# Behavior and Control of Power Electronic Interfaces in DC Microgrids

**Alexis Kwasinski**

**Thank you to Mr. Chimaobi N. Onwuchekwa**

**May, 2011**

# Overview

- Introduction

- Constant-power-load (CPL) characteristics and effects

- Dynamical characteristics of DC micro-grids

- Conclusions/future work

# Introduction

- ac vs. dc micro-grids

- Some of the issues with Edison's dc system:
    - Voltage-transformation complexities
    - Incompatibility with induction (AC) motors

- Power electronics help to overcome difficulties
    - Also introduces other benefits – DC micro-grids

- DC micro-grids
    - Help eliminate long AC transmission and distribution paths
    - Most modern loads are DC – modernized conventional loads too!
    - No need for frequency and phase control – stability issues?
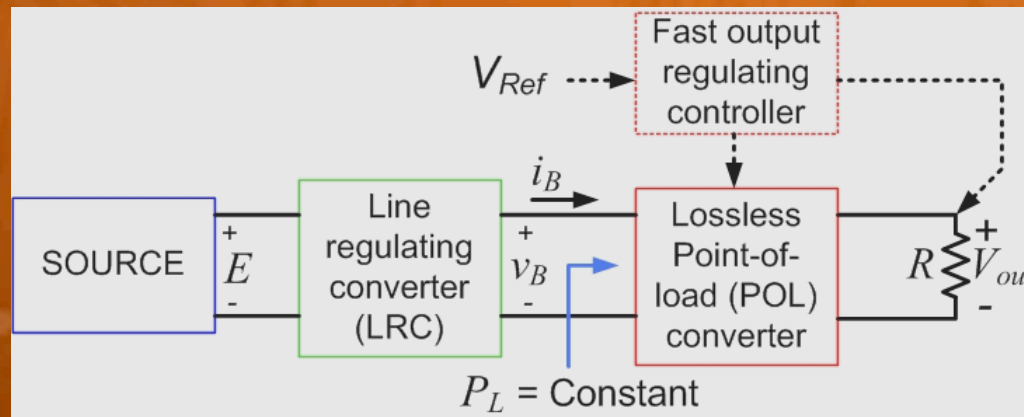
- ac vs. dc micro-grids

- DC is better suited for energy storage, renewable and alternative power sources

# Constant-power loads
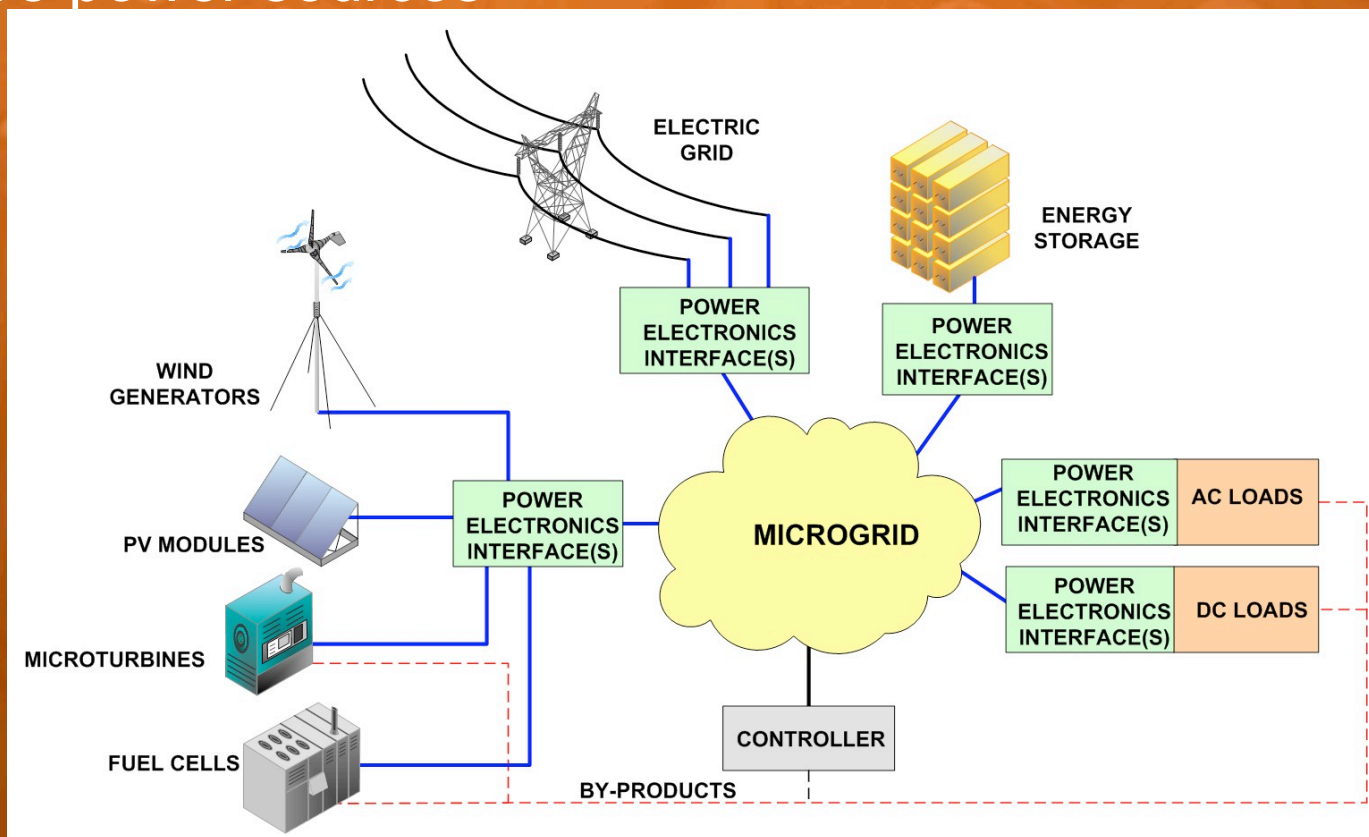
- Characteristics

•DC micro-grids comprise cascade distributed power architectures – converters act as interfaces

