

mGrid Operation and Control



PSERC

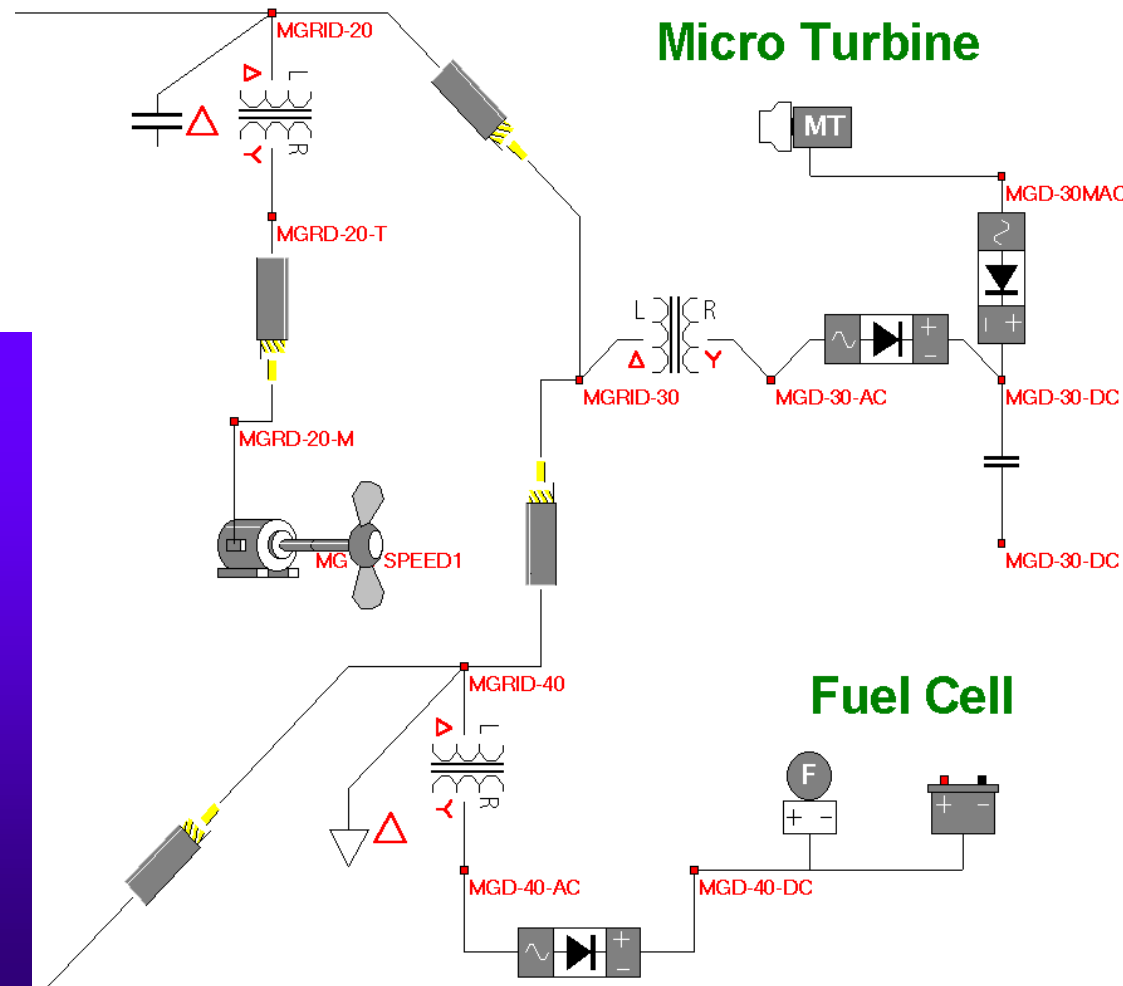
Robert H. Lasseter
University of Wisconsin

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University of Wisconsin

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HICSS-34

Tutorial 14

Micro-Grid Operation and Control

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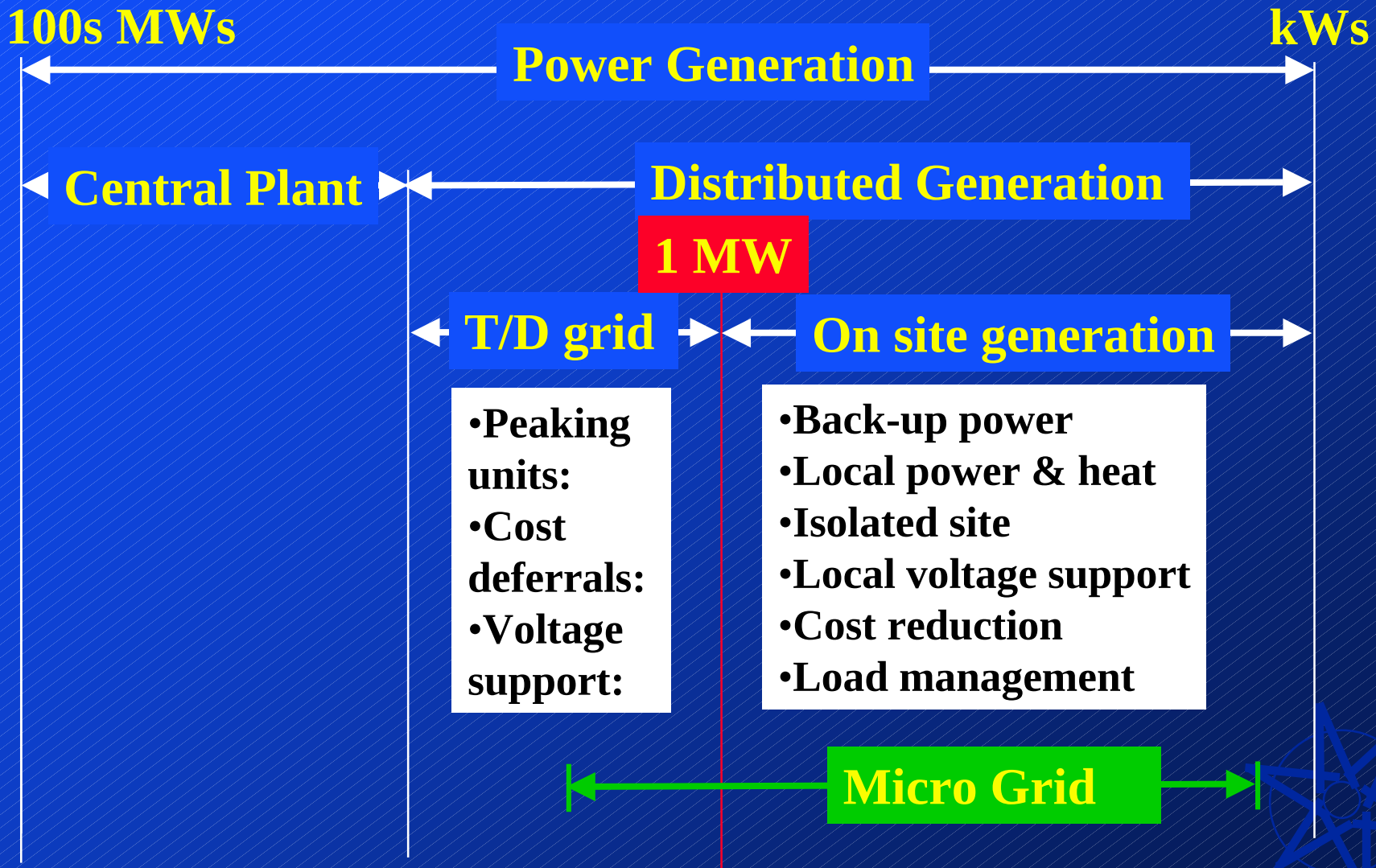
Giri Venkataramanan

**University of
Wisconsin**

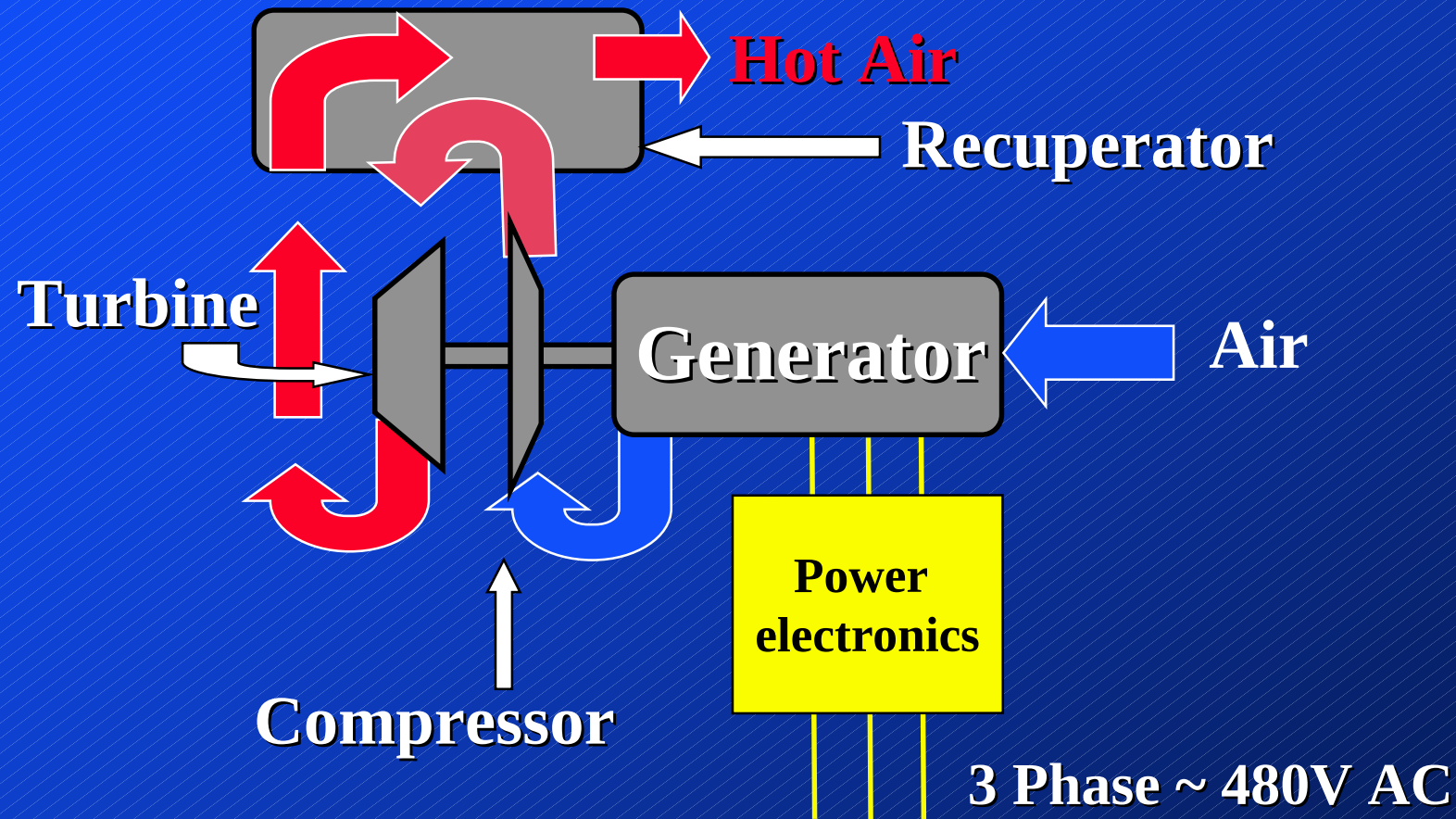
Outline

1. Overview of Micro-sources (1/2 hr)
2. Problems and Issues related to Distribution Systems (1 hr)
3. Power Electronics (1hr)
4. Operation and Control of Micro-Grids Needs and Challenges (1/2Hr)

Power Generation Applications



Micro-Turbine Basics

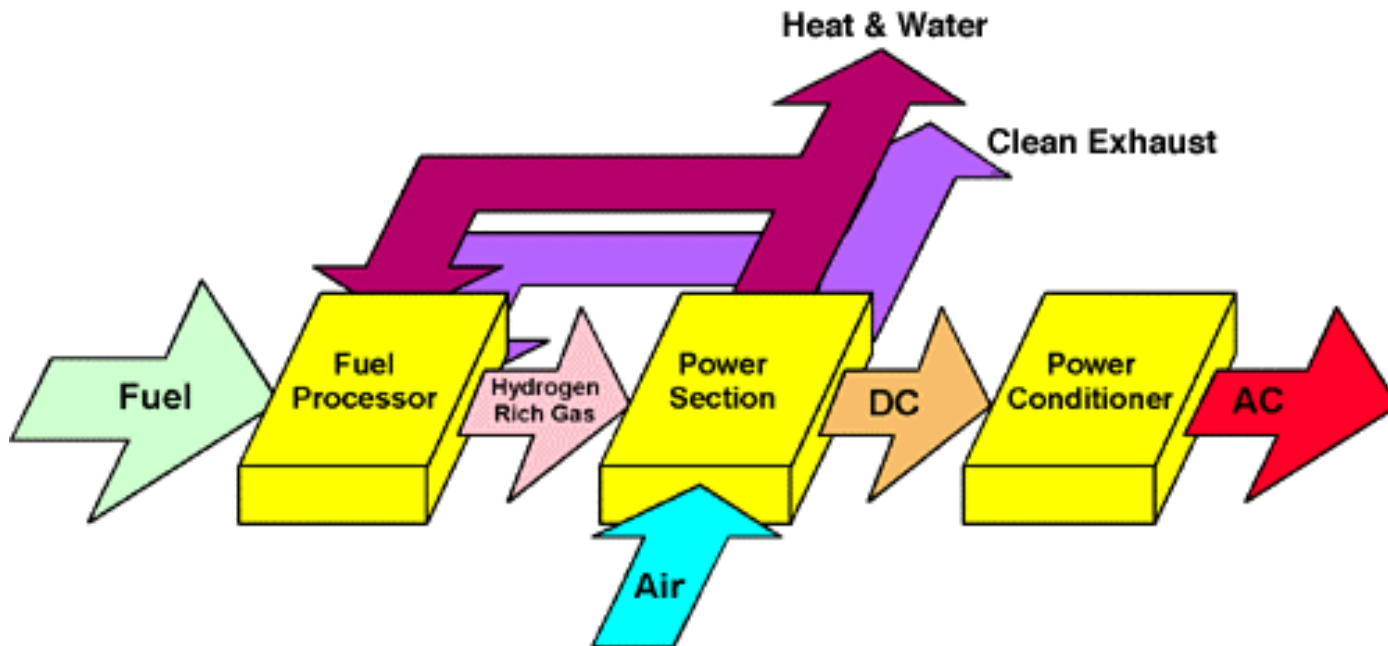


70kW Micro turbine

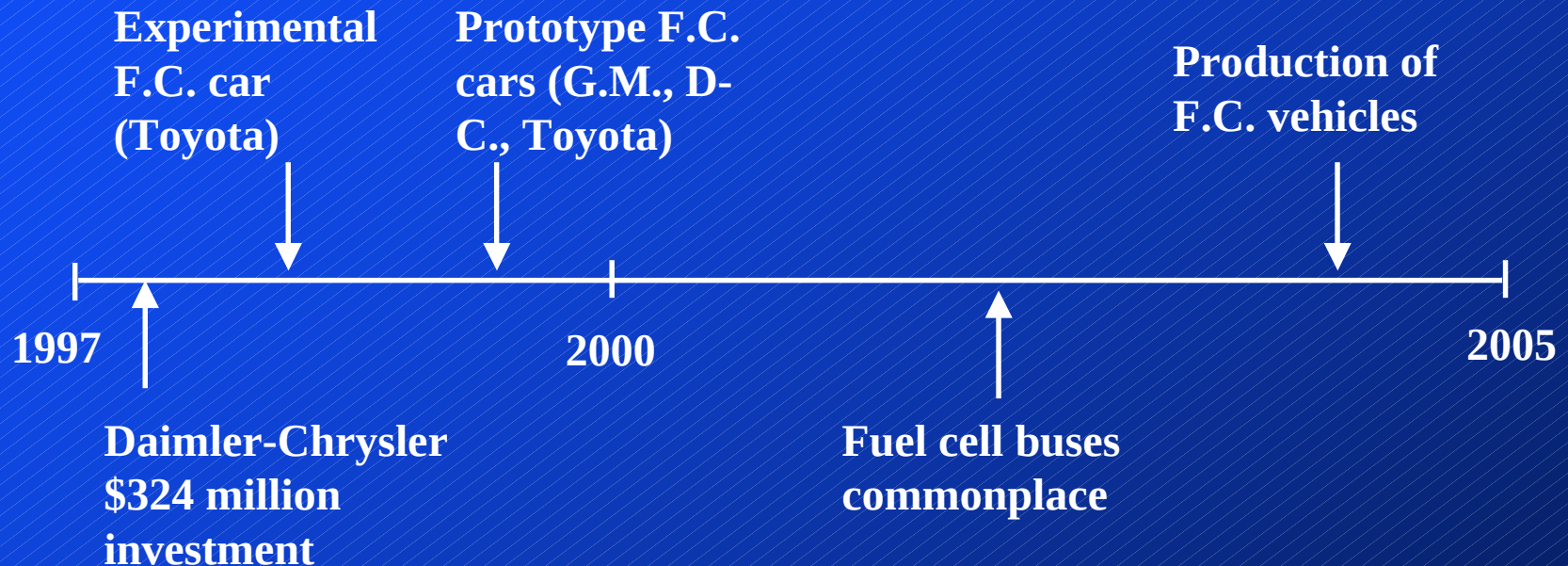


- Installed at \$1000/kW (target is \$350/kW)
- Efficiency 30%
- Air foil bearings
- expect in excess of 40,000 hours of reliable operation.
- Operation speed 90,000-100,000 RPMs

Fuel cell System



Automotive Influence on Fuel Cell Development



**Car Fuel Cells must be under
\$100/kW**

Ballard PEM Fuel Cell



7 kW Plug Power System

PEM Fuel Cell/water heater

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Distributed Generation Business Characterization

