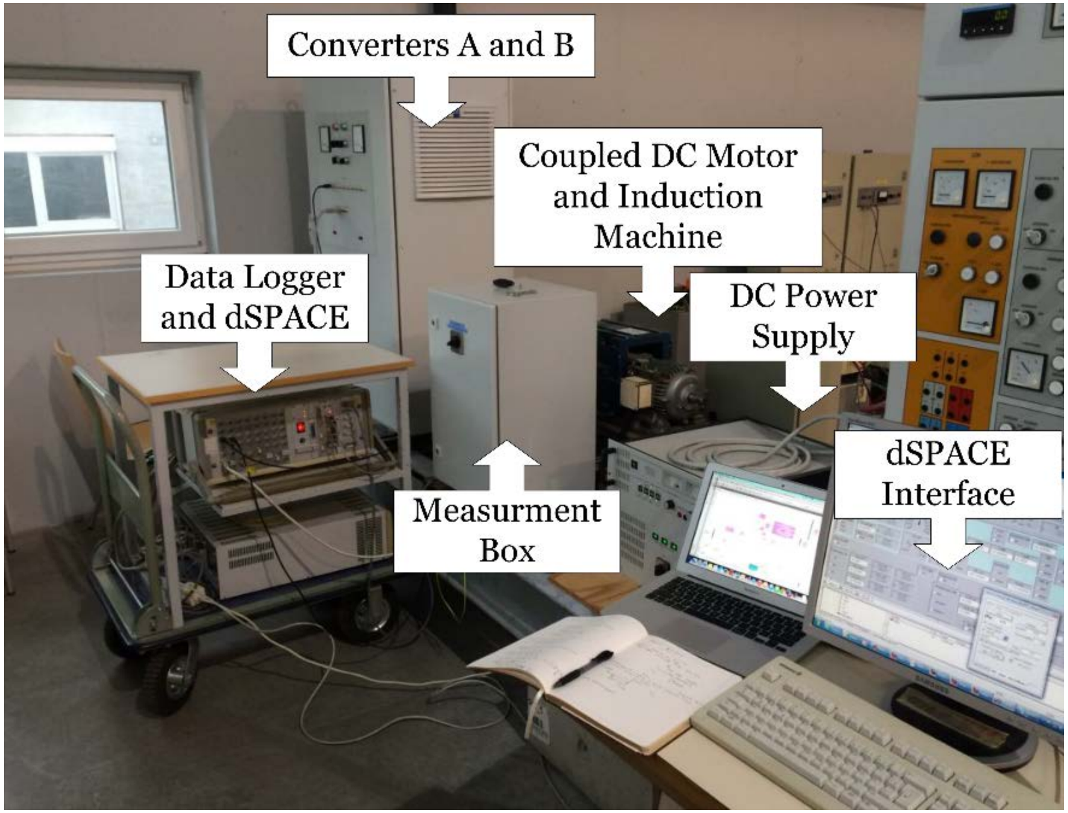
$$x'_{sp}(t) = \begin{cases} x_{sp}, & e_{\min} \le e_{\text{pred}}(t) \le e_{\max} \\ x_{sp} + m(t), & \text{otherwise}, \end{cases}$$