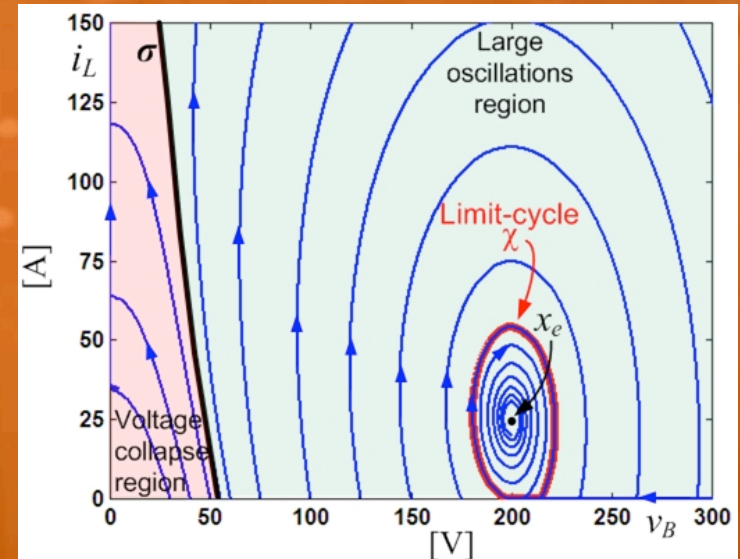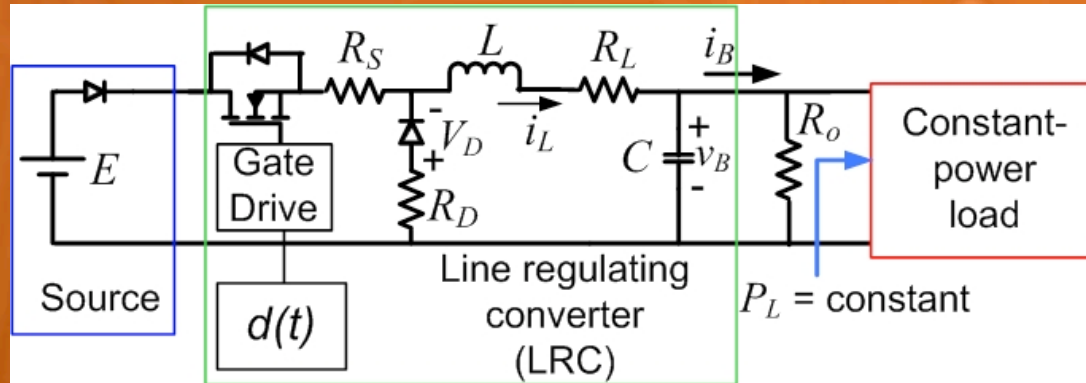•Point-of-load converters present constant-power-load (CPL) characteristics



$$i(t) = \begin{cases} 0 & \text{if } v(t) < V_{\text{lim}} \\ \dfrac{P_L}{v(t)} & \text{if } v(t) > V_{\text{lim}} \end{cases}$$

$$\delta z = \frac{dv_B}{di_B} = -\frac{P_L}{i_B^2}$$

•CPLs introduce a destabilizing effect

# Constant-power loads

- ## Characteristics



Simplified cascade distributed power architecture with a buck LRC.

$$\begin{cases} L\dfrac{di_L}{dt} = q(t)(E - R_S i_L) - (1 - q(t))(V_D + i_L R_D) - i_L R_L - v_C \\[2mm] C\dfrac{dv_C}{dt} = i_L - \dfrac{P_L}{v_C} - \dfrac{v_C}{R_o} \end{cases},$$

$$\text{with } i_L \geq 0, v_C > \varepsilon$$

- Constraints on state variables makes it extremely difficult to find a closed form solution, but they are essential to yield the limit cycle behavior.