U. S. Electricity Market \$250 Billion Per Year

Distributed Generation Expected to Capture 10-20% of Market in 10 years

Players - Illustrative List

Allied-Signal

- Micro-Turbines

Siemens

- Fuel Cells

Solar Turbine/Caterpillar Tractor

- Engines/turbines

Capstone Turbine

- Micro-Turbines

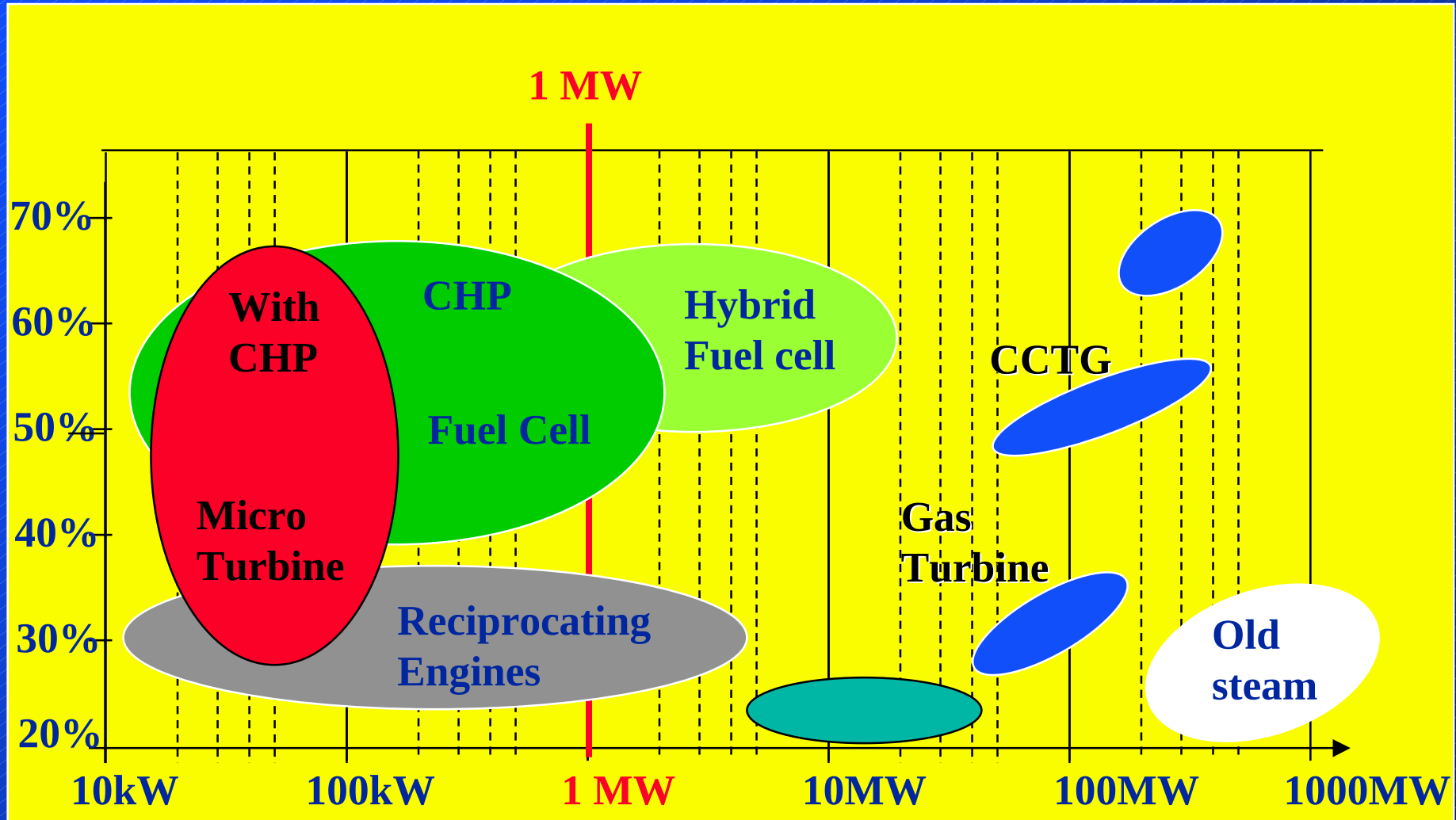
GE

- Fuel Cells/Turbines

**Others - Ballard, Allison, Williams, Plug Power, PowerCell
Commercial Units/Packaged Solutions Coming to Market**



Generation Efficiencies



On Site Generation

Efficiencies

Microturbine	30-200 kW	30/80%
PA Fuel Cells	200-2000 kW	40/78%
PEM Fuel Cells	5-250 kW	40/78%
Hybrid FC/MT	200-2500 kW	<70%
Roof top PV	1-10 kW	
Recip Engine	0.5-4 MW	38/80%

Power
Electronic
interface

Factors Impacting Grid Connectivity

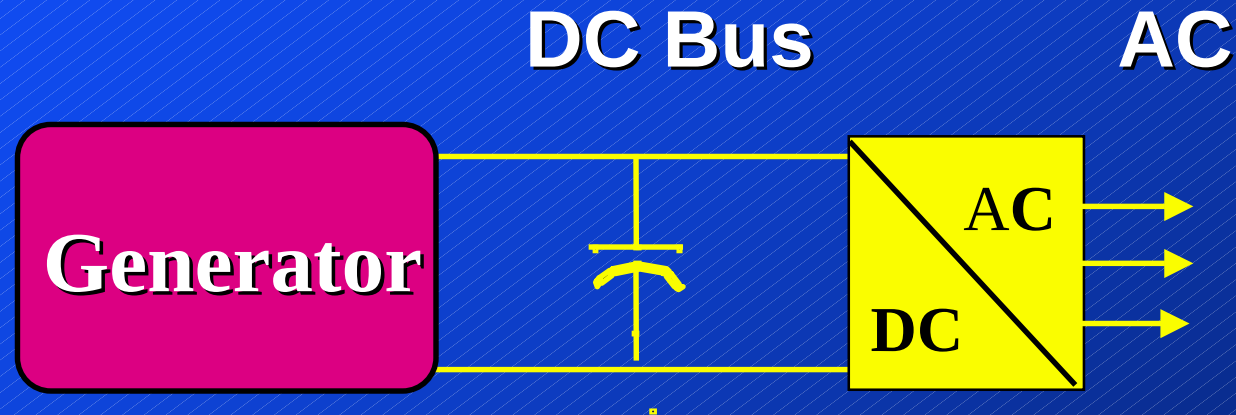
GENERATOR TYPE	Synchronous - hydro, engine-driven Induction - wind turbines, small hydro Power electronic - micro turbines, fuel cells, self-commutated line-commuted
INTERCONNECTION VOLTAGE	Transmission > 66 kV Sub transmission 24-66 kV Distribution 4-16 kV Customer 120-480 V
GENERATOR ELECTRIC CHARACTERISTICS	Rating Small Fault Current Islanding Voltage Control



Micro-source Issues

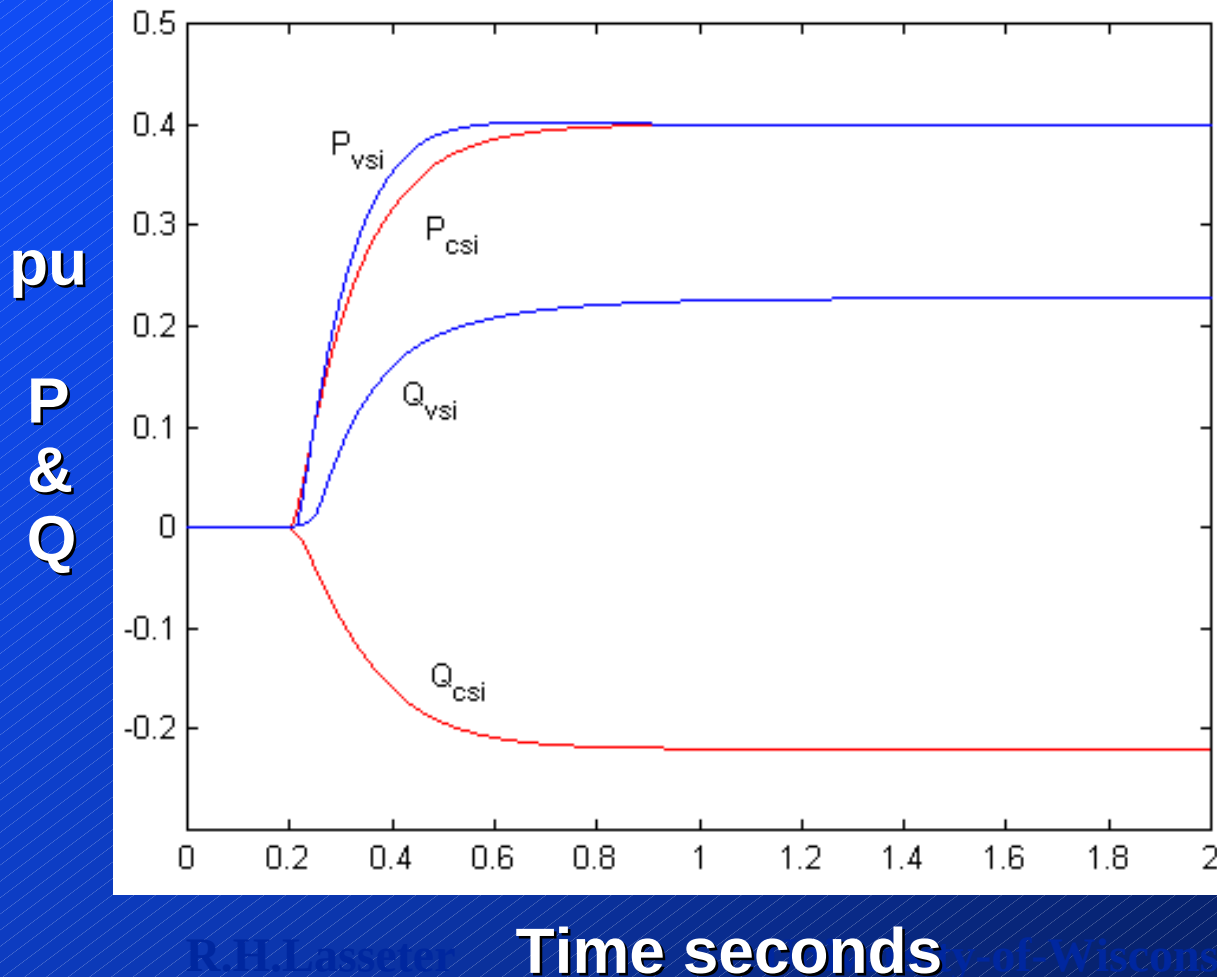
- Low power < 100 kw
- Low voltage 120-480 volts
- Inertia-less
- Power electronic interface
- Interconnection cost
- Control (large numbers)
- Market interactions

Micro Source Dynamics



- Type of Inverter
- Response of “Prime Mover”

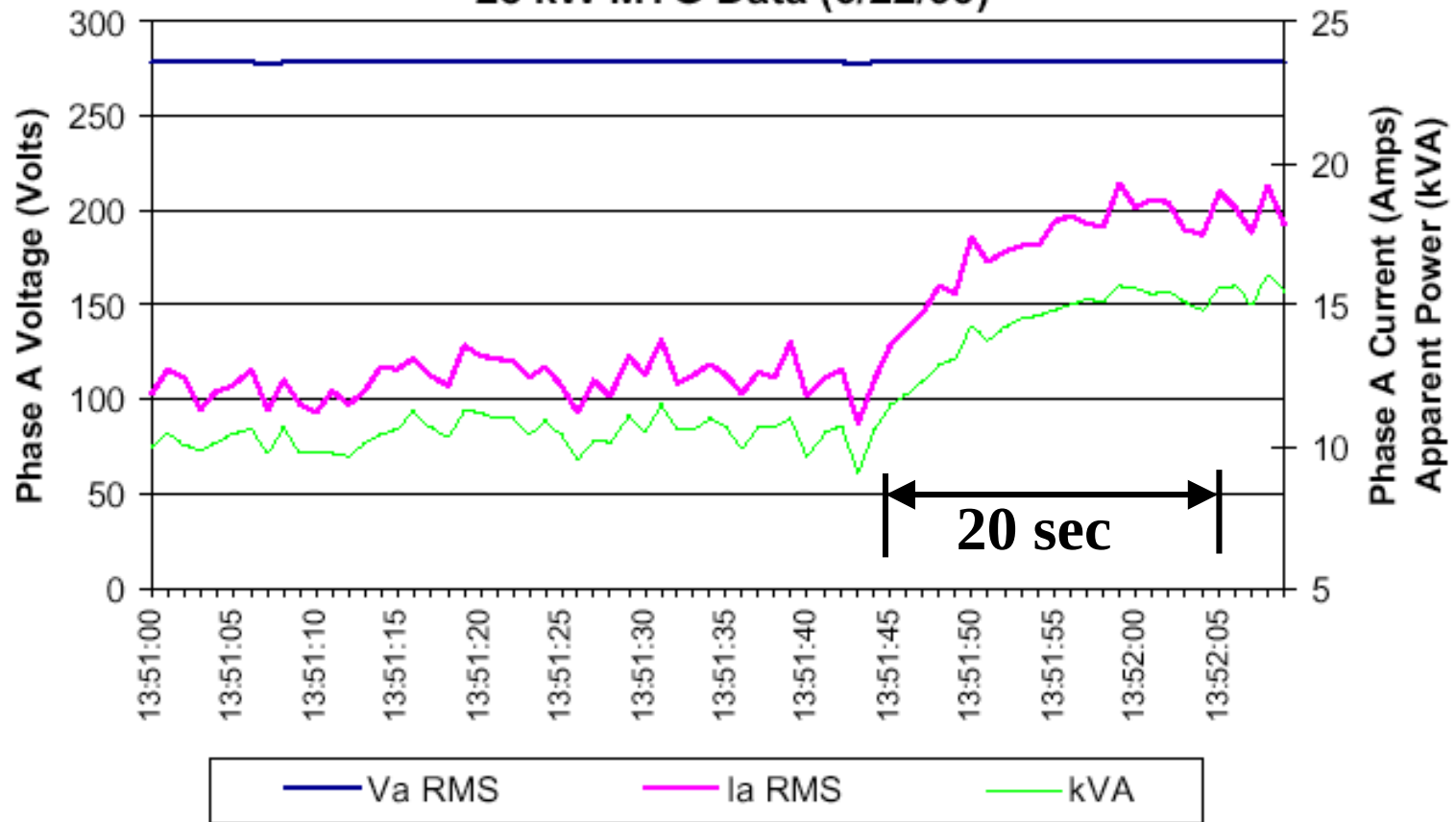
Inverter P-Q response



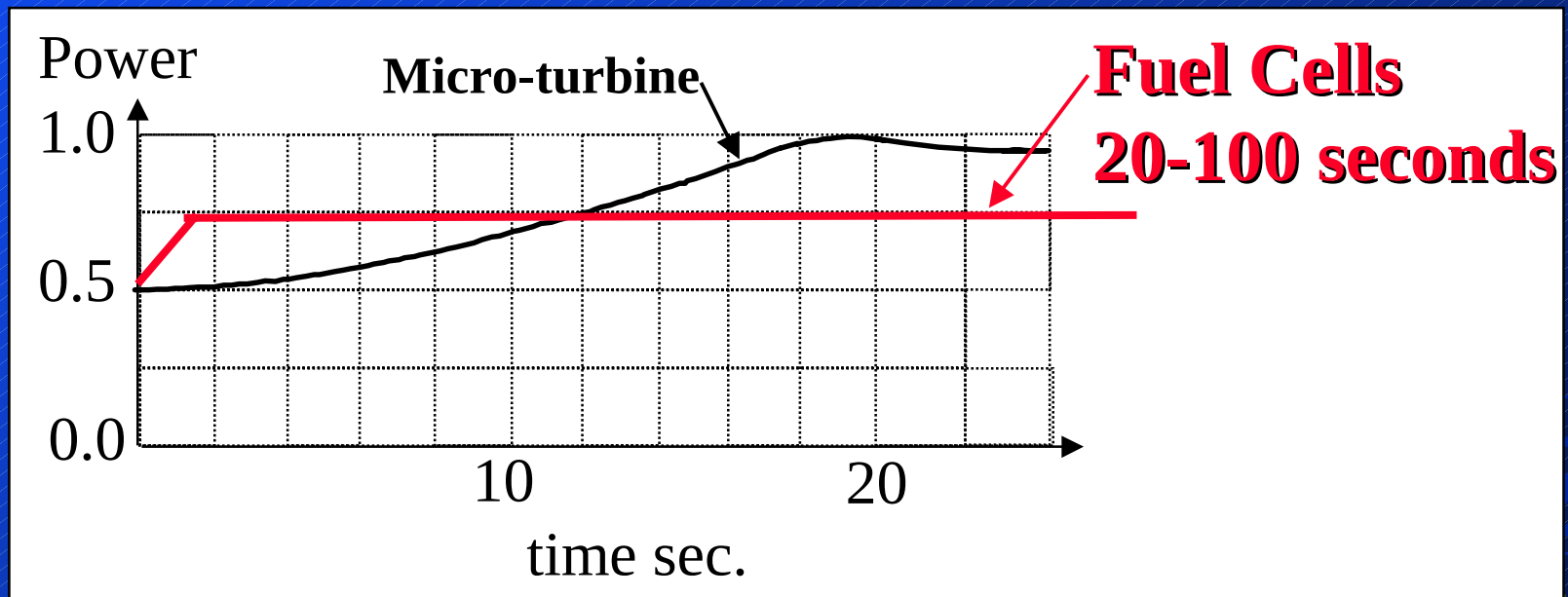
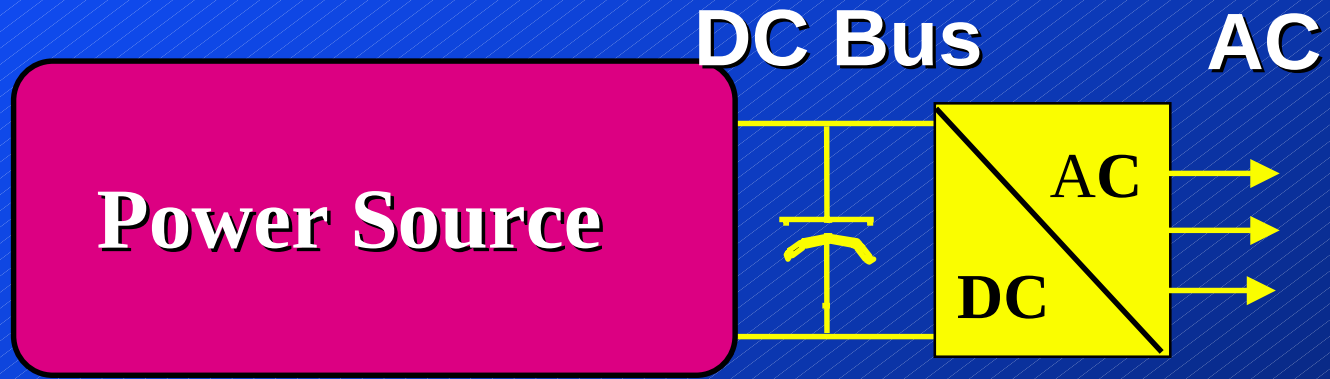
**CSI - Line
Commutated**

**VSI - PWM
with
Voltage control**

**Test # 6, 10kW to 15kW
28 kW MTG Data (6/22/99)**



Micro-Source Dynamics



Load Tracking Problem

Power electronics

- Inertia-less system
- Fast response

Instantaneous power balance

- Connect to grid
- Use storage on dc bus
- Storage on the ac bus
- Include rotating machines in Micro-grid

Quality of Power Perspectives

UTILITIES

There are less than four interruptions per year with a cumulative interrupted average of less than 2-hours/year

95 percent of interruptions are due to faults or outages on the T/D system

80 percent of the interruptions are due to distribution system components

CUSTOMER'S

Electricity problems disrupting equipment and production are originated by voltage sags, with duration less than 1/2 second

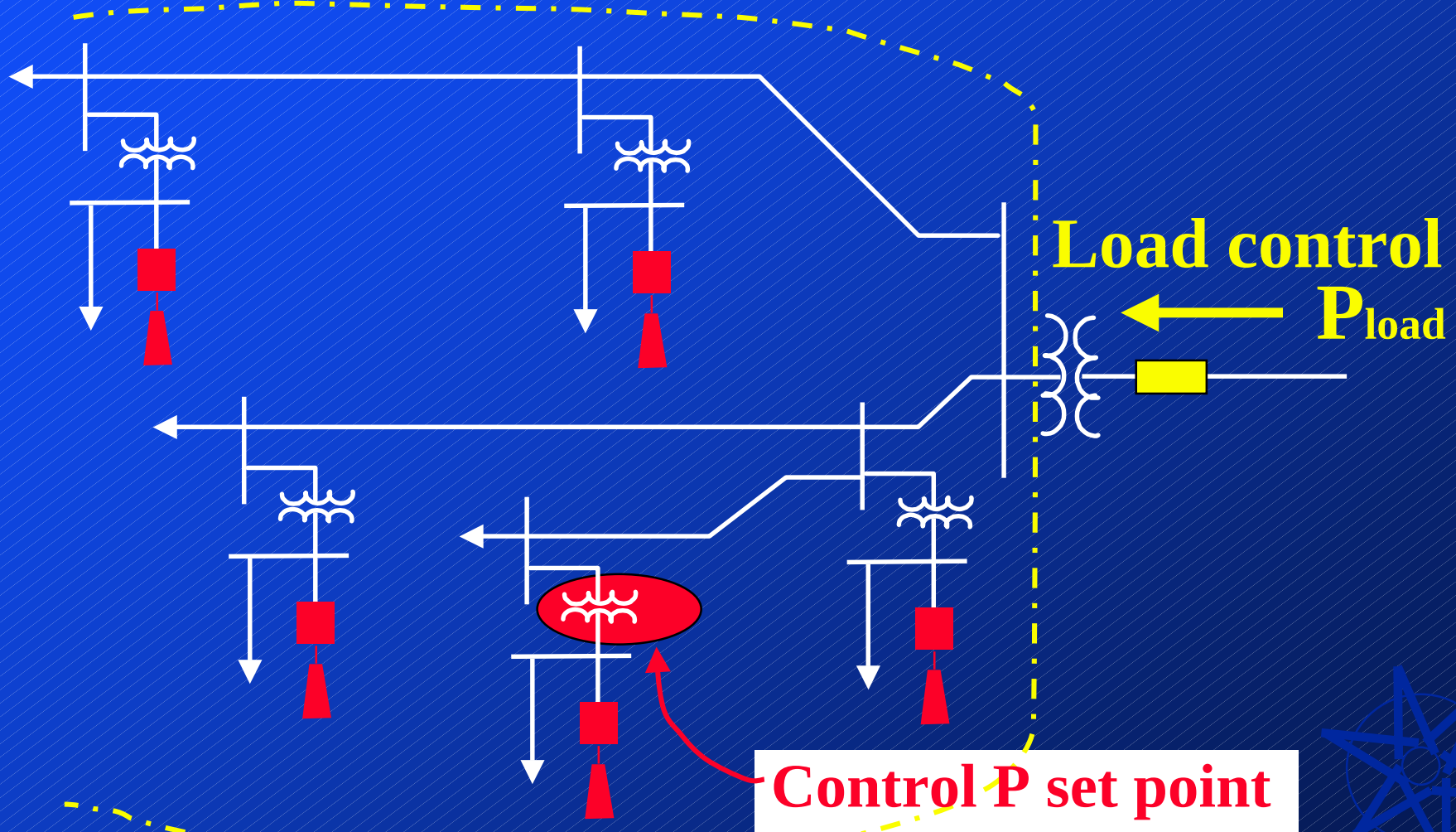
There are about 10-15 times per year that voltage sags occur with the voltage dropping below 70%

