Control Design of DC Microgrid Considering CPL Instability

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DC Micro Grid:Advantages and Challenges

AC Micro Grids are widely used but DC Micro Grids are also becoming Popular

Advantages:

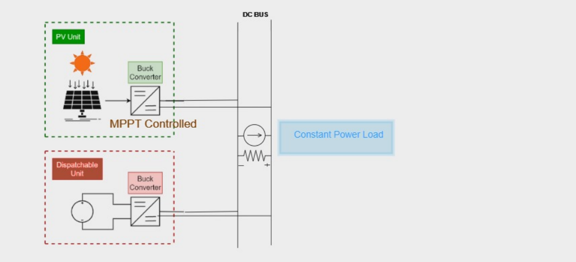
- Simpler Controllability due to absence of frequency controlling and phase unbalance.
- Losses like Skin Effect automatically eliminated.

Disadvantages:

- Complicated and Costly Protection System.

Challenges Addressed:

- Addressing CPL Instability
- Lack of Inertia leading to high ROCOV



Dispatchable Unit(Grid Forming Unit):

- Output voltage is tracked keeping the *DC Bus Link Voltage constant*

PV Unit:

- Idea is to track Input Voltage To Maximum Power Point Voltage by Implimenting MPPT Algorithms

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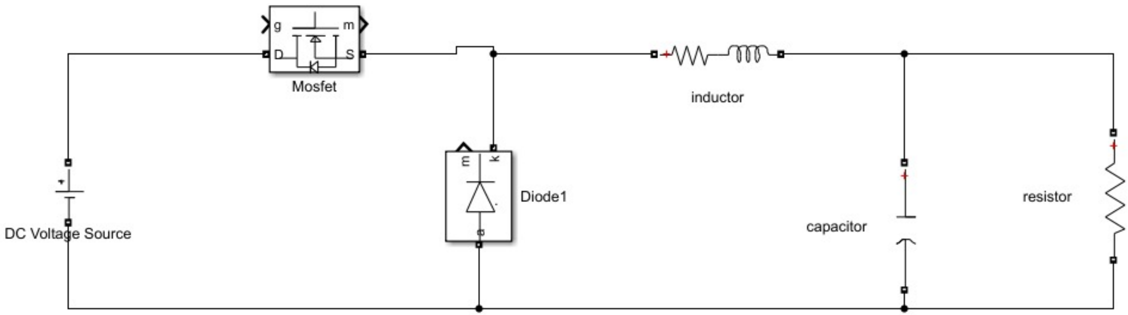
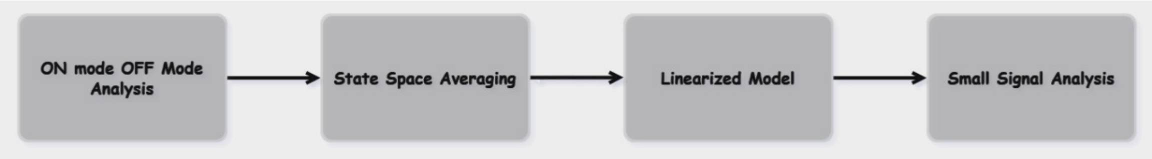
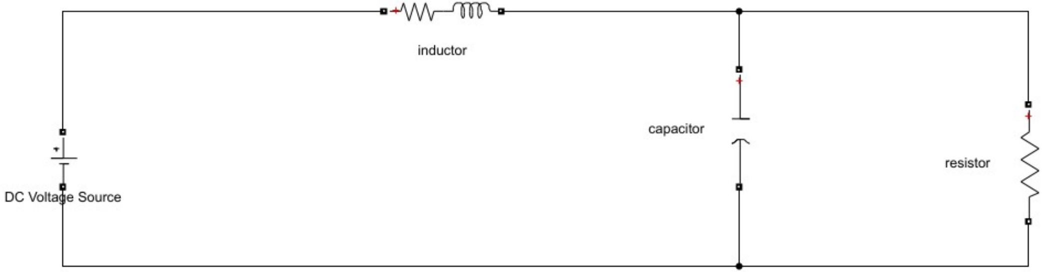
Buck Converter Topology