UT ECE | THE UNIVERSITY OF TEXAS AT AUSTIN
DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

• Characteristics

• The steady state fast average model yields some insights:

$$LC\frac{d^2 x_2}{dt^2} - \frac{LP_L}{x_2^2}\frac{dx_2}{dt} + x_2 = DE$$

with $x_2 > \varepsilon$ and $x_1 = C\frac{dx_2}{dt} + \frac{P_L}{x_2} \geq 0$
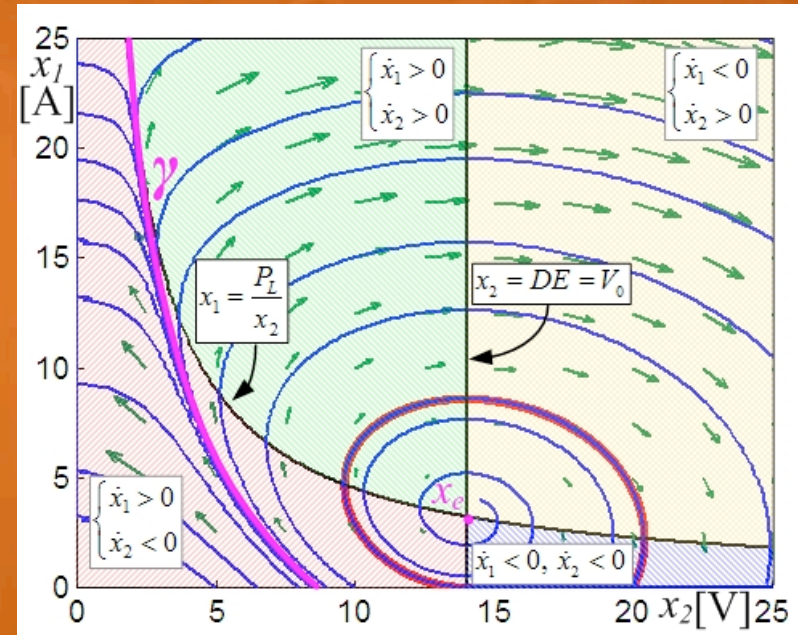


• Lack of resistive coefficient in first-order term

• Unwanted dynamics introduced by the second-order term can not be damped.

• Necessary condition for limit cycle behavior: $\dfrac{d(t)E - v_C}{L} > \dfrac{1}{C}\left(\dfrac{P_L}{v_C} - i_L\right)\dfrac{P_L}{v_C^2}$

• Note: $x_1 = i_L$ and $x_2 = v_C$
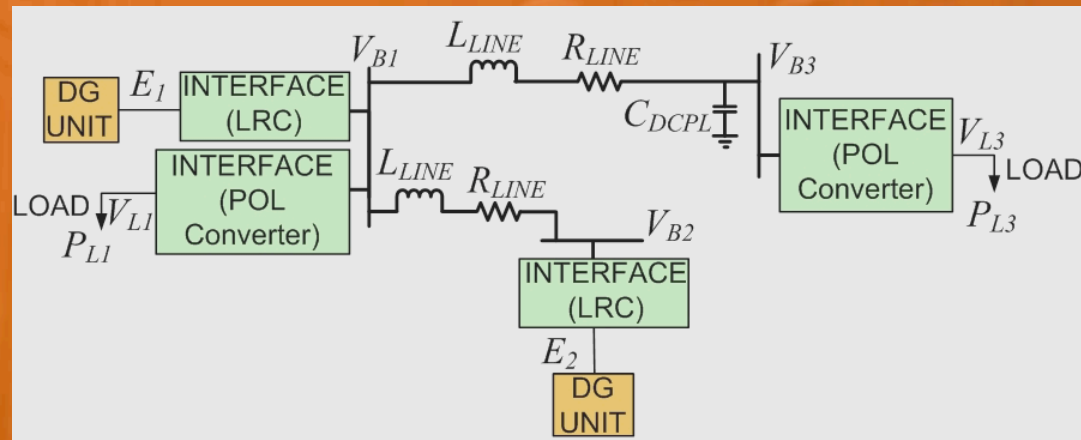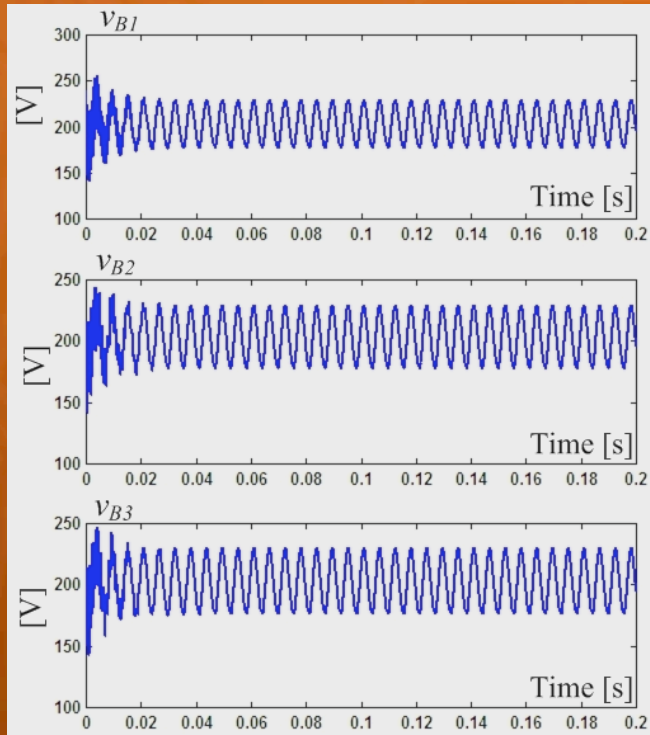
# Constant-power loads