Production equipment contains electronics sensitive to power quality problems

Micro-grid concept assumes:

- Large clusters of micro-sources and storage systems
- Close to loads with possible CHP applications
- Provide Quality of Power required by Customer
- Presented to the grid as a single controllable unit (load & source)

Load Control using a Connected Micro Grid



Next

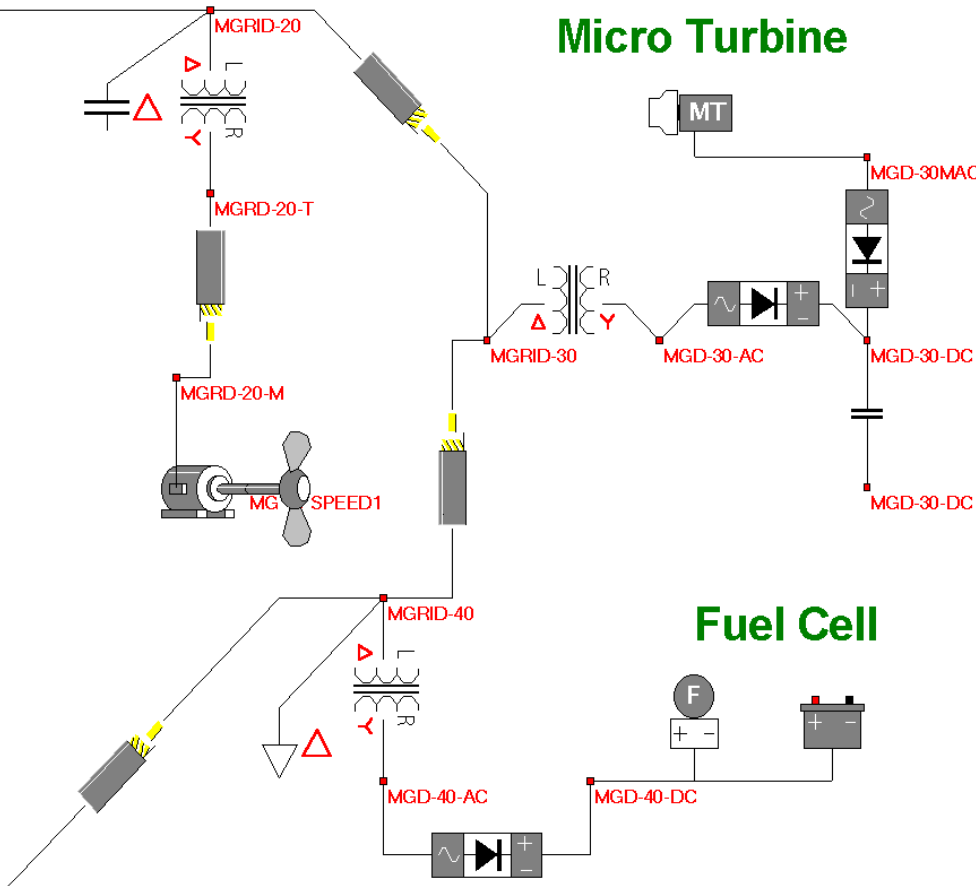
1. Problems and Issues related to Distribution Systems Power
2. Power Electronics Sources

mGrid Operation and Control

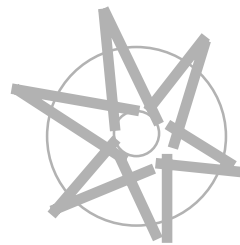
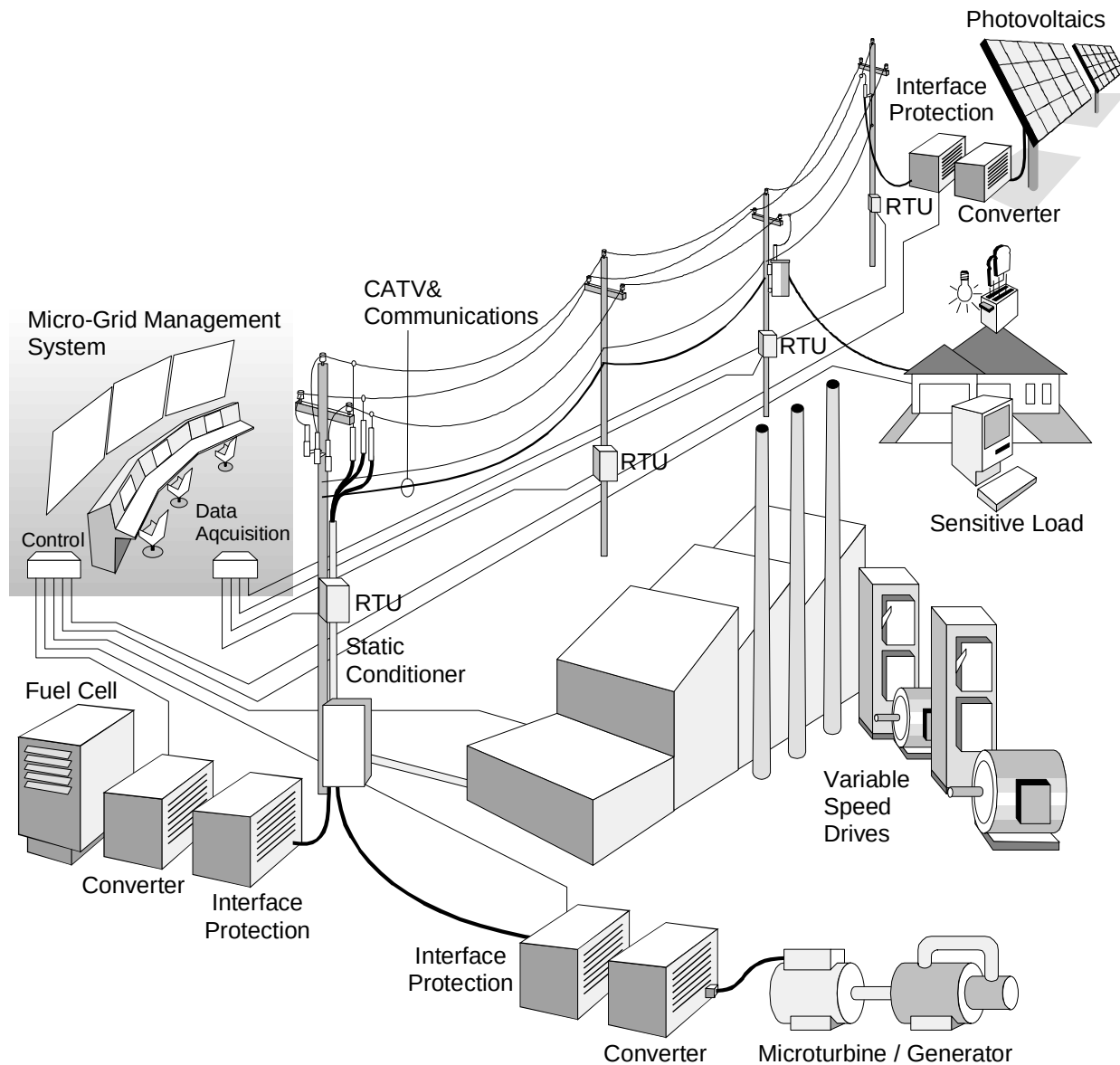
Problems and Issues Related to Distribution Systems

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Georgia Institute of Technology

Tutorial 14
HICSS-34
Jan 3, 2001



The mGRID Concept – Distribution System Backbone



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Distribution System Backbone Issues

Safety

Voltage Profile

Power Quality

Reliability

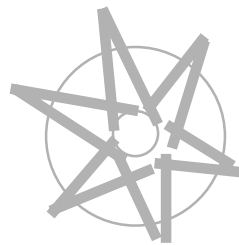
Protection

Unbalance/Asymmetry

Stray Voltages and Currents

Electromagnetic Compatibility Issues

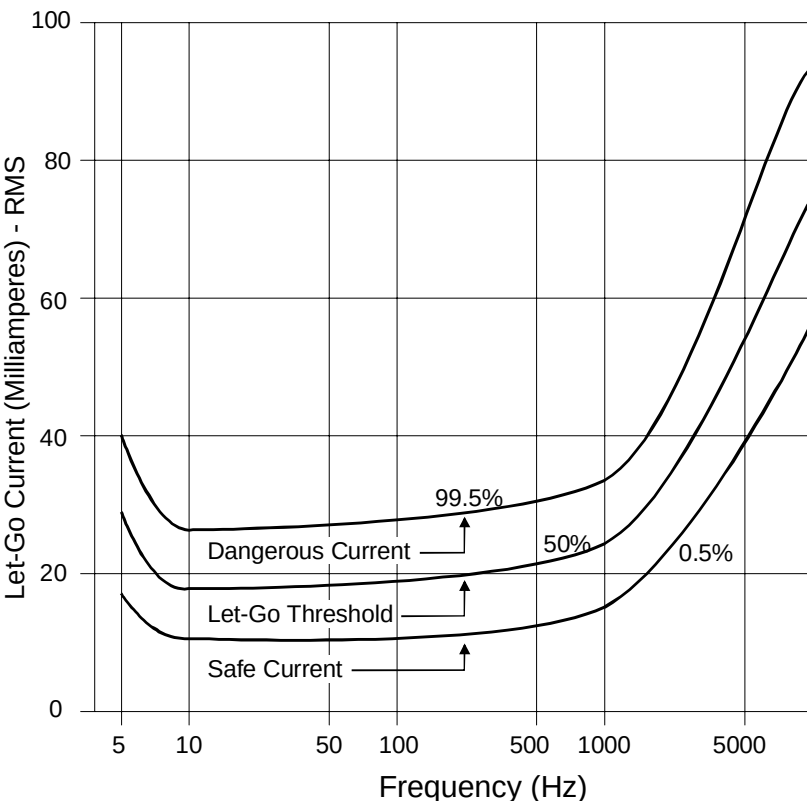
Non-autonomous/Autonomous Operation



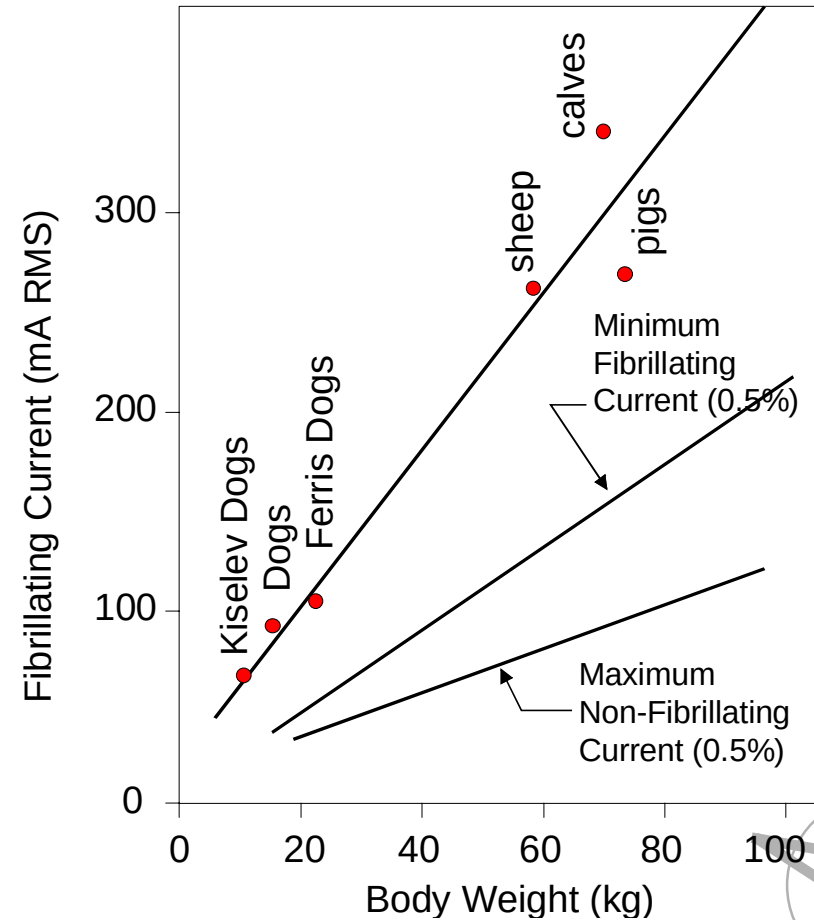
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Safety

Let-Go Current



Ventricular Fibrillation

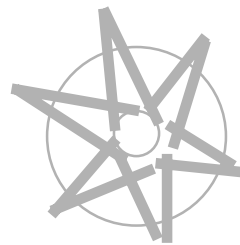
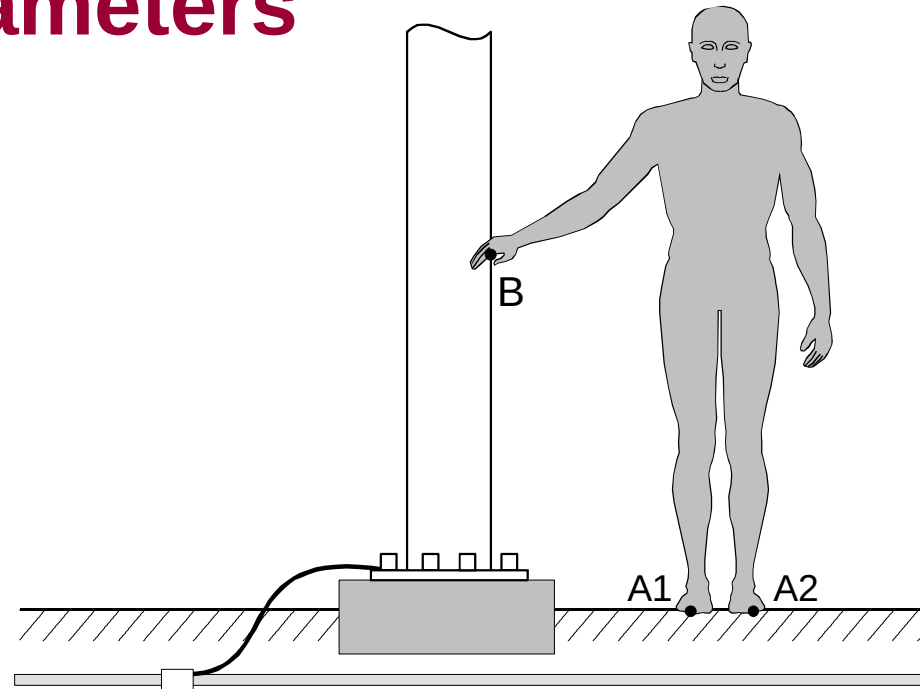
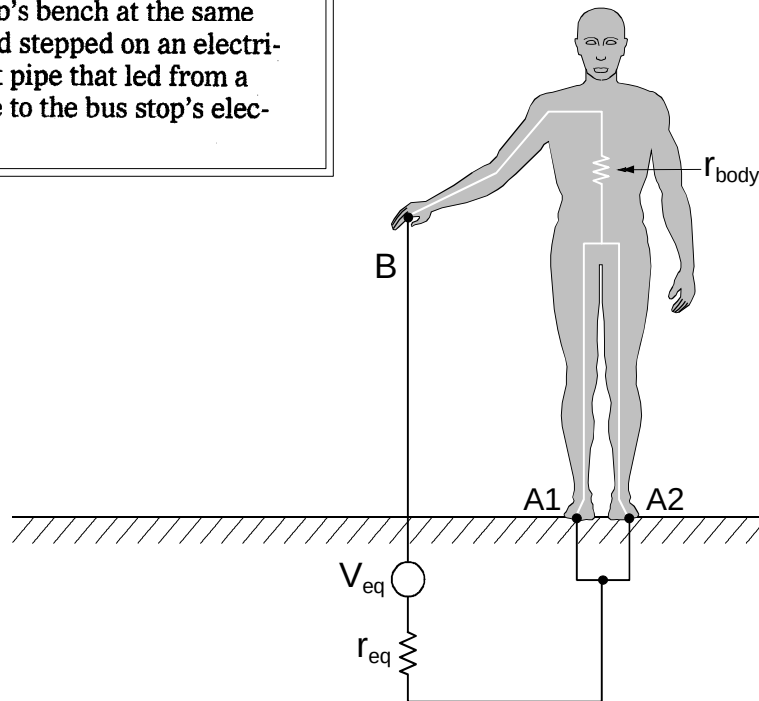


The Electrocution Parameters

A12 Wednesday, Oct. 14, 1998 ★★
The Atlanta Journal-Constitution

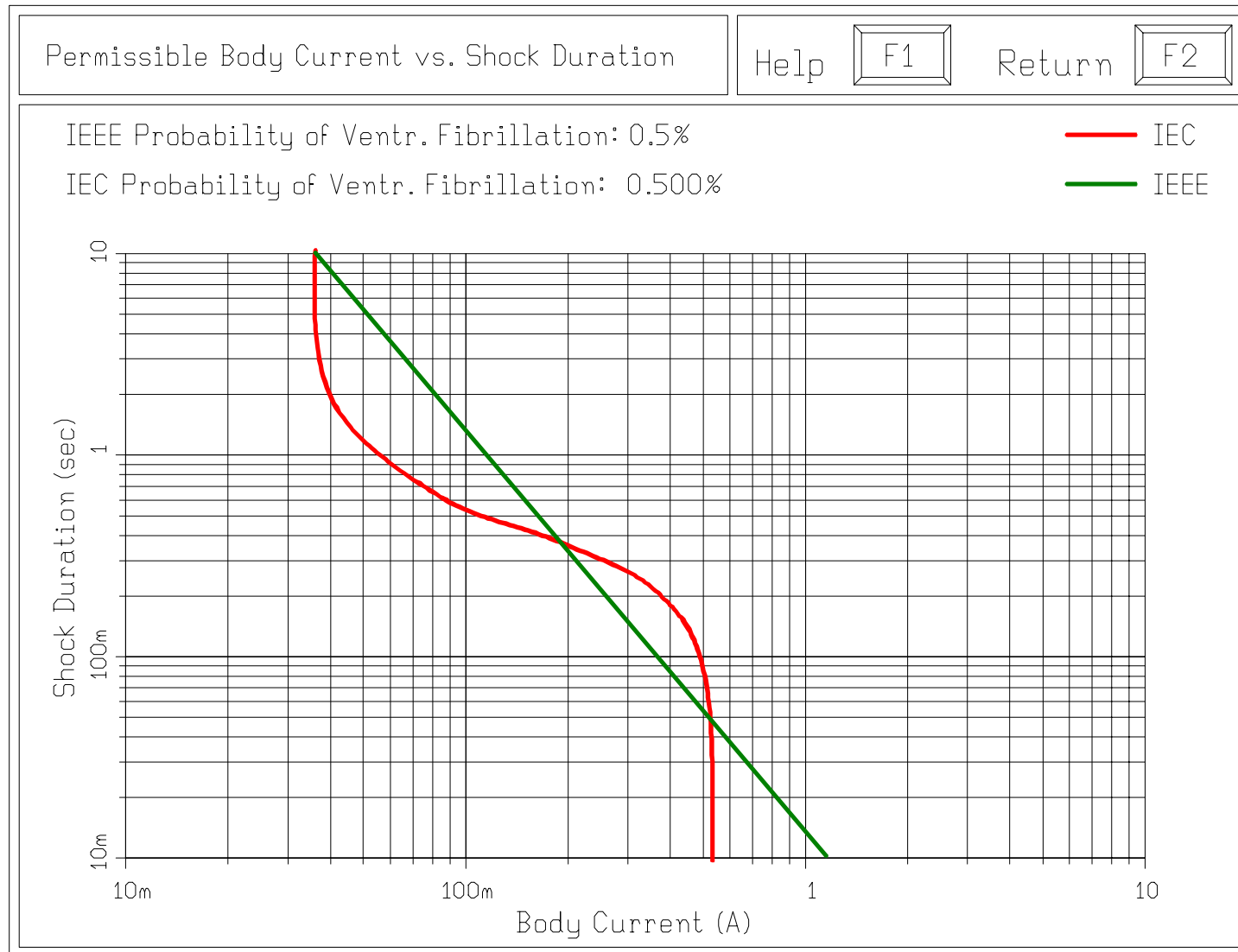
Boy electrocuted at Miami bus stop

A 12-year-old **Miami** boy reported missing by his parents was found dead after he apparently was electrocuted in a metal bus stop. Police said Jorge Luis Cabrera, who had run away from home, apparently was touching the metal frame of the bus stop's bench at the same time he had stepped on an electrical conduit pipe that led from a power pole to the bus stop's electrical box.

