Stability Considerations in Microgrids

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Outline

- **Objective**

- **Reachability Analysis**

- **Study System: Voltage-Sourced Converter (VSC)**

- **Reachability Analysis: Simulation and Experiments**

- **Contributions**

Objective and Motivation

- **For accurate analysis of a system, knowledge of its model, parameters, initial conditions, and inputs is needed.**

  - However, this is quite a luxury! Finding the precise value of these variables is not always possible.

  - Also, it is not possible to use simulation-based techniques to study the behavior of a system in all possible scenarios.

- **Uncertainty of a system cannot be easily considered in conventional methods for system analysis.**

  - For example, to design a PI controller with conventional methods (e.g., Bode-plot, Nyquist, and root locus methods), the system state matrix should be accurately known.

Objective and Motivation

- Reachability analysis can be used to analyze a system while considering a specific <u>continuous set</u> of state matrix, inputs, and initial conditions.

- Reachability analysis finds the reachable sets for the system states with unknown-but-bounded state matrix, inputs, and initial conditions.

- Uncertain matrix (unknown-but-bounded):

$$\begin{bmatrix} [a_{min}, a_{max}] & [b_{min}, b_{max}] & \dots \\ [c_{min}, c_{max}] & [d_{min}, d_{max}] & \dots \\ \vdots & \vdots & \ddots \end{bmatrix}$$

Reachability Analysis Applications

- **Objective:**

  – To analyze and design a controller for an uncertain system with unknown inputs, initial conditions and parameters, and errors in measurements.

- **Examples:**

  – Controller design for an uncertain VSC system, PV, or wind turbine.

  – Safety assessment of autonomous cars.

  – Voltage ride-through capability verification of wind turbines.

Reachability Analysis

⬢ **Dynamic model of a linear system:**

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t), \text{ with } x_0 \in \mathcal{X}_0 \subset R^n, u(t) \in \mathcal{U} \subset R^m$$

⬢ **The reachable set that includes all possible scenarios through the time can be computed by solving the above equation.**

⬢ **However, in practice, computing the overapproximated reachable set is more trackable than computing the exact reachable set.**

– There are some equations with no exact analytical solutions.

– This overapproximation leads to conservative results, which sometimes can take into account the differences between simulation and experimental results.

Zonotope

⬡ **To compute the reachable set, a method based on zonotopes is used. A zonotope is defined as**

$$Z = \left\{ x \in \mathbb{R}^n : x = c + \sum_{i=1}^{p} \beta^{(i)} \cdot g^{(i)}, \quad -1 \leq \beta^{(i)} \leq 1 \right\}$$

where *c* is the center of the zonotope and $g^{(i)}$ variables are generators of the zonotope. Assume $l_i = \beta^{(i)} \cdot g^{(i)}$:

(a) $c + l_1$ (b) $c + l_1 + l_2$ (c) $c + l_1 + l_2 + l_3$
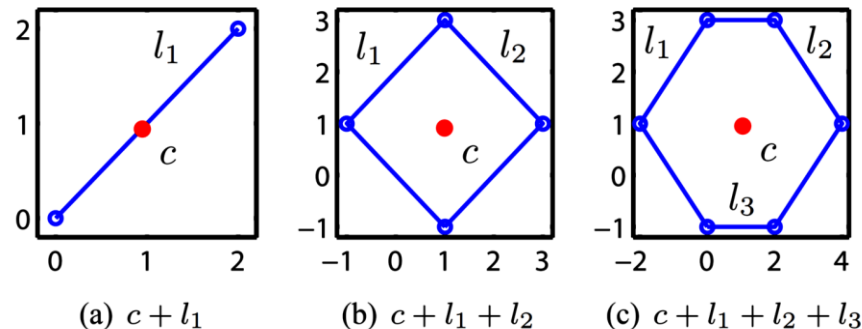
⬡ **Zonotopes are convenient representation of the reachable sets since they are closed under Minkowski sum (summation of two sets) and linear transformation.**

Reachable Set

● **The reachable set is found in two steps:**

  – Homogenous solution: Reachable set with respect to the initial state and zero input.

$$\Delta \mathcal{R}^h([t_k, t_{k+1}]) = CH(\Delta \mathcal{R}(t_k), \Delta \mathcal{R}(t_{k+1})) \oplus \mathcal{F} \Delta \mathcal{R}(t_k)$$