- Characteristics

• Large oscillations may be observed not only when operating converters in open loop but also when they are regulated with most conventional controllers, such as PI controllers.
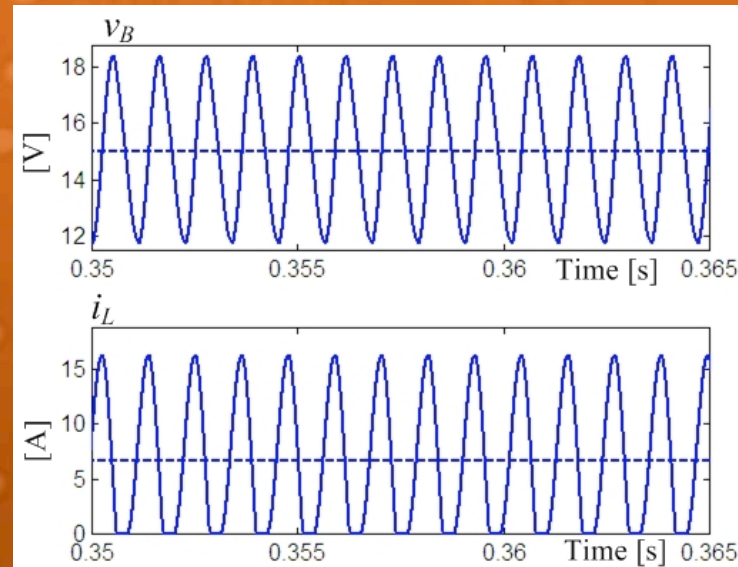


Simulation results for an ideal buck converter with a PI controller both for a 100 W CPL (continuous trace) and a 2.25 Ω resistor (dashed trace); E = 24 V, L = 0.2 mH, PL = 100 W, C = 470 μF.

- Characteristics



$$E_1 = 400V, E_2 = 450V, P_{L1} = 5kW, P_{L2} = 10kW,$$

$$L_{LINE} = 5\mu H, R_{LINE} = 10m\Omega, C_{DCPL} = 1mF$$

LRC parameters:

$$L = 0.5mH, C = 1mF, D_1 = 0.5, D_2 = 0.54, R_L = 0.8\Omega$$

- Due to constant-power loads in micro-grids without proper controls large oscillations and/or voltage collapse is observed

# Stabilization
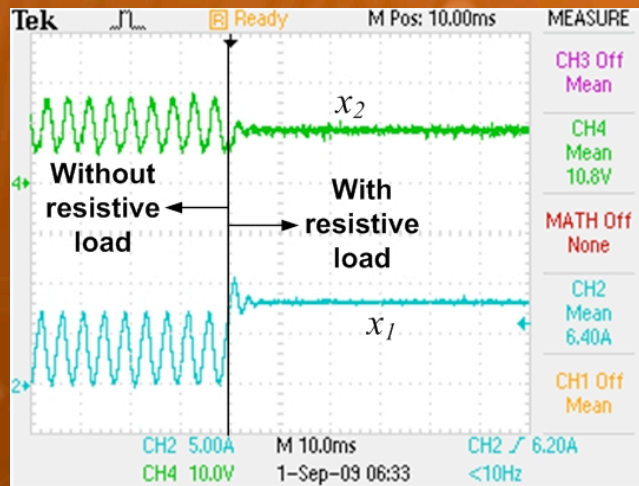
- Passive methods – added resistive loads
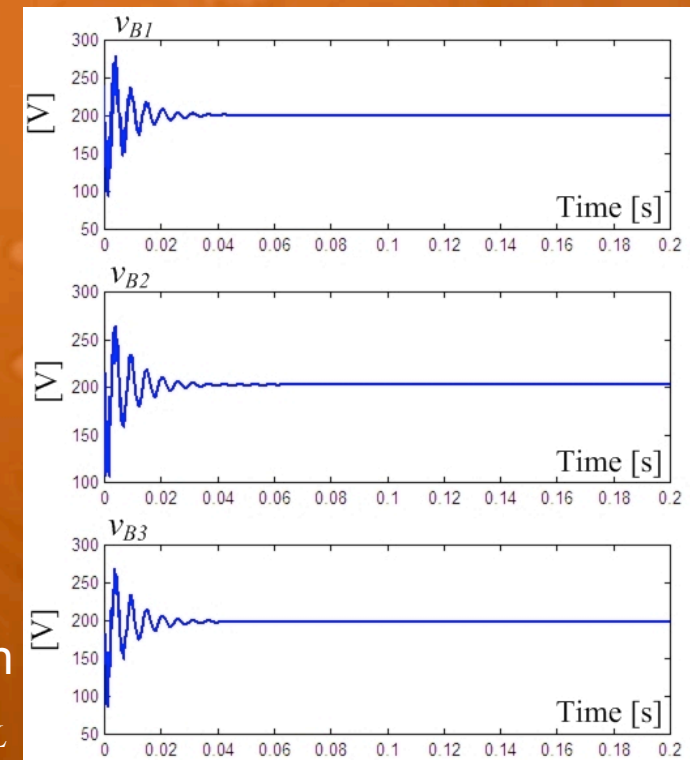
- Linearized equation:
$$\lambda^2 + \lambda\left(\frac{R_i}{L} - \frac{P_L}{CV_o^2} + \frac{1}{R_oC}\right) + \frac{R_i}{L}\left(\frac{1}{R_oC} - \frac{P_L}{CV_o^2}\right) + \frac{1}{LC} = 0$$