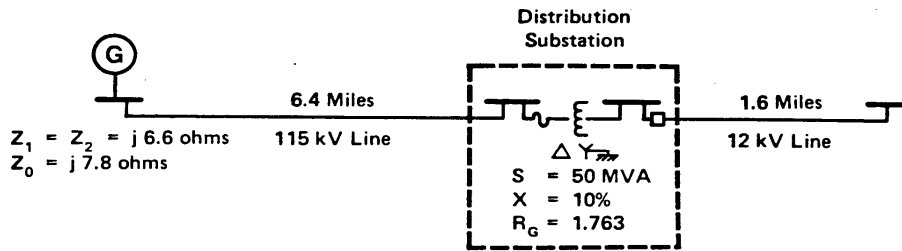


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Applicable Standards (IEEE & IEC): Non-Fibrillating Body Current as a Function of Shock Duration

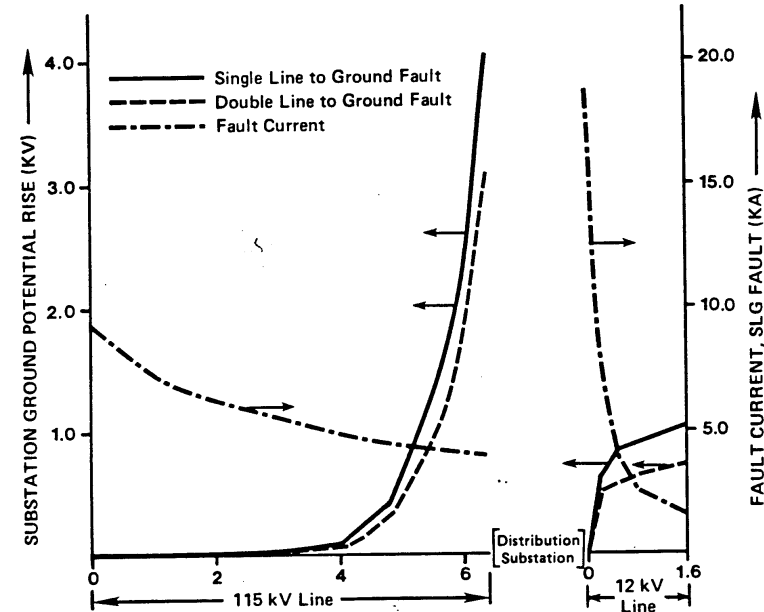
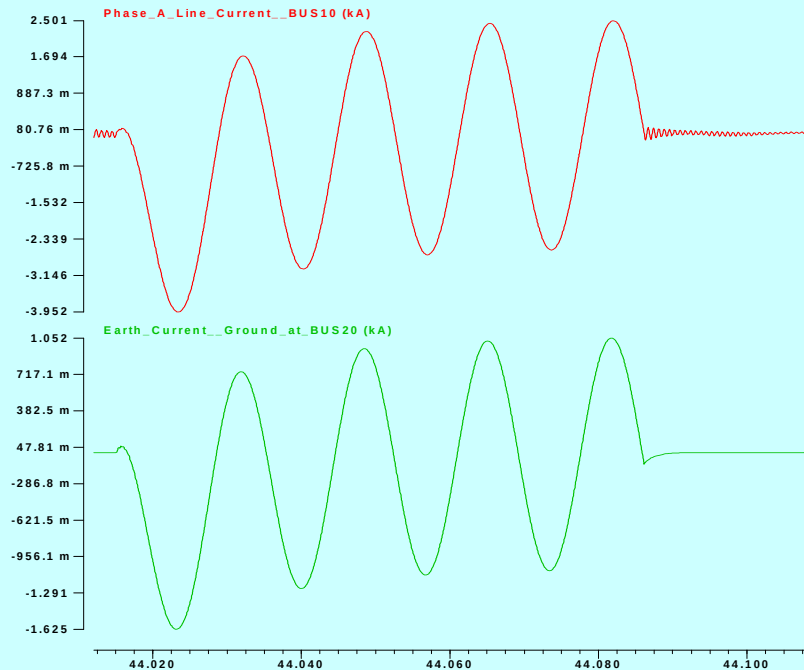


Earth Current / GPR / Worst Case Condition



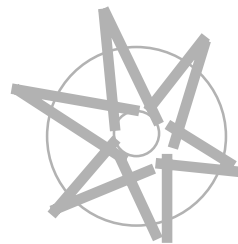
Program XFM - Page 1 of 1

c:\wmaster\lgsl\data\gpr_ex01 - May 14, 2000, 01:51:44.000000 - 2000000.0 samples/sec - 24000 Samples



Important Issues

Grounding and Bonding
Single Ground/Multi Ground
Load/DER Configuration
Transmission Interconnection



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Power Quality

Disturbances

Lightning

Switching

Power Faults

Feeder Energization inrush currents, Motor Start

Loading imbalance

Harmonics, Resonance

EMI

Impact on End User

Voltage Distortion, Sags, Swells, Outages and Imbalances

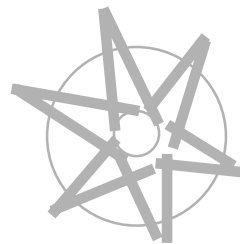
Design Options

Configuration

Grounding

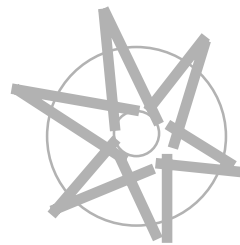
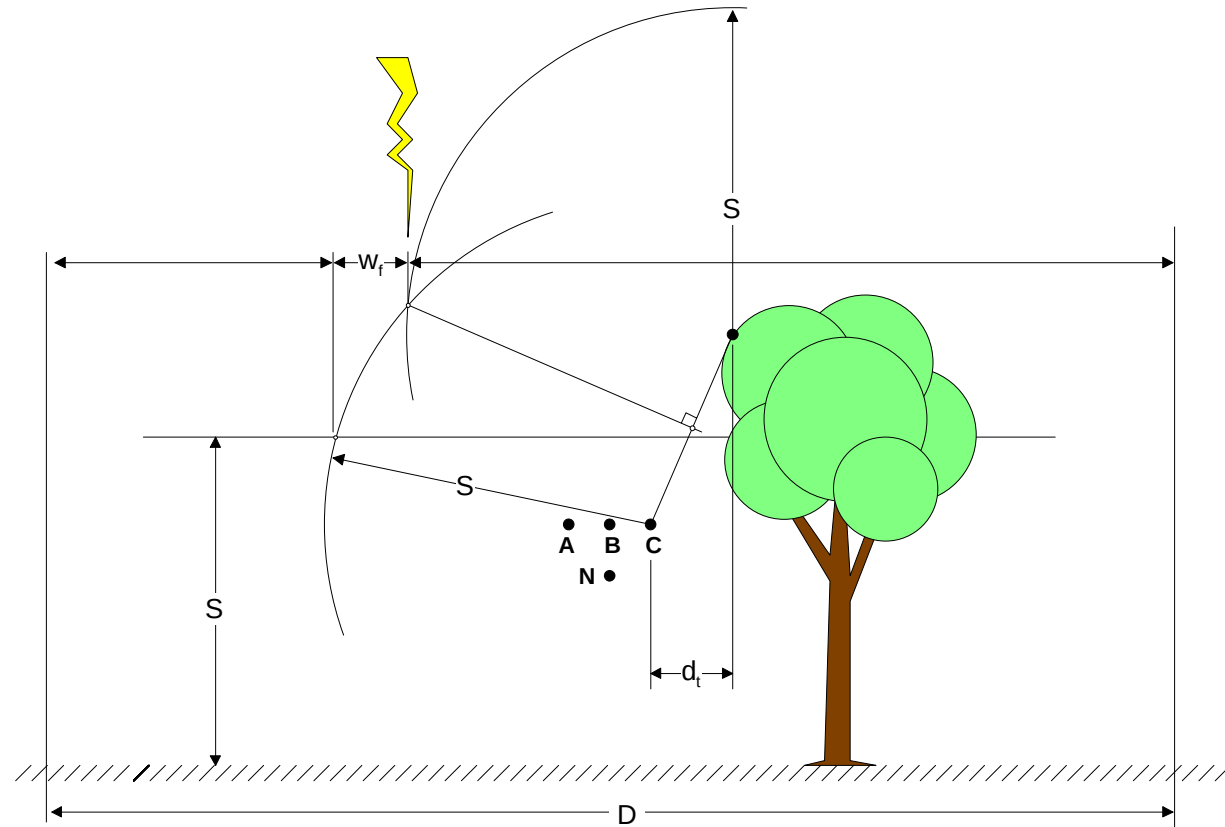
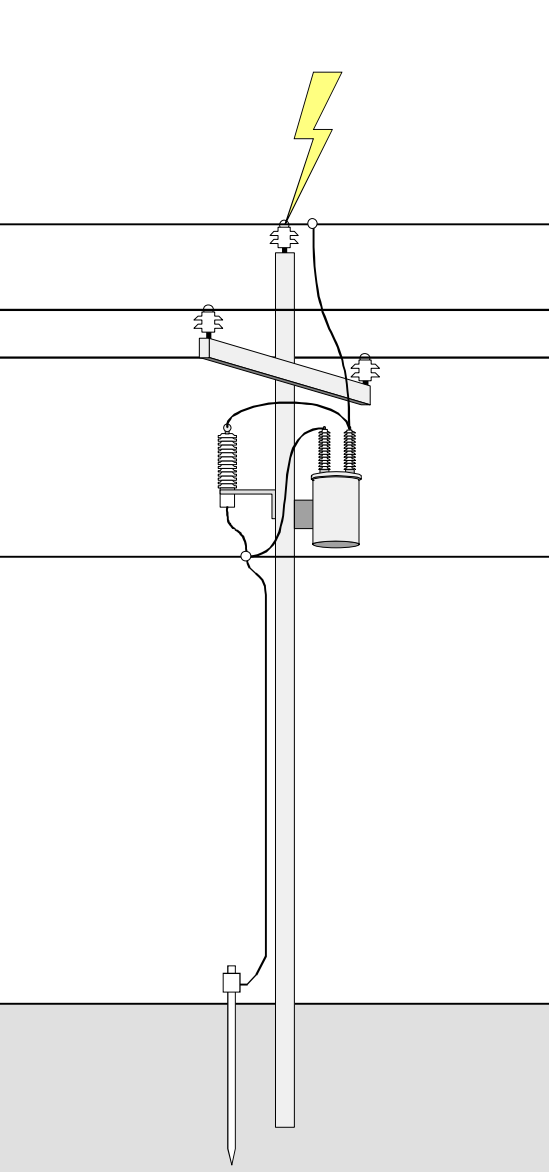
Overvoltage Protection (arresters), Fault Protection

Use of Steel/Aluminum conduit, Etc.



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Lightning Caused Voltage Sags, Swells and Outages

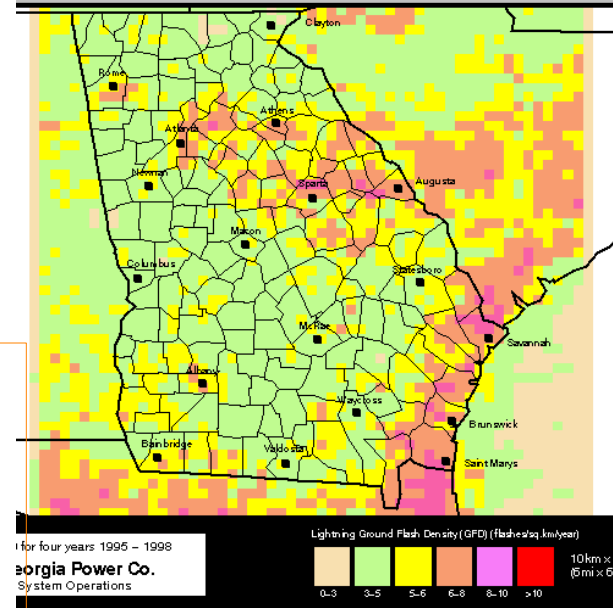
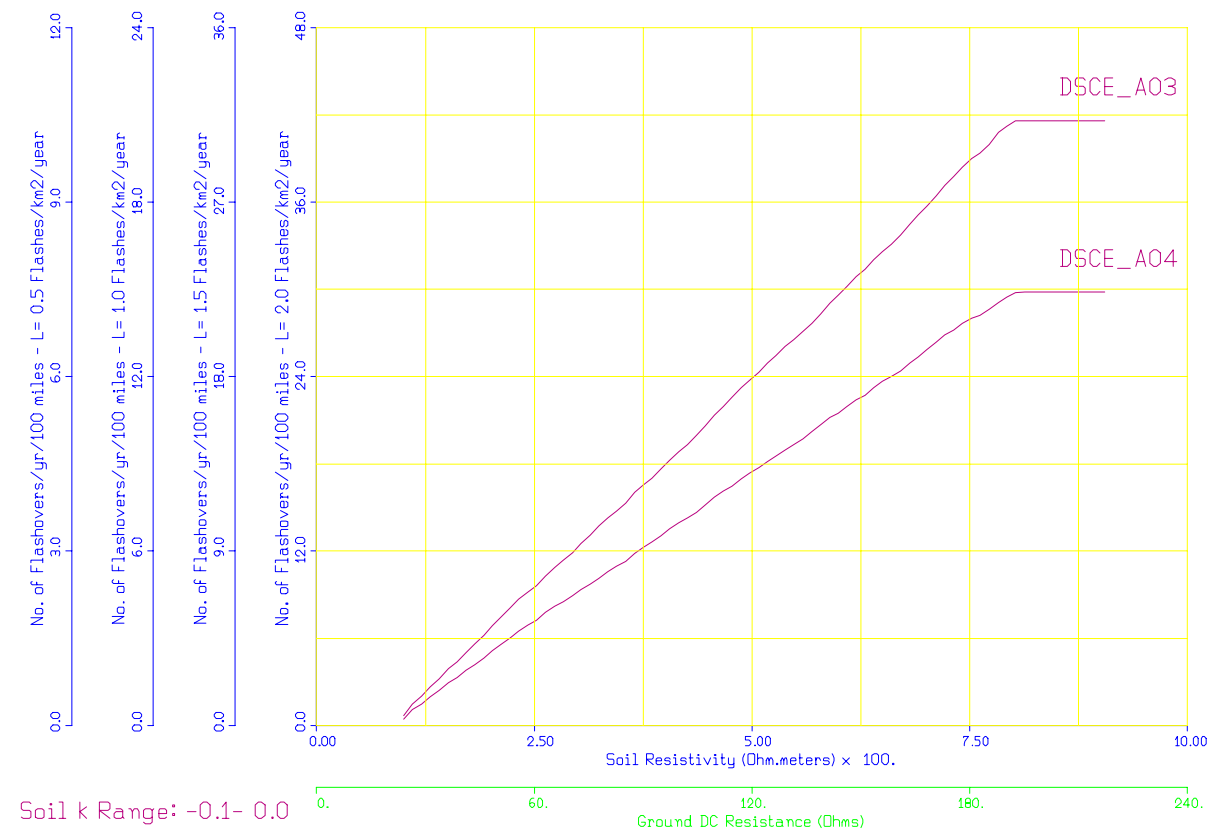


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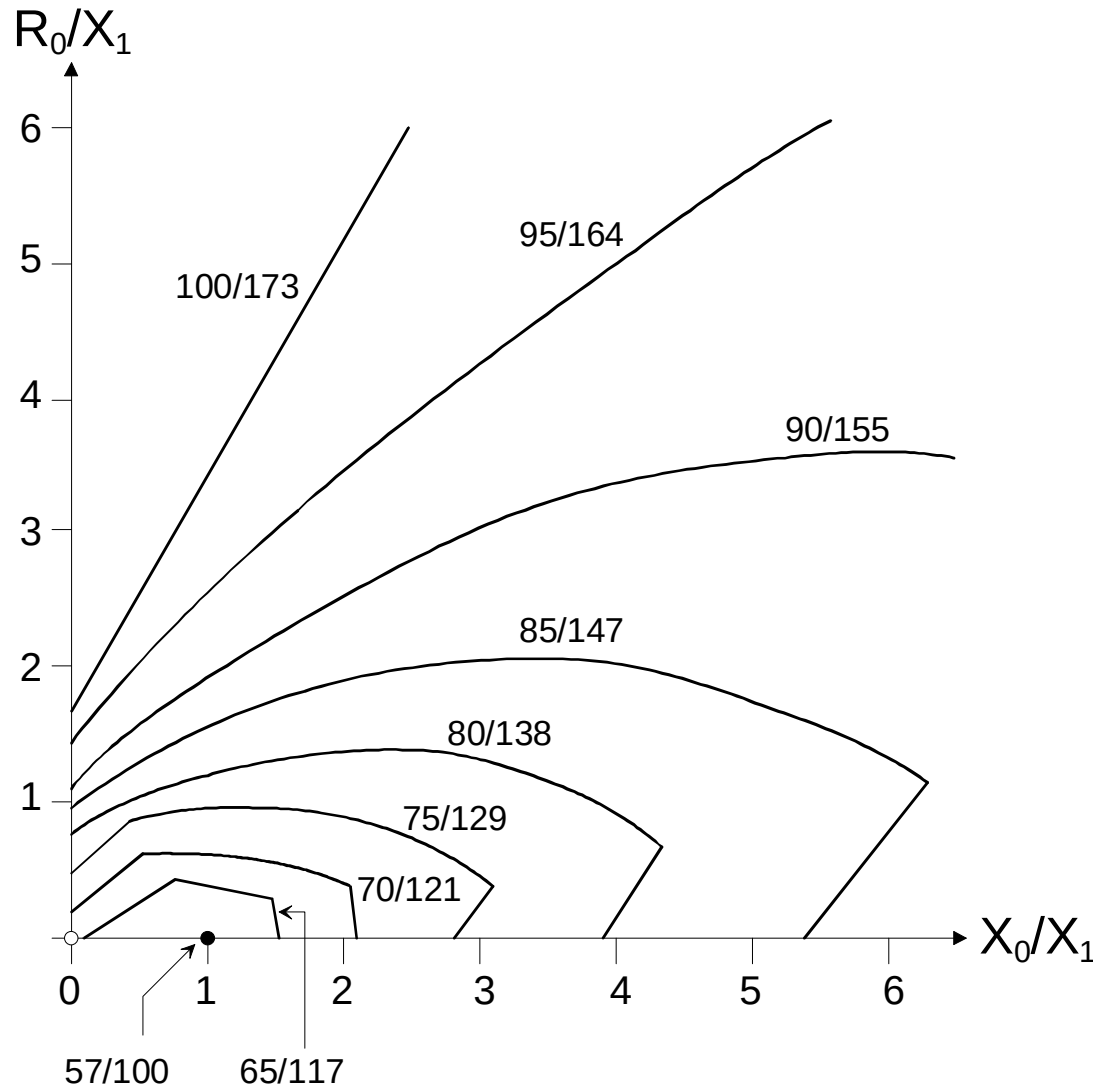
Lightning Caused Voltage Sags, Swells and Outages