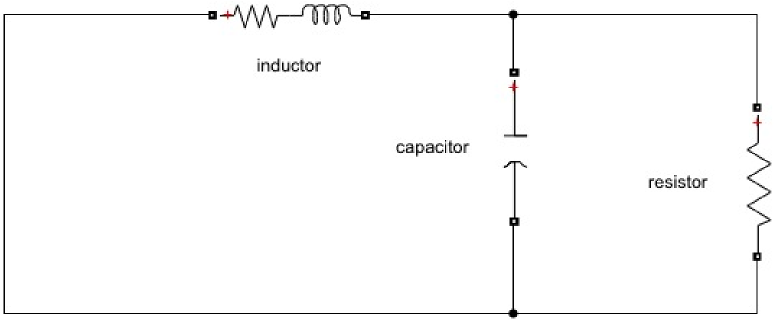
Mode 1



$$V_i = L\frac{di}{dt} + ir_s + V \tag{1}$$

$$i = C\frac{dV}{dt} + \frac{V}{R} \tag{2}$$

Mode 2



$$0 = L\frac{dV}{dt} + ir_s + V \tag{3}$$

$$i = C\frac{dV}{dt} + \frac{dV}{dt} \tag{4}$$

State Space Averaging

$$DV_i = L\frac{di}{dt} + iR_s + V \qquad (5)$$

$$i = C\frac{dV}{dt} + \frac{V}{R} \qquad (6)$$

Linearizing the Model Under Steady State With Small Ripple Approximation

Linearizing

$$D = D_o + \hat{d}$$

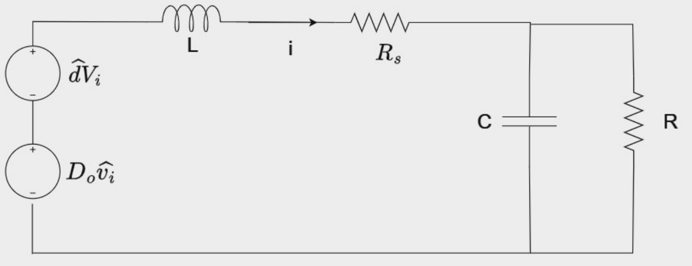
$$V = V_o + \hat{v}$$

$$I = I_o + \hat{i}$$

Small Ripple Approximation

$$D_o V_i = I_o r_s + V_o \qquad (7)$$

$$I_o = \frac{V_o}{R} \qquad (8)$$



$$D_o\hat{v}_i + \hat{d}V_i = L\frac{d\hat{i}}{dt} + r_s\hat{i} + \hat{v}$$

$$\hat{i} = C\frac{d\hat{v}}{dt} + \frac{\hat{v}}{R}$$

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Controller Design

Voltage Controller Design

From Small Signal Model:

$$\hat{i} = C\frac{d\hat{v}}{dt} + \frac{d\hat{v}}{dt}$$

$$I(s) = CsV(s) + \frac{V(s)}{R}$$

$$\frac{V(s)}{I(s)} = \frac{R}{1 + RCs}$$

Current Controller Design

From Small Signal Model:

$$\hat{d}V_i - \hat{v} = L\frac{d\hat{i}}{dt} + r_s\hat{i} = u$$

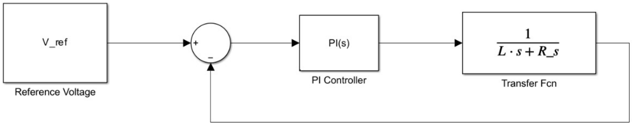
$$U(s) = sLI(s) + R_sI(s)$$

$$\frac{I(s}{U(s)} = \frac{1}{R_s + sL}$$

PI Parameter Tuning

Current Controller

$$G(s) = \frac{sK_p + K_i}{s(R_s + sL)} = \frac{K_i(1 + \frac{sK_p}{K_i})}{sR(1 + \frac{sL}{R})}$$



By *Pole Zero Cancellation*

$$G(s) = \frac{K_i}{sR} = \frac{1}{s\tau}$$

Thumb Rule

Bandwidth of Inner Loop Should be 10 to 20 Times Lower that of Switching Frequency

Where

$$\tau = \frac{R_s}{K_i} \quad and \quad \omega_o = \frac{1}{\tau} = \frac{2\pi f_s}{20}$$