- Conditions:

$$P_L < V_o^2\left(\frac{C}{L}R_i + \frac{1}{R_o}\right), \quad P_L < V_o^2\left(\frac{1}{R_i} + \frac{1}{R_o}\right)$$
$$\text{where } R_i = R_S D + R_D(1-D) + R_L$$

- Issue: Inefficient solution



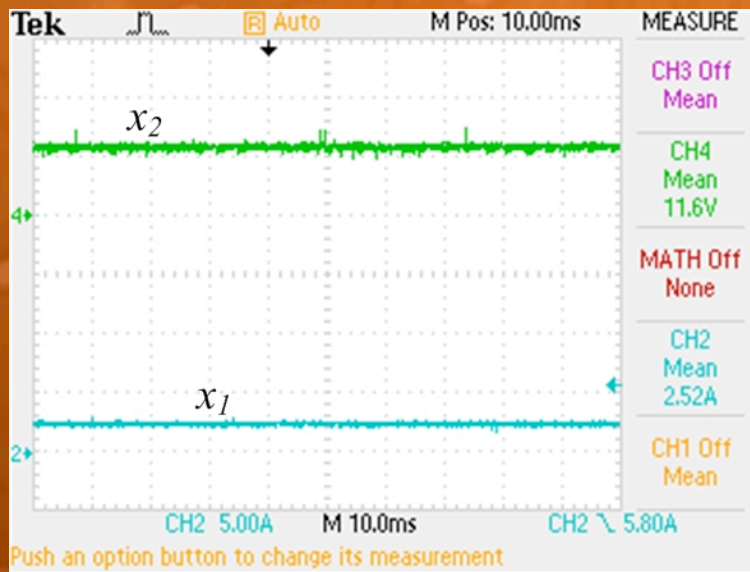1Ω resistor $R_o$ in parallel to $C_{DCPL}$

$$E = 12.5V, L = 480\mu H, C = 480\mu F, R_o = 2\Omega, D = 0.9, P_L = 43.8W$$

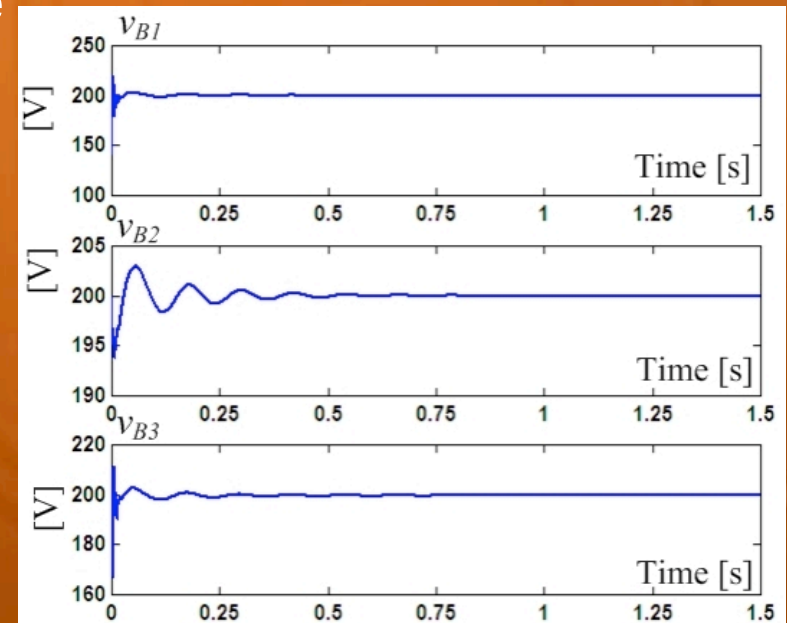# Stabilization

• Passive methods – added capacitance

• Condition: $C > \dfrac{P_L L}{V_o^2 R_i}$

• Issues: Bulky, expensive and may reduce reliability. But may improve fault detection and clearance



$E = 12.5V, L = 480\mu H, C = 480\mu F + 200mF,$
$D = 0.9, P_L = 35W$

60 mF added in parallel to $C_{DCPL}$

# Stabilization

• Passive methods – added bulk energy storage

• It can be considered an extension of the previous approach.

• Energy storage needs to be directly connected to the main bus without intermediate power conversion interfaces.

• Issues: Expensive, it usually requires a power electronic interface, batteries and ultracapacitors may have cell equalization problems, and reliability, operation and safety may be compromised.