$$m(t) = m \times e_{\text{pred}}(t)$$

$$e_{\text{pred}}(t) = \frac{sT+1}{\alpha sT+1} e(t), \qquad [\alpha < 1]$$

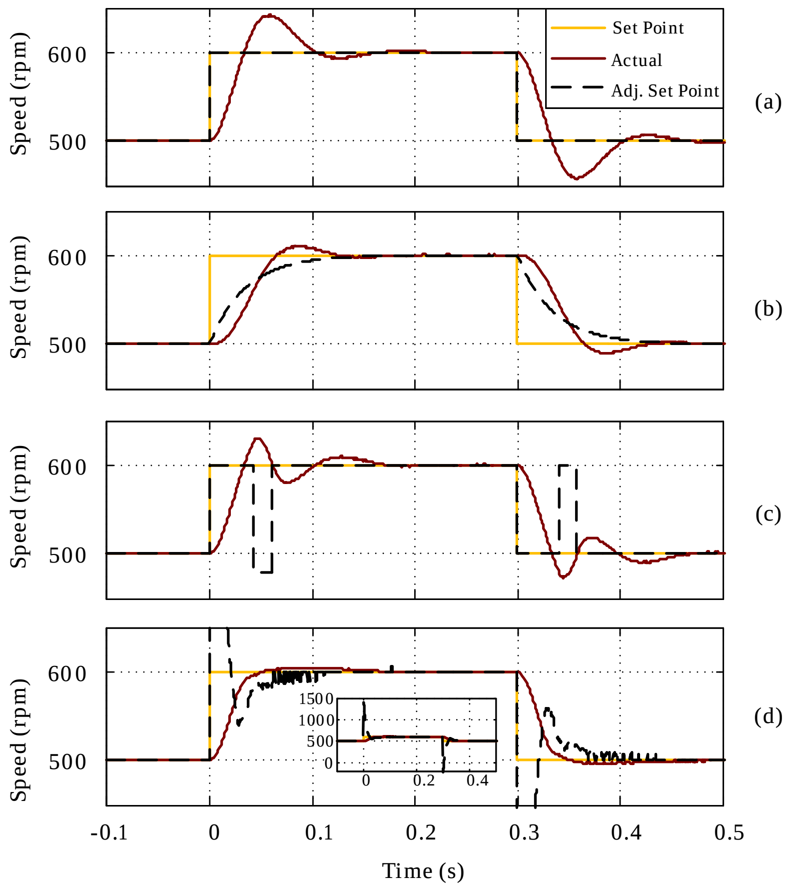
Study System

Parameter	Value
General Parameters	
Incremental encoder resolution, R	10 kPPR
Sampling frequency, f_s	5 kHz
Switching frequency, f_{sw}	5 kHz
DC Machine	
Rated power, P_{rated}	3.5 kW
Rated armature voltage, $V_{a,\text{rated}}$	120 V
Rated armature current, $I_{a,\text{rated}}$	35.5 A
Rated excitation voltage, $V_{e,\text{rated}}$	120 V
Rated excitation current, $I_{e,\text{rated}}$	0.79 A
Rated speed, ω_{rated}	3780 rpm
Armature resistance, R_a	389 mΩ
Armature inductance, L_a	1.389 mH
Excitation resistance, R_e	117.14 Ω
Moment of inertia, J_{dc}	0.013 26 kgm^2
Induction Machine	
Rated power, P_{rated}	3 kW
Rated voltage, V_{rated}	72 V
Rated current, I_{rated}	37 A
Number of poles, P	4
Rated frequency, f_{rated}	150 Hz
Rated speed, ω_{rated}	4278 rpm
Stator resistance, R_s	170.62 mΩ
Stator leakage inductance, $L_{l,s}$	0.339 mH
Rotor resistance, R_r	116.29 mΩ
Rotor leakage inductance, $L_{l,r}$	0.339 mH
Magnetizing inductance, L_m	7.3 mH
Moment of inertia, J_{im}	0.003 74 kgm^2