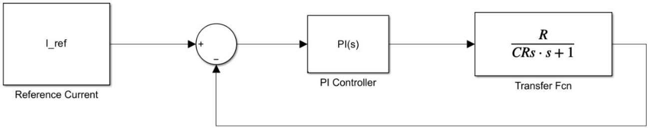
$$K_i = \frac{R_s}{\tau} = \frac{2\pi f_s R_s}{20}$$

$$K_p = \frac{2\pi f_s L}{20}$$

PI Parameter Tuning

Voltage Controller

$$G(s) = \frac{(sK_p + K_i)R}{s(1+sCR)} = \frac{RK_i(1+\frac{sK_p}{K_i})}{s(1+sCR)}$$



By *Pole Zero Cancellation*

$$G(s) = \frac{K_i R}{s} = \frac{1}{s\tau}$$

Thumb Rule

Outer Loop Should be 10 Times Slower Than The Inner Loop

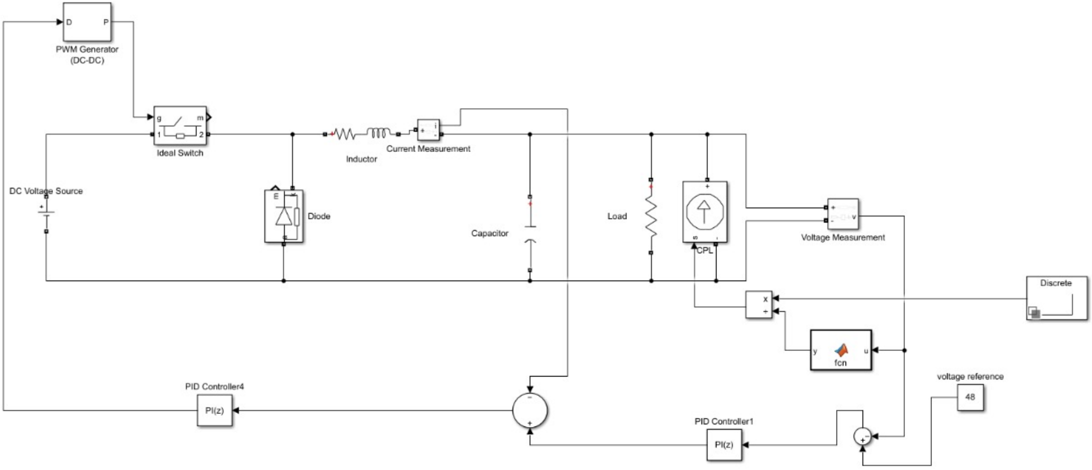
Where

$$\tau = \frac{1}{K_i R} \quad and \quad \omega_o = \frac{1}{\tau} = \frac{2\pi f_s}{100}$$

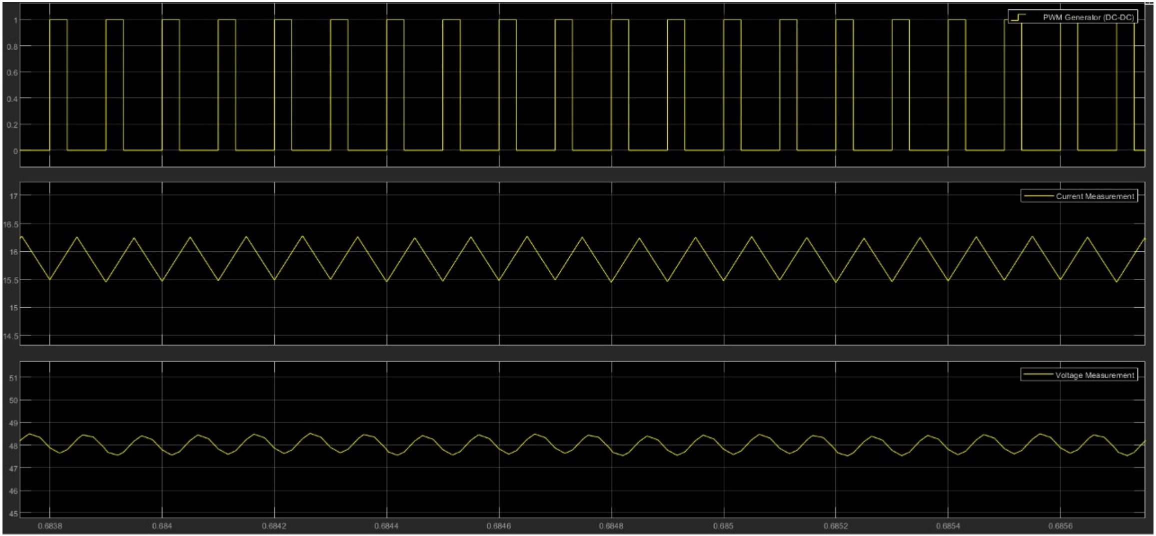
$$K_i = \frac{1}{R\tau} = \frac{2\pi f_s}{100R}$$