  – Inhomogenous solution: Reachable set with respect to input of the system when the initial state is zero.
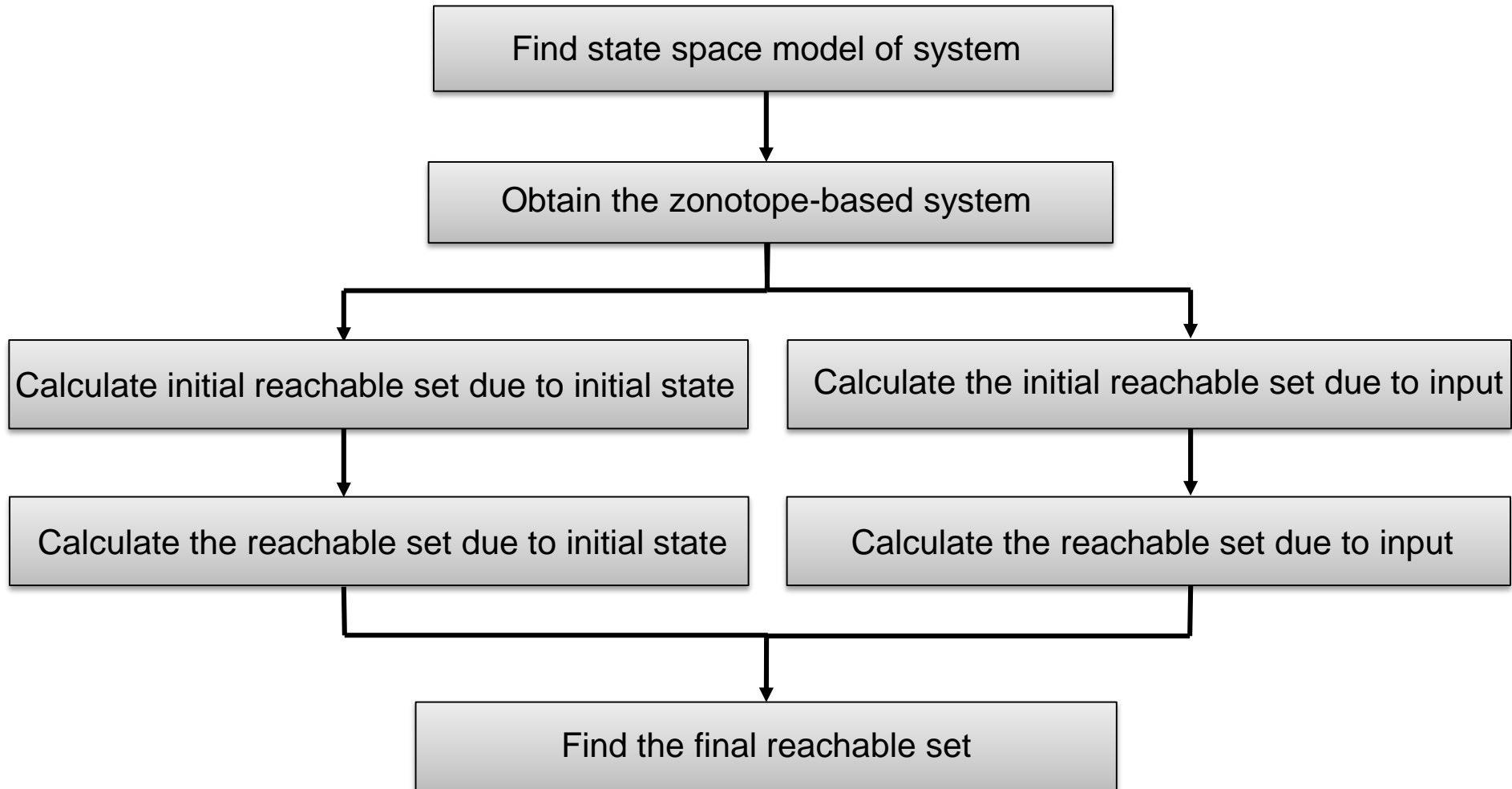
$$\mathcal{R}^f(t_{k+1}) = \left[\sum_{i=0}^{\eta} \frac{r^{i+1}}{(i+1)!} A^i \mathcal{V}(t_k) \right] \oplus E(r) r \mathcal{V}$$