# Stabilization
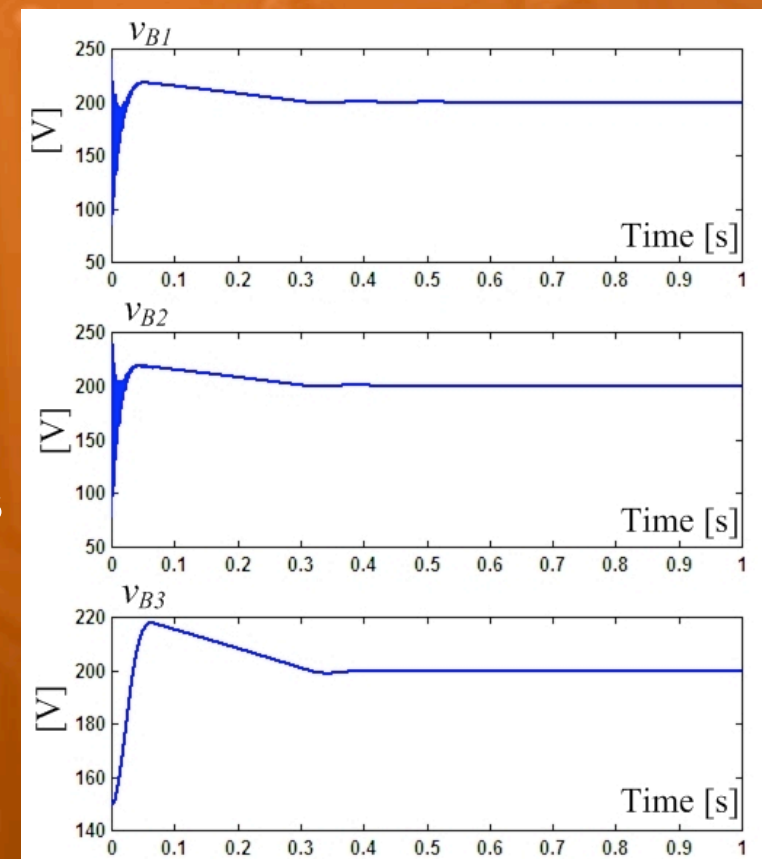
- Passive methods – load shedding

- It is also based on the condition that: $C > \dfrac{P_L L}{V_o^2 R_i}$

- Issues: Not practical for critical loads
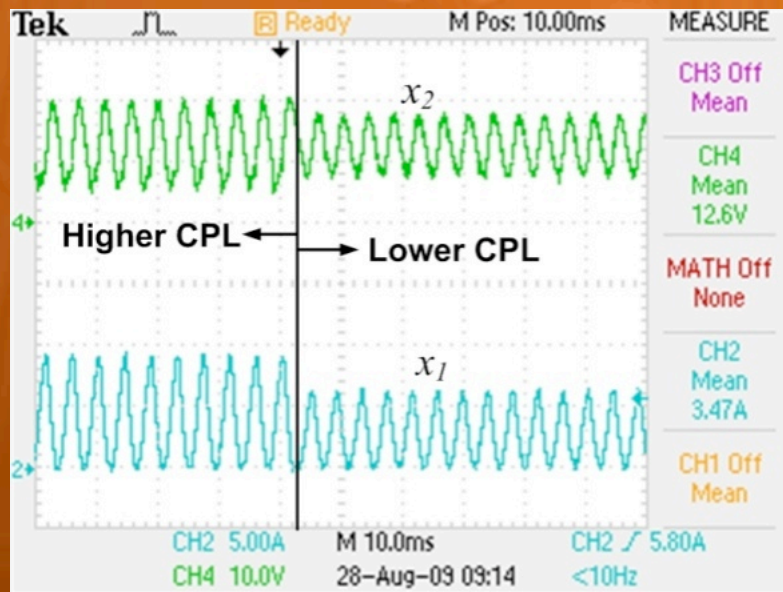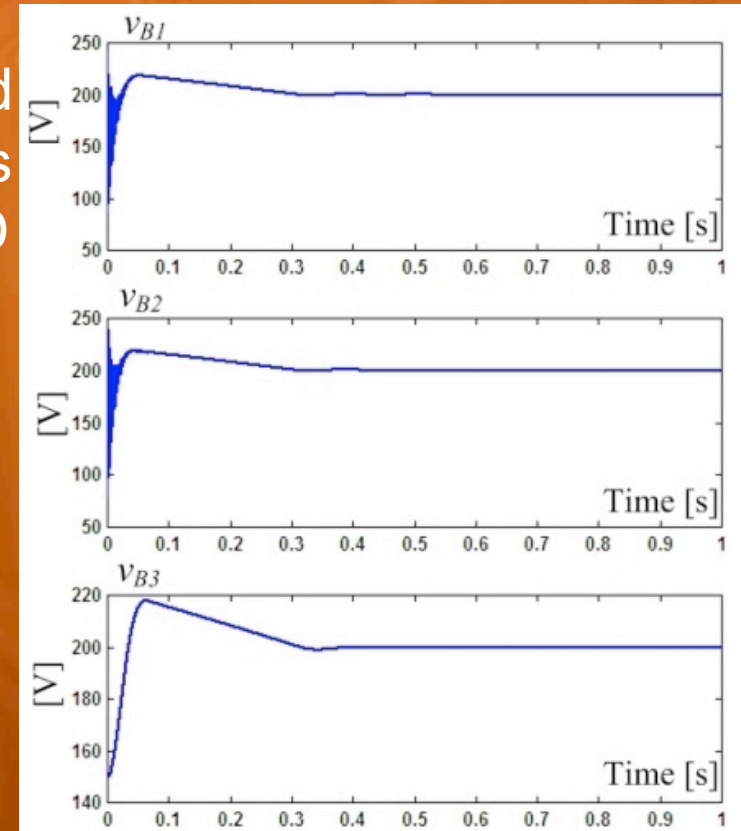