Effects of Grounding and Protection

DSCE_A03: SCE: 33/12kV,PELICAN,1#4,Post/pin,spaced,80',2400
DSCE_A04: SCE: 33/12kV,PELICAN,1#4,Post/pin,spaced,80',800

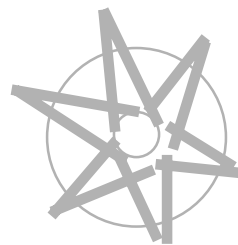


Voltage Sags & Swells and Grounding



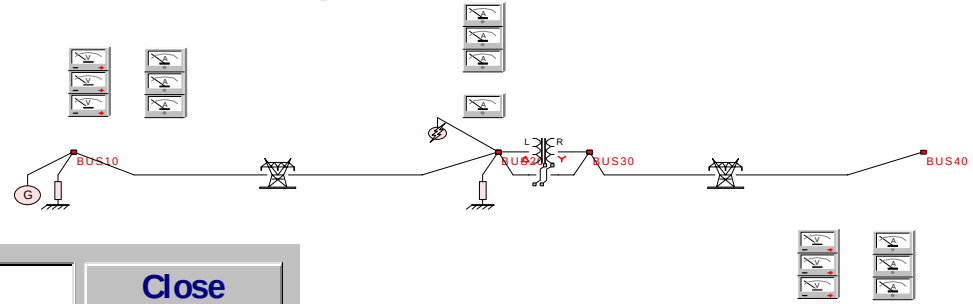
Coefficient of
Grounding

$$C_g = \frac{V_{LG}^{actual}}{V_{LG}^{no\ min\ al}}$$



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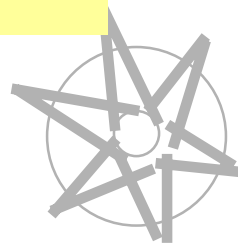
Voltage Sags & Swells During a Ground Fault



Comments

The Data of the Figure can be used to generate nomograms and statistical distributions of voltage sags and swells for a specific location (IEEE P1346)

A better approach is outlined next



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Transmission Line Voltage & Current Profile

Close

Distribution Line, 12 kV

Displayed Quantity

- ☒ Voltage
☐ Current

Voltage Reference

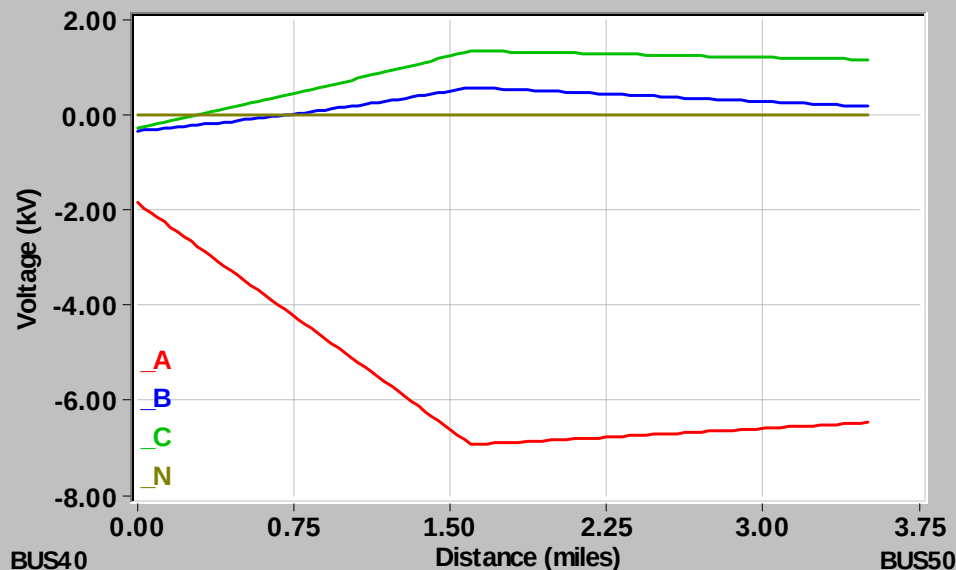
- ☐ Remote Earth
☒ Neutral
☐ Ground

Nominal Voltage

6.92 kV (L-L)

Plot Mode

- ☐ Absolute
☒ Deviation



Distance

1.250

_A

-5.810

_B

0.3334

_C

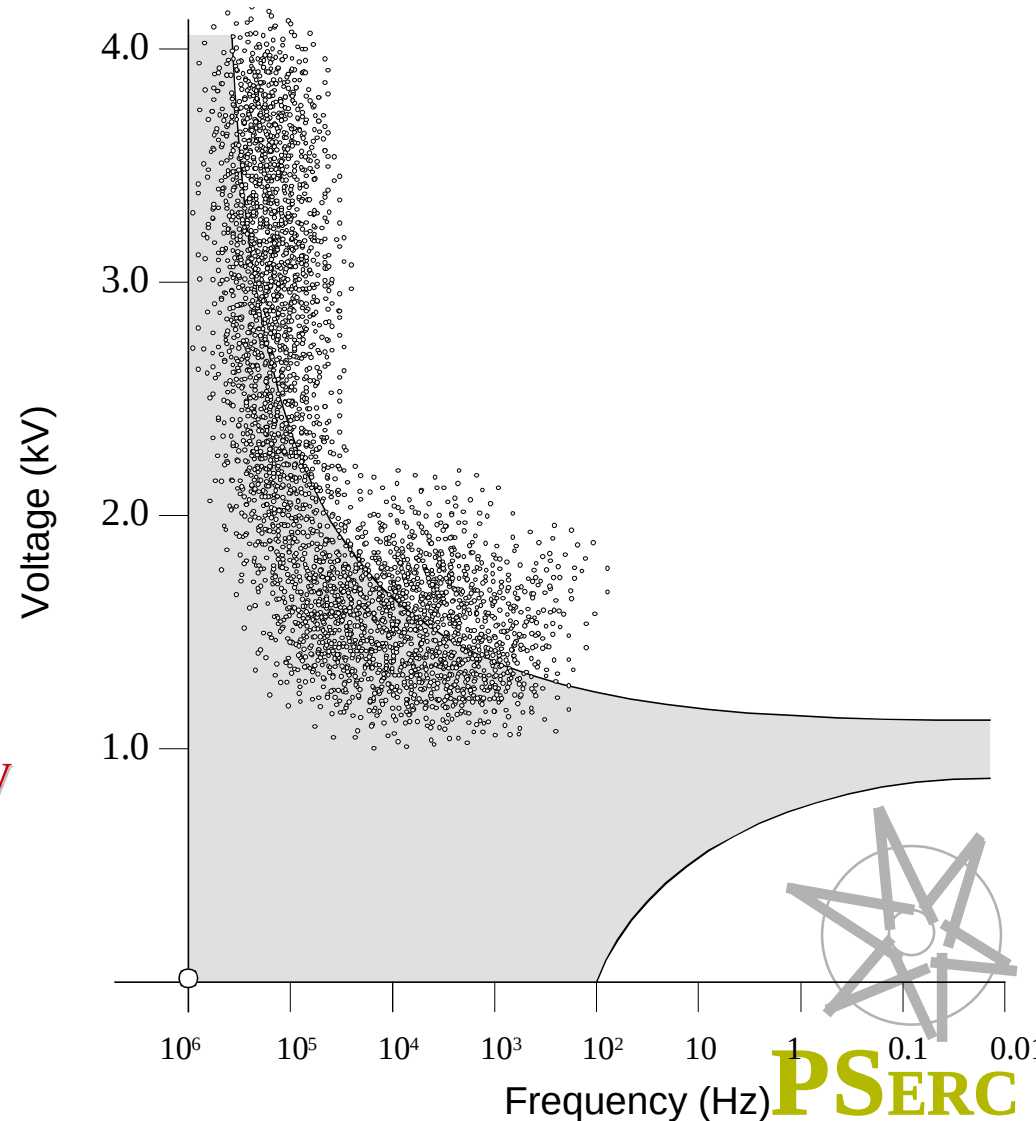
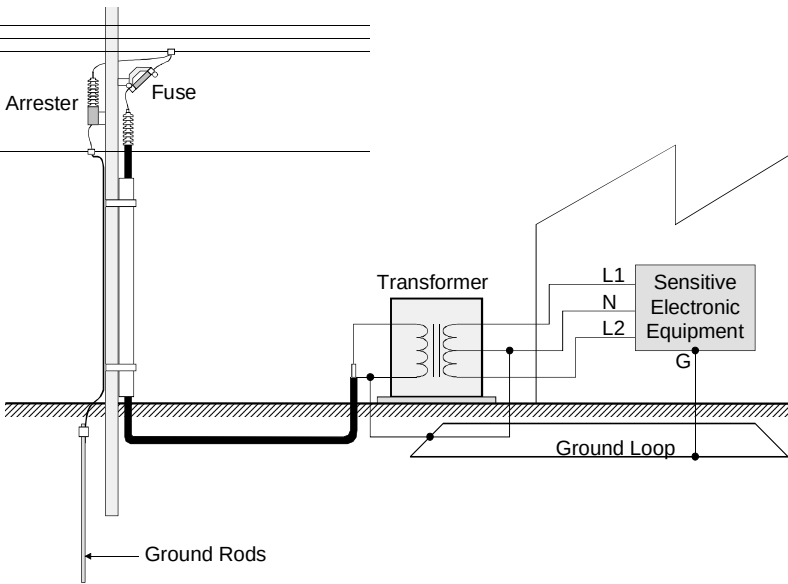
0.9744

_N

0.00

Program IGS - Form CODE_102A

Statistical Distribution of Voltage Sags/Swells

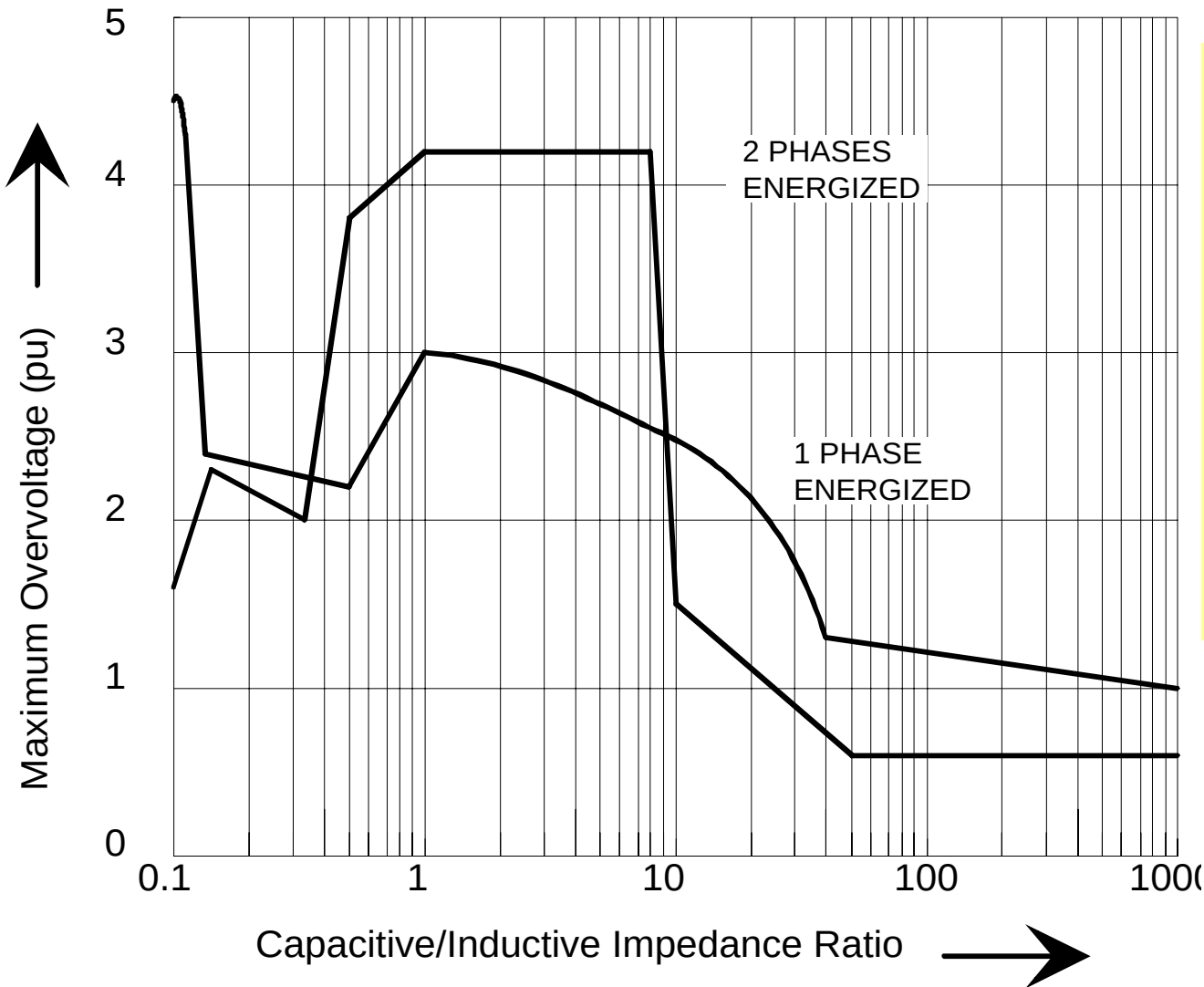


Probabilistic Approach to Power Quality Analysis

PQ Characterization

Design Options for PQ Enhancement

Ferroresonance

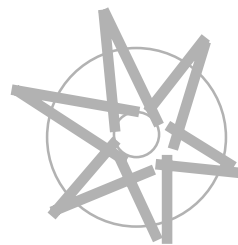


Comments

Resonance Between the Inductance of a Steel Core and the Circuit Capacitance

Vulnerable Systems: Medium Voltage Cable with Transformers/Regulators

Cases of “Stuck” Pole – Single Phase Protection



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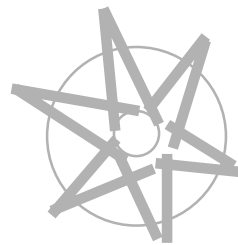
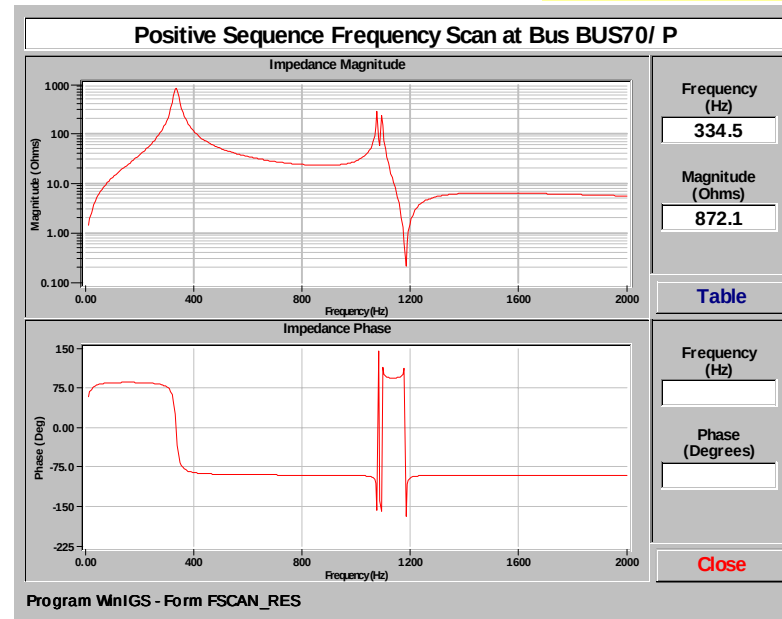
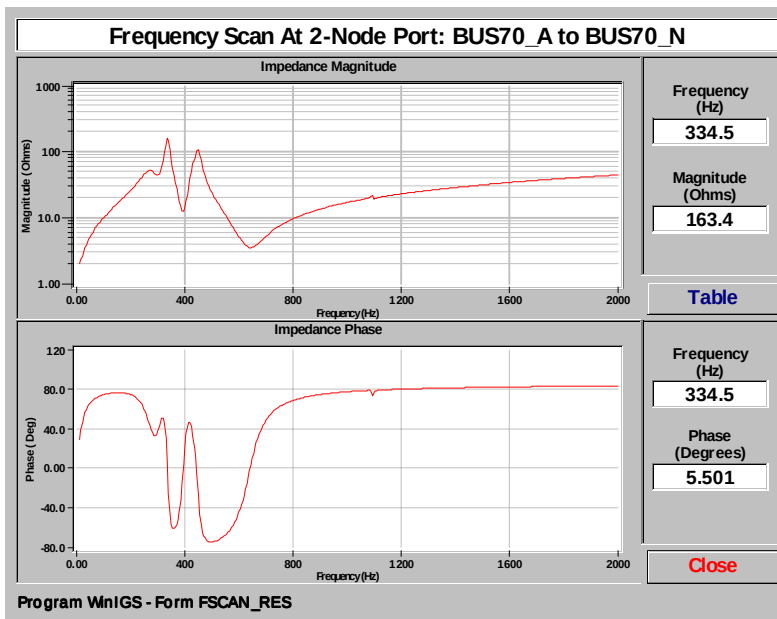
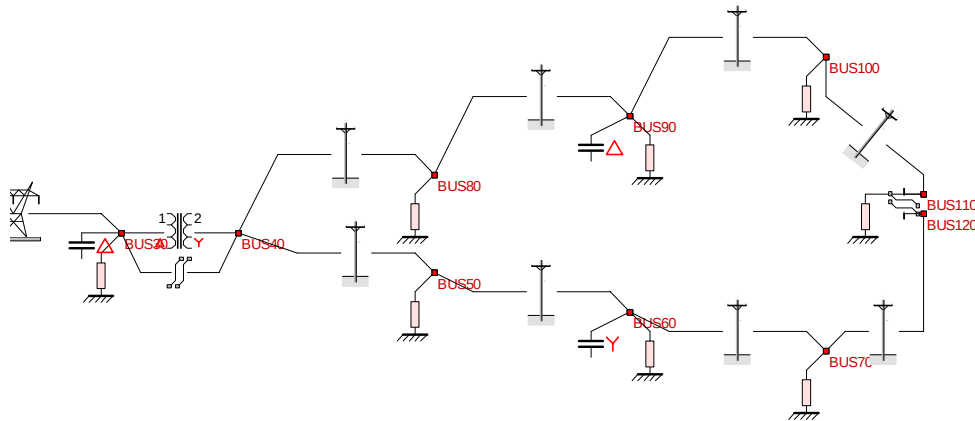
Harmonic Resonance

Comments

Harmonic Resonance Has Multiple Modes and Resonance Frequencies

System May Be Vulnerable When Resonance Coincides with a Harmonic Frequency

When Problem is Known, Solution is Very Simple - Detuning



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Reliability

Reliability Indices for Distribution Systems (Utility Perspective)

SAIFI: System Average Interruption Frequency Index
(interruptions/year and customer)

$$SAIFI = \frac{\text{Total Number of Customer Interruptions per Year}}{\text{Total Number of Customers Served}}$$

SAIDI: System Average Interruption Duration Index
(hours/year and customer)

$$SAIDI = \frac{\text{Total Number of Customer Interruptions Durations per Year}}{\text{Total Number of Customers Served}}$$

CAIDI: Customer Average Interruption Duration Index
(hours/interruption)

$$CAIDI = \frac{\text{Total Number of Customer Interruption Durations per Year}}{\text{Total Number of Customer Interruptions}}$$

ASAI: Average Service Availability Index

$$ASAI = \frac{\text{Total Customer Hours Service Availability per Year}}{\text{Customer Hours Service Demand}}$$

Reliability Measures (Customer Perspective)

Voltage Sags

Voltage Swells

Momentary Outages

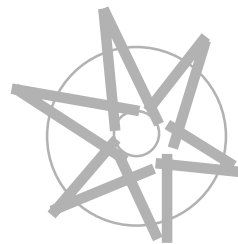
Load Interruption

EMI

Comments

Good Methods for Utility
Applications Exists
(Markovian)

End User/DER Methods
Needs Further Research
(NonMarkovian Processes)