● **Since the zonotopes are closed under Minkowski sum, the final reachable set is the Minkowsi sum of the homogenous and inhomogenous solutions.**
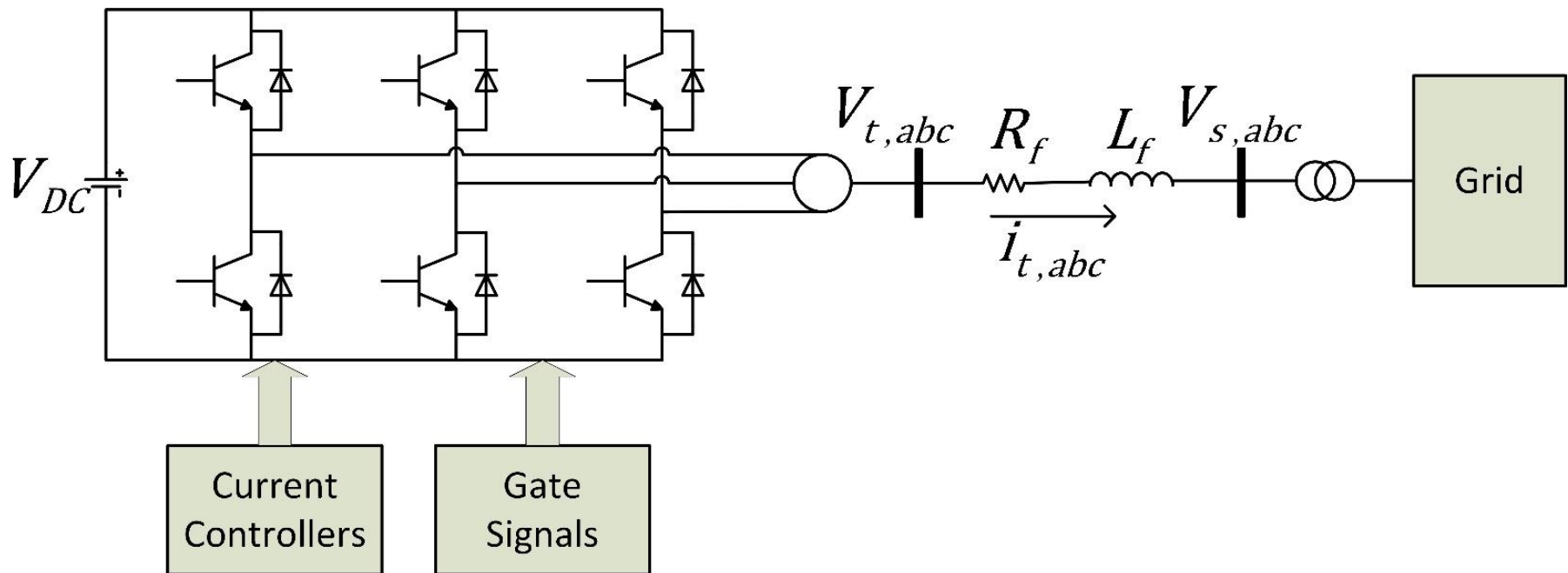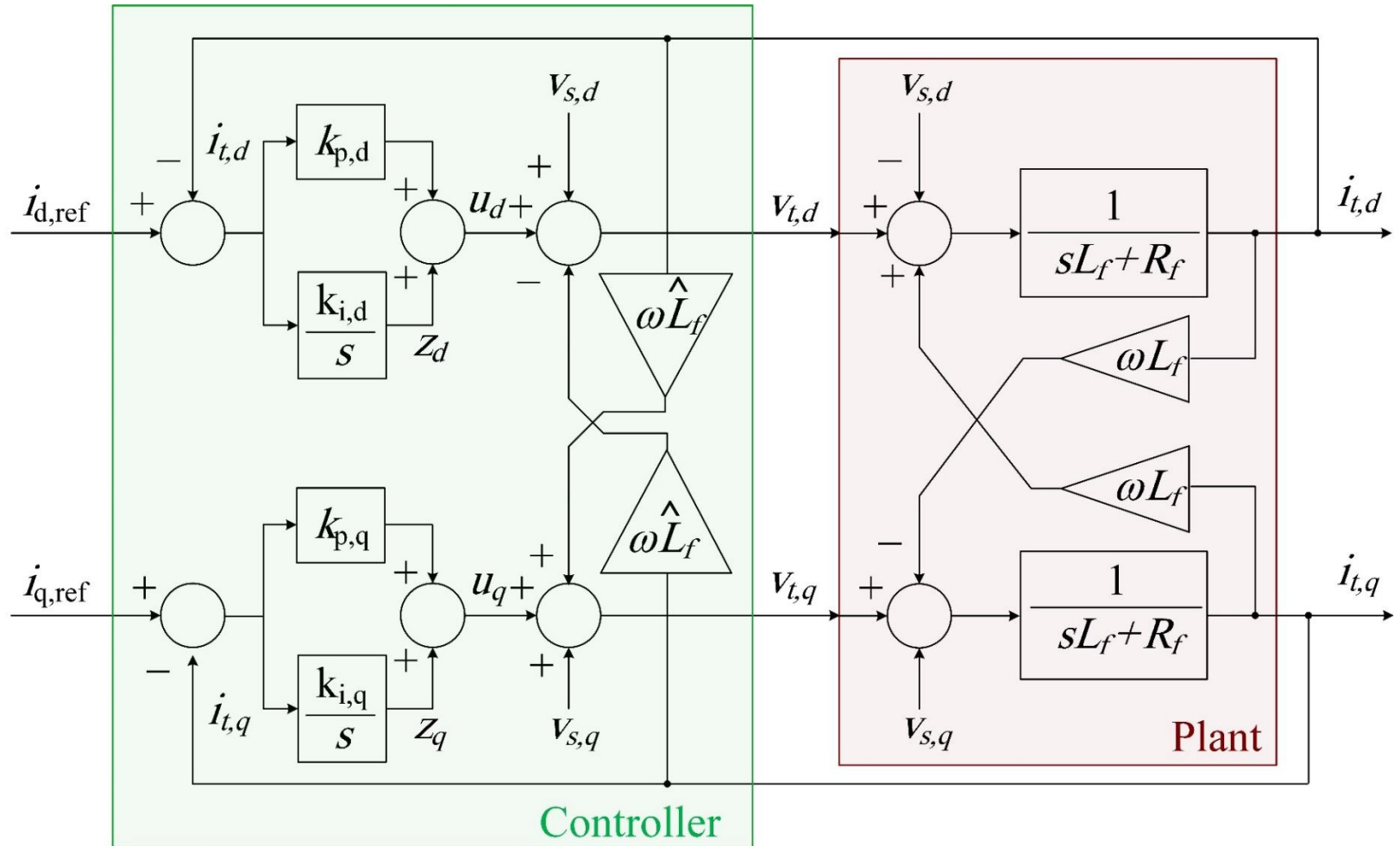
Reachability Algorithm