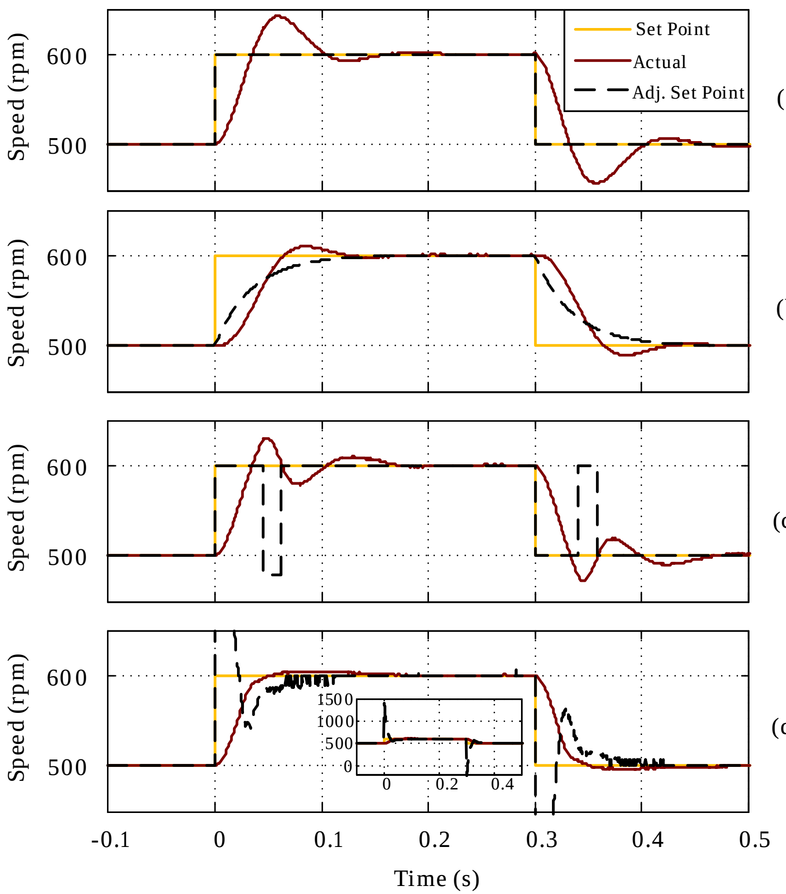
Setup at Graz University of Technology, Austria

Step Change in the Speed Set Point



Simulation Results

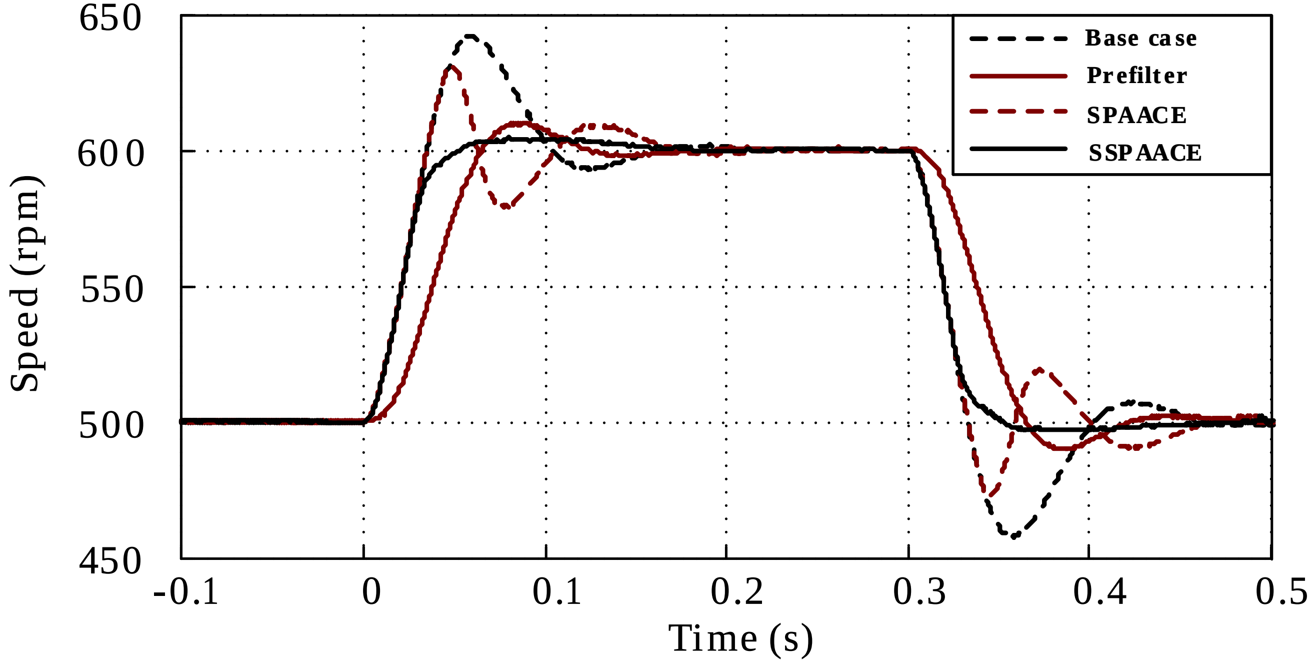
Step change in ω_{ref} from 500 to 600 rpm: a) base case, b) prefilter, c) SPAACE, and d) SSPAACE.