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Cost of Reliability

Example

Power requirements: 3000 VA power

Average power consumption is 2000 Watts

Power utility reliability: SAIFI = 1.5, SAIDI = 45, Momentary = 30

Sector customer damage function: commercial per Table Below

Calculations

MWhrs consumed: 17.52

Cost of two 20 minute outages: $(3.0)(17.52)(2) = 105.12$

Cost of five 1 minute outages: $(1.0)(17.52)(5) = 87.60$

Cost of momentary: $(1.0)(17.52)(30) = 525.60$

Annual cost of interruptions: 718.32

Comments

Cost of utility power (assuming \$0.10 pwr kWhr): \$1,752 per year

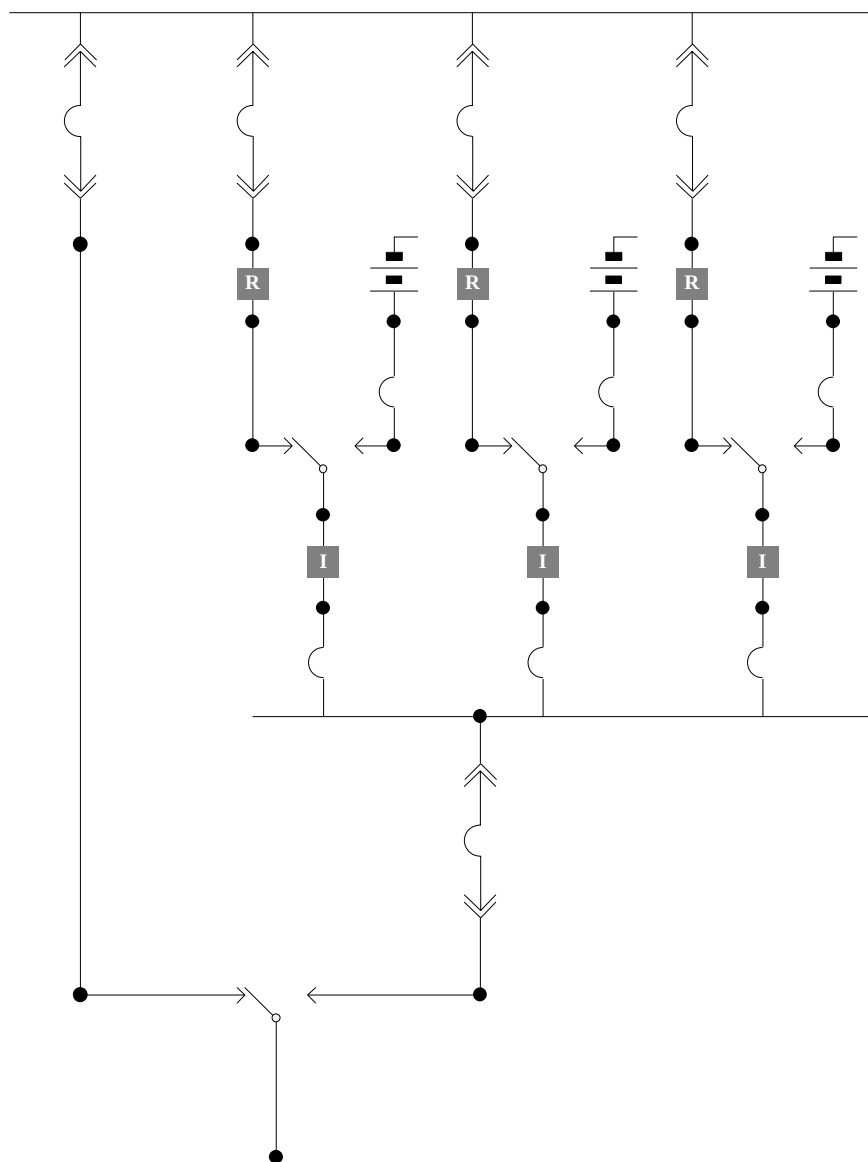
Survey of Cost of Interruption Sector Customer Damage Function (\$/MWhr)

Sector\Duration	Mom	1 Min	20 min	1 hr	4 hr	8 hr	24 hrs
Residential	0	0	0.1	0.4	3.0	6.0	20
Commercial	1.0	1.0	3.0	10.0	36.0	74.0	94.0
Industrial	6.0	6.0	13.0	24.0	64.0	106.0	135.0
Large User	2.0	2.0	2.0	3.0	3.0	4.0	5.0



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Reliability Research Issues



Battery Energy = 15 min

Cap	Prob	Freq	Dur
0	5e-4	13.0	0.3
300	3e-6	9e-4	30
600	3e-3	0.46	58
900	0.996	13.5	648

Battery Energy = 30 min

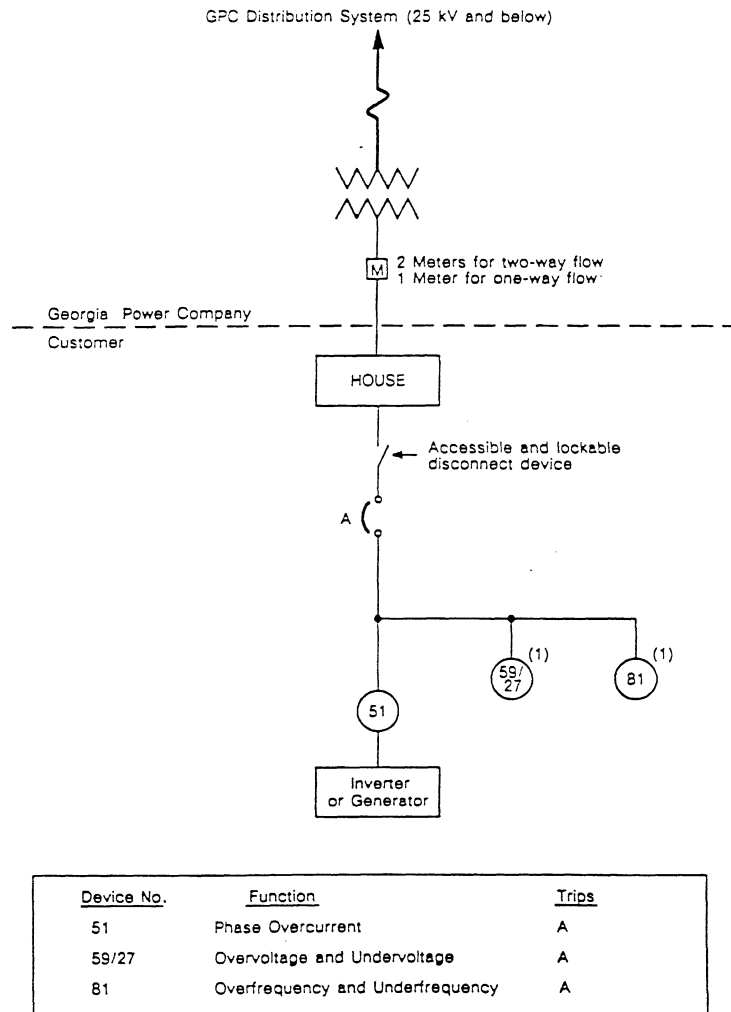
Cap	Prob	Freq	Dur
0	7.2e-5	13.0	0.3
300	2.7e-5	5e-3	47
600	3.8e-3	0.52	65
900	0.9961	13.5	648



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Protection

Typical DERs Protection



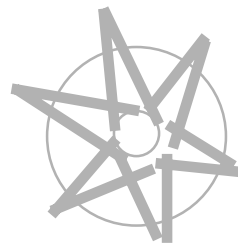
Protection Issues

Fault Protection (Current Limited DERs, Remote Contribution, Ground Impedance, etc.)

Faulted Circuit Indication

Fault Location and Isolation

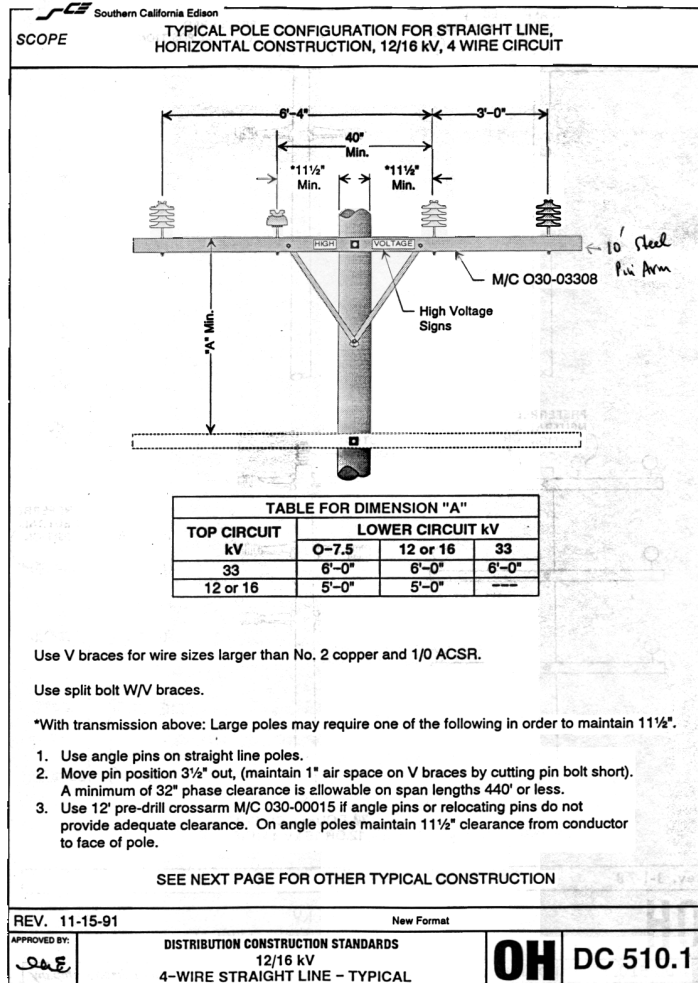
Detection of Hot "Down" Conductors



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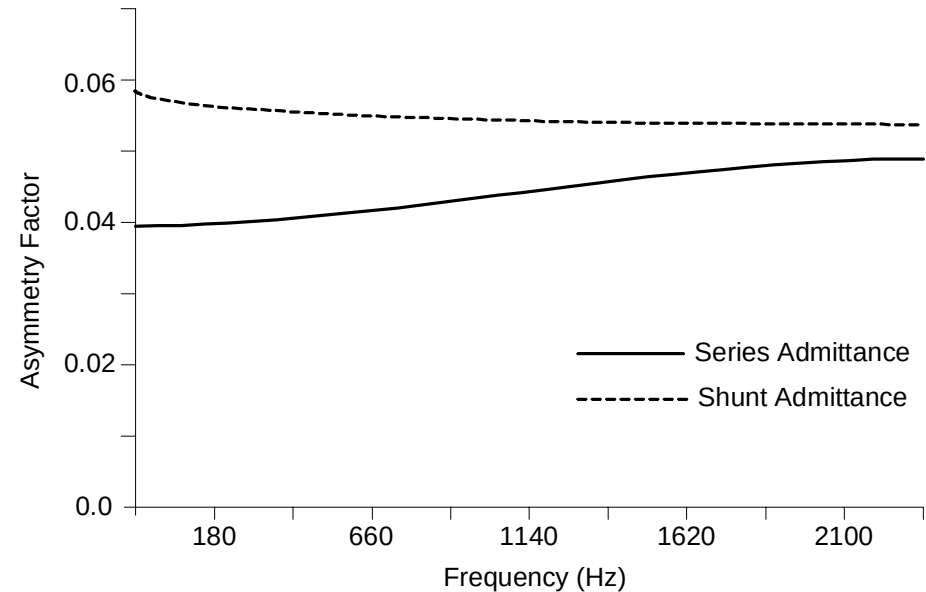
Unbalance/Asymmetry

Most Power Circuits Are Asymmetric



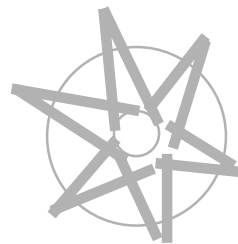
$$S_1 = \frac{1}{2} \frac{|z_{\max} - z_{\min}|}{|z_1|}$$

$$S_2 = \frac{1}{2} \frac{|y_{\max} - y_{\min}|}{|y_1|}$$



Other Sources

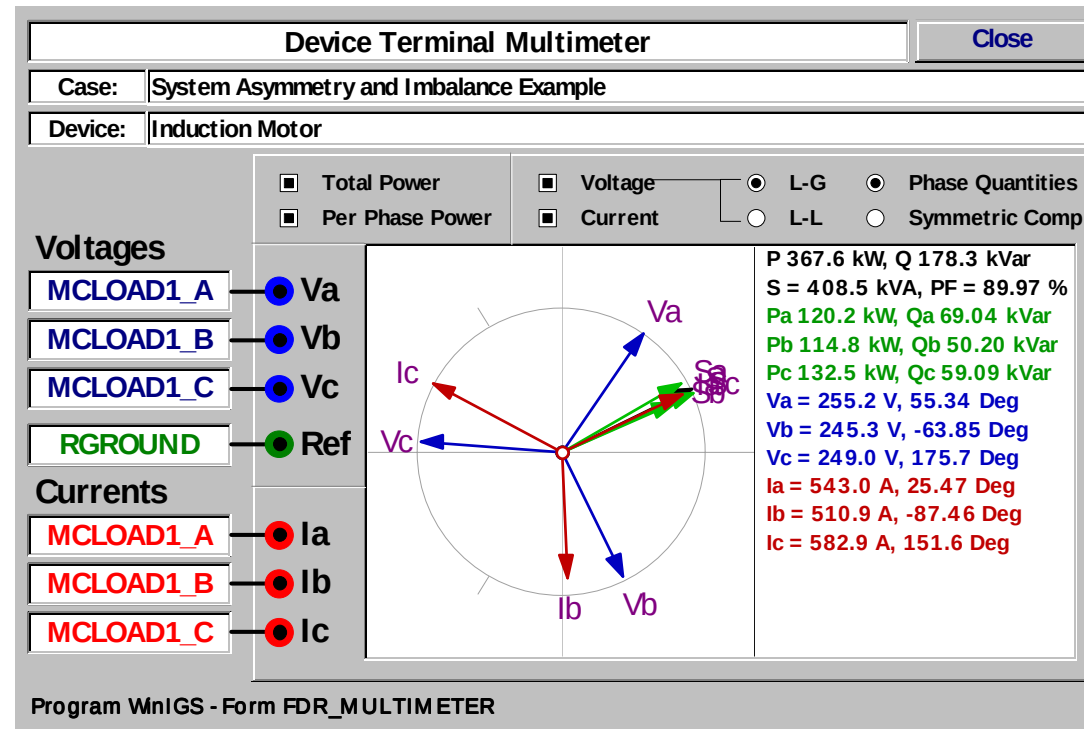
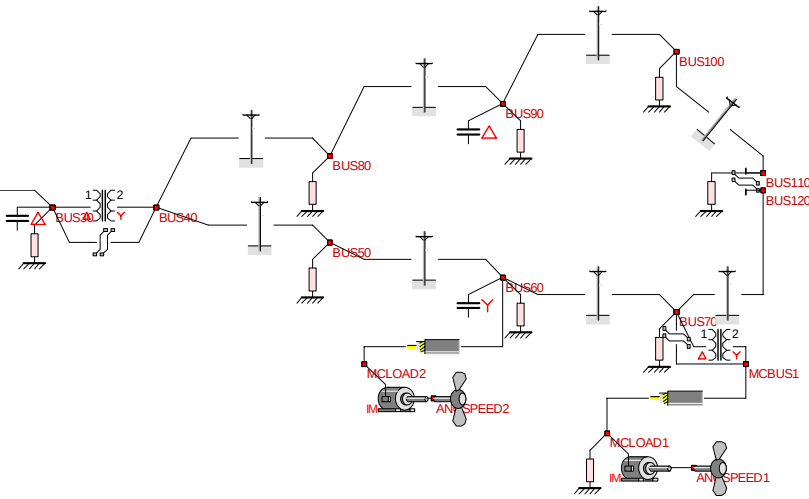
Single Phase Loads
End Use Equipment
Induction Motors



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Induction Motor Response to Unbalance/Asymmetry

Typical Distribution System Example

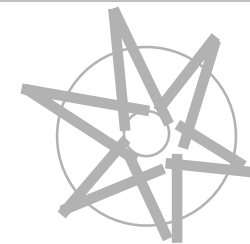


Comments

Combined Effects of System
Component Asymmetry and
Imbalanced Loads

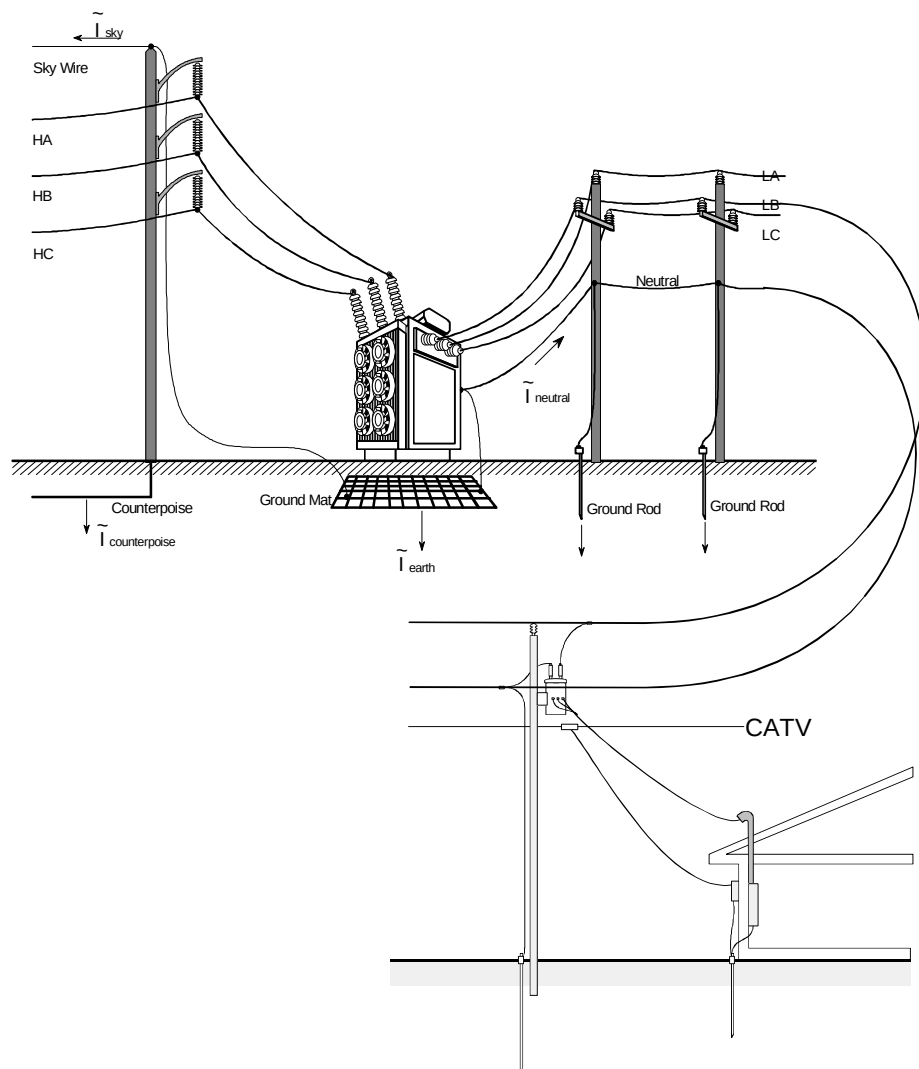
Important Factors:

Configuration
Transformers
Load Balancing



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Stray Voltages and Currents



Comments

Single Phase Loads Generate Current Flow in the Parallel Path of Neutral and Soil/Grounds