$$K_p = \frac{2\pi f_s C}{100}$$

Implementation of Control Loop in Buck Converter



Simulation Results



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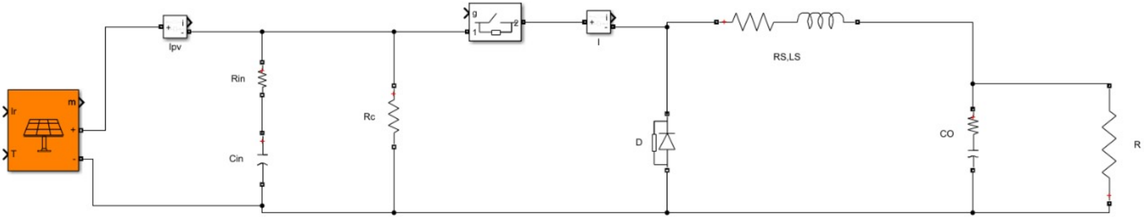
Non Dispatchable Unit



ON mode OFF Mode Analysis → State Space Averaging → Linearized Model → Small Signal Analysis

State Space Averaging

State Space Average Model is Given by:

$$i_{pv} = C_i \frac{dV_i}{dt} + Di + \frac{V_i}{R_c}$$

$$DV_i = L\frac{di}{dt} + R_s i + V_o$$

Small Signal Model is Given as:

$$\hat{i_{pv}} = C_i \frac{d\hat{V}_i}{dt} + \hat{d}i_o + D_o\hat{i}$$

$$D_o\hat{V}_i + \hat{d}V_{io} = L\frac{d\hat{i}}{dt} + R_s\hat{i}$$

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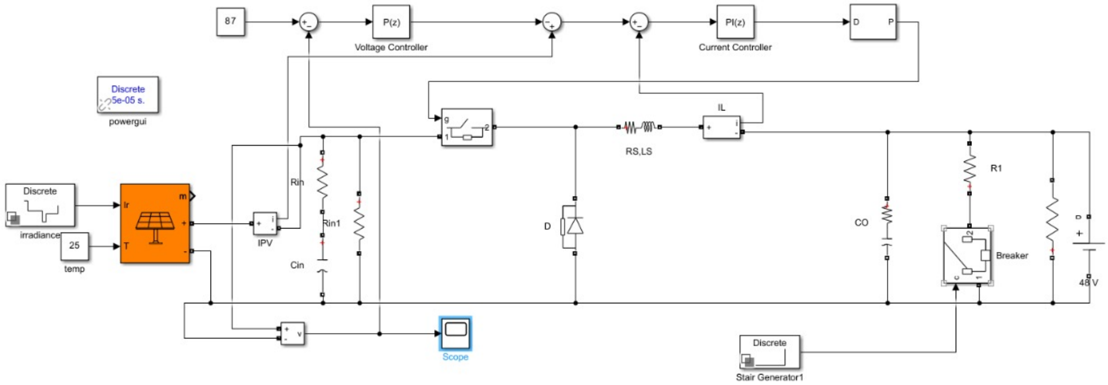
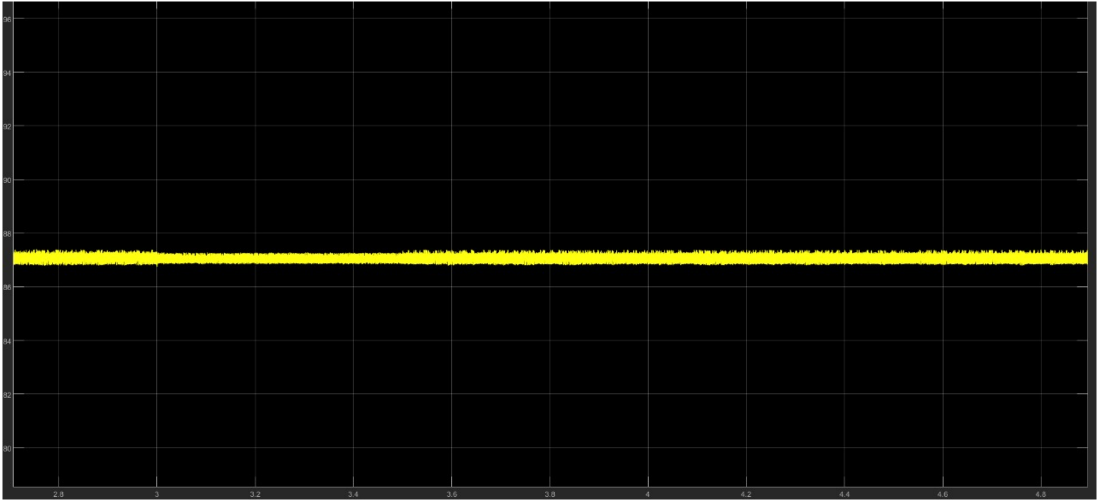
Simulating the Control Loop