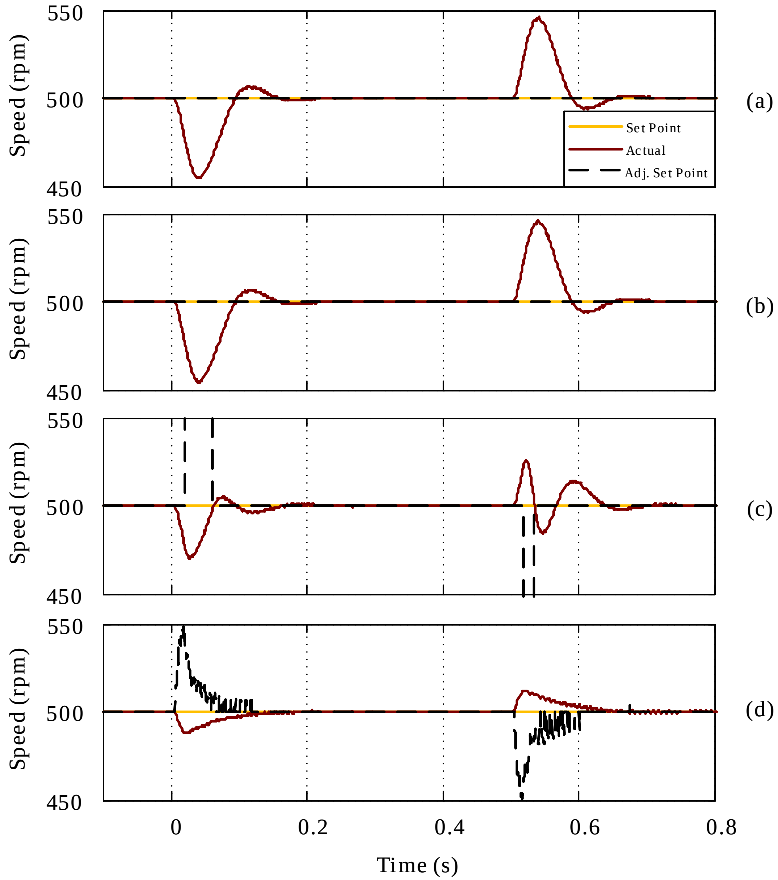
Experimental Results

Step Change in the Speed Set Point

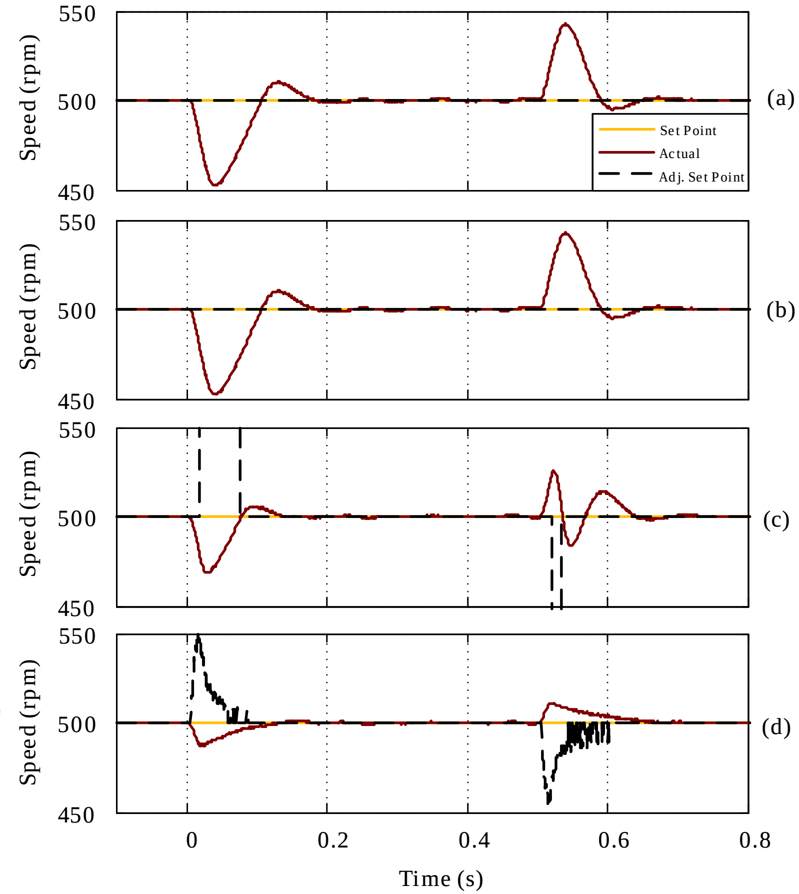
Approach	Overshoot (%)	Rise time (ms)	Settling time (ms)
Base case	42	32	140
Prefilter	10	57	110
SPAACE	30	32	140
SSPAACE	4	35	42