Typical Distribution 50-70% in Neutral, 50-30% in Soil/Grounds

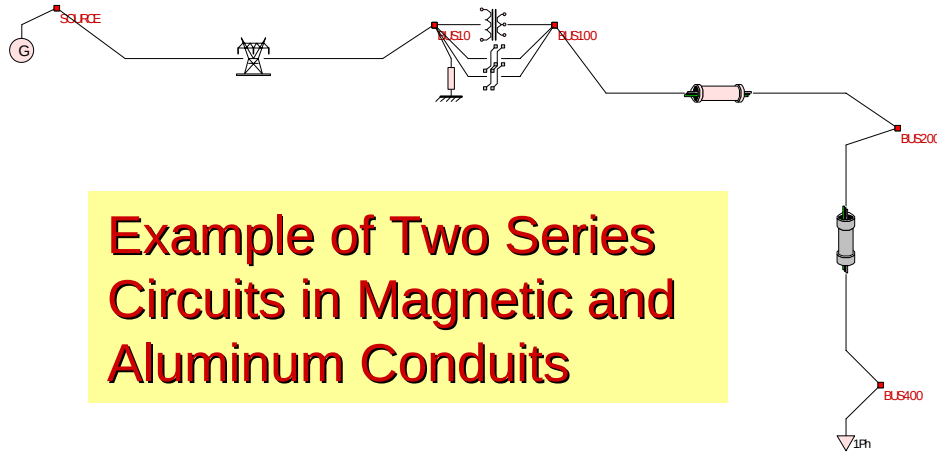
Neutral Voltage Typically 2 to 12 Volts

Properly Designed mGRIDs can Practically Eliminate Stray Voltages and Currents

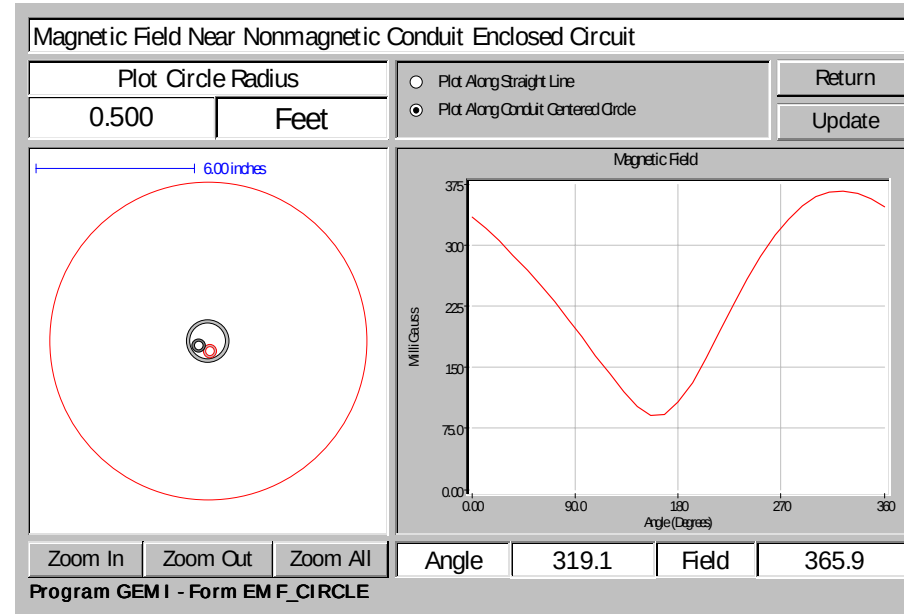
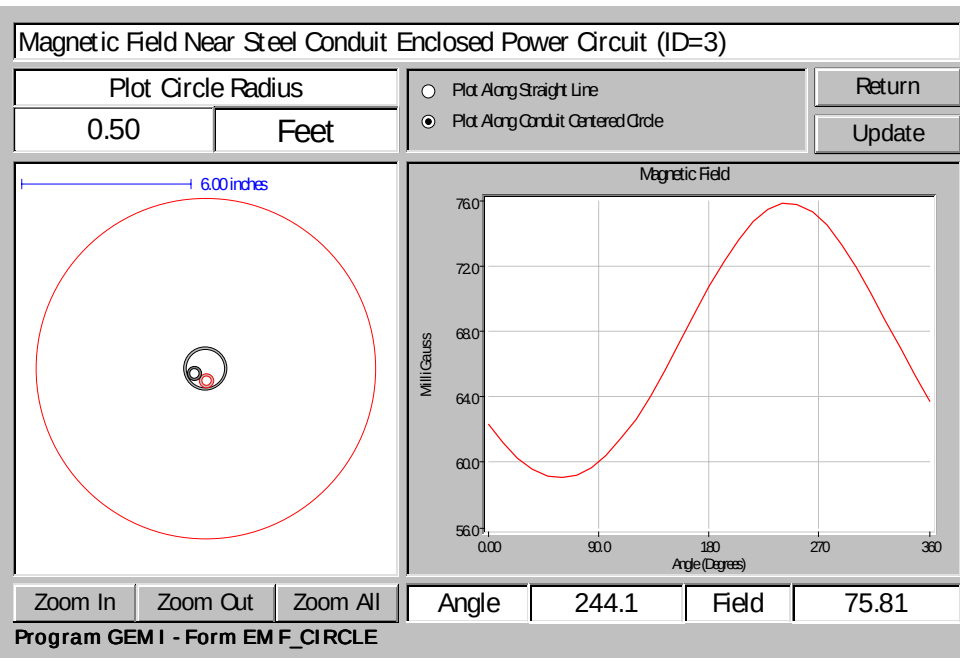


PSERC

Electromagnetic Compatibility Issues



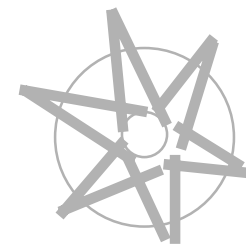
Example of Two Series Circuits in Magnetic and Aluminum Conduits



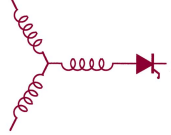
Comments

EMI can generate serious problems

The mGRID concept offers an opportunity to rethink design issues and optimize EMI performance



PSERC



Inverters in Microgrids

Giri Venkataramanan
Department of Electrical and Computer Engineering
University of Wisconsin-Madison

3 Jan 2001

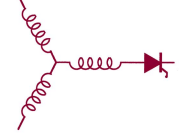
Giri@engr.wisc.edu

Outline

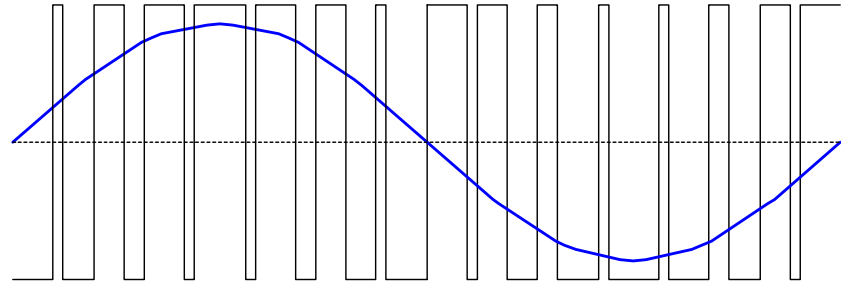
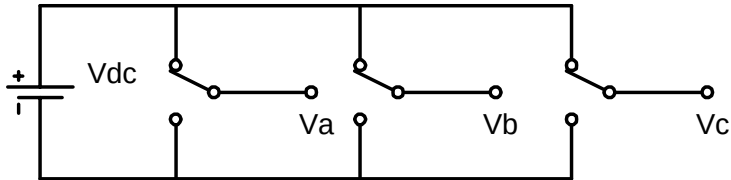
- Description of inverter types and characteristics
- Inverter control objectives
- Inverter dynamic modeling
- Summary

Inverter types

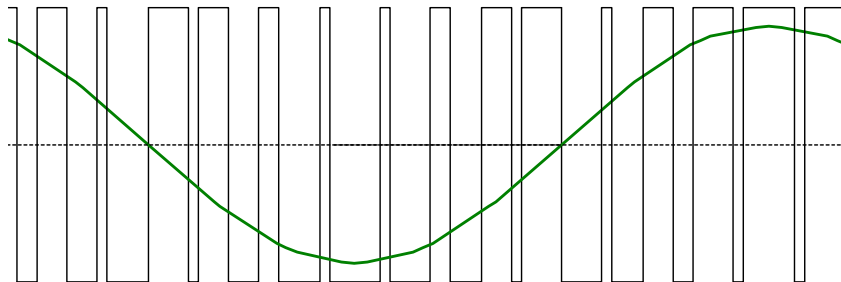
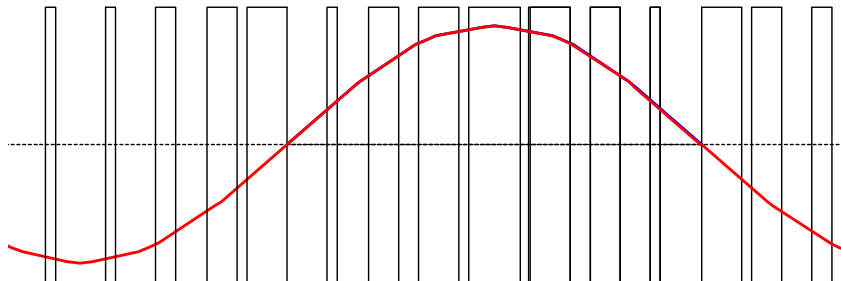
- PWM inverter
- Multilevel inverter
- Naturally commutated current source inverter

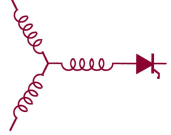


PWM Synthesis – A, B & C phases

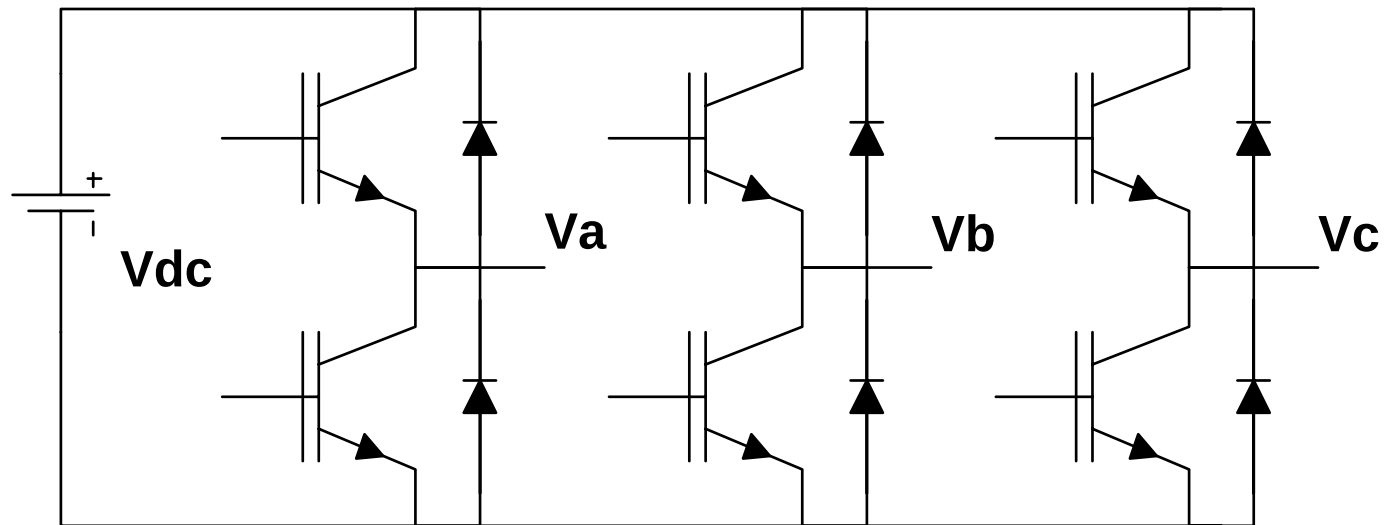


- Phase shift between waveforms may be varied
- Amplitude of waveforms may be dissimilar
- All the three phase voltages could have an average $V_{dc}/2$ common mode voltage
- Causes a neutral shift
- Will cancel out in the line-line voltages

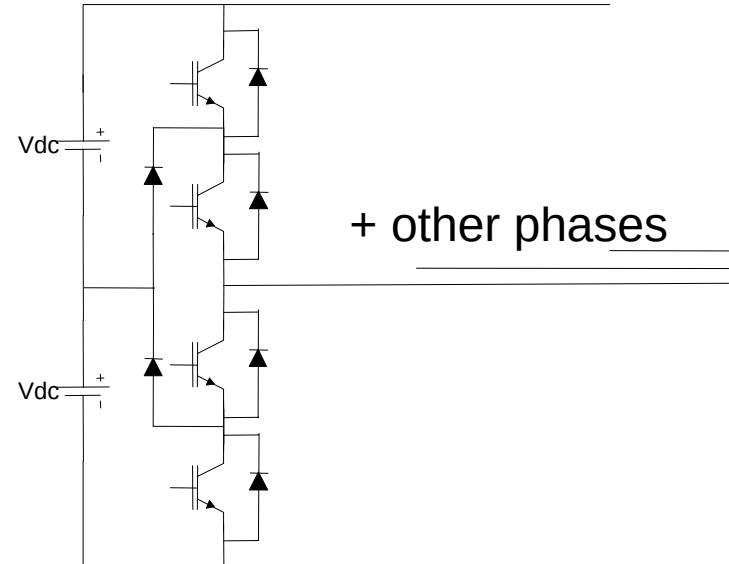
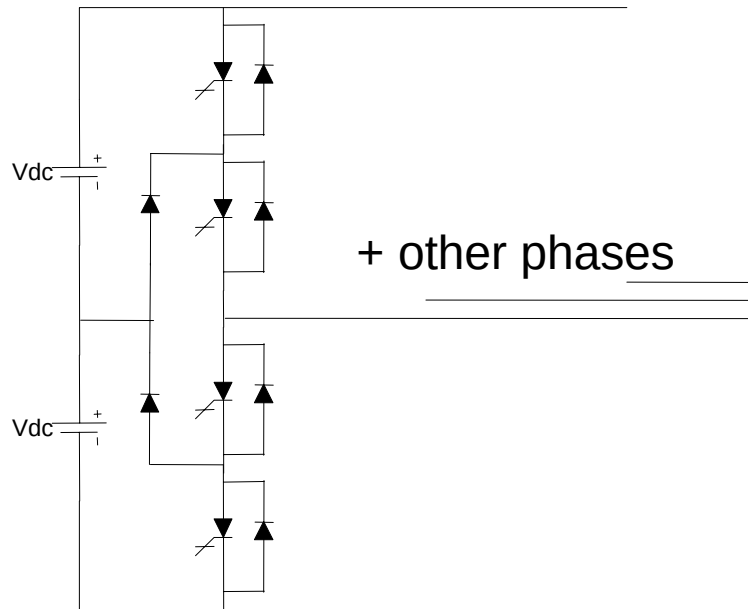