NOTE

A DC source is used to maintain output voltage at 48. Practically however the DC Bus Link Voltage is maintained by the Dispatchable Unit(Grid Forming Unit)

Simulation Results



Maximum Power Point Voltage = 87 was Tracked

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State Space Model

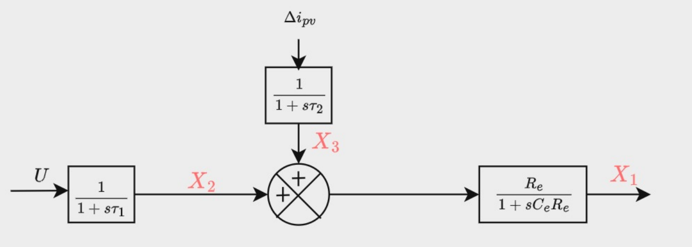
State Space Model is Given By:

$$\frac{dx}{dt} = Ax + B_1 W + B_2 U$$

x : state space variables
W : disturbances
U : input *State Space Model for*

Dispatchable + Non-Dispatchable Unit

$$A = \begin{bmatrix} \frac{-1}{R_e C_e} & \frac{1}{C_e} & \frac{1}{C_e} \\ 0 & \frac{-1}{\tau_1} & 0 \\ 0 & 0 & \frac{-1}{\tau_2} \end{bmatrix}$$



R_e = Equivalent Resistance
C_e = Equivalent Resistance
τ_1 = Time Constant of Current Controller of Dispatchable Unit
τ_2 = Time Constant of Current Controller of Solar Unit

Small Signal Model

For constant Power Load:

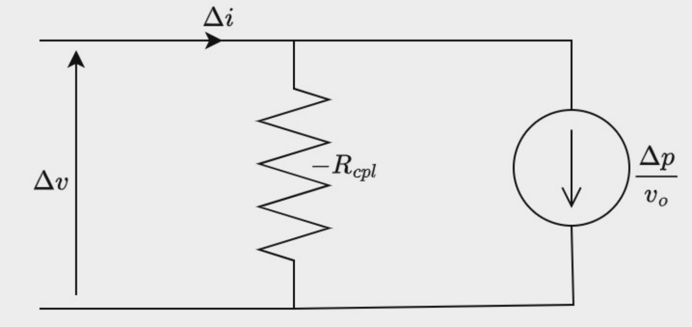
$$P = VI$$

$$P_o + \Delta p = (V_o + \Delta v)(I_o + \Delta i)$$

$$\Delta p = \Delta v I_o + V_o \Delta i$$

$$\Delta i = \frac{\Delta p}{V_o} - \frac{\Delta v}{\left(\frac{V_o}{I_o}\right)}$$

$$\Delta i = \frac{\Delta p}{V_o} - \frac{\Delta v}{R_{cpl}}$$



- CPL introduces a negative resistance in the small signal model.
- The negative resistance causes instability in the physical system.