External Disturbance: Load Change



Simulation Results

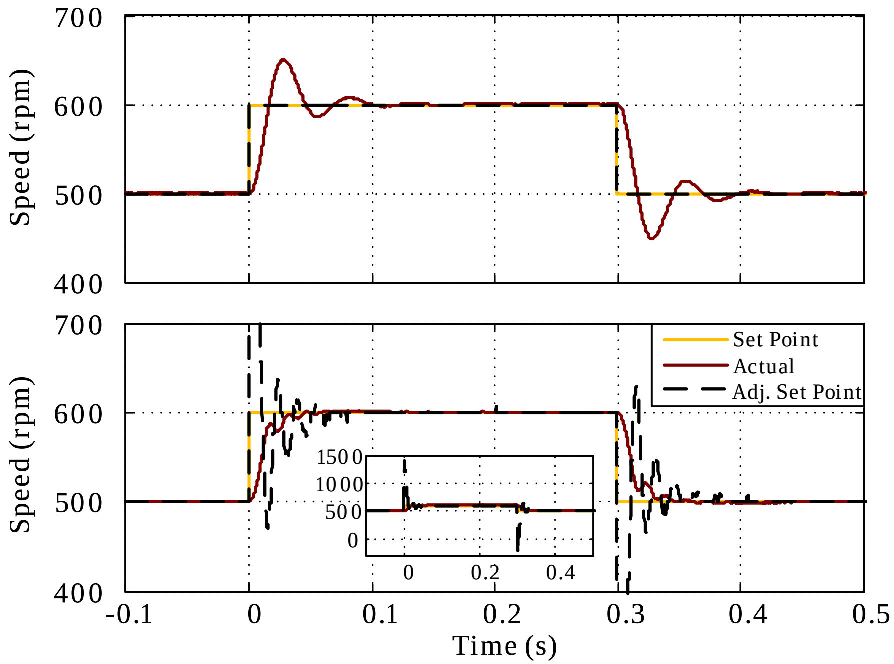


Experimental Results

Step change in i_{sq} from 0 to -20 to 0 A: a) base case: 48 rpm, b) prefilter: 48, c) SPAACE: 42, and d) SSPAACE: 12.

Sensitivity to System Parameters

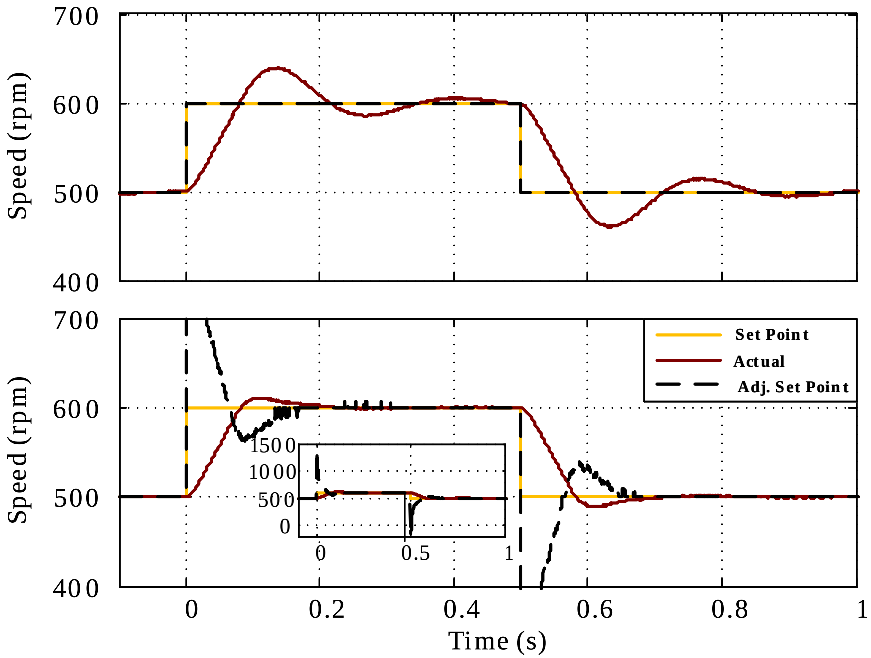
- *J* is changed to (a) one-third and (b) three times the design value. Step change in ω_{ref} from 500 to 600 to 500 rpm.