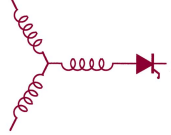


Realization using IGBTs

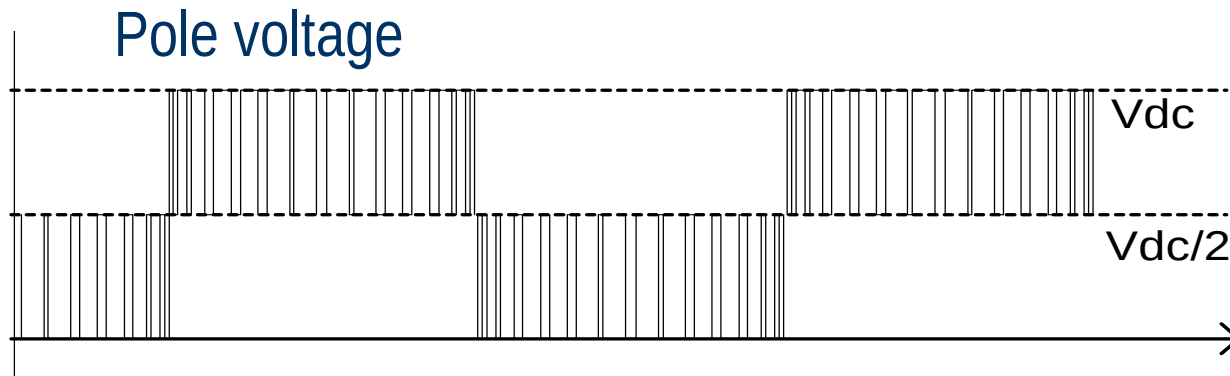


Multilevel Inverters

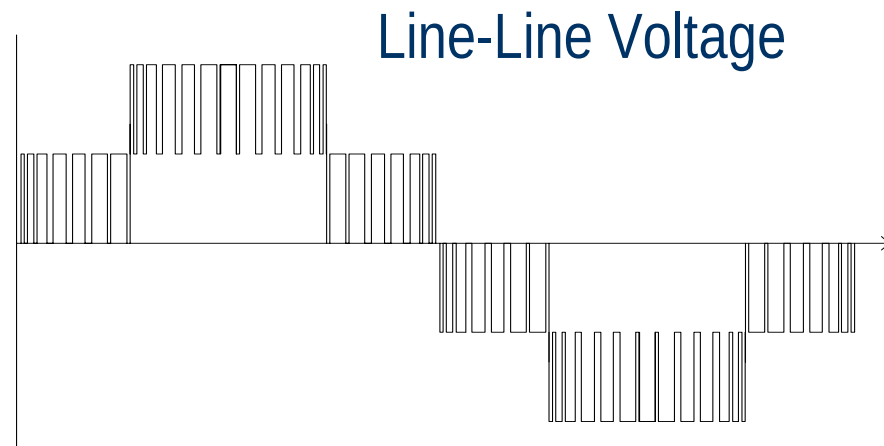




Typical waveforms

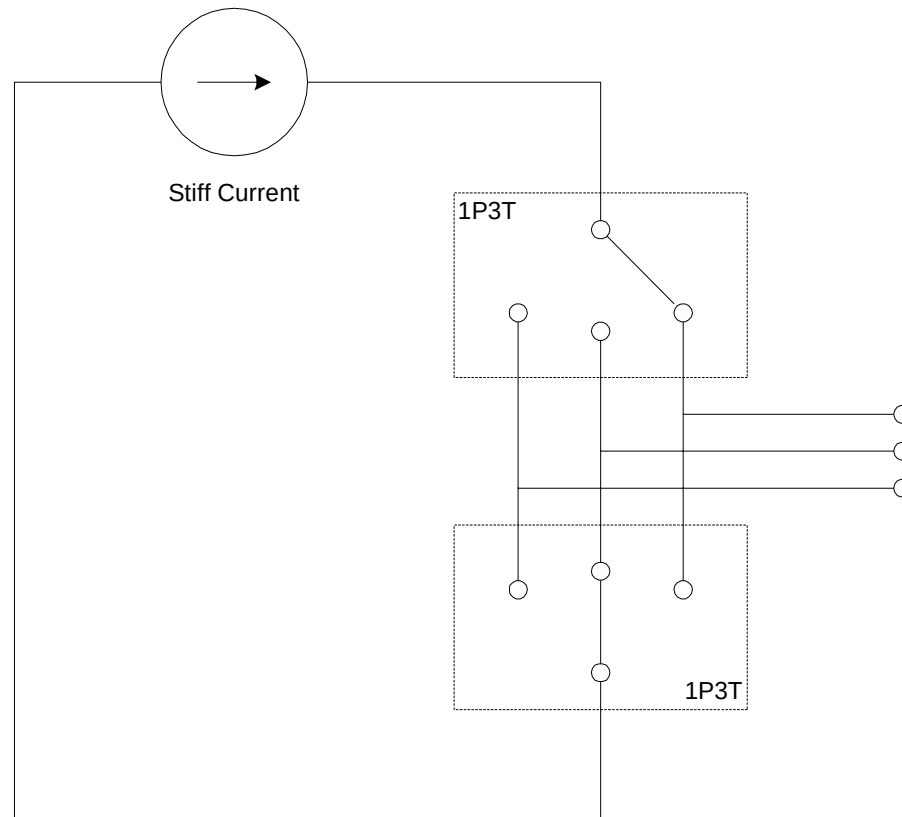


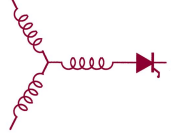
Stepped synthesis
also possible



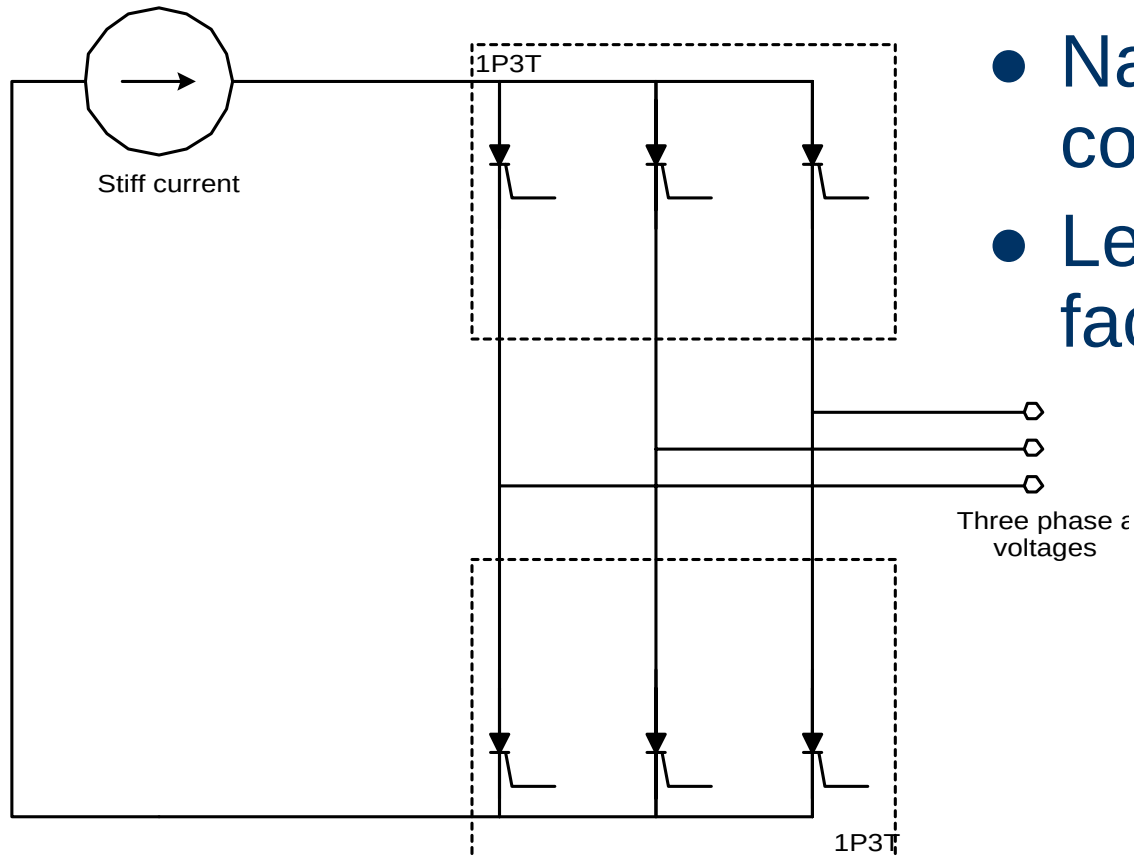
Three Phase Current Source Inverter

- Two Pole Three Throw Switches

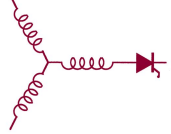




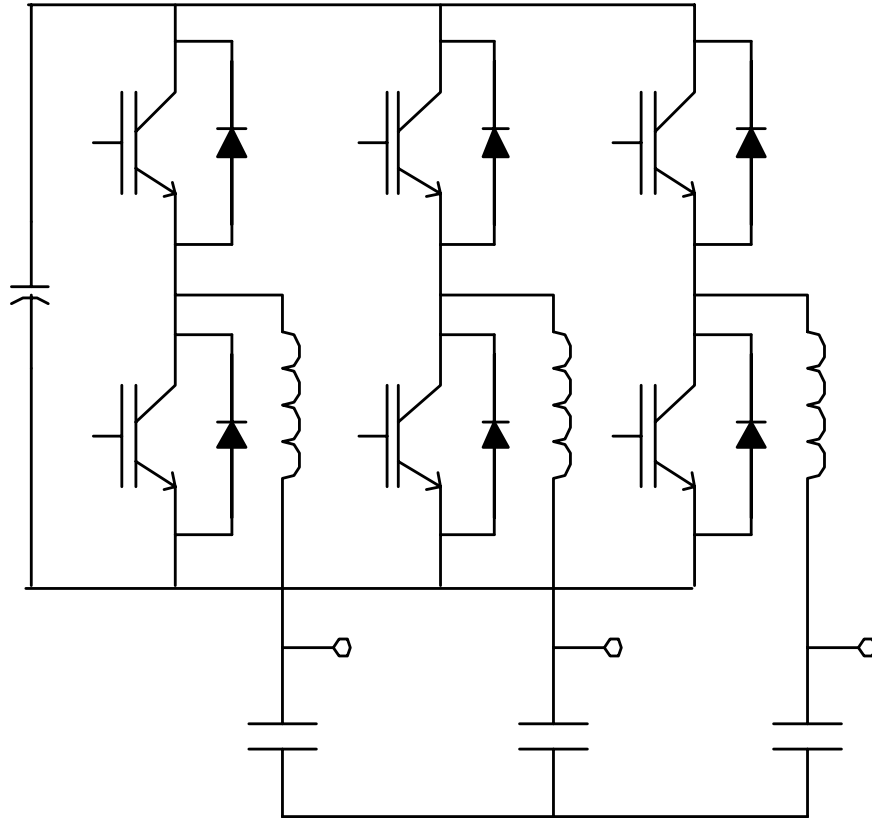
CSI Converter Realization (Thyristors)



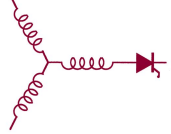
- Natural commutation
- Leading power factor load



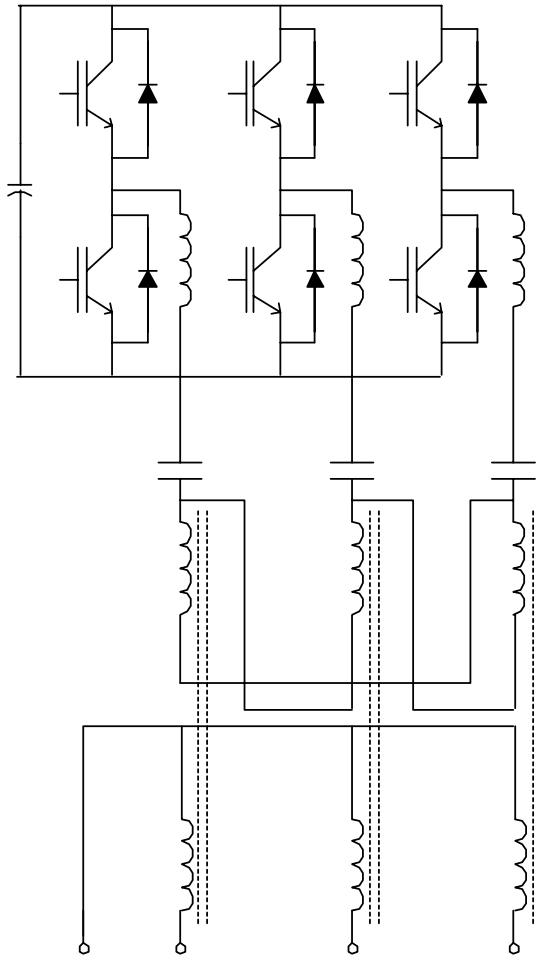
3 wire direct output



- DC voltage level has to be bigger than peak line-line voltage
- No path for zero sequence currents from inverter

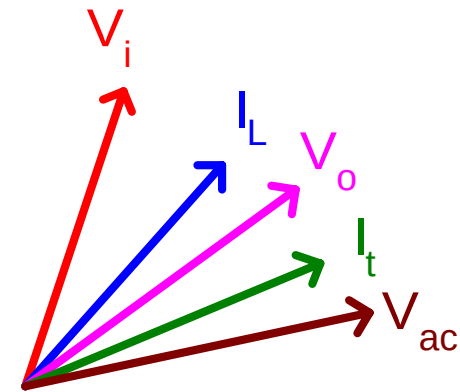
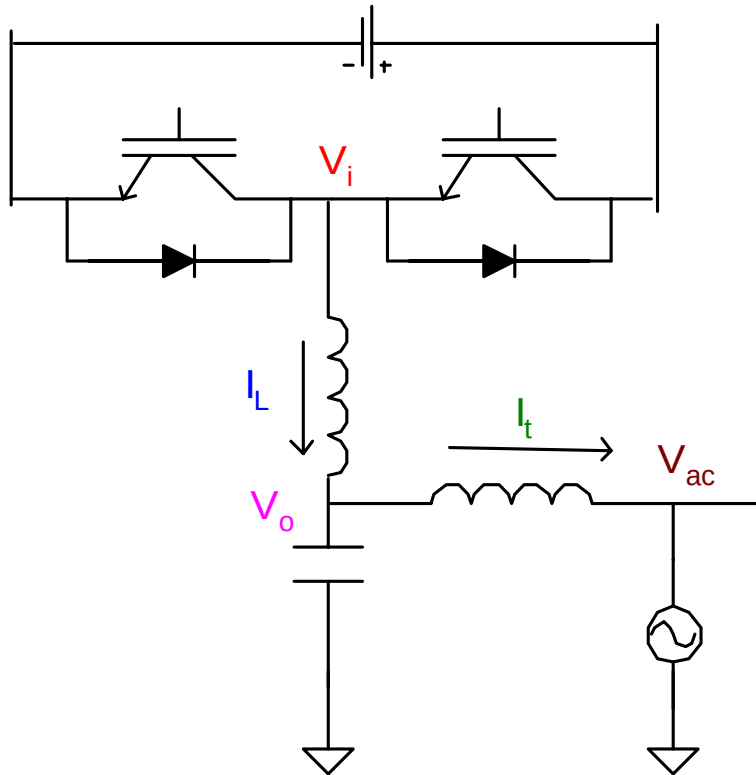


4 wire interface using star-delta transformer

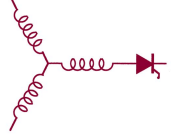


- DC voltage level free variable because of transformer turns ratio
- Zero sequence currents on star side circulates within the loop of the delta side

Single line equivalent circuit and phasor diagram



- V_{ac} – PCC voltage
- V_o – Point of Load (POL) Voltage

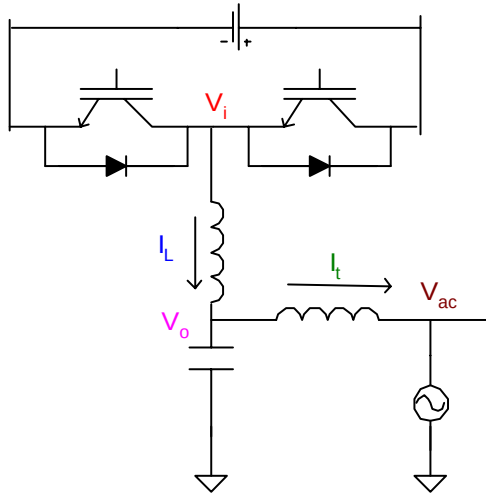


Microgrid Energy and Power Quality Management Functions

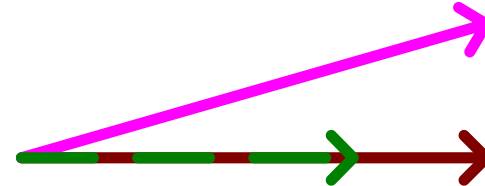
- Load profile control
- Source utilization
- Peak-shaving
- Reactive power injection

- POL voltage control
- Voltage imbalance correction

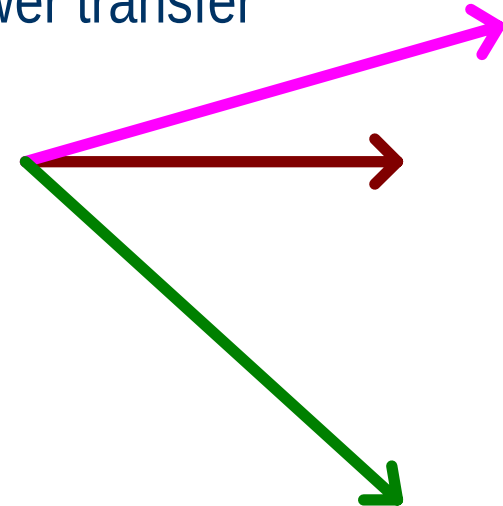
Voltage sag correction



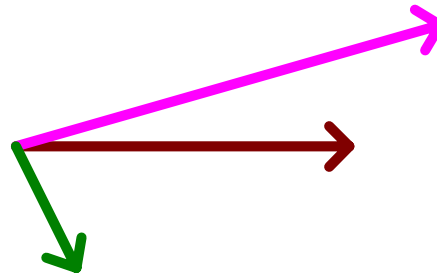
Nominal condition

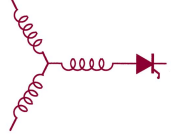


Operation under sag
(Same real power transfer level)

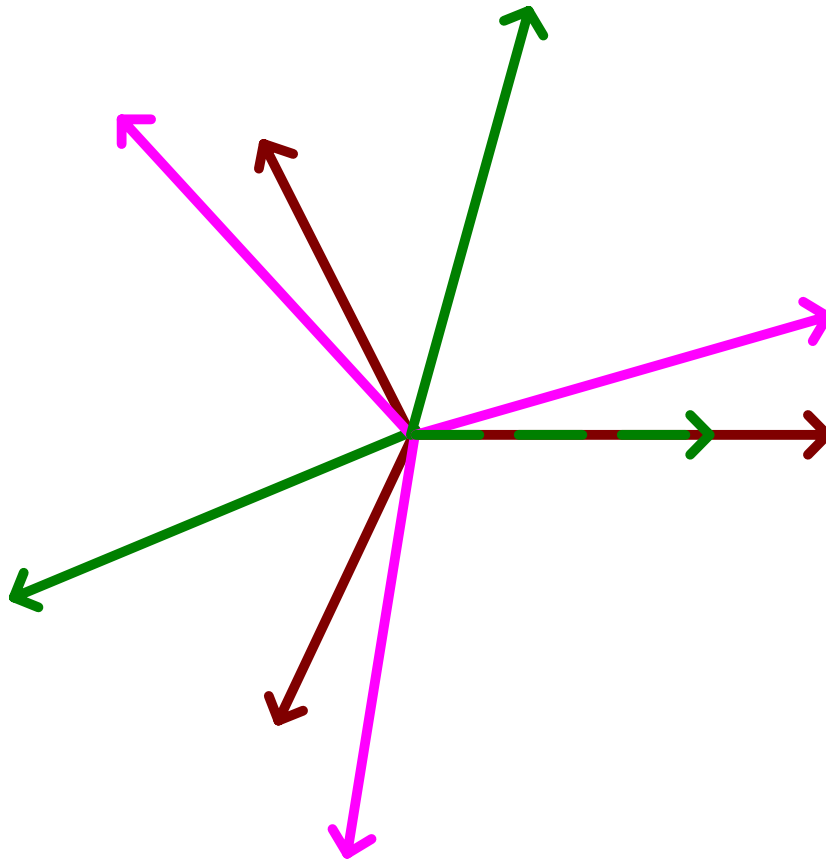


Operation under sag
(Reduced real power to grid)

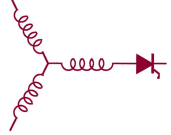




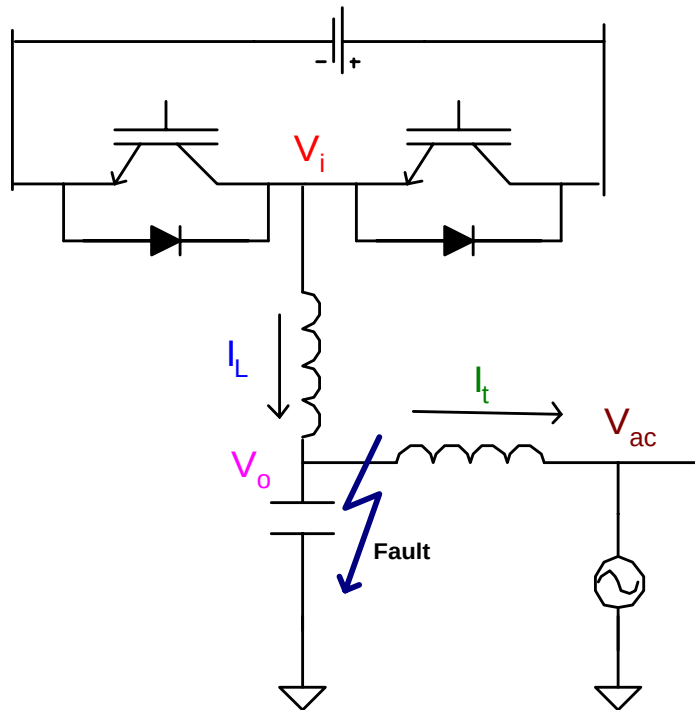
Voltage imbalance correction



- Input voltage – Brown
 - Output voltage – Cyan
 - Phase currents – Green
-
- Note increase in current stress on phases with large sag



Fault Management

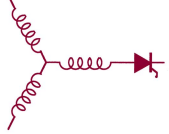


Operation under transients

- Load transients
- System transients
 - Capacitor switching
 - Power quality events
- Delayed source response
- Islanding
- Reconnection

Key Control Issues

- Power flow control
 - Frequency control
 - Local voltage control
 - Reactive power control
-
- Power sharing
 - Frequency matching



Power throughput of inverter

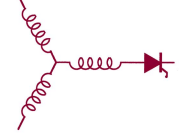
$$P = \frac{V_{ac} V_o}{X_t} \sin \delta$$

$$Q = \frac{V_o^2}{X_t} - \frac{V_{ac} V_o}{X_t} \cos \delta$$

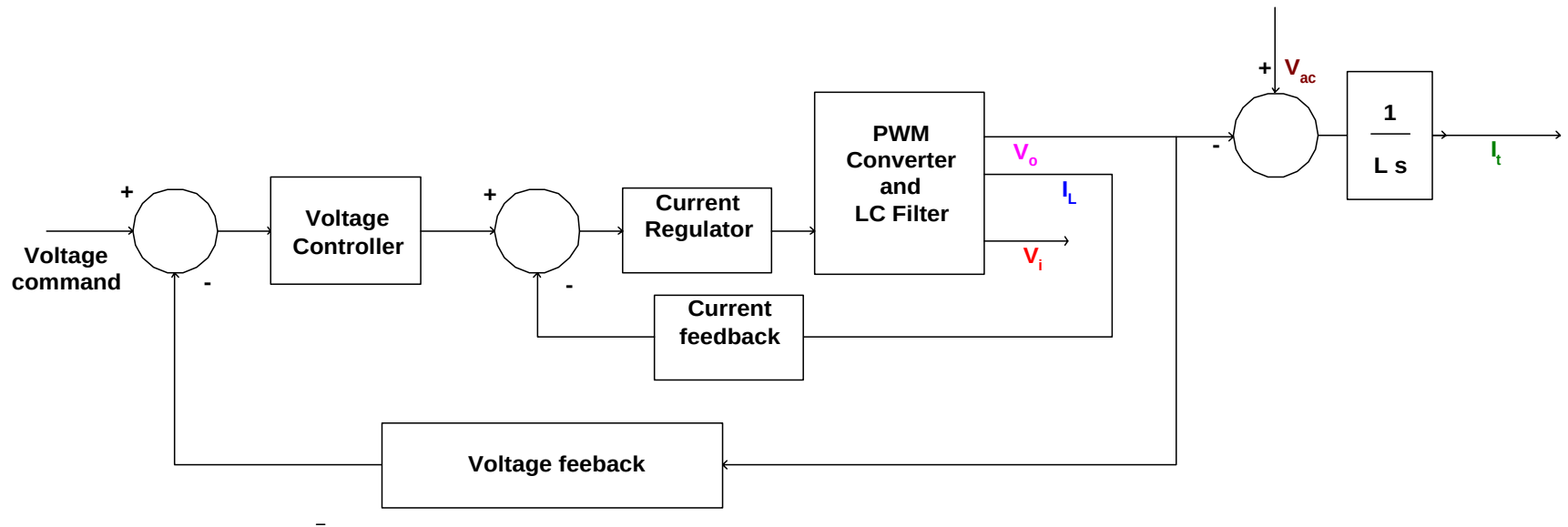
- Angle between V_{ac} and V_o determines power flow
- Magnitude of V_o determines reactive power flow