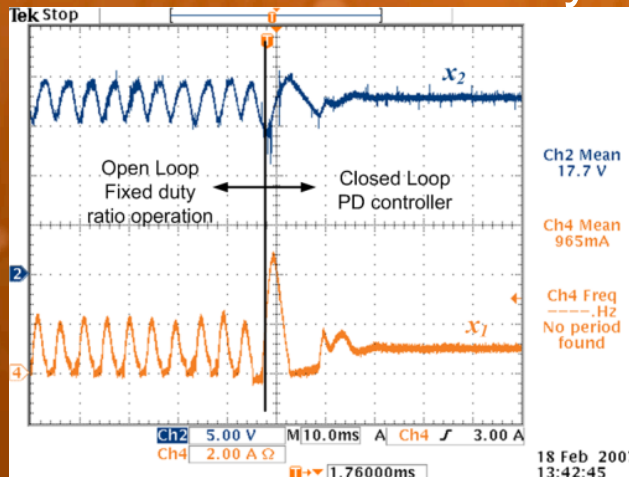
Load reduced from 49 W to 35 W
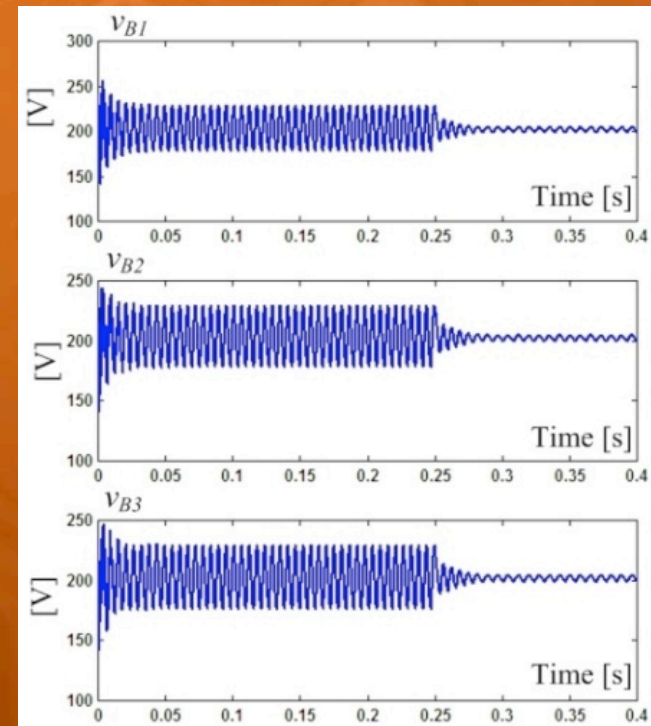


Load dropped from 10 to 2.5 kW at 0.25 seconds

# Stabilization

- Linear Controllers - passivity-based analysis

- Buck converters $d(t) = \dfrac{R_{i1}C}{E}\dot{e}(t) + \dfrac{R_{i1}}{R_{i2}E}e(t) + D$

- Boost and buck-boost converters yield nonlinear inverse-square PD controllers that can be reduced to conventional PD controllers
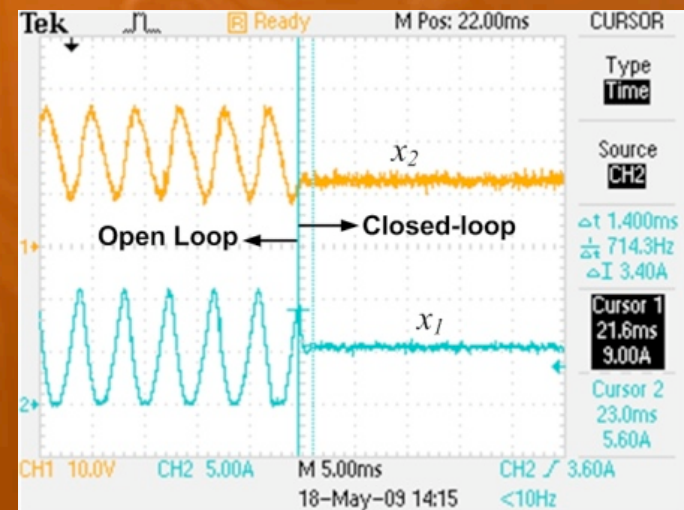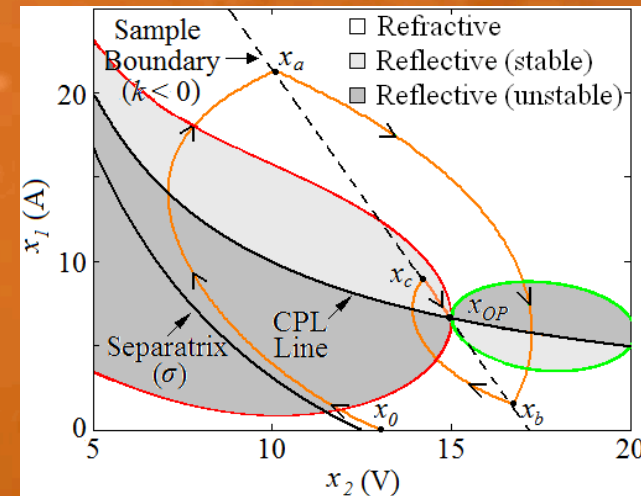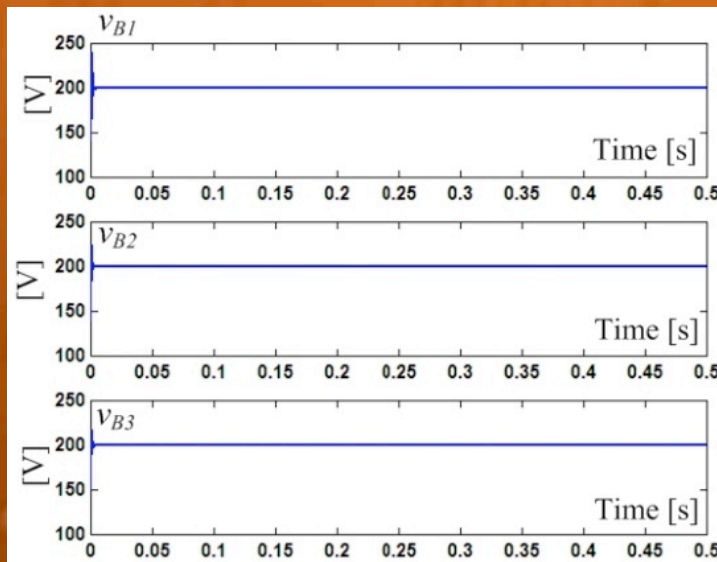
- Issues: Noise sensitivity