Eigenvalue Calculation For Varying CPL

- Eigenvalues of Matrix A for 4 different values of CPL are tabulated

Eigenvalues	R = 10	R = 5	R = -5	R = -10
λ_1	-475.8	-951.6	951.6	475.8
λ_2	-314.16	-314.16	-314.16	-314.16
λ_3	-314.16	-314.16	-314.16	-314.16

$$\lambda_i = i^{th} eigenvalue$$

- All eigenvalues in left half plane for positive CPL
- Some eigenvalues in left half plane for negative CPL

	λ_1	λ_2	λ_3
X_1	1	0	0
X_2	0	1	0
X_3	0	0	1

Table: Participation Factor Analysis

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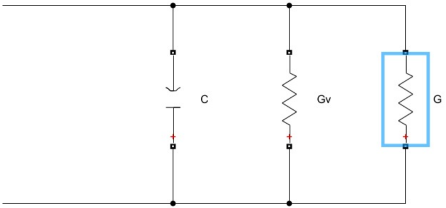
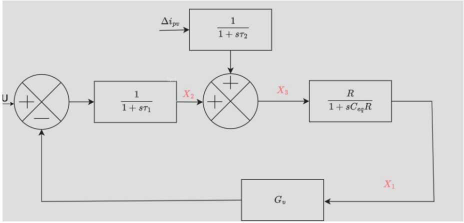
Mitigating CPL Instability Using Virtual Conductance

$$i = C\frac{dv}{dt} + G_v v - Gv$$



- Virtual Conductance neutralizes effect of negative CPL
- Magnitude of Gv should be *greater than maximum magnitude of negative CPL*
- Called virtual because it is not a physical impedance but implemented in control loop



$$A = \begin{bmatrix} \frac{-1}{R_e C_e} & \frac{1}{C_e} & \frac{1}{C_e} \\ \frac{G_v}{\tau_1} & \frac{-1}{\tau_1} & 0 \\ 0 & 0 & \frac{-1}{\tau_2} \end{bmatrix}$$

Eigenvalue Tabulation(with Virtual Conductance)

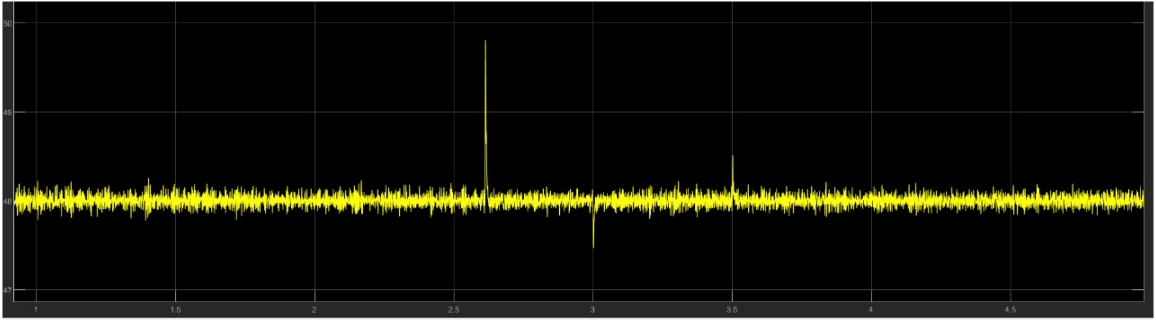
Eigenvalues	R = 10	R = 5
λ_1	-0.0181 + 1.2225i	-0.0205 + 1.2226i
λ_2	-0.0181 - 1.2225i	-0.0205 - 1.2226i
λ_3	-0.0314	-0.0314

Eigenvalues	R = -5	R = -10
λ_1	-0.0109 + 1.2224i	-0.0133 + 1.2225i
λ_2	-0.0109 - 1.2224i	-0.0133 - 1.2225i
λ_3	-3.1416	-0.0314

$\lambda_i = i^{th} eigenvalue$

All Eigenvalues Lie in the Left Half Plane

Simulation Results



2nd Challenge

Overshoots undershoots seen due to *changes in Irradiance*

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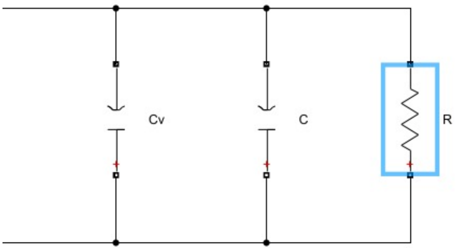
Virtual Capacitance