Find state space model of system

Obtain the zonotope-based system

Calculate initial reachable set due to initial state

Calculate the initial reachable set due to input

Calculate the reachable set due to initial state

Calculate the reachable set due to input

Find the final reachable set

Study System: Grid-Connected VSC

VSC Current PI-Based Controller

VSC State Space Model

$$\frac{d}{dt}\begin{bmatrix} \dot{i}_{t,d} \\ \dot{i}_{t,q} \\ z_d \\ z_q \end{bmatrix} = \begin{bmatrix} -\frac{R_f+k_{p,d}}{L_f} & \frac{L_f-\hat{L}_f}{L_f}\omega & \frac{1}{L_f} & 0 \\ -\frac{L_f-\hat{L}_f}{L_f}\omega & -\frac{R_f+k_{p,q}}{L_f} & 0 & \frac{1}{L_f} \\ -k_{i,d} & 0 & 0 & 0 \\ 0 & -k_{i,q} & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{t,d} \\ i_{t,q} \\ z_d \\ z_q \end{bmatrix} + \begin{bmatrix} \frac{k_{p,d}}{L_f} & 0 \\ 0 & \frac{k_{p,q}}{L_f} \\ k_{i,d} & 0 \\ 0 & k_{i,q} \end{bmatrix}\begin{bmatrix} \dot{i}_{d,ref} \\ i_{q,ref} \end{bmatrix}$$

- **We assume that the measured inductance of the filter has $\pm 20\%$ error ($\widehat{L}_f \in [0.8L_f, 1.2L_f]$).**

- **Inputs are $i_{q,ref} \in [-I_{nom}, I_{nom}]$ and $i_{d,ref} \in [0, I_{nom}]$.**

PI Controller Design

⊙ **PI controller:**

– Initial PI controller is designed based on Bode plot method for a system without uncertain parameter ($\widehat{L}_f$=L_f).

– Improved PI controller is designed based on reachability analysis by trial and error for the uncertain system. The PI controller with the lowest limits in reachability analysis results is considered as the improved controller.

⊙ **In a system with improved PI controller, current limits decrease 7.6% by reachability analysis method.**

VSC Parameters

| VSC Parameters	Value
Filter resistance	$R_f = 1.2\ \Omega$
Filter inductance	$L_f = 23\ mH$
DC link voltage	$V_{DC} = 150\ V$
Grid voltage	$V_s = 35\ V$
Initial PI controller	$k_p = 9.4$ $k_i = 480$
Improved PI controller	$k_p = 15.4$ $k_i = 800$

Reachability Analysis Results

⊙ **The red boxes show the limits in different steps of reachability analysis. The yellow boxes show the final reachable set.**
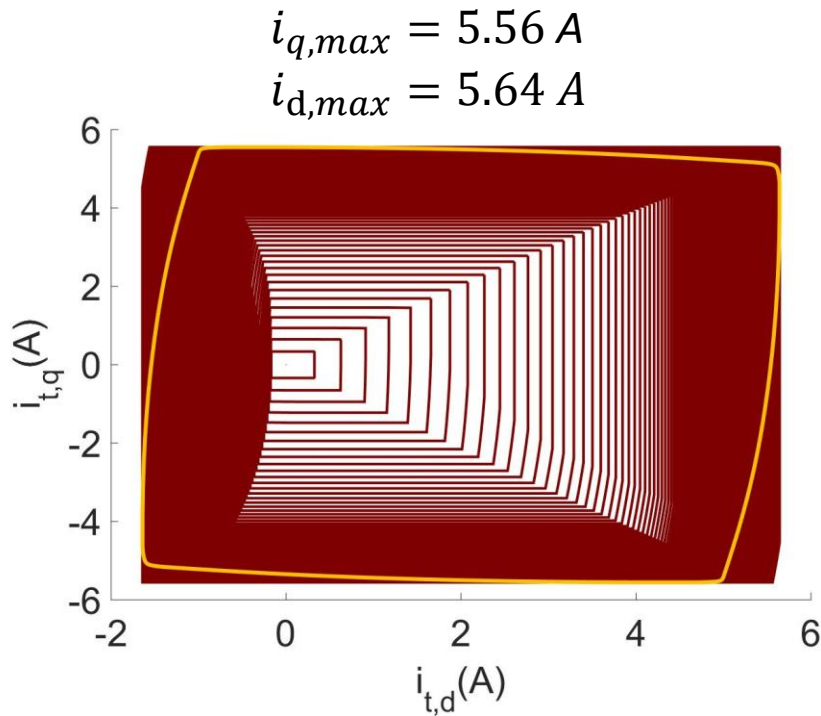
$$i_{q,max} = 5.56\ A$$
$$i_{d,max} = 5.64\ A$$

$$i_{q,max} = 5.31\ A$$
$$i_{d,max} = 5.21\ A$$
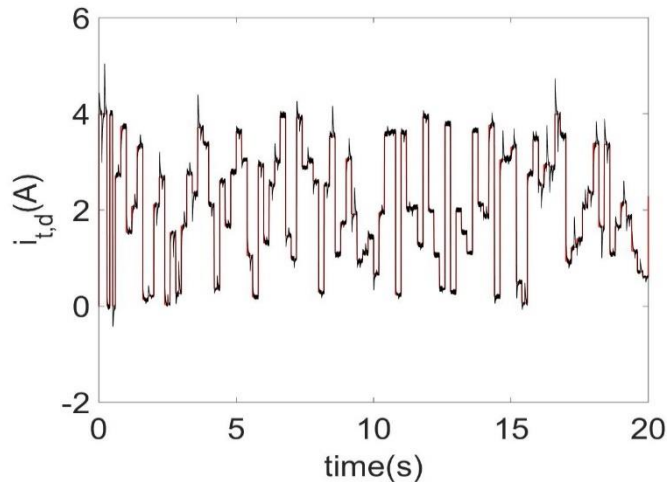

(a)
Initial PI controller based
on Bode plot method
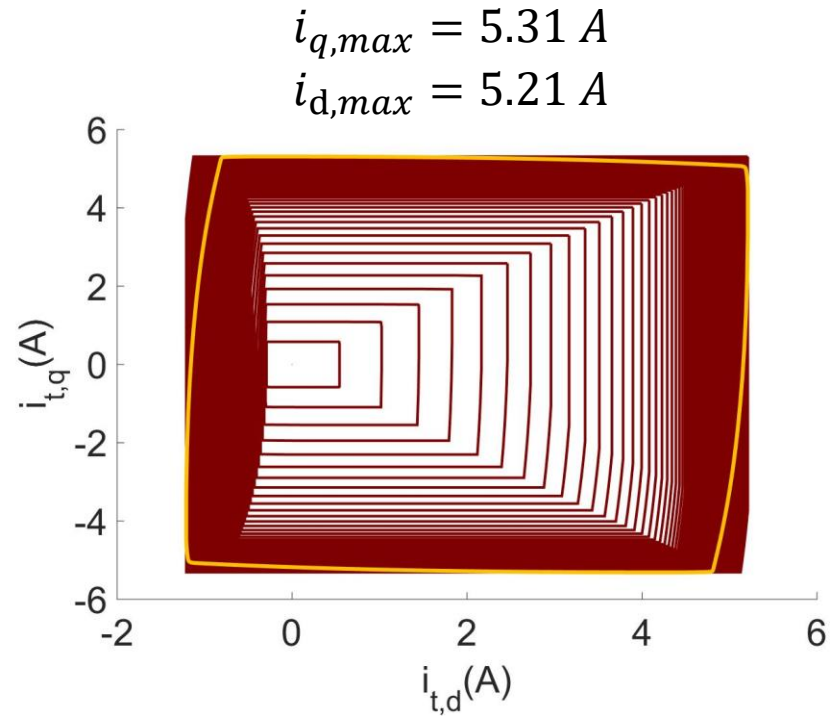
(b)
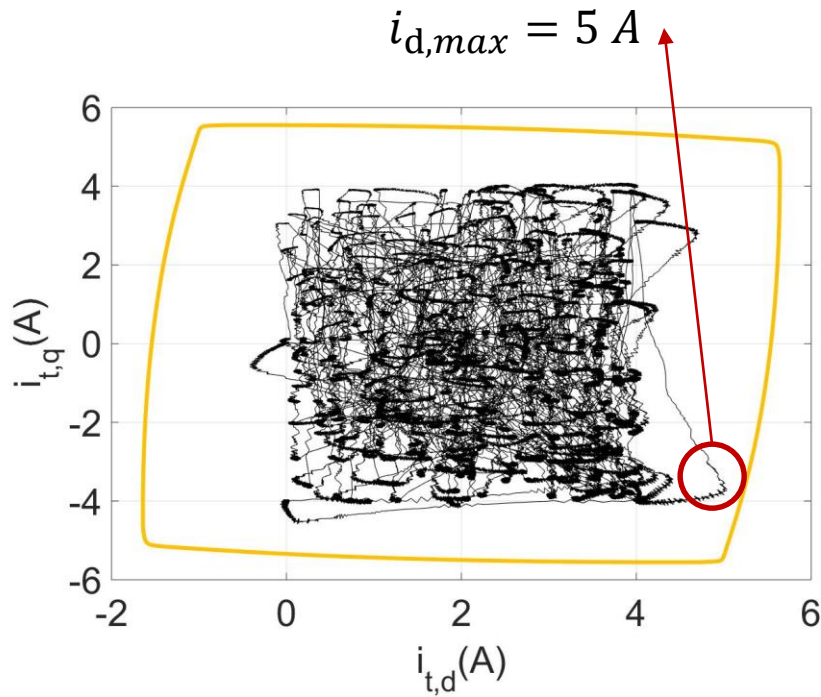PI controller designed
by reachability analysis

Simulation Considerations

In order to simulate many possible scenarios, Simulink's random block is used to specify $i_{d,ref}$, $i_{q,ref}$, and $\widehat{L}_f$.
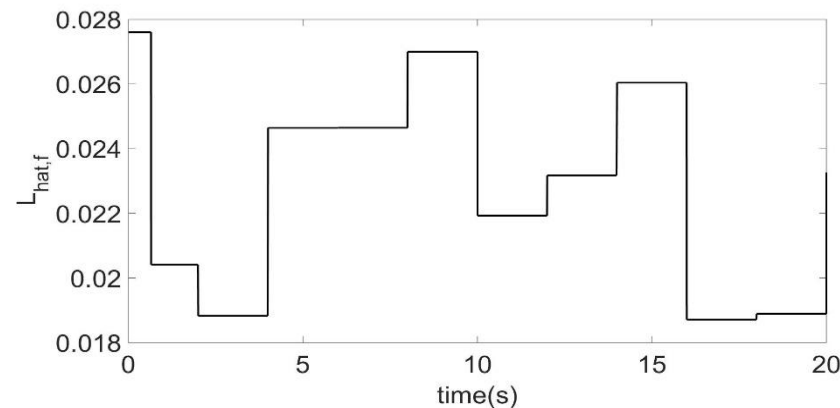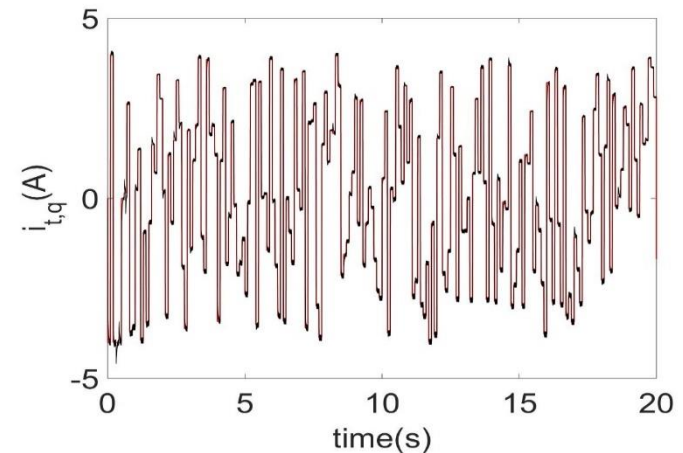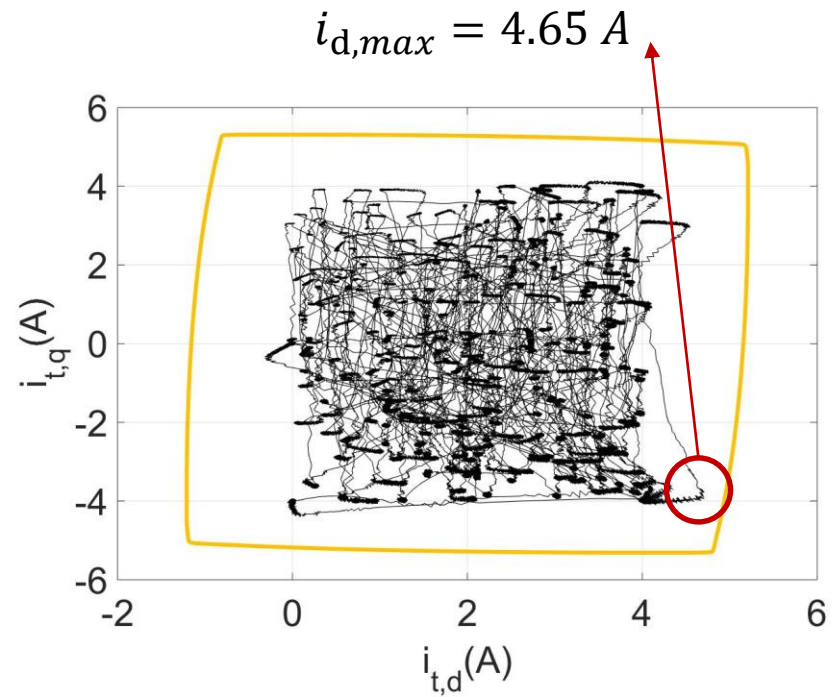
Simulation Results

$i_{\text{d},max} = 5\ A$

$i_{\text{d},max} = 4.65\ A$

(a)
Initial PI controller based
on Bode plot method

(b)
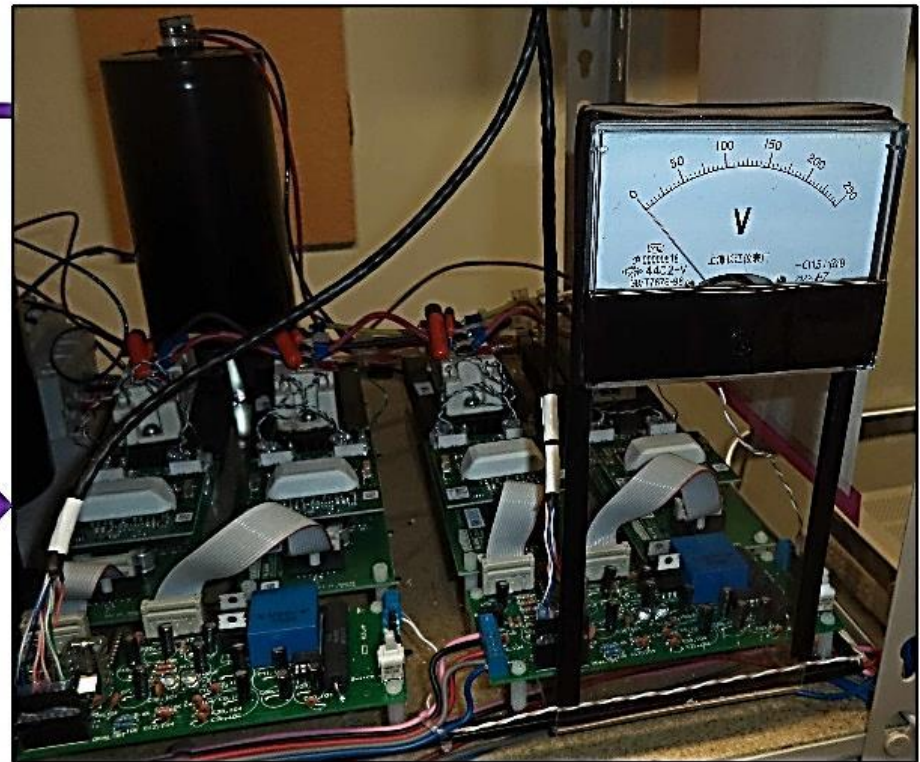PI controller designed
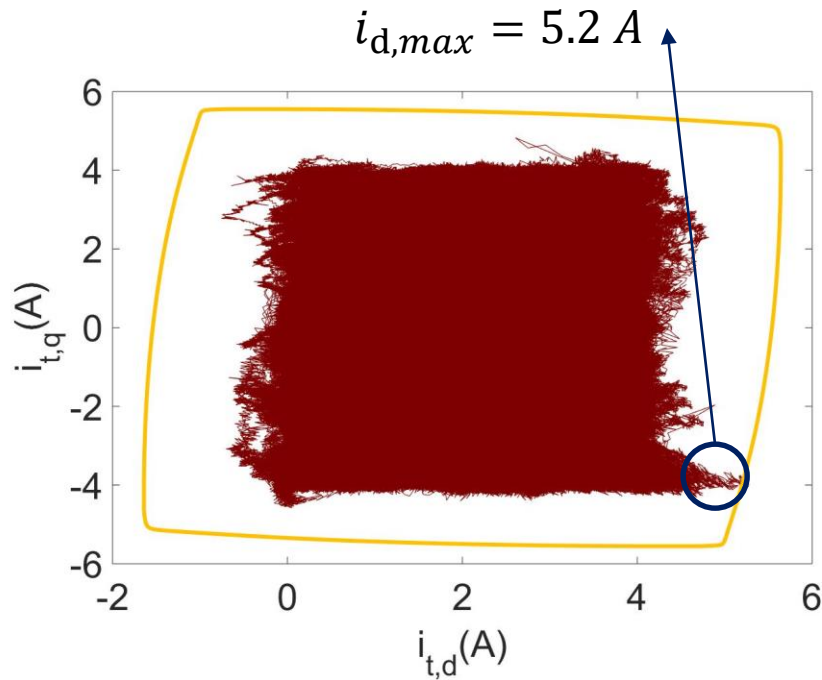by reachability analysis