# Stabilization

- Geometric controllers – 1st order boundary

- Boundary control: state-dependent switching (q = q(x))
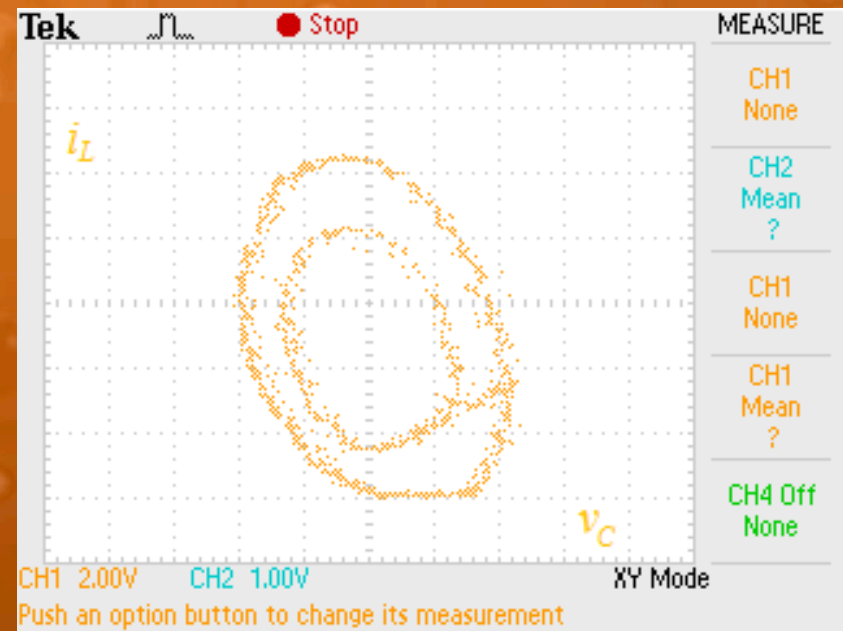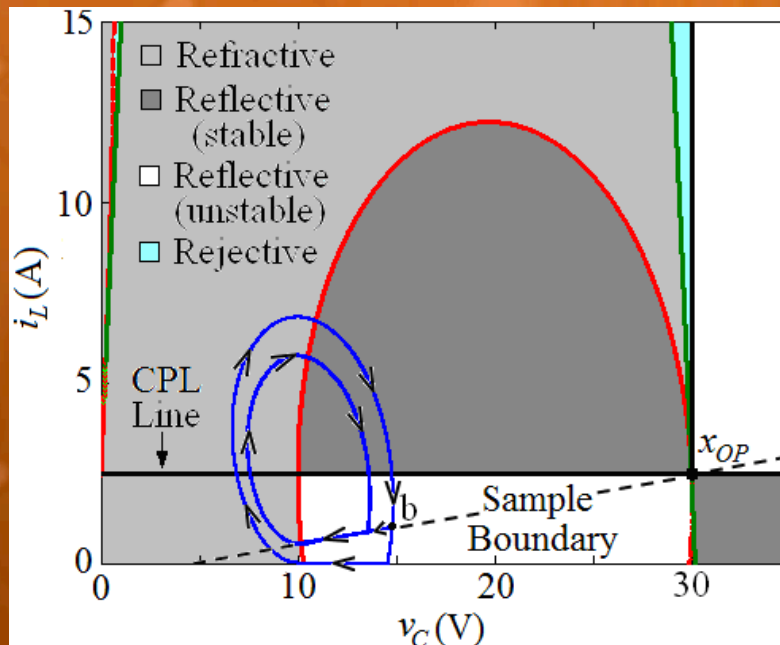
- Linear switching surface with a negative slope:
$$x_1 = k(x_2 - x_{2OP}) + x_{1OP}$$

# Controls

• Geometric controllers

• First order boundary with a negative slope is valid for all types of basic converter topologies.

Advantages:  Robust, fast dynamic response, easy to implement .



Example of a wrongly chosen positive slope in a boost converter

# Conciusions

• Most renewable and alternative sources, energy storage, and modern loads are dc.

• Integration can be achieved through power electronics, but other stability issues are introduced due to CPLs.

• Control-related methods appear to be a more practical solution for CPL stabilization  without reducing system efficiency.

• Nonlinear analysis is essential due to nonlinear CPL behavior.

•Boundary control offers more advantages than linear controllers and are equally simple to implement.