Simulation Results: 1/3x

Base case—M_p: 50%; $t_{settling}$: 80 ms

SSPAACE—M_p: ~0%; $t_{settling}$: 50 ms



Simulation Results: 3x

Base case—M_p: 40%; $t_{settling}$: 0.4 s

SSPAACE—M_p: 10%; $t_{settling}$: 0.2 s

Conclusions

- **By designing the trajectory to reduce overshoots, it is possible for a system to operate closer to its limits.**
- **Offline (PSCAD and MATLAB) and real-time (RTDS and Opal-RT) simulation studies as well as experimental results show that S/SPAACE is effective in mitigating transients:**
  - Step change: Mitigating overshoots
  - Load energization: Eliminating peaks
  - Load disconnection in an 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.**

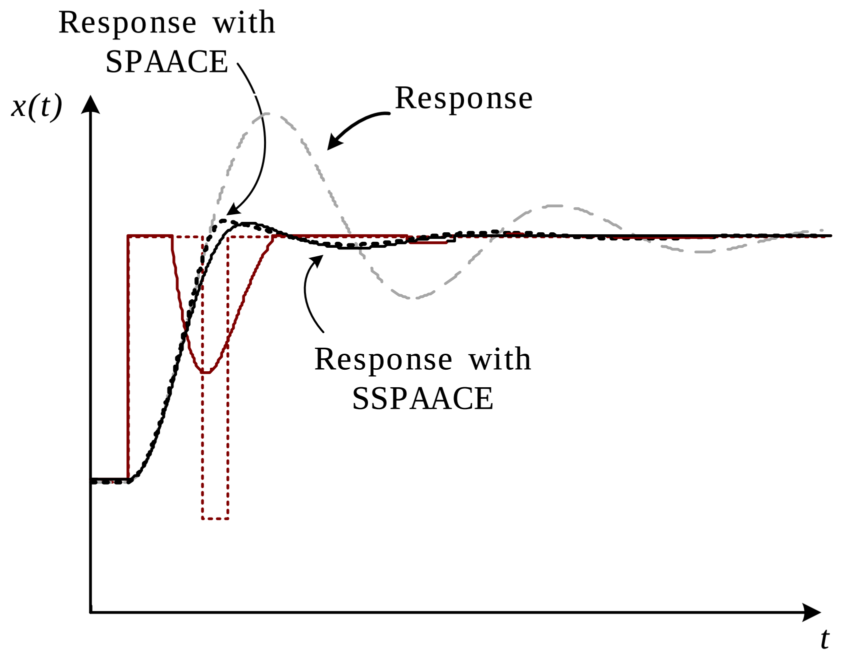
SSPAACE with a Hybrid Structure

- **SSPAACE utilizes a supervisory switching scheme based on observing the set point and the predicted error.**

$$x'_{sp}(t) = \begin{cases} x_{sp}, & e_{\min} \le e_{\text{pred}}(t) \le e_{\max} \\ x_{sp} + m(t), & \text{otherwise,} \end{cases}$$

$$m(t) = m \times e_{\text{pred}}(t)$$

$$e_{\text{pred}}(t) = \frac{sT + 1}{\alpha s T + 1} e(t),$$



Thank You

Power Electronics for Integration of Renewables

Ali Mehrizi-Sani

mehrizi@eecs.wsu.edu

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