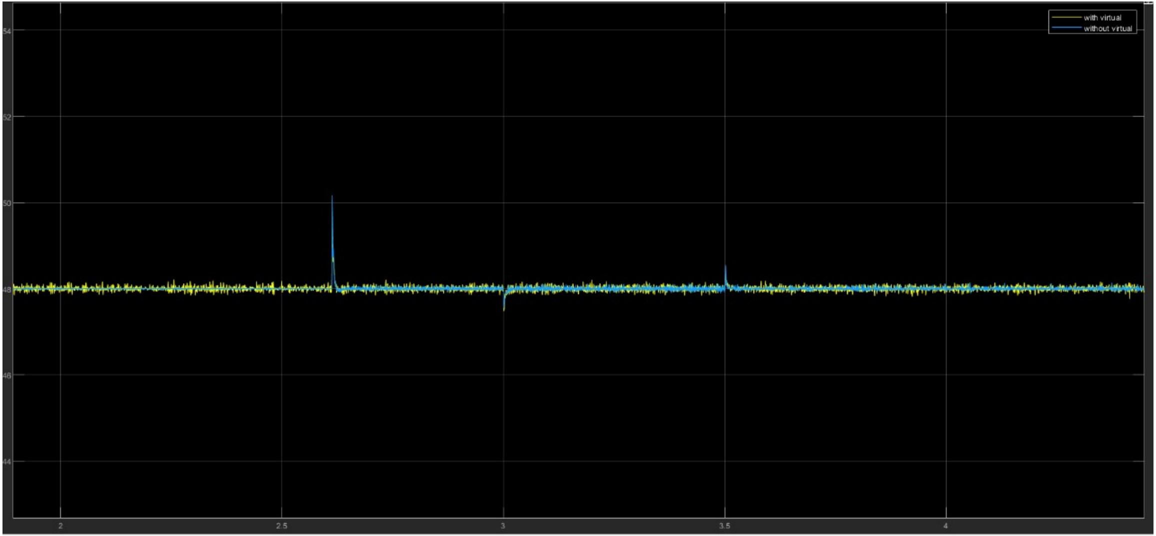
$$i = C\frac{dv}{dt} + \frac{v}{R} + C_v\frac{dv}{dt}$$

$$i - C_v\frac{dv}{dt} = C\frac{dv}{dt} + \frac{v}{R}$$

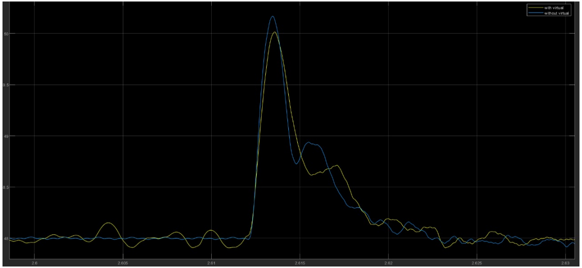
- Virtual Capacitance helps in reduction of ROCOV
- Positive voltage slope decreases current and negative slope increases it
- Physical implementation of capacitor is *expensive* so it is implemented in control loop

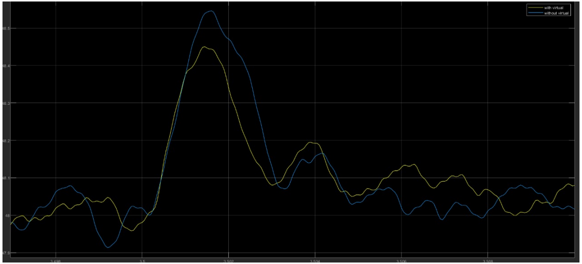


Simulation Results



Simulation Results





Magnitudes of overshoots is more for system without virtual capacitance

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Conclusion

- CPL instability due to introduction of negative resistance in the small signal model is addressed by Implementing Virtual Conductance in the Control Loop
- Lack of Inertia Causing high ROCOV mitigated by Implementing Virtual Capacitance.

Future Works

- Designing of Bidirectional Converter to handle Situations of Overgeneration of Power
- Real Time Implementation using **DSP Signals and RTDS Integration**