<u>Control</u> and <u>Estimation</u> Techniques for the Safe Operation of Critical DC Microgrids

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University at Buffalo The State University of New York

Background

- **Education**
  - PhD, Electrical Engineering, The Ohio State University, 2015
  - BS, Engineering, University of Tennessee at Martin, 2010

- **Professional Experience**
  - Research Engineer, University of Dayton Research Institute, 2015-2016
  - Assistant Professor, Rochester Institute of Technology, 2016-2018
  - Assistant Professor, University at Buffalo, 2018-present

- **Collaborators:**
  - Dr. Xiu Yao, Dr. Jin Wang, Dr. Wei Zhang
  - Students: Kaushik Gajula, Lalit Marepalli

Outline

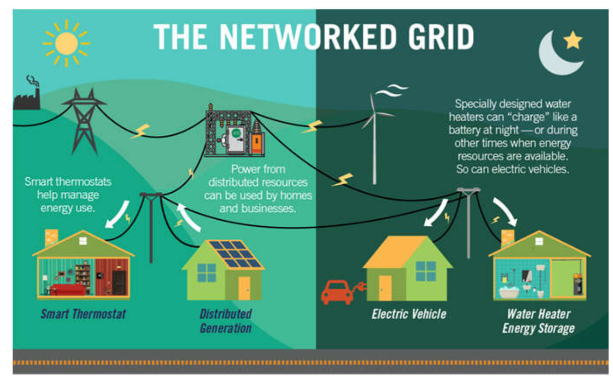
- Introduction and Motivation
- Stability Analysis and Control Techniques
  - ✓ Constant power loads
  - ✓ Analysis of large dc networks
- Fault Types and Estimation Strategies
  - ✓ Series dc arc faults
  - ✓ Continuous time parameter estimation techniques
  - ✓ Discrete time parameter estimation techniques
- Summary

Clean Energy and Electrification

- The rise and adoption of renewables and clean energy has been enabled in part by:
  - Power electronics
  - Electric machines
  - Control theory
  - Communication
  - ….
- **DC Microgrids** are primarily used nowadays in transportation and mobile networks

http://www.dvidshub.net/image/935698/aerial-refueling-f-35-lightning-ii-joint-strike-fighters-eglin-afb-fla#.UZyEMrVU8QY

https://insideevs.com/features/343599/2021-electric-vehicles-the-future-generation-of-evs/



https://www.carolinacountry.com/departments/more-power-to-you/the-grid-will-connect-us-to-our-energy-future

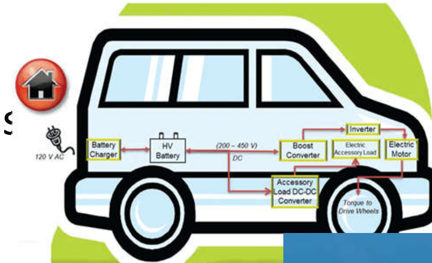
Modern DC Microgrids

- **Electric Vehicles (EV)**
  - Power electronics, electric motors, electronic loads
  - DC bus voltage: 200-800 Vdc

- **(More) Electric Aircraft**
  - Increased power demand (up to MW), complexity
  - Weight, size, constraints
  - DC bus voltage: 270 Vdc, +/- 270 Vdc

- **Electric Ships**
  - High power, complex networks
  - Variety of energy sources
  - DC bus voltage: ~1000 Vdc

- **Others:** spacecraft, mobile networks (army), HVDC/MTDC, etc.



http://powerelectronics.c
electronics-systems/invert

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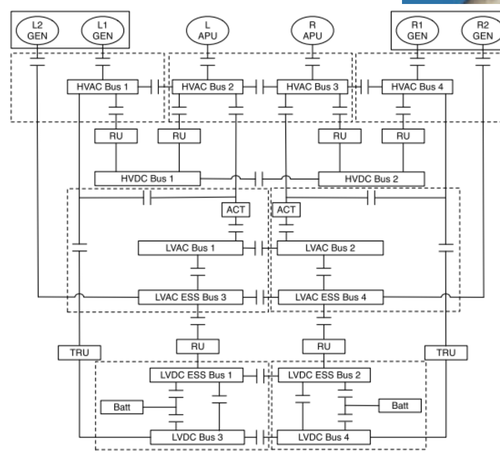
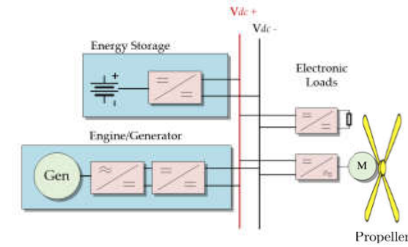


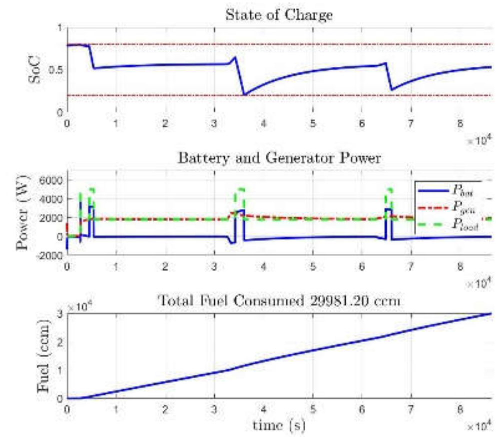
R. Michalko. "Electrical starting, generation, conversion
and distribution system archite
vehicle." U.S. Patent No. 7,439,

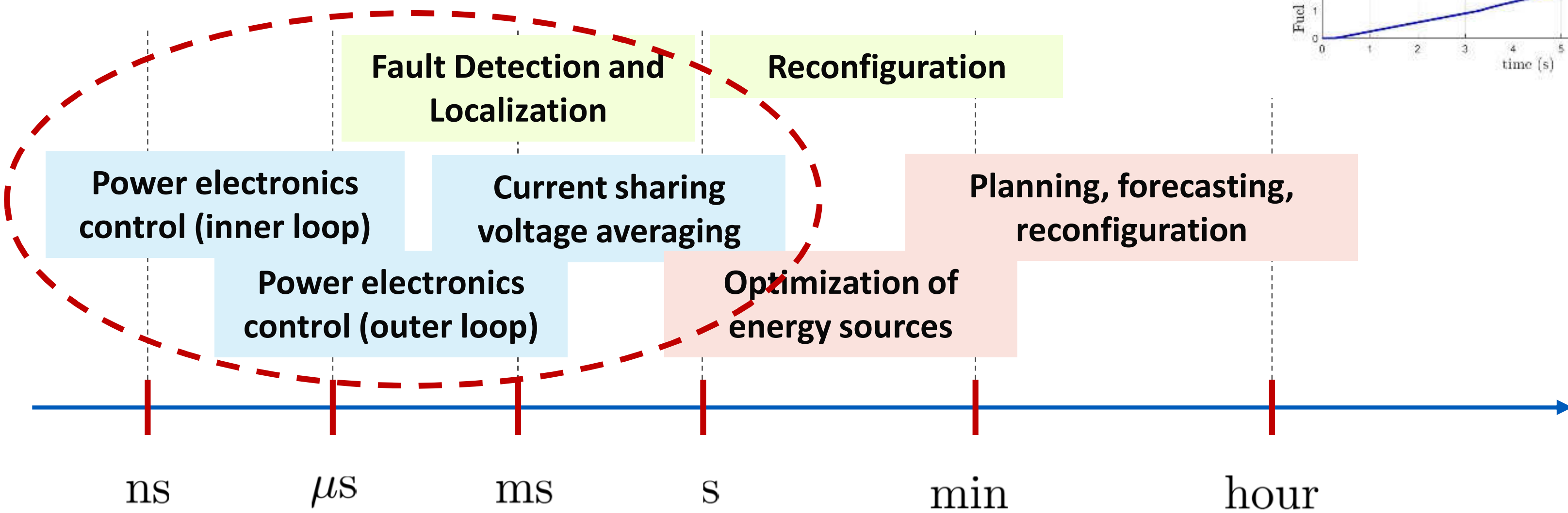
https://defense-update.com/20160522_zumwalt-4.html

DC Microgrid Operation – Time Constants

- The operation of dc microgrids can be decomposed into several aspects based on their **time constants**
- At the faster level, power electronics control and fault detection/localization are fundamental for safe operation
- At slower level, optimization of energy sources and planning is necessary



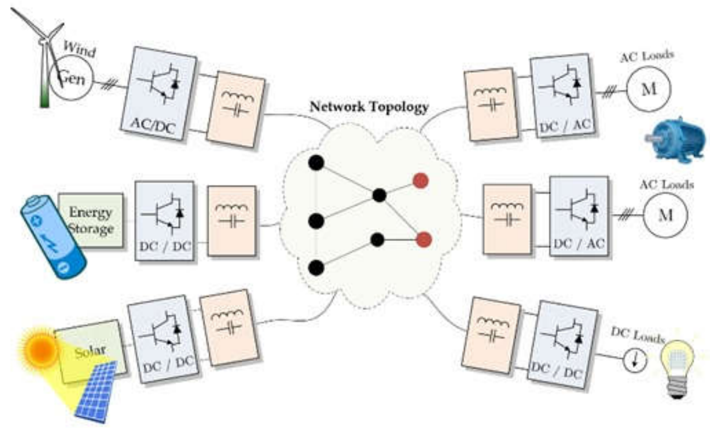




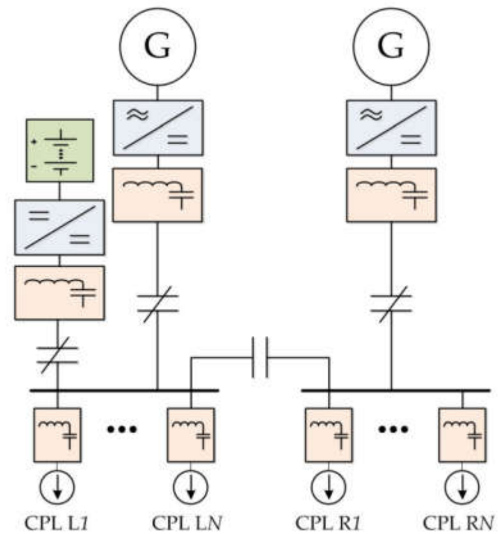
L. Herrera, et al, "Hierarchical Power Management of Unmanned Aerial Vehicles" Power Sources Conference, 2018.

DC Microgrid Challenges - Stability

- Sources and loads interfaced through power electronics
  - **Source:** fast dc bus voltage regulation
  - **Load:** fast output (V/I) regulation – constant power load

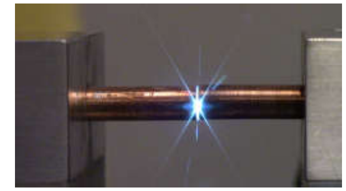


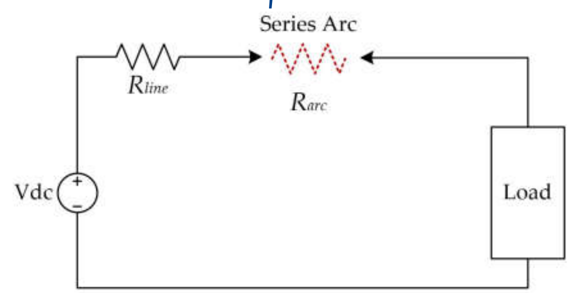
- Constant power loads exhibit dynamic negative resistance
  - Stability analysis
  - Controller design
  - Network level analysis

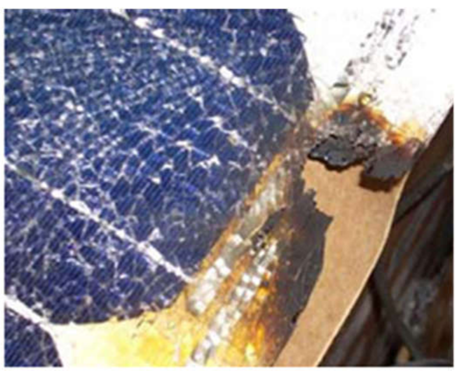


DC Microgrid Challenges – Fault Detection

- **Series dc arc faults – high impedance faults**
  - Caused by loose connections, age wires, etc.
  - High temperature arcing channel
  - Difficult to detect
- Low impedance parallel faults (high energy capacitive discharge)
- Faults within the source/load itself (power electronics, motors, etc/)







Fire accident caused by dc arc in a PV plant
Source: energy.sandia.gov

Aging wires on airplane
Source: www.iasa.com.au

Arcing event of a crashed Volt
Source: en.wikipedia.org

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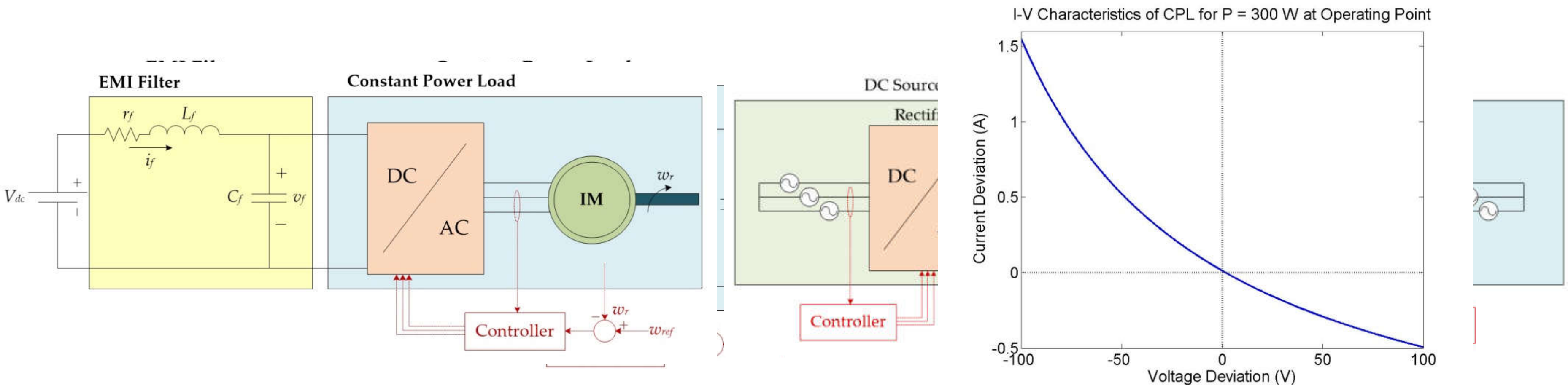
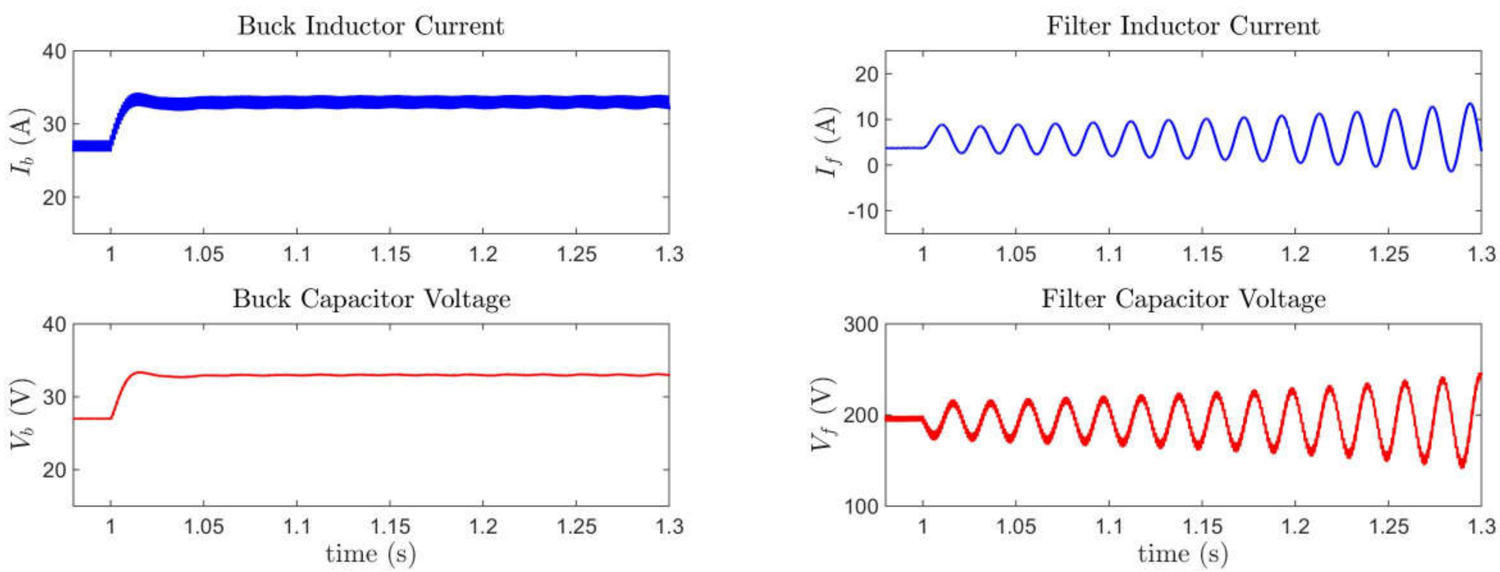
Constant Power Load Behavior

- Most active power loads are interfaced to the network with EMI filters



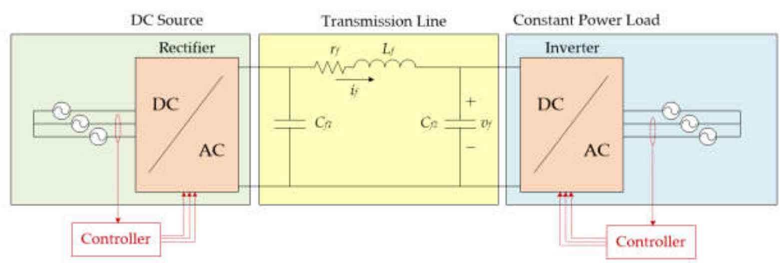
$P_{\text{load}} = 400\text{ W} \Rightarrow 1000\text{ W}$

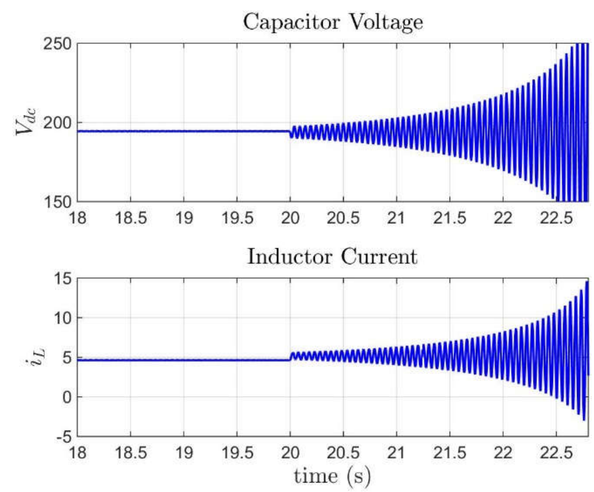


Why is the system unstable?