Experimental Setup

Experimental Results

$i_{\text{d},max} = 5.2\ A$

$i_{\text{d},max} = 4.8\ A$
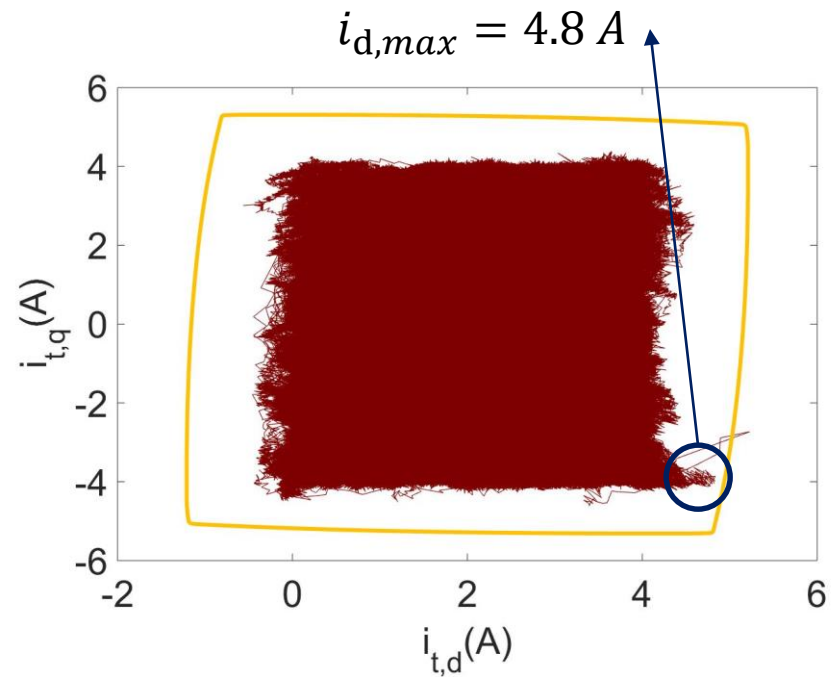
(a)
Initial PI controller based
on Bode plot method

(b)
PI controller designed
by reachability analysis

Contributions

- **Reachability analysis is used to find limits for the terminal current of the VSC.**

- **Simulation and experimental results validates reachability limits.**

- **Reachability analysis is used to design an improved PI controller for a VSC system with unknown-but-bounded inputs, initial conditions and state matrix.**

- **The terminal current limits of the VSC system with the improved PI controller decrease 7.6% by reachability analysis method.**

Thank You

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