Previous Studies

- Much of the results presented in literature can be characterized as
  - **Frequency domain methods**
    - Study the interaction of the transfer functions of the converters $\left|Z_{\text{source}}(\omega)\right| \left|Y_{\text{load}}(\omega)\right| < 1, \quad \forall\omega$
    - Infinity norms, singular value, etc.
    - **Guarantees local stability only**
  - **Time domain methods**
    - Considers the nonlinear system
    - Control methods based on feedback linearization, Lyapunov functions, etc.
    - Genetic algorithms, Mixed Lyapunov Functions, Takagi-Sugeno Fuzzy Models
- **Most methods study small dc microgrids**
- **Computation of stability margins is difficult for large number of loads**





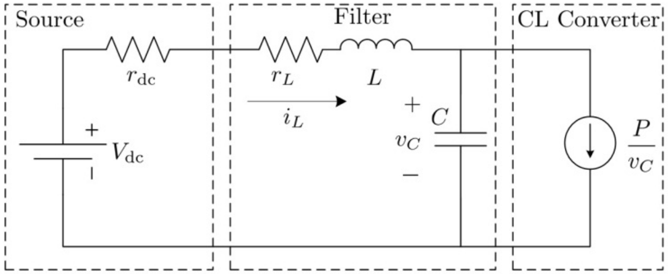
Stability Analysis of Nonlinear Systems

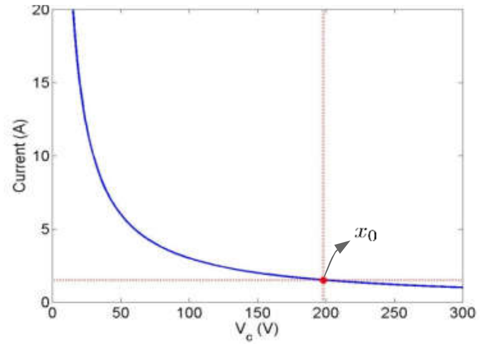
- Consider a nonlinear dynamical system of the form

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

where u is the input, d is disturbance

- Let $u = d = 0 \quad \Rightarrow \quad \dot{x} = f(x)$, and x^* be an equilibrium point $(f(x^*) = 0)$





- The eq. point $x^* = 0$ is **globally asymptotically stable** if there exists a radially unbounded function $V(x) : \mathbb{R}^n \to \mathbb{R}$ such that:

$$V(x) > 0, \quad \text{and} \quad \dot{V}(x) = \frac{\partial V}{\partial x} \cdot f(x) < 0 \quad \forall x \neq 0$$

- What are good/common functions to test as $V(x)$?

Quadratic Lyapunov Functions and Linear Systems

- In the case of a closed loop or unforced **linear systems**: $\dot{x} = Ax$

- A quadratic Lyapunov function can be used to test for stability:

$$\begin{aligned} V(x) &= P_{11}x_1^2 + 2P_{12}x_1x_2 + \cdots + P_{nn}x_n^2 \\ &= x^T P x \end{aligned}$$

$$P = \begin{pmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{12} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{1n} & P_{2n} & \cdots & P_{nn} \end{pmatrix} \qquad x = \begin{pmatrix} x_1 & x_2 & \cdots & x_n \end{pmatrix}^T$$

where P is a **symmetric** $n \times n$ matrix

- How can we show $V(x)$ is positive definite?

$V(x) = x^T P x > 0 \quad \Leftrightarrow \quad P \succ 0$ (P has only positive eigenvalues)

- What about $\dot{V}(x)$?

$\dot{V}(x) = x^T (A^T P + PA) x < 0 \quad \Leftrightarrow \quad A^T P + PA \prec 0$

These are Linear Matrix Inequalities (LMI): $\begin{cases} P \succ 0 \\ A^T P + PA \prec 0 \end{cases}$

Gain Optimization for Linear Systems

- It is possible to expand the previous analysis to optimize controller gains:

$$\dot{x} = Ax + Bu, \quad u = Kx \quad \Rightarrow \quad \dot{\mathbf{x}} = (\mathbf{A} + \mathbf{BK})\mathbf{x} = \mathbf{A_{cl}x} \quad \text{(closed loop system)}$$

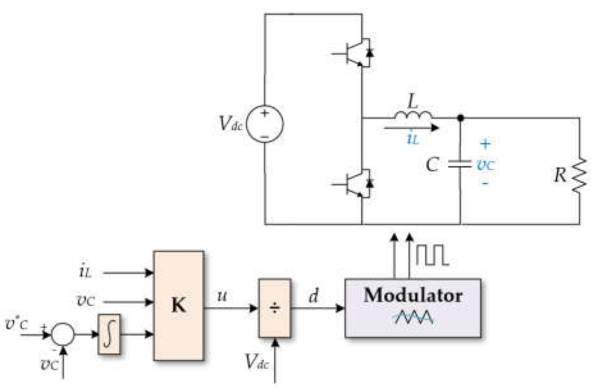
- Stability of the closed loop system amounts to:

$$\begin{cases} P \succ 0 \\ A_{cl}^T P + P A_{cl} \prec 0 \end{cases} \Rightarrow \begin{cases} P \succ 0 \\ A^T P + PA + K^T B^T P + PBK \prec 0 \end{cases} \Rightarrow \begin{cases} Y \succ 0 \\ YA^T + AY + L^T B^T + BL \prec -\gamma Y \end{cases}$$

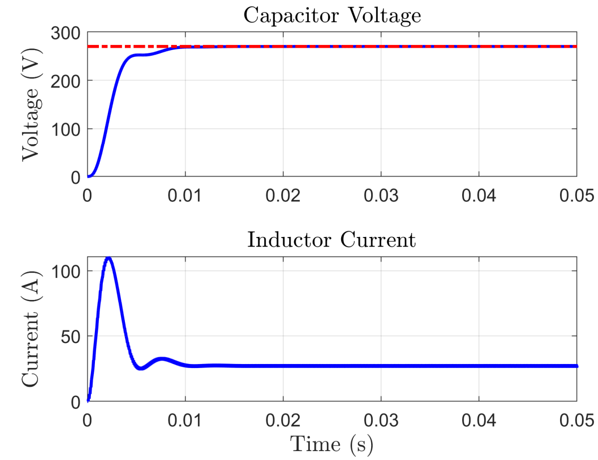
where $K = LY^{-1}$, $Y = P^{-1}$, $\gamma > 0$ (tuning parameter)

- Example for a buck converter:

$$\frac{d}{dt}\begin{pmatrix} i_L \\ v_C \\ e_i \end{pmatrix} = \begin{pmatrix} 0 & \frac{-1}{L} & 0 \\ \frac{1}{C} & \frac{-1}{RC} & 0 \\ 0 & -1 & 0 \end{pmatrix}\begin{pmatrix} i_L \\ v_C \\ e_i \end{pmatrix} + \begin{pmatrix} \frac{1}{L} \\ 0 \\ 0 \end{pmatrix} u, \quad u = dV_{\mathrm{dc}}$$

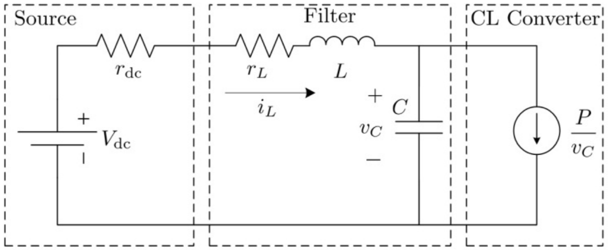



```
% Build the basic matrices first
A = [0 -1/L 0; 1/C -1/(R*C) 0; 0 -1 0];
B = [1/L; 0; 0];

dampfac = 1e3;

% Controller design
cvx_begin sdp
    variable Y(3,3) symmetric
    variable Lsdp(1, 3)
    Y >= 1*eye(3);
    Y*A'+A*Y+Lsdp'*B'+B*Lsdp+dampfac*Y < 0;
cvx_end
K  = full(Lsdp*inv(Y));
```

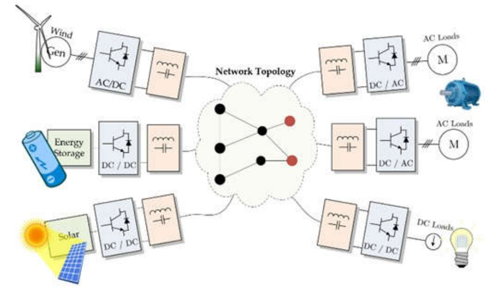


Analysis of Constant Power Loads in DC Networks

- Stability issues of a single CPL:

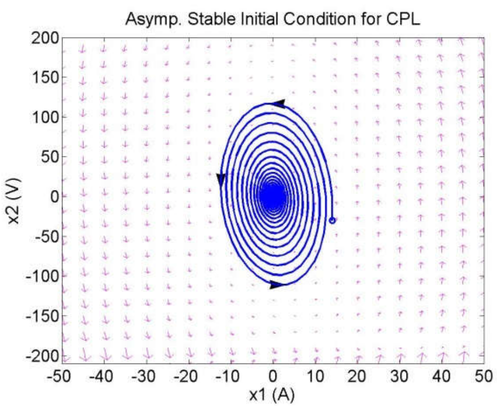


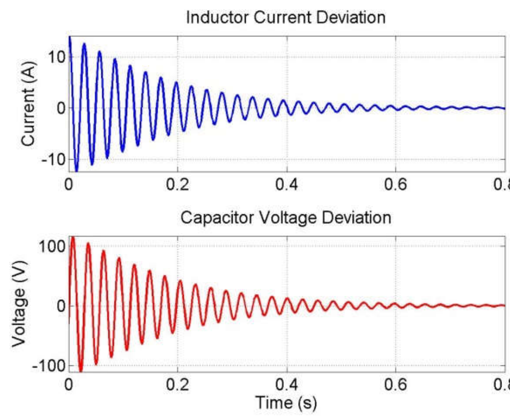
$$\dot{x}_1 = \frac{-r}{L}x_1 - \frac{1}{L}x_2 + \frac{1}{L}V_{\mathrm{in}}$$
$$\dot{x}_2 = \frac{1}{C}x_1 - \frac{1}{C}h(t,x,P)$$



$$x_1 = i_L, \quad x_2 = v_C \quad h(t,x,P) = \frac{\bar{P}}{x_2}$$

$\tilde{x}_{10} = 14$ A
$\tilde{x}_{20} = -30$ V





System Parameters

$r = 1.1\ \Omega$

$L = 39.5$ mH

$C = 500\ \mu$F

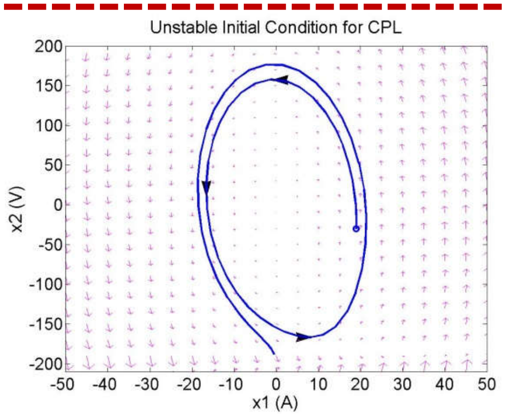
$V_{\mathrm{in}} = 200$ V

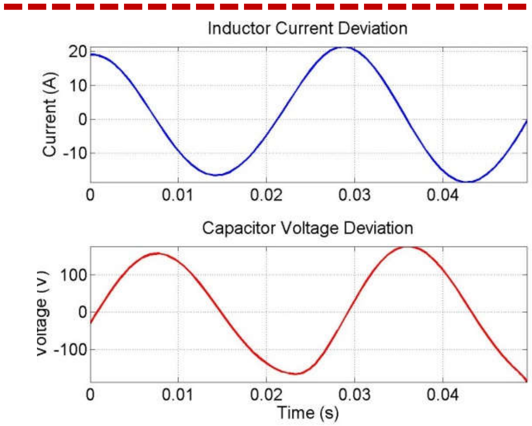
$P_0 = 300$ W

$x_{10} = 1.5$ A

$x_{20} = 198.34$ V

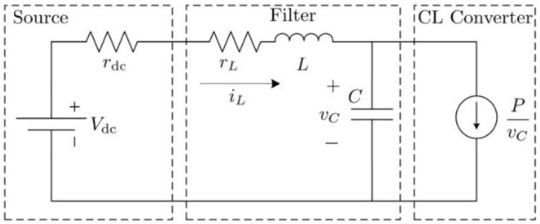
$\tilde{x}_{10} = 19$ A
$\tilde{x}_{20} = -30$ V

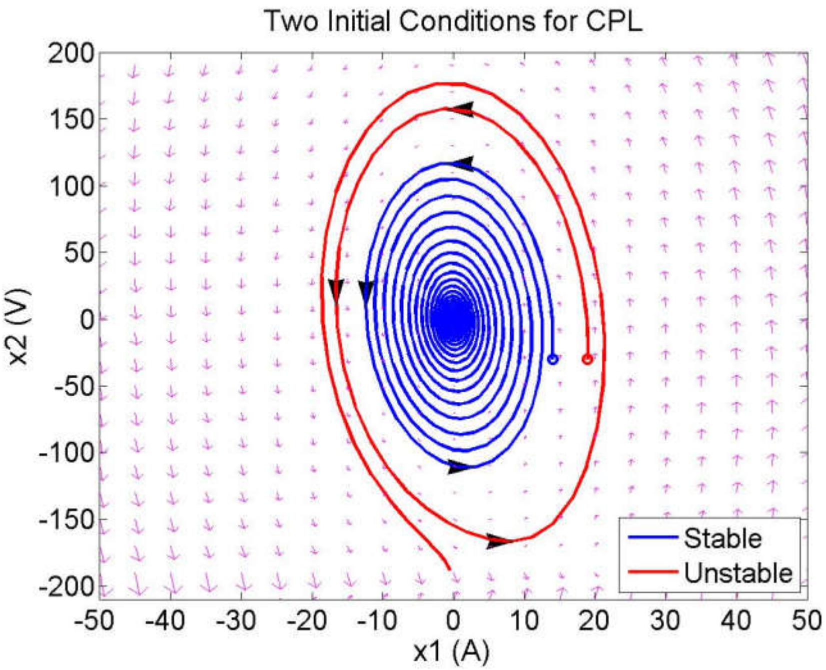




Region of Attraction

- A difference of 5A in the initial inductor current of the inductor caused it to go unstable
- Is it possible to find a bound on the maximum tolerance any microgrid can sustain?
  - We can estimate the ***"Region of Attraction (ROA)"***





$$\dot{\tilde{x}}_1 = -\frac{r}{L}\tilde{x}_1 - \frac{1}{L}\tilde{x}_2$$

$$\dot{\tilde{x}}_2 = \frac{1}{C}\tilde{x}_1 + \frac{P}{Cx_{20}}\frac{\tilde{x}_2}{\tilde{x}_2 + x_{20}}$$

System Parameters

$r = 1.1\ \Omega$	$V_{\text{in}} = 200$ V
$L = 39.5$ mH	$P_0 = 300$ W
$C = 500\ \mu$F	$x_{10} = 1.5$ A
	$x_{20} = 198.34$ V

Proposed Stability Analysis Technique

- Formulated the stability problem using Quadratic Lyapunov functions

$$\dot{x} = Ax + Dh(t,x) \qquad h^T h \leq \alpha^2 x^T M x$$

1. $V(x) = x^T P x > 0$
2. $\dfrac{dV(x)}{dt} = x^T(A^T P + PA)x + h^T D^T P x + x^T P D h < 0$

   whenever $\quad h^T h \leq \alpha^2 x^T H^T H x$

Linear Matrix Inequalities

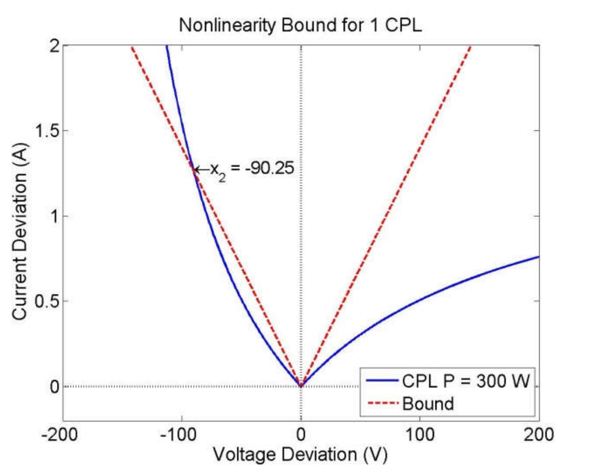
min γ

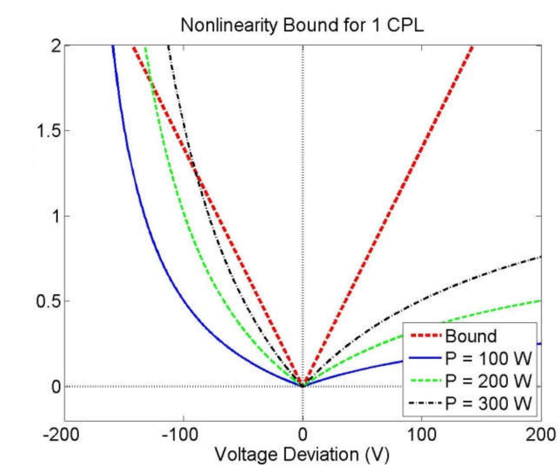
subject to

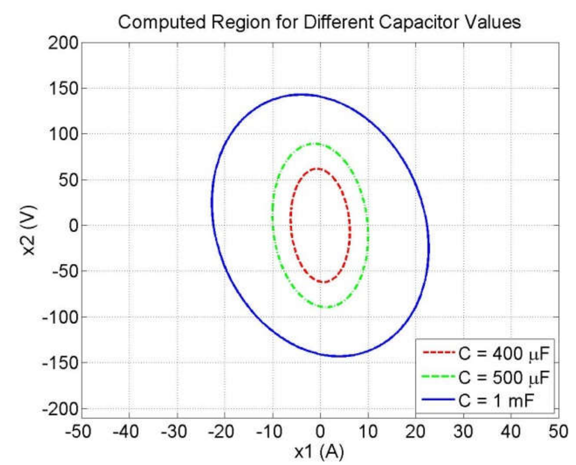
1. $P \succ 0$ / $Y \succ 0$
2. $\begin{pmatrix} A^T P + PA & PD \\ D^T P & 0 \end{pmatrix} \prec 0 \quad$ whenever $\quad \begin{pmatrix} \alpha^2 H^T H & 0 \\ 0 & -I \end{pmatrix} \succeq 0$

$$\begin{pmatrix} AY + YA^T & D & YH^T \\ D^T & -I & 0 \\ HY & 0 & -\gamma I \end{pmatrix} \prec 0 \qquad \gamma = \frac{1}{\alpha^2}, \quad Y = \tau P^{-1}$$

- Solution is the bounding parameter α = 0.014 and the matrix *P*







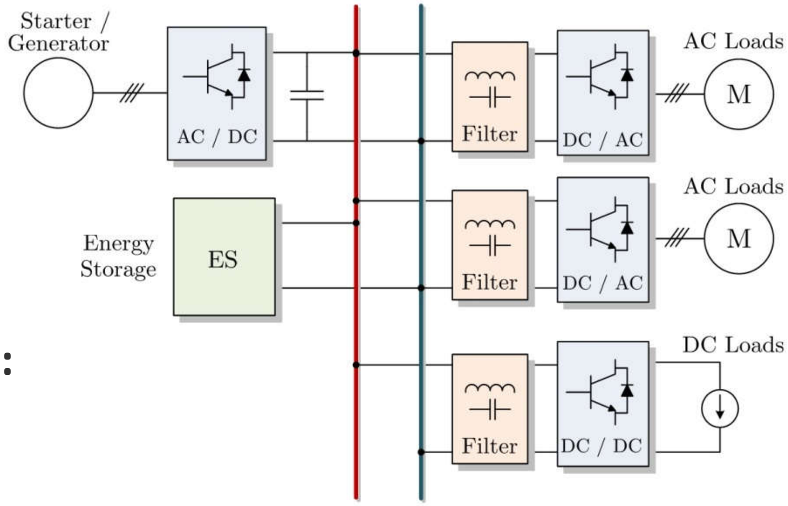
- **The parameter α gives a measure of robustness for the circuit – easy to expand for larger systems**

Stability Analysis for Larger DC Microgrids

- The proposed method considers the following state space characterization of the dc microgrid:

$$\dot{x} = Ax + B_{\text{es}} i_{\text{es}} + B_s V_{\text{dc}} + D \overbrace{h(x)}^{\text{CPLs}}$$

$$x \in \mathbb{R}^n, \quad i_{\text{es}} \in \mathbb{R}, \quad V_{\text{dc}} \in \mathbb{R}, \quad h(x) : \mathbb{R}^n \to \mathbb{R}^Q$$



- **We can similarly bound the CPLs' nonlinear terms:**

$$h^T(x)h(x) = \sum_{j=1}^{Q} h_j^T h_j \leq \frac{1}{\gamma} \tilde{x}^T H^T H \tilde{x}$$

$$\begin{aligned} & \min \ \gamma \\ & \text{subject to:} \\ & Y \succ 0 \\ & \begin{pmatrix} AY + YA^T & D & YH^T \\ D^T & -I & 0 \\ HY & 0 & -\gamma I \end{pmatrix} \prec 0 \end{aligned}$$

$$\begin{aligned} & \min \ \ b\gamma + b_L \kappa_L + b_Y \kappa_Y \\ & \text{subject to} \\ & Y \succ 0 \\ & \begin{pmatrix} AY + YA^T + B_{\text{es}} L + L^T B_{\text{es}}^T & D & YH^T \\ D^T & -I & 0 \\ HY & 0 & -\gamma I \end{pmatrix} \prec 0 \\ & \begin{pmatrix} -\kappa_L I & L^T \\ L & -I \end{pmatrix} \prec 0, \qquad \begin{pmatrix} Y & I \\ I & \kappa_Y I \end{pmatrix} \succ 0 \\ & \gamma - \frac{1}{\bar{\alpha}^2} < 0 \end{aligned}$$

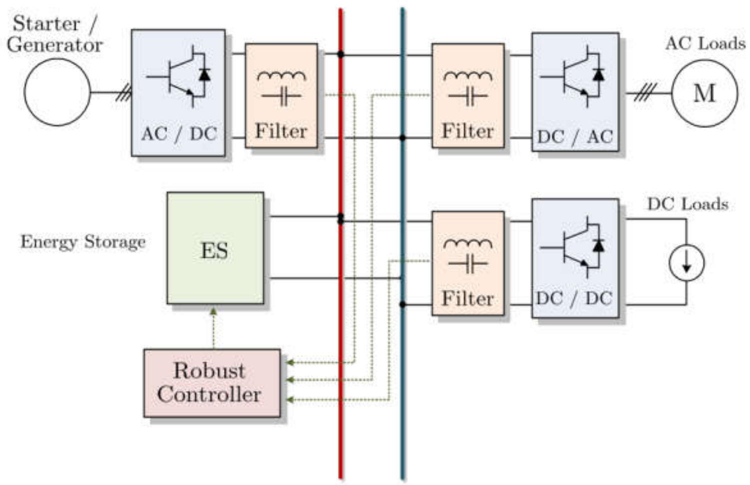
$$\text{With Control} \ \ i_{\text{es}} = K\tilde{x}, \quad K = LY^{-1}$$

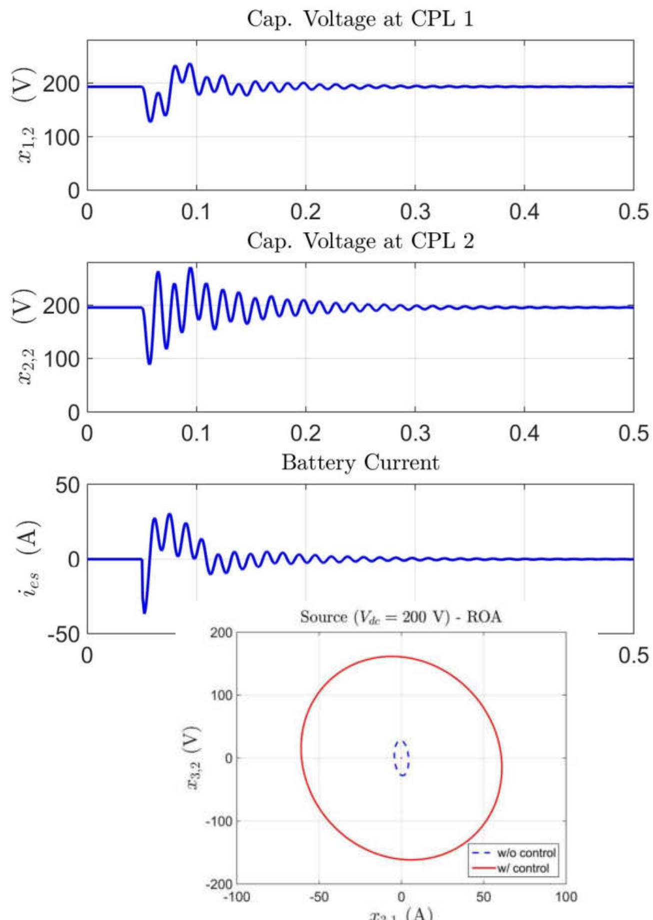
[1] L. Herrera, W. Zhang, and J. Wang, "Stability analysis and controller design of dc microgrids with constant power loads," *IEEE Trans. On Smart Grid*, vol. 8, no. 2, pp. 881-888, Mar. 2017.

Controller Implementation and Results

- Tested the proposed controller using simulation, considering a disturbance in the main dc bus

r_1	$0.8\ \Omega$	r_2	$0.42\ \Omega$	r_3	$0.4\ \Omega$
L_1	40 mH	L_2	19.6 mH	L_3	17.3 mH
C_1	1 mF	C_2	1.05 mF	C_3	1.05 mF
P_1	900 W	P_2	600 W	V_{in}	200 V





Short term disturbance (2 ms)

$$\alpha_n = 0.0233 \ \text{ to } \ \alpha = 0.045$$

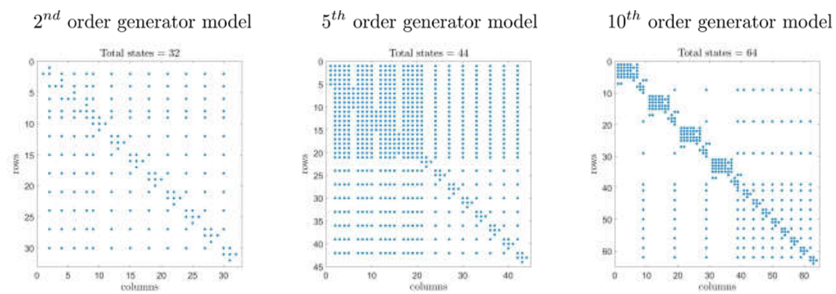
$$K = (1.406 \quad -0.116 \quad 0.47 \quad 0.354 \quad 0.653 \quad 0.121)$$

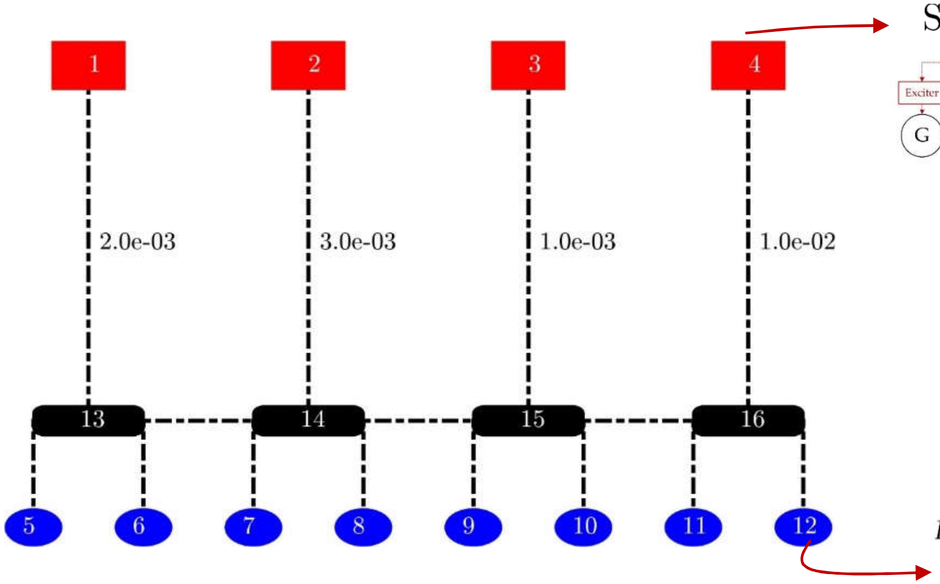
- **The system is stable even for severe disturbances in the dc bus voltage**

[1] L. Herrera, W. Zhang, and J. Wang, "Stability analysis and controller design of dc microgrids with constant power loads," *IEEE Trans. On Smart Grid*, vol. 8, no. 2, pp. 881-888, Mar. 2017.

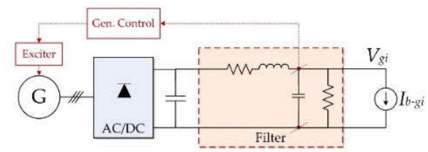
What about DC Microgrids with Multiple Sources?

- We can consider the power system as a graph with three kinds of nodes:
  - Generator/source nodes, $\mathcal{N}_G$
  - Load nodes, $\mathcal{N}_L$
  - Interior nodes, $\mathcal{N}_I$
- Due to the relatively short distances, line are considered resistive
- Graph Laplacian = Admittance matrix

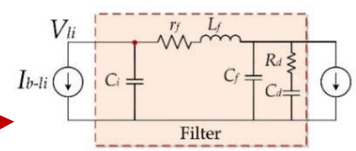




Sources

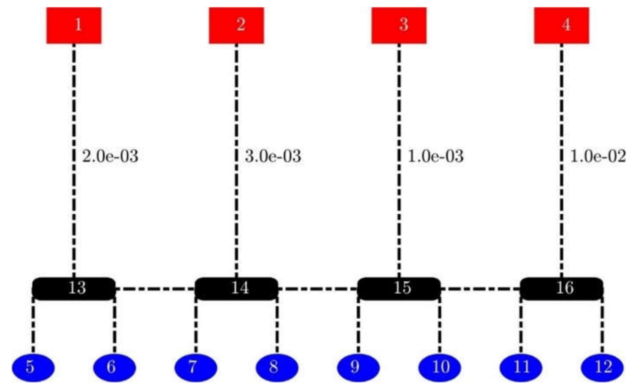


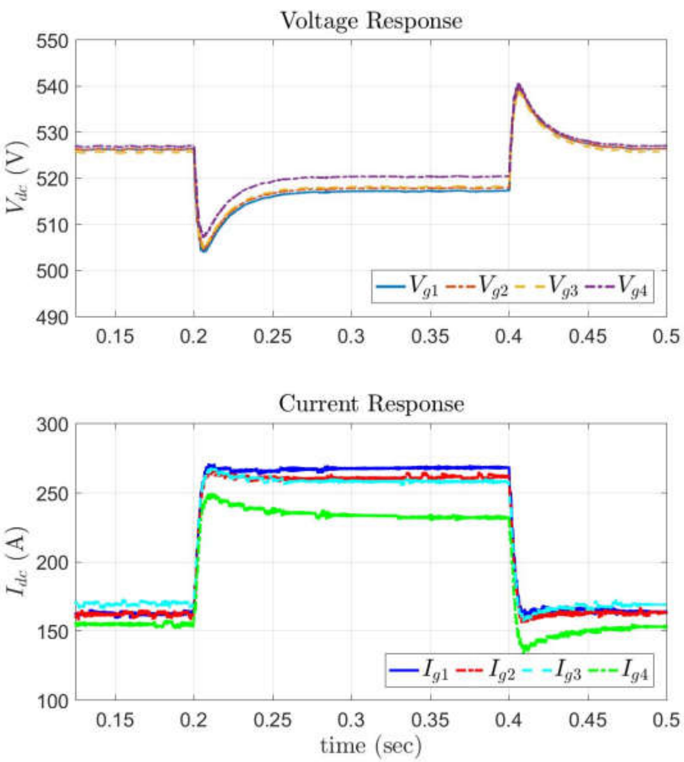
Loads



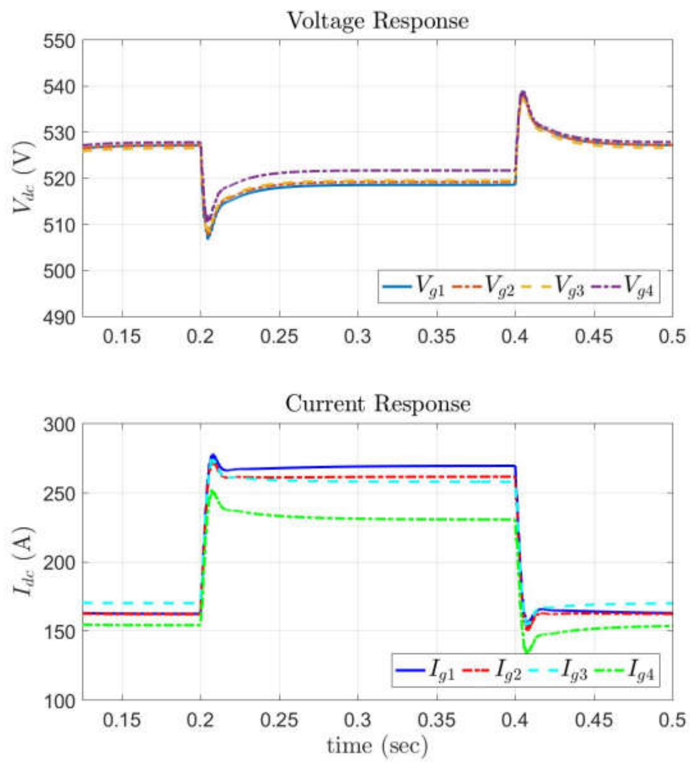
What about DC Microgrids with Multiple Sources?

- Verification of the proposed dynamic model for the dc microgrid
- Detailed simulation results were obtained using Matlab Simpower systems





Detailed simulation



Simplified mathematical model

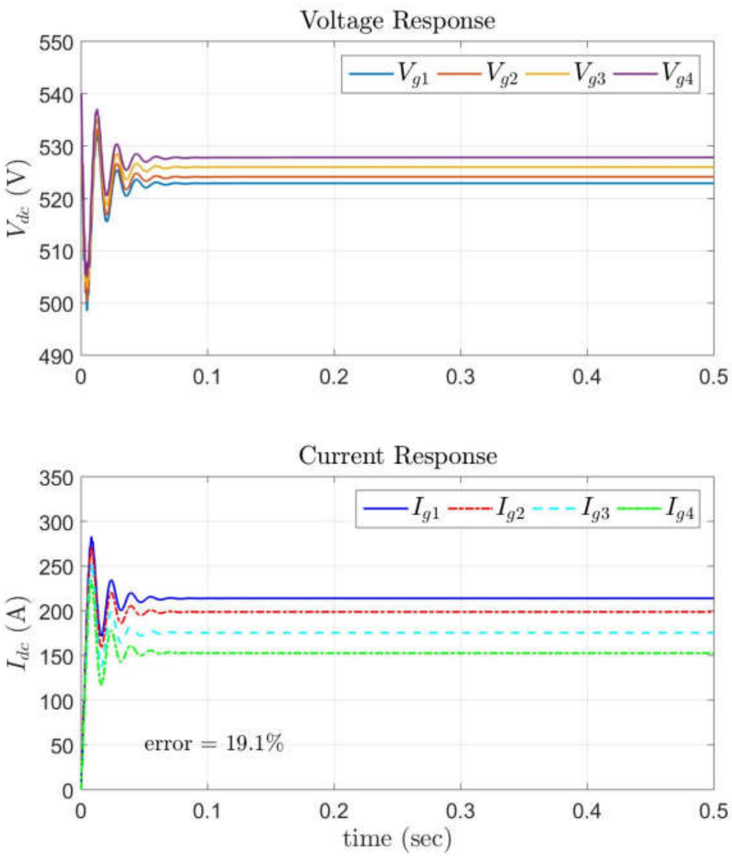
Droop Control – No Communication

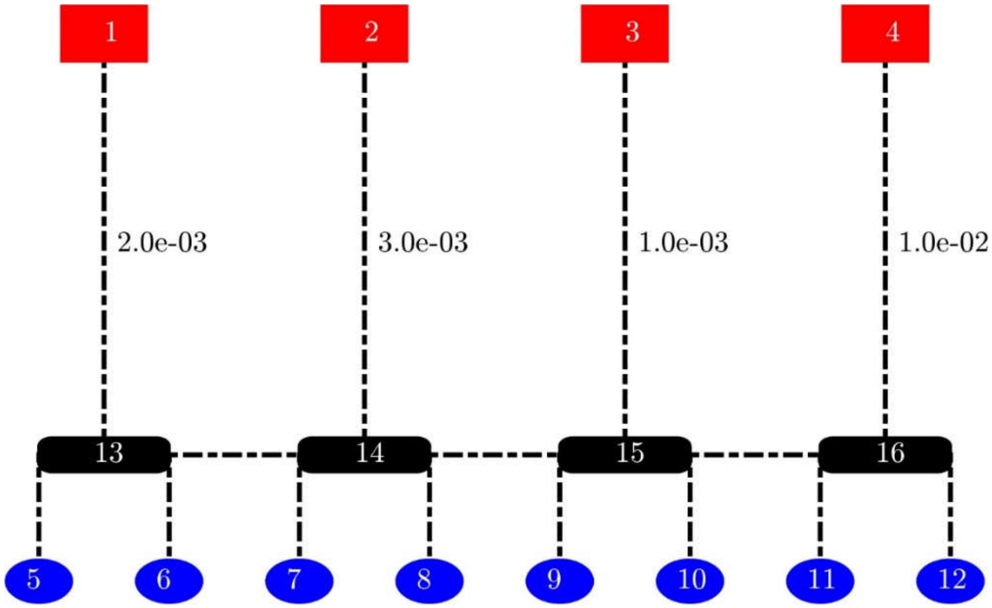
- Error in current sharing can be high with only droop control

$$\dot{x} = (A + B_b\tilde{Y}C)x + Bu + Dh(x,P)$$

$$u = -K_{\text{droop}} i_g$$

$$K_{\text{droop}} \triangleq \text{diag}\left(K_{\alpha_1},\ \dots,\ K_{\alpha_{n_G}}\right)$$



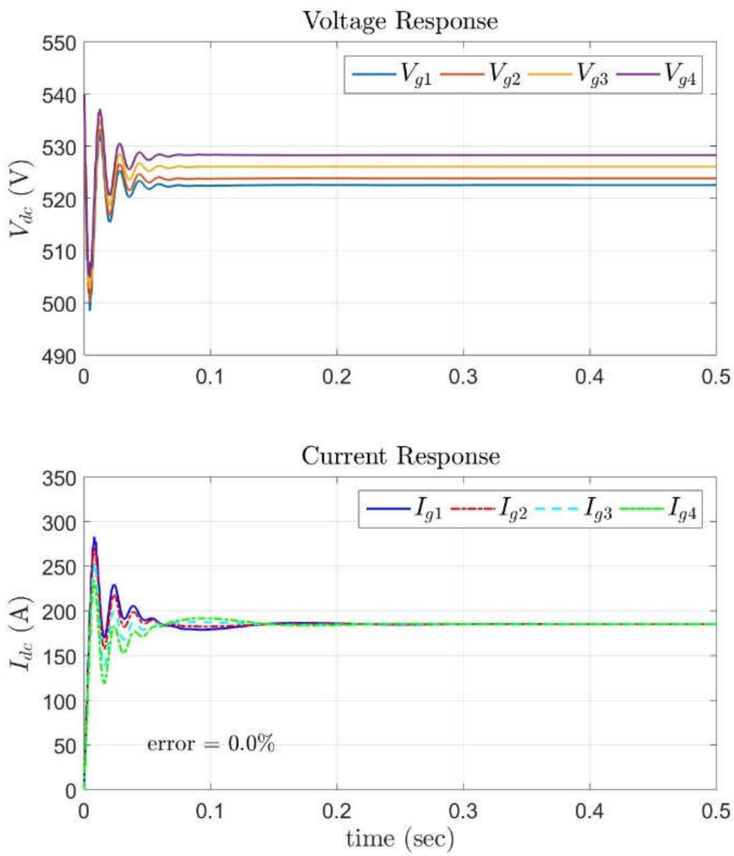


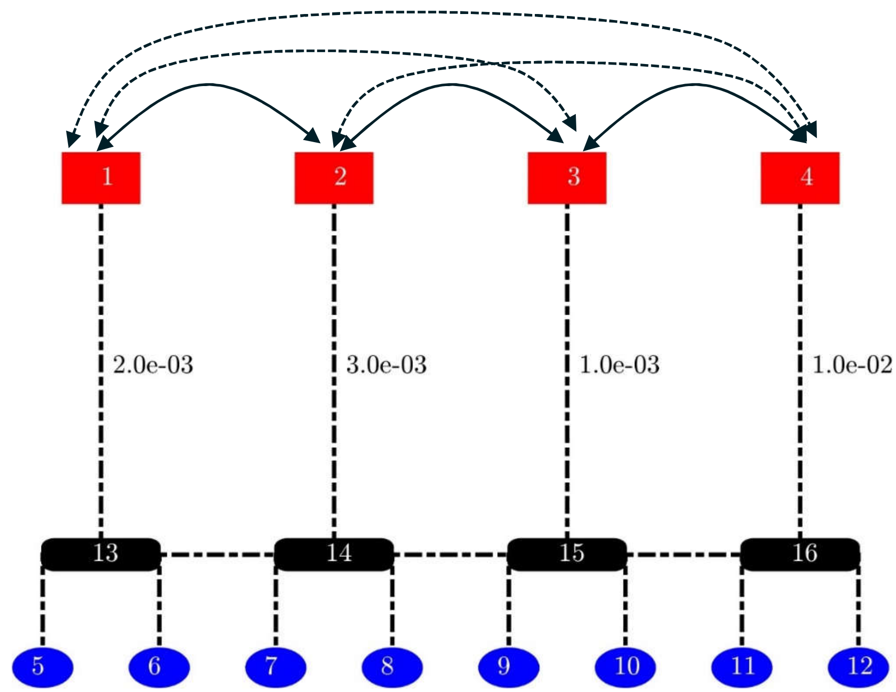
Dynamic Consensus + Gain Optimization

- A connected communication network is needed to achieve consensus (zero error)

$$\begin{pmatrix} \dot{x} \\ \dot{x}_{\mathrm{cs}} \end{pmatrix} = \begin{pmatrix} A + B_b\tilde{Y}C - BK_{\mathrm{droop}}\tilde{Y}_{\alpha,a}C & BK_{\mathrm{cs}} \\ L\tilde{Y}_{\alpha,a}C & 0 \end{pmatrix} \begin{pmatrix} x \\ x_{\mathrm{cs}} \end{pmatrix} + \begin{pmatrix} D \\ 0 \end{pmatrix} h(x, P)$$

$$\begin{aligned} &\min \gamma \\ &\text{s.t.} \\ &Y \succ 0 \\ &\begin{pmatrix} YA_e^T + A_eY + B_eNC_e + C_e^TN^TB_e^T & D_e & YH^T \\ D_e^T & -I & 0 \\ HY & 0 & -\gamma I \end{pmatrix} \prec 0 \\ &C_eY = MC_e \end{aligned}$$

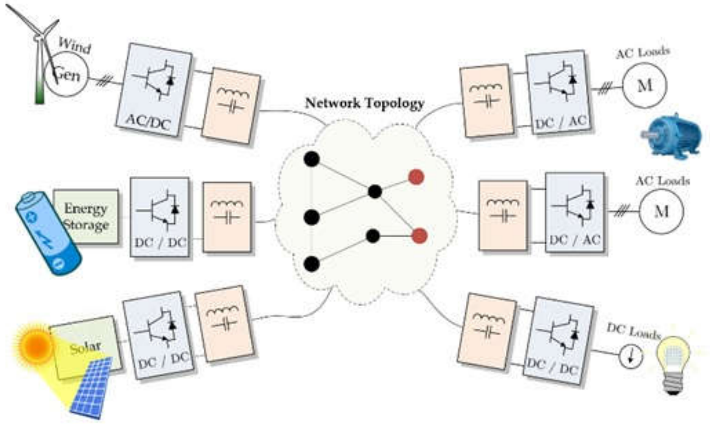


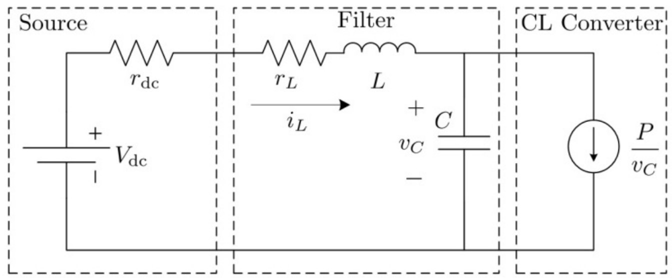


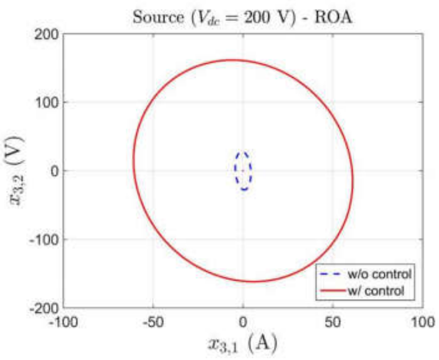
[1] L. Herrera, B. Palmer, X. Yao, and B. Tsao, "Controller design of dc microgrids with multiple sources and constant power loads," presented at IEEE Energy Conversion Congress and Expo. (ECCE), 2017

Key Takeaways – Control of DC Microgrids

- The wide use of power electronics at the load side can have detrimental effects on the network stability
- If the loads are controlled with very high bandwidth, they can behave as Constant Power Loads
- Important to ensure the network is stable and has good stability margins
- Using quadratic Lyapunov functions, a SDP can be used to compute the region of attraction
- Similar SDP can be used to optimize gains to enlarge the stability margins







Outline

- Introduction and Motivation
- Stability Analysis and Control Techniques
  - ✓ Constant power loads
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  - ✓ Series dc arc faults
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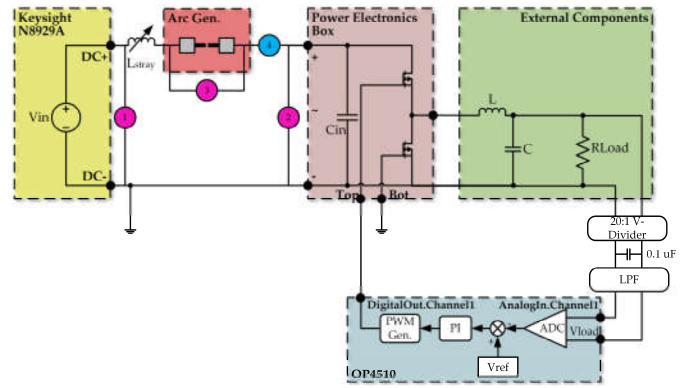
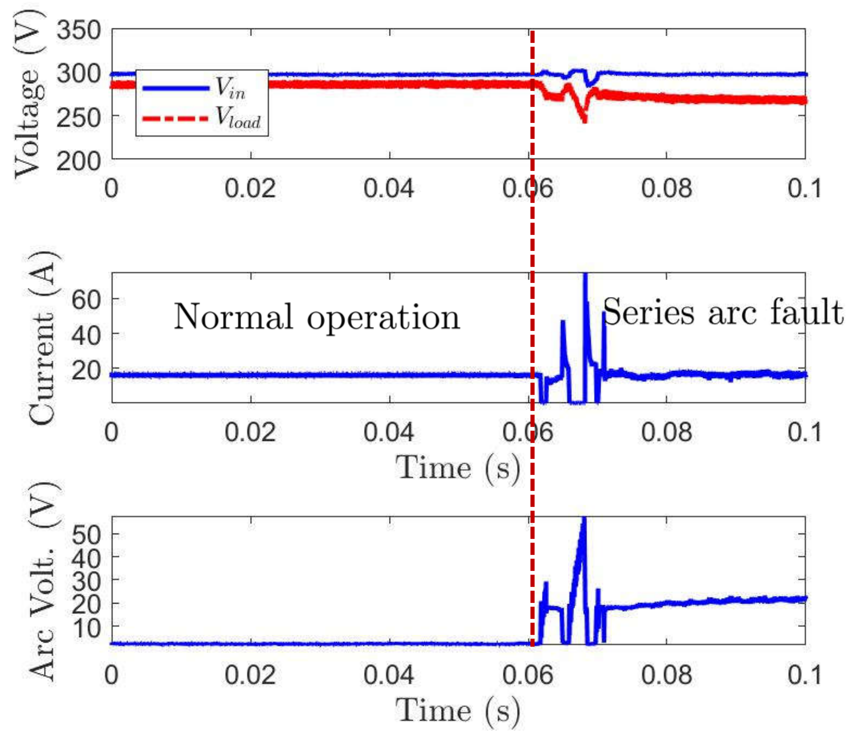
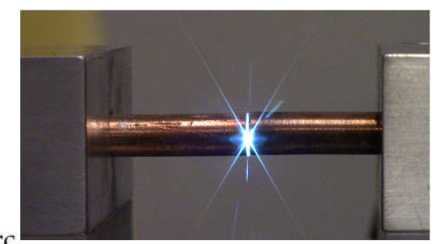
  - ✓ Discrete time parameter estimation techniques
- Summary

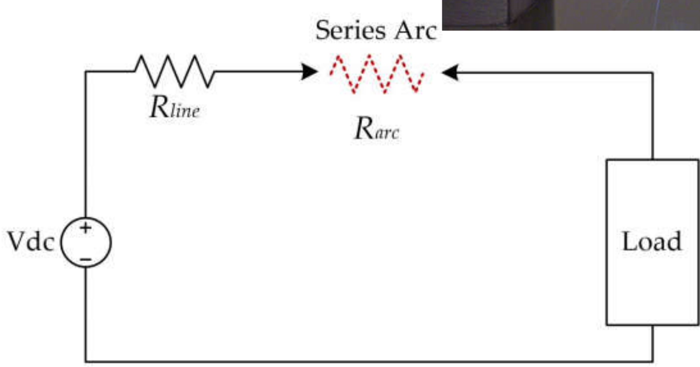
DC Series Arc Faults – High Impedance Fault

- Series dc arc fault is a high impedance fault which occurs in series with a line
- Typically caused by loose connections, chafed wires, etc.
- Due to the high impedance/series connection, this type of fault can be difficult to detect



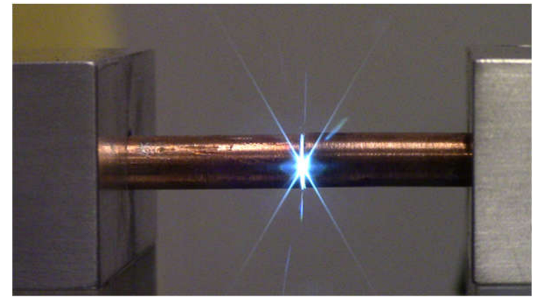


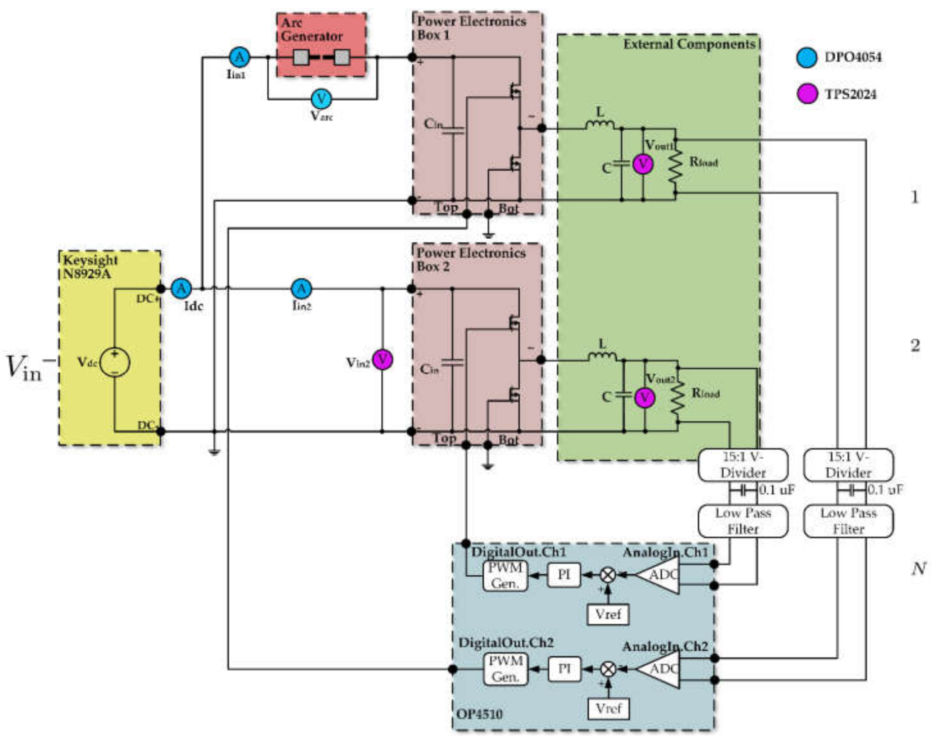


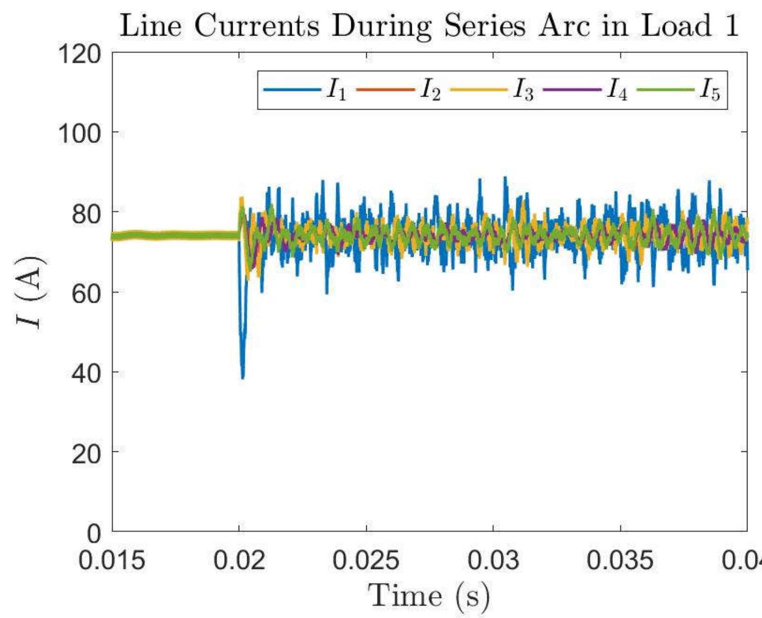


Series High Impedance Faults in DC Microgrids

- The high noise produced by series arc in a line can travel to adjacent line sections
- Example of simulation and experimental tests





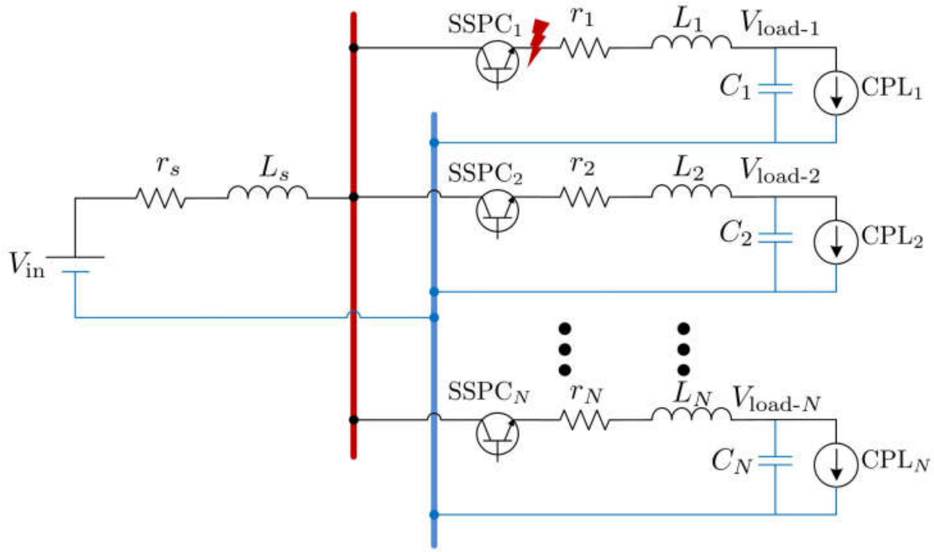


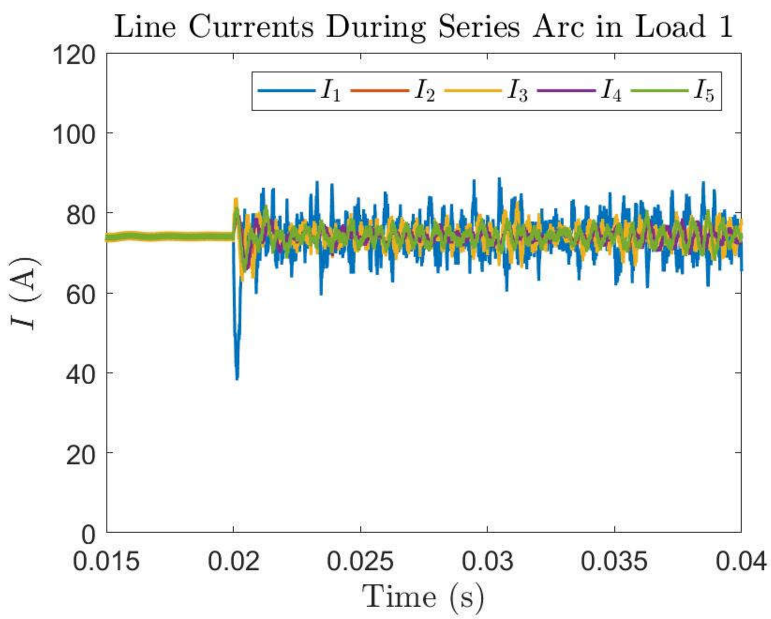
- **Goal:** detect and localize faulted line

[1] X. Yao, "Study on dc arc faults in ring-bus dc microgrids with constant power loads," *IEEE ECCE, 2016*

Fault Localization within Distribution Node

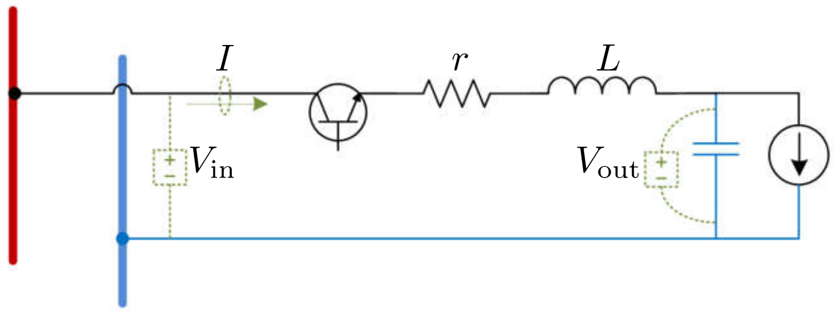
- Consider a distribution node with multiple active loads in parallel
- Main idea/goal is to be able to detect/localize the fault to avoid multiple load interruption
- **Proposed approach: line/filter parameter estimation** $\theta = (r_1, \ L_1)^T$





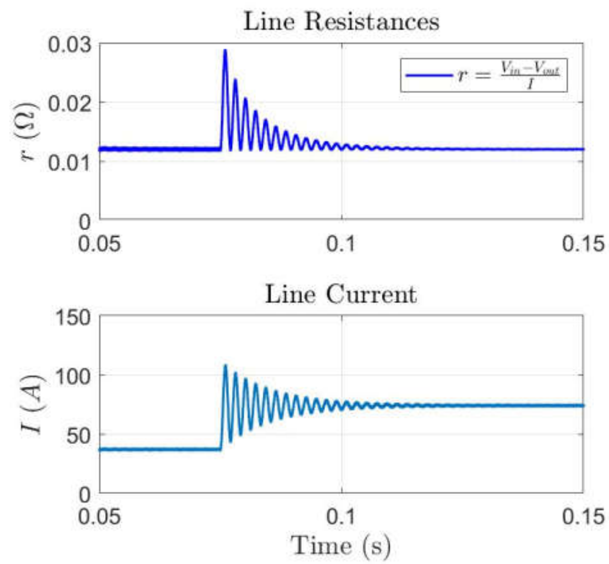
Sensor Placement

- Consider the following sensor placement for a line:



- Why is parameter identification needed if we can simply $r \approx \dfrac{V_{\text{in}} - V_{\text{out}}}{I}$?

During load transients, the current may oscillate
This will affect the r magnitude and settling time



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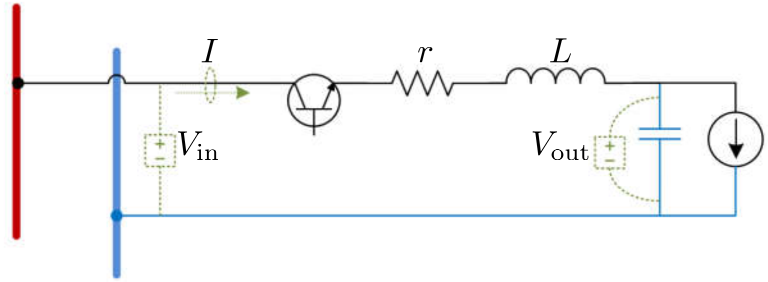
Line/Load Regression Form

- Consider the following line equation:



$$\frac{dI}{dt} = -\frac{r}{L}I + \frac{1}{L}\left(V_{\text{in}} - V_{\text{out}}\right)$$

- Which can be translated into frequency domain:

$$y(s) = \frac{\frac{1}{L}}{s + \frac{r}{L}}\tilde{u}(s) \longrightarrow \underbrace{sy(s) = \begin{pmatrix} b & a \end{pmatrix}\begin{pmatrix} \tilde{u}(s) \\ -y(s) \end{pmatrix}}_{z = {\theta^*}^T\phi} \quad \text{where } b \triangleq \frac{1}{L},\ a \triangleq \frac{r}{L}$$

  - The parameters to be identified are defined in $\theta^* = \begin{pmatrix} b & a \end{pmatrix}^T$
  - $z = {\theta^*}^T\phi$ is of linear regression form

- Can use the following estimation model: $\hat{z} = \theta^T\phi$ and $e = z - \hat{z}$

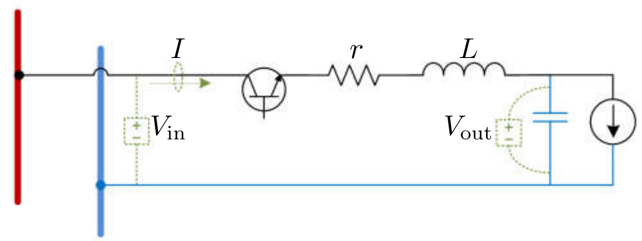
- **Challenge:** The output $z(s) = sy(s)$ needs a derivative, i.e. $z(t) = \dfrac{dI}{dt}$

Gradient Descent Algorithm

- Multiply both sides by a filter $H(s)$:

$$sH(s)y(s) = \begin{pmatrix} b & a \end{pmatrix} \begin{pmatrix} H(s)\tilde{u}(s) \\ -H(s)y(s) \end{pmatrix} \Leftrightarrow z = \theta^{*T}\phi$$

where $b \triangleq \frac{1}{L}$, $a \triangleq \frac{r}{L}$



and the same estimator: $\hat{z} = \theta^T\phi$

Goal: $\theta \to \theta^*$ as $t \to \infty$

- Defined a normalized error: $e = \dfrac{z - \hat{z}}{m^2} = \dfrac{z - \theta^T\phi}{m^2}$, $\quad m^2 = 1 + \phi^T P\phi,\ P \succeq 0$

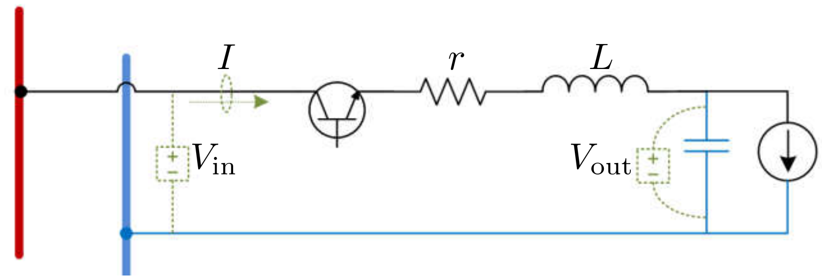
and a cost function $J = \dfrac{e^2 m^2}{2} \Rightarrow \min\limits_{\theta} J(\theta)$

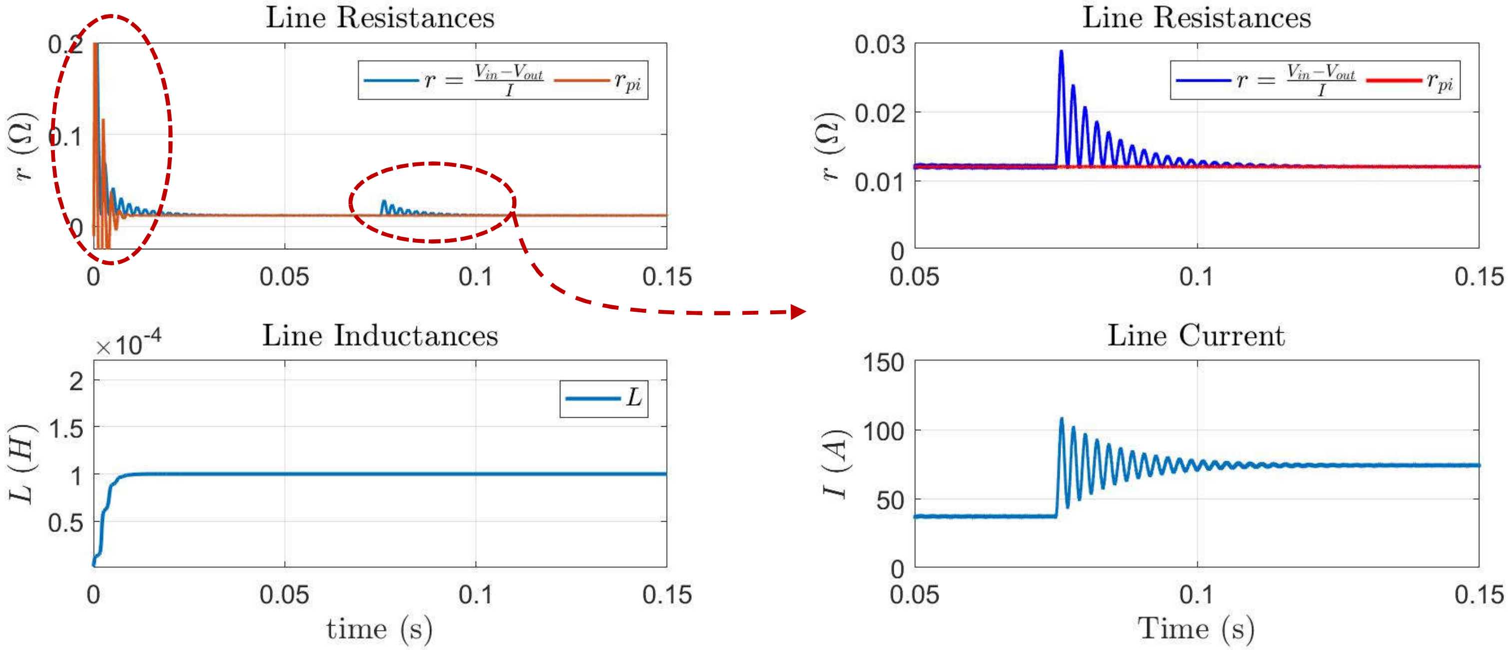
- A continuous time gradient descent algorithm can be used to obtain estimate:

$$\dot{\theta} = -\Gamma\nabla_\theta J = \Gamma e\phi,$$

Performance of the Gradient Descent Algorithm

- Consider the same scenario as before with a step load at t = 0.075 s

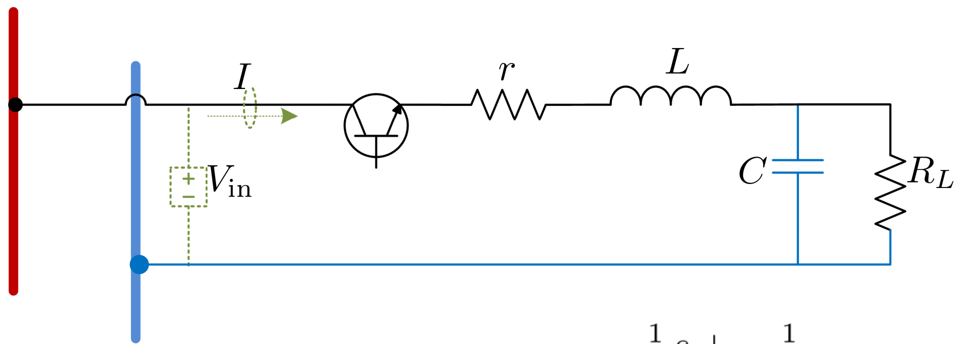




1. Gradient descent algorithm is not affected by the step change and converges faster
2. **However, estimated values oscillate significantly at the beginning**

Extension to Second Order System

- The techniques can be extended to second order systems where **only two sensors are needed**



- In this case, the system is of the form: $$y(s) = \frac{\frac{1}{L}s + \frac{1}{CLR_L}}{s^2 + \frac{CR_L r + L}{CLR_L}s + \frac{r+R_L}{CLR_L}} u(s) \ .$$

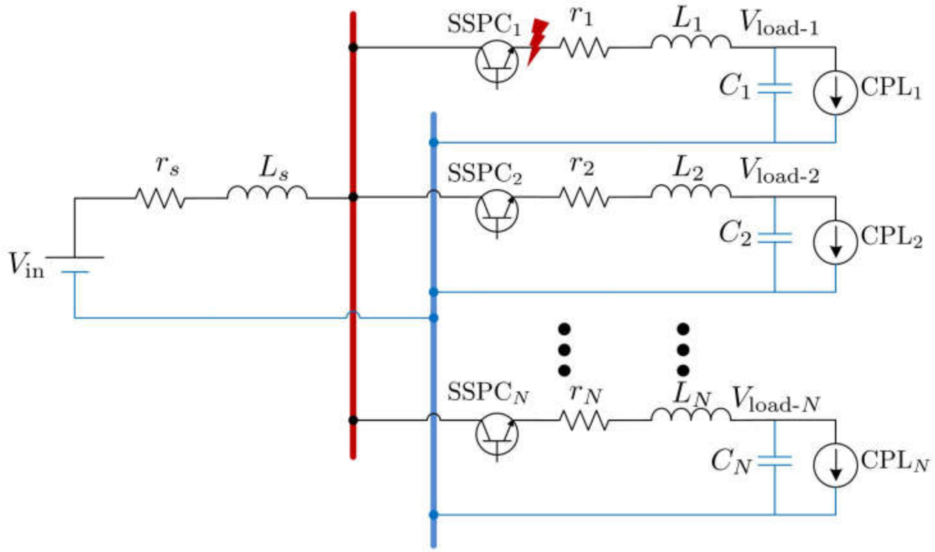
- Which can similarly be placed in linear regression with filtering:

$$s^2 H(s)y(s) = \begin{pmatrix} b_1 & b_0 & a_1 & a_0 \end{pmatrix} \begin{pmatrix} sH(s)u(s) \\ H(s)u(s) \\ -sH(s)y(s) \\ -H(s)y(s) \end{pmatrix} \quad \Leftrightarrow \quad z(s) = (\theta^*)^T \phi$$

- **Challenges:** Design of the filter H(s) and the need for more frequencies (persistent excitation)

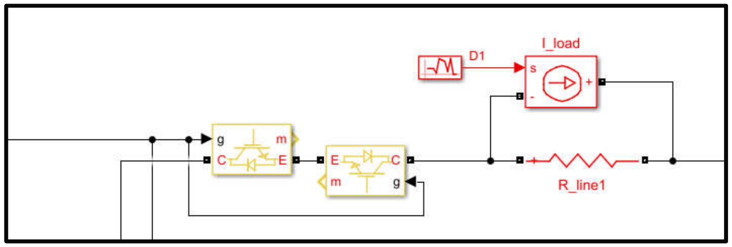
Simulation Results of Series Arc in Distribution Node

- Distribution node with five loads in parallel



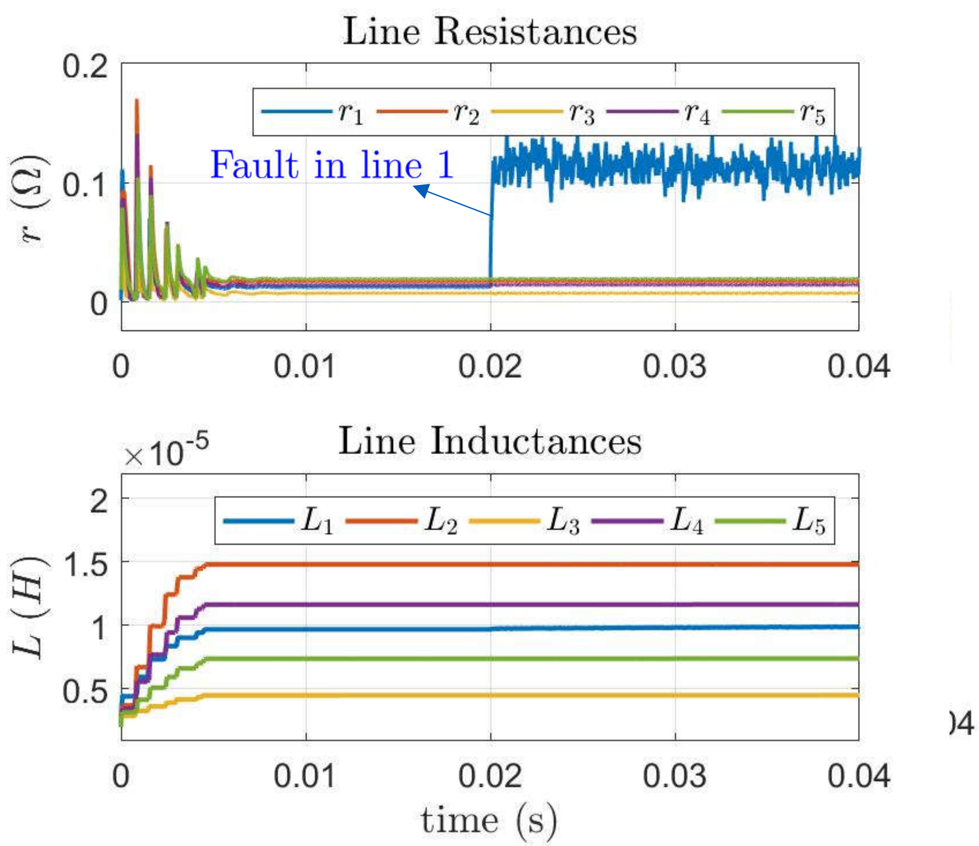
Load Number	Line r (Ω)	Line L (μH)
Load 1	0.010	10
Load 2	0.015	15
Load 3	0.005	5
Load 4	0.012	12
Load 5	0.017	8

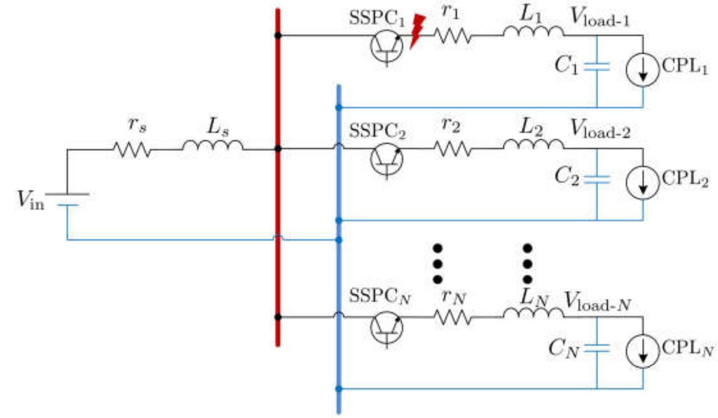
- Series arc is simulated by a resistance in parallel with a current source
- The current source injects Gaussian noise



Simulation Results of Series Arc in Distribution Node

- Distribution node with five loads in parallel
- DC series arc occurs in load 1 only at t = 0.02 s





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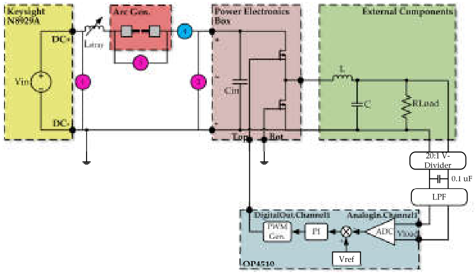
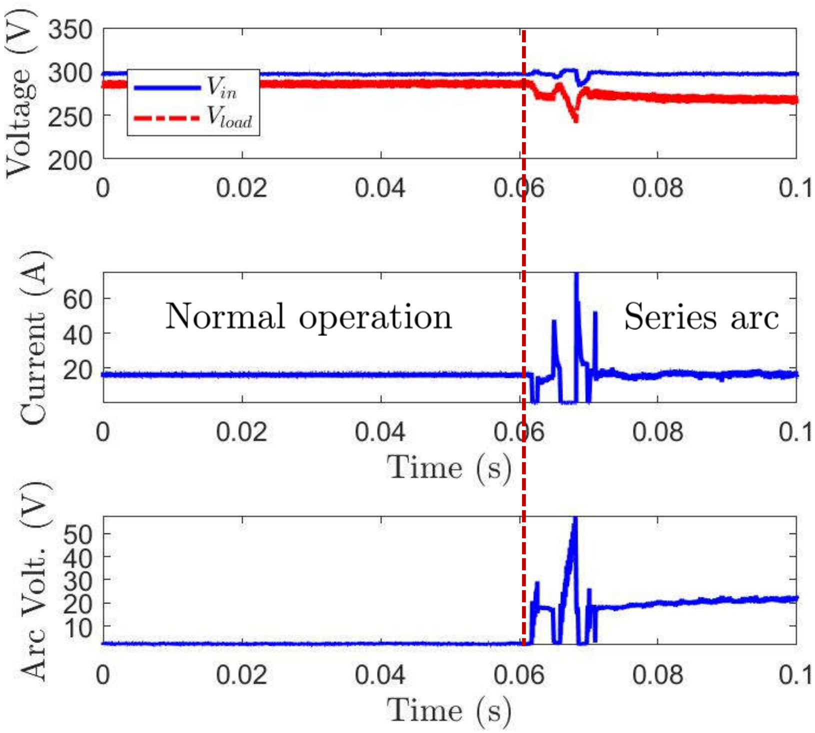
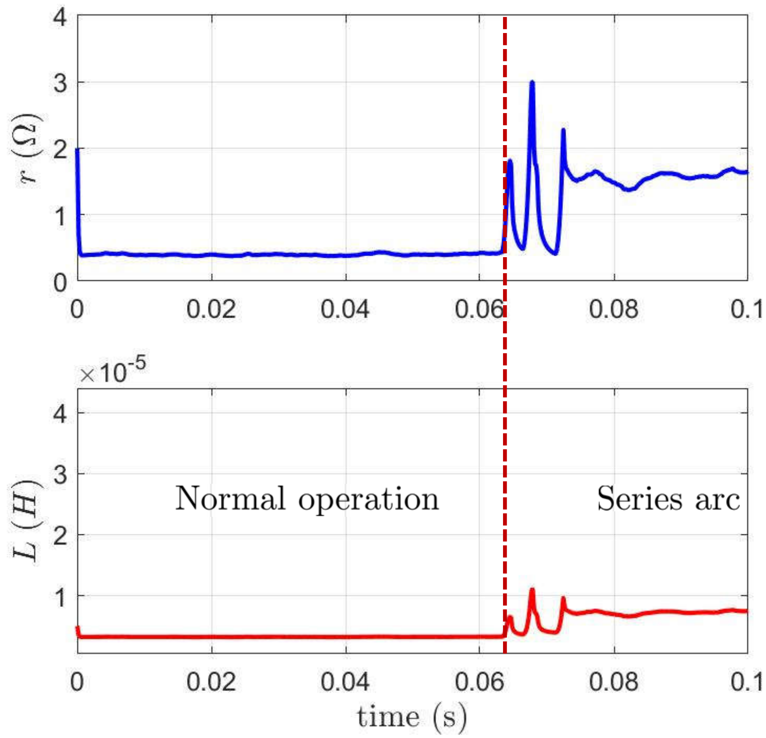
Experimental Results

- The experimental testbed consists of one dc source, dc arc generator, and constant power load (closed loop buck converter)







- **The gradient algorithm is able to estimate the line resistance and inductance***

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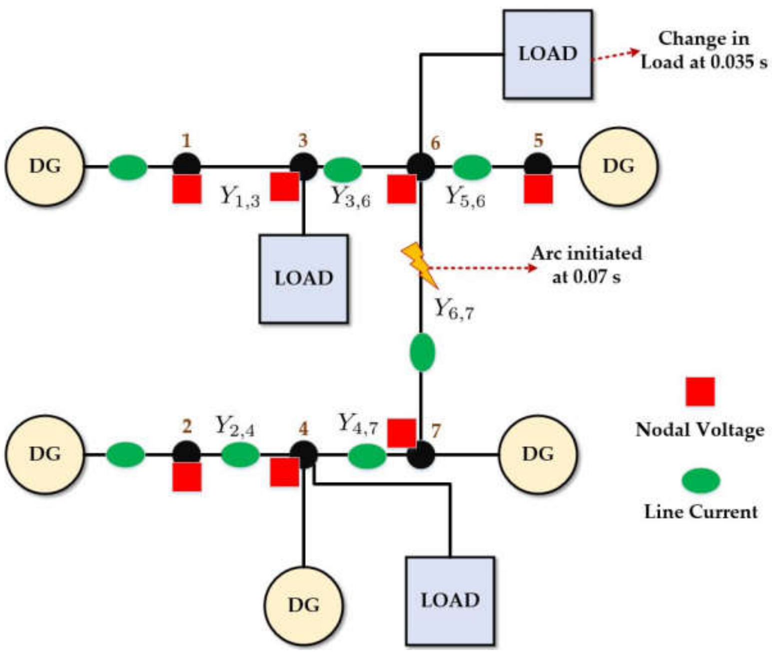
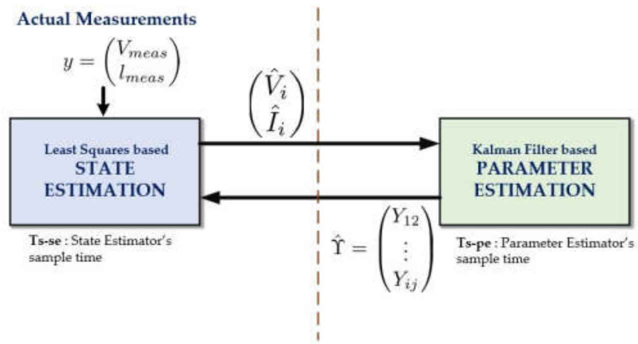
State and Parameter Estimation

- **Problem Definition:** Utilize available measurements to approximate the “true” value of the states (voltage, currents, etc.) and the line resistances/conductance
- **What are the states?** Voltage magnitudes, line currents
- **What are the parameters?** Line resistances
- **Motivation:** Only a few sensors may be available in a network





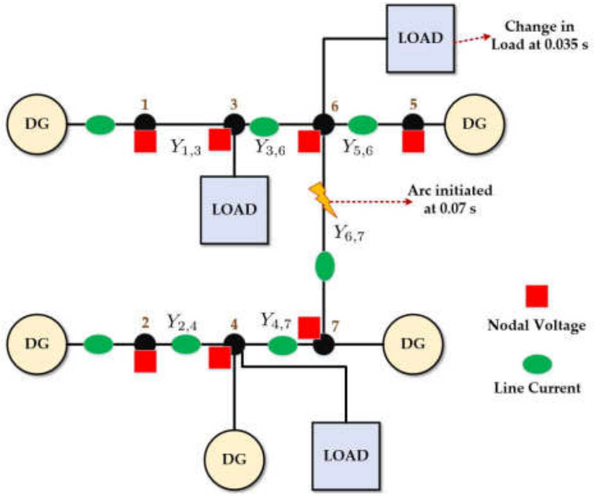
$$\mathcal{G} = \left\{ \underbrace{\mathcal{N}}_{\text{nodes/buses}} , \underbrace{\mathcal{E}}_{\text{edges/lines}} \right\}$$

$$\mathcal{N} = \{1, \cdots, 7\}$$

$$\mathcal{E} = \{(1,3),\ (2,4),\ \cdots,\ (6,7)\}$$

Sparse Tableau Analysis for DC Systems

- States are voltage at every bus $x = [V_1, \cdots, V_7]^T$
- It is not always possible to relate the following sensors to the states
  - Load current sensor, e.g. $i_{(3-g)}$
  - Generator current sensor, e.g. $i_{(1-g)}$



- We can consider **Sparse Tableau Analysis (STA)***

$$\begin{pmatrix} 0 & 0 & A \\ I & -A^T & 0 \\ K_e & 0 & K_l \end{pmatrix} \begin{pmatrix} e \\ V \\ l \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \Rightarrow \; Tx = 0$$

$$x = (e, \; V, \; l)^T \qquad \text{where} \quad \begin{aligned} e &: \text{ Voltage drops} \\ V &: \text{ Node voltages} \\ l &: \text{ Line currents} \end{aligned}$$

- **Advantage:** any sensor can be written as a function of the states $\Rightarrow \; y = Cx + n$

[1] L. Chua, C. Desoer, and E. Kuh. *Linear and nonlinear circuits*. 1987.
[2] D. Gorinevsky, S. Boyd, and S. Poll, “Estimation of faults in dc electrical power system,” in 2009 American Control Conference, June 2009, pp. 4334–4339

Least Squares based State Estimation

- Using the sparse tableau formulation for dc networks, we can estimate all of the states using the following optimization problem:

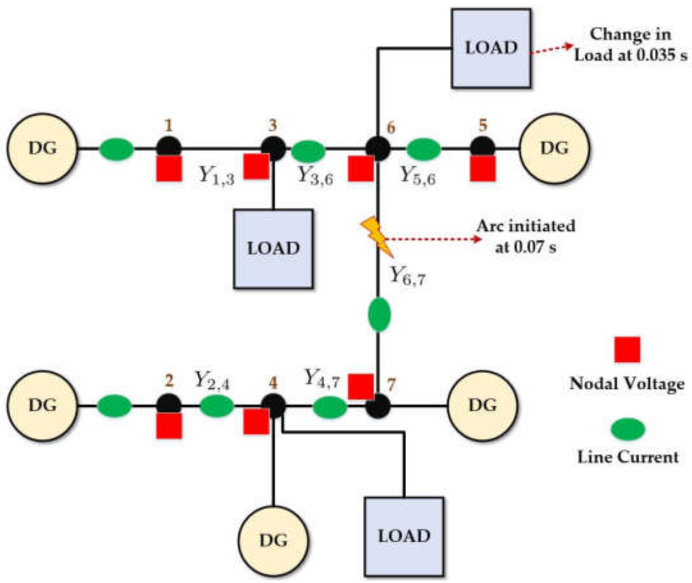
$$\min_{x} \underbrace{\frac{1}{2}\|y_{win} - C_{win}x\|_J^2}_{\text{measurement}} + \underbrace{\frac{1}{2}\|Tx\|_D^2}_{\text{network}}$$

where

$$y_{win} = \begin{pmatrix} y(j) & y(j+1) & \cdots & y(j+w-1) \end{pmatrix}^T$$

$$C_{win} = \mathbf{1}_w \otimes C$$

$$\underbrace{\begin{pmatrix} V_{meas}^T & I_{meas}^T \end{pmatrix}^T}_{y} = C \underbrace{\begin{pmatrix} \hat{e}_i^T & \hat{V}_j^T & \hat{I}_j^T \end{pmatrix}^T}_{\hat{x}}$$



System Modeling for Parameter Estimation

- Nodal analysis for a dc network in steady state:

$$I(k) = Y(k)\,V(k)$$

- We can then form a similar optimization problem to estimate Y

$$\min_{Y} \;\; ||I(k) - Y(k)V(k)||_2^2 \qquad \Leftrightarrow \qquad \min_{Y} \;\; ||I(k) - \left(V(k)^T \otimes I_N\right) \text{vec}\left(Y(k)\right)||_2^2$$

- This problem can be similarly solved by choosing a window of samples as before

- However, we consider a Kalman filter algorithm to do this recursively instead:

State: $x(k+1) = Ix(k) + w(k)$

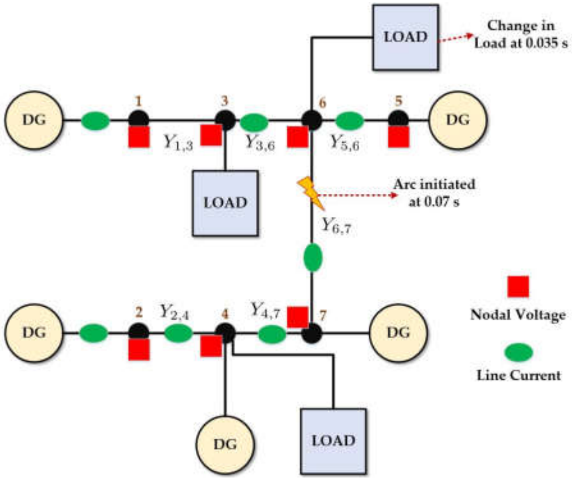
Output: $I(k) = \left(V(k)^T \otimes I_N\right) x(k) + v(k)$

Step 1: $K(k) = P^-(k)\Phi^T(k)\left[\Phi(k)P^-(k)\Phi^T(k) + R\right]^{-1}$

Step 2: $\hat{\Upsilon}^+(k) = \hat{\Upsilon}^-(k) + K(k)\left[y(k) - \Phi(k)\hat{\Upsilon}^-(k)\right]$
$P^+(k) = P^-(k) - K(k)\Phi(k)P^-(k)$

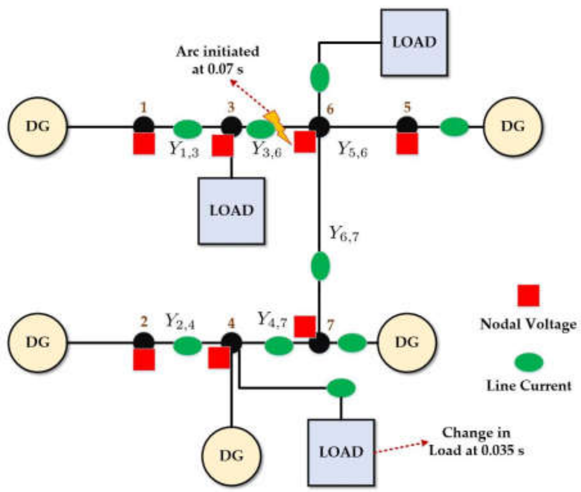
Step 3: $\hat{\Upsilon}^-(k) = \mathcal{I}\hat{\Upsilon}^+(k-1)$

Step 4: $P^-(k) = P^+(k-1) + Q$

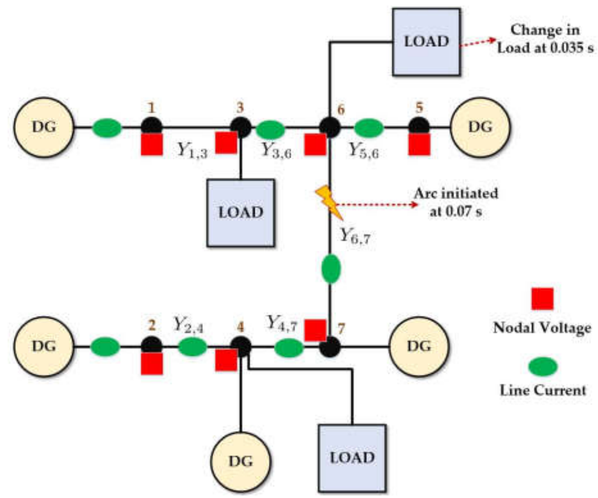


DC Microgrid Configuration

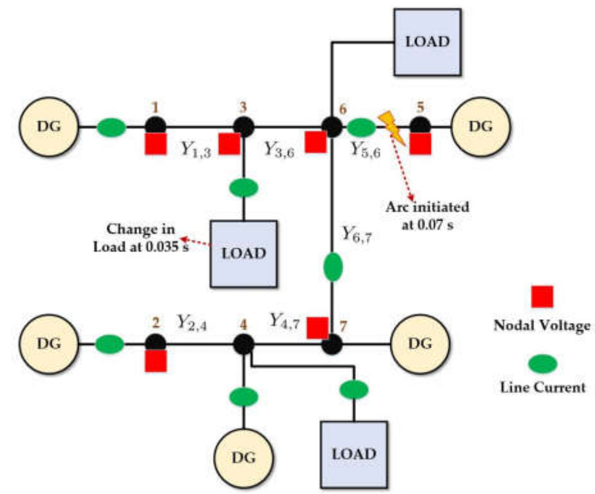
- Three of the following scenarios were considered :



Case 1: 16 sensors



Case 2: 14 sensors



Case 3: 13 sensors

- DC buck converters were coupled at every load and generator on the grid

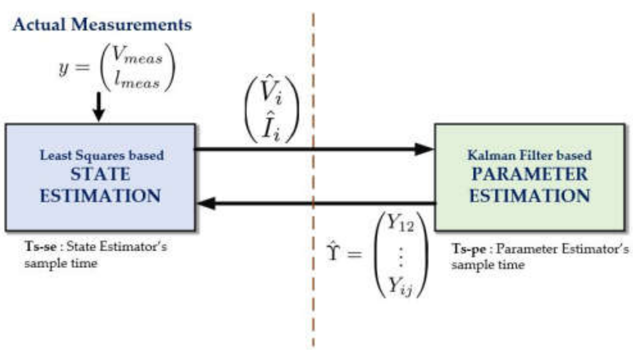
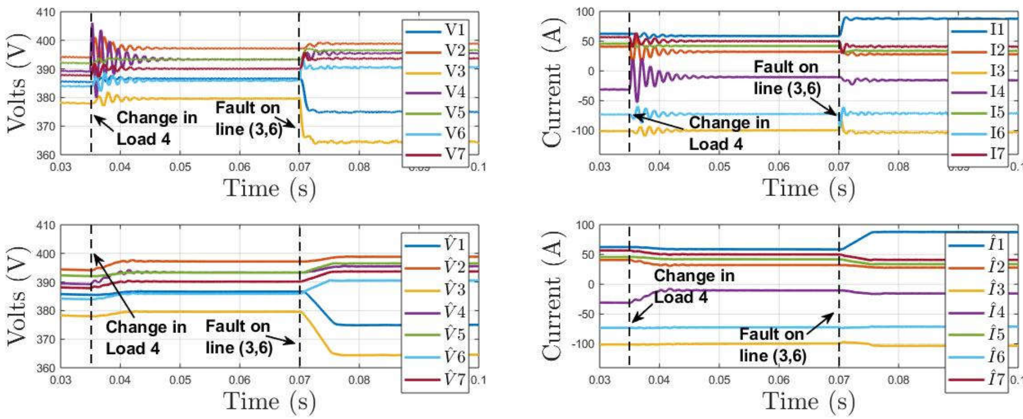


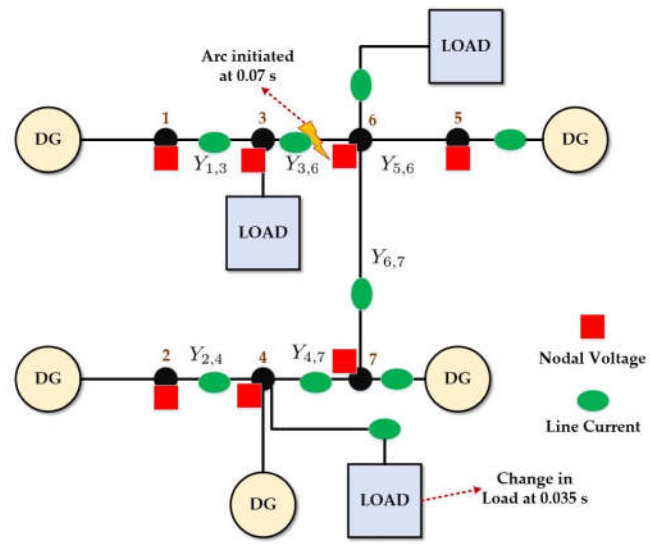
TABLE I. DC microgrid simulation parameters

Line	Length (miles)	Inductance (H)	Resistance (Ω)	Conductance (Ω^{-1})
(1,3)	0.1	1.6e-4	0.12	8.33
(2,4)	0.1	1.6e-4	0.12	8.33
(3,6)	0.125	2e-4	0.15	6.67
(4,7)	0.125	2e-4	0.15	6.67
(5,6)	0.15	2.4e-4	0.18	5.55
(6,7)	0.05	8e-5	0.06	16.67

Case 1: Simulation Results

- There are 16 sensors in this dc microgrid configuration
- Load 4 changes the current being drawn from 150 A to 90 A at t = 0.035 s
- The fault is set to occur on line (3,6) at t = 0.07 s
  - Voltage and current estimation:





  - Parameter estimation:

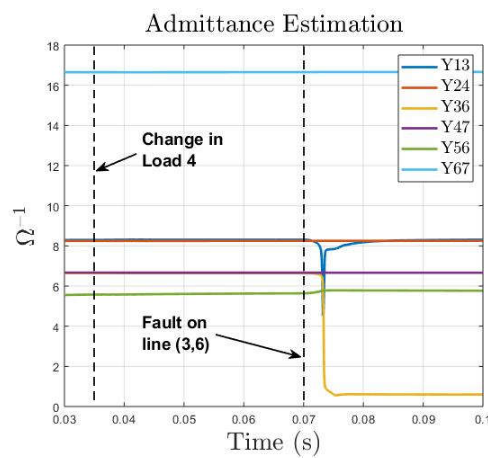
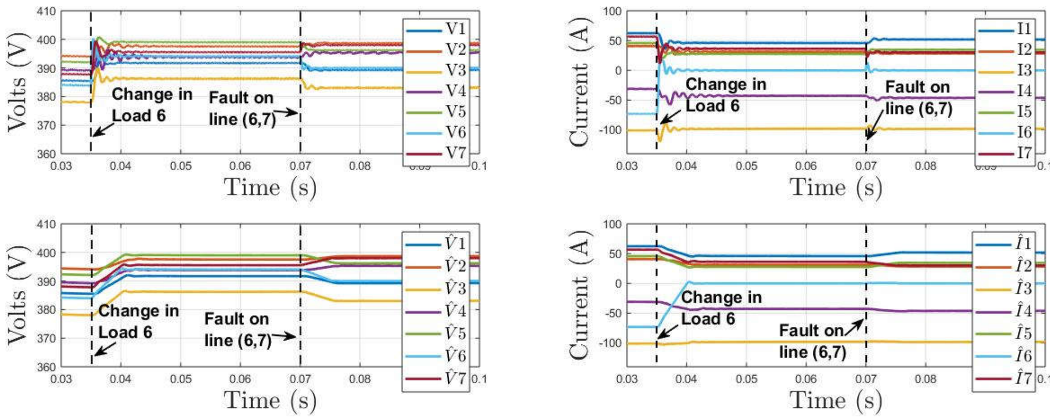


TABLE I. DC microgrid simulation parameters

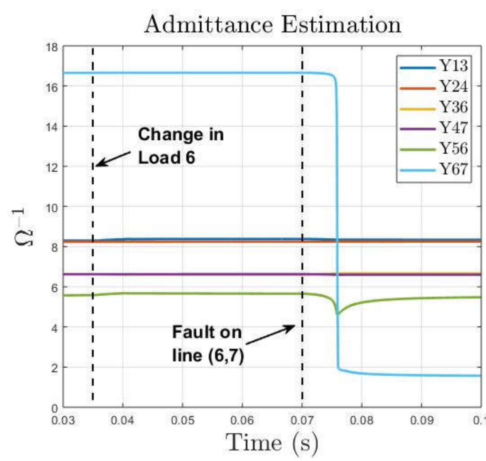
Line	Length (miles)	Inductance (H)	Resistance (Ω)	Conductance (Ω^{-1})
(1,3)	0.1	1.6e-4	0.12	8.33
(2,4)	0.1	1.6e-4	0.12	8.33
(3,6)	0.125	2e-4	0.15	6.67
(4,7)	0.125	2e-4	0.15	6.67
(5,6)	0.15	2.4e-4	0.18	5.55
(6,7)	0.05	8e-5	0.06	16.67

Case 2: Simulation Results

- There are 14 sensors in this dc microgrid configuration
- Load 6 changes the current being drawn from 125 A to 0 A at t = 0.035 s
- The fault is set to occur on line (6,7) at t = 0.07 s
  - Voltage and current estimation:



  - Parameter estimation:



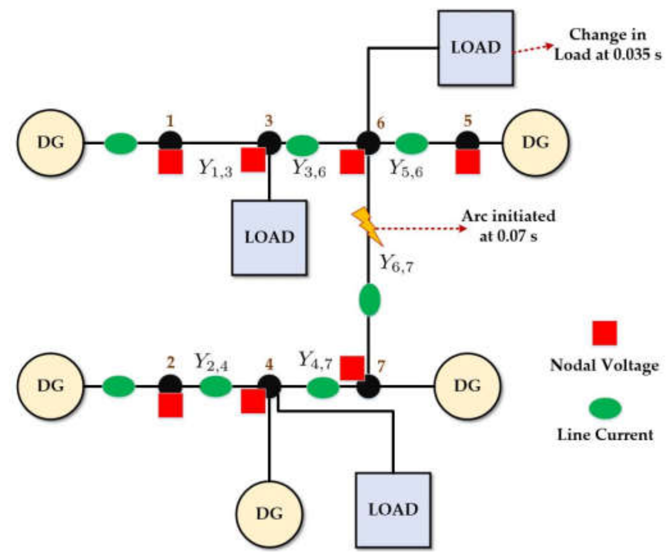
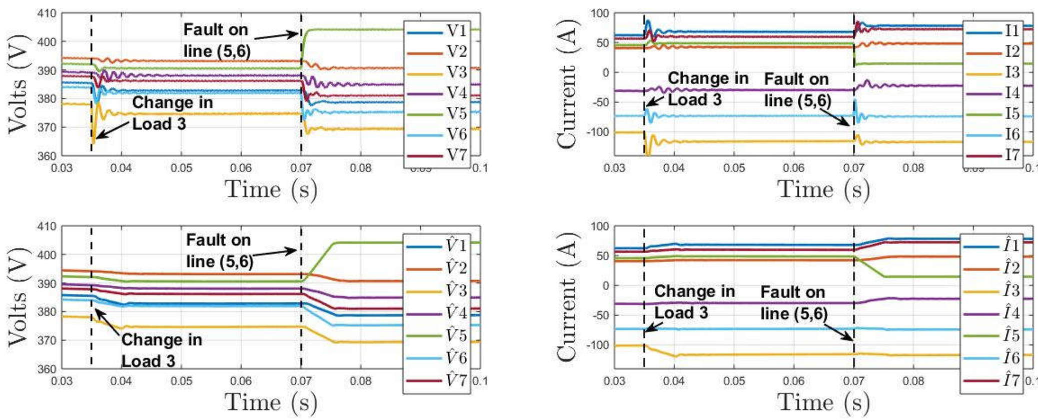


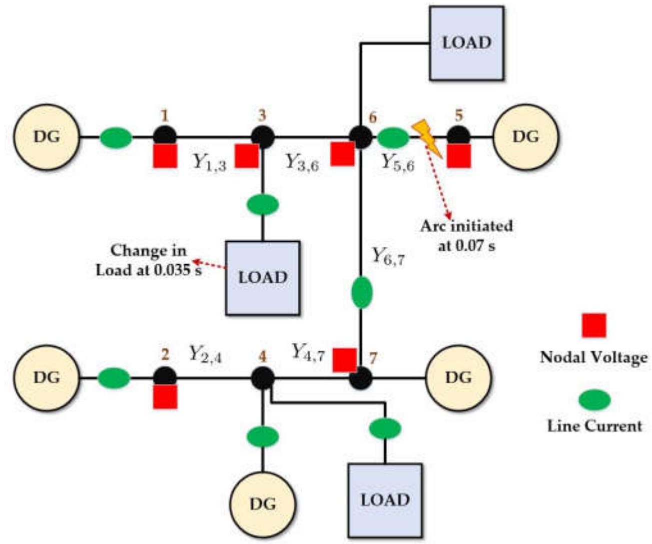
TABLE I. DC microgrid simulation parameters

Line	Length (miles)	Inductance (H)	Resistance (Ω)	Conductance (Ω^{-1})
(1,3)	0.1	1.6e-4	0.12	8.33
(2,4)	0.1	1.6e-4	0.12	8.33
(3,6)	0.125	2e-4	0.15	6.67
(4,7)	0.125	2e-4	0.15	6.67
(5,6)	0.15	2.4e-4	0.18	5.55
(6,7)	0.05	8e-5	0.06	16.67

Case 3: Simulation Results

- There are 13 sensors in this dc microgrid configuration
- Load 3 changes the current being drawn from 175 A to 205 A at t = 0.035 s
- The fault is set to occur on line (5,6) at t = 0.07 s
  - Voltage and current estimation:





  - Parameter estimation:

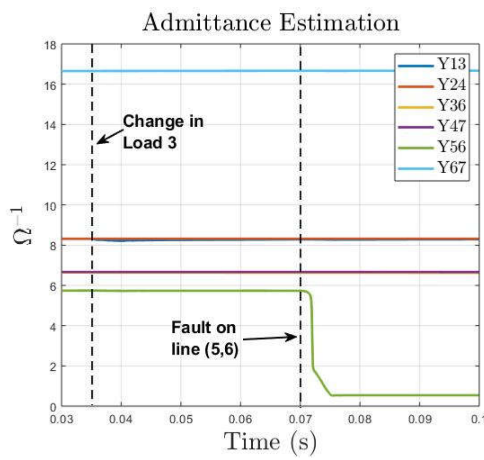
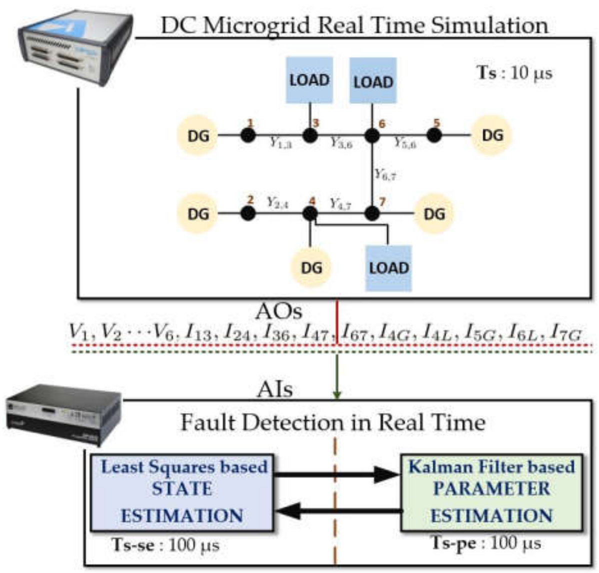


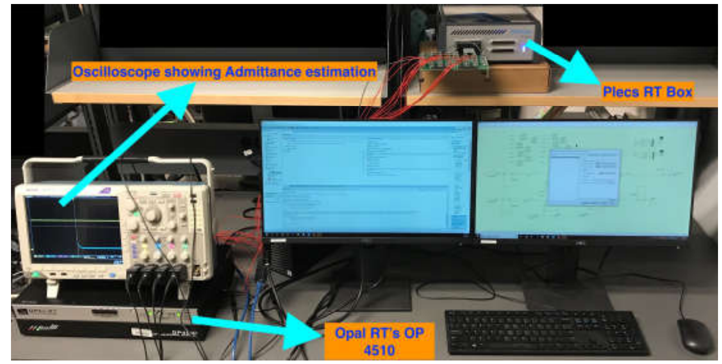
TABLE I. DC microgrid simulation parameters

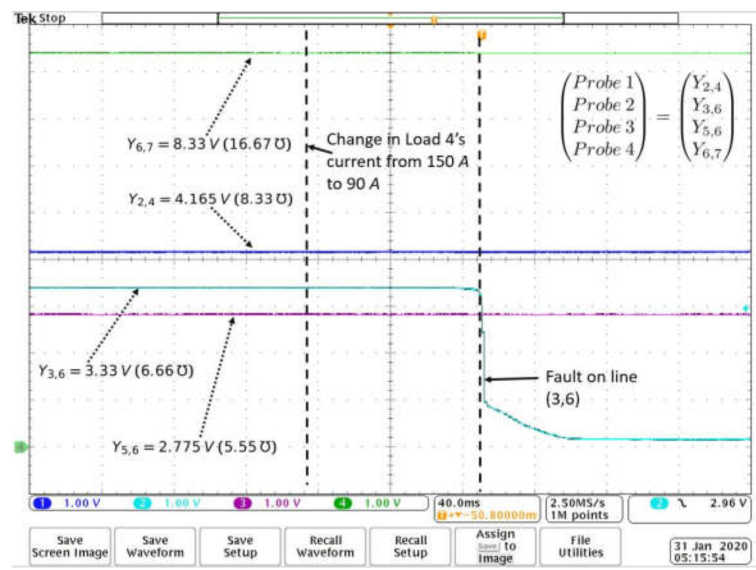
Line	Length (miles)	Inductance (H)	Resistance (Ω)	Conductance (Ω^{-1})
(1,3)	0.1	1.6e-4	0.12	8.33
(2,4)	0.1	1.6e-4	0.12	8.33
(3,6)	0.125	2e-4	0.15	6.67
(4,7)	0.125	2e-4	0.15	6.67
(5,6)	0.15	2.4e-4	0.18	5.55
(6,7)	0.05	8e-5	0.06	16.67

Control Hardware in Loop Results

- The CHIL setup and the real time interaction of the PLECS RT box and the OPAL RT are shown below



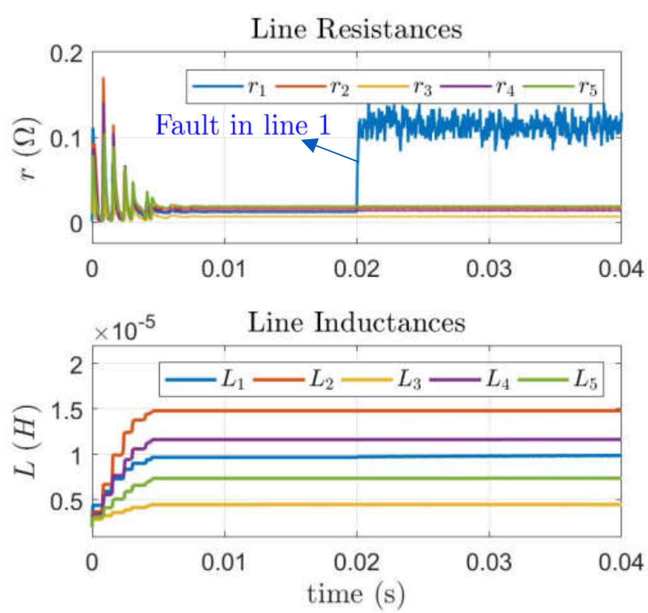


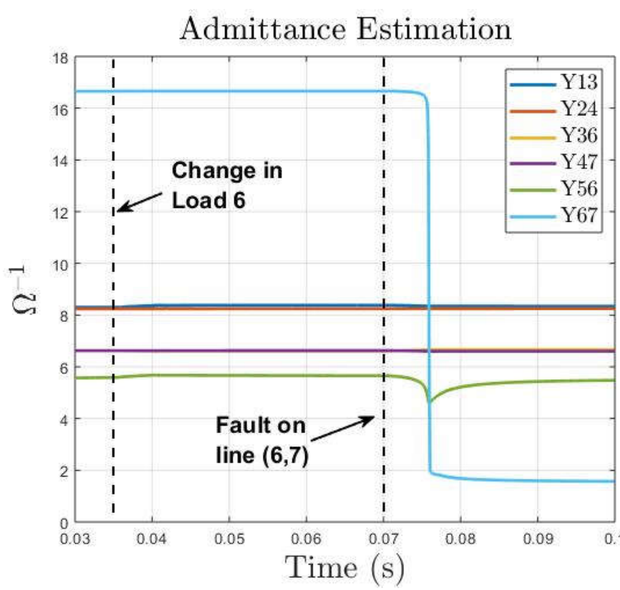


- 16 sensors were used on the microgrid
- Fault detection on line $(3, 6)$ was successfully detected

Key Takeaways – Estimation/Fault Detection

- Parameter estimation techniques can be used to identify line resistances/conductance
- Series dc arc can change the steady state resistance of a line (high impedance fault)
- Estimation techniques can be used to detect and identify faulted lines
- These techniques are robust to normal operation of the system, e.g. source and load changes





Outline

- Introduction and Motivation
- Stability Analysis and Control Techniques
  - ✓ Constant power loads
  - ✓ Analysis of large dc networks
- Fault Types and Estimation Strategies
  - ✓ Series dc arc faults
  - ✓ Continuous time parameter estimation techniques
  - ✓ Discrete time parameter estimation techniques
- Summary

Summary

- DC microgrids are widely used nowadays in transportation industry, mobile networks, etc.
- Presented optimization techniques for the computation of stability metrics of networks with nonlinear constant power loads
- DC series arc fault can be challenging to detect: series/high impedance, low fault current
- Fault noise can propagate to the network
- Parameter estimation methods can detect and localize faulted line sections accurately and fast

http://www.dvidshub.net/image/935698/aerial-refueling-f-35-lightning-ii-joint-strike-fighters-eglin-afb-fla#.UZyEMrVU8QY

https://insideevs.com/features/343599/2021-electric-vehicles-the-future-generation-of-evs/

Thank you for your attention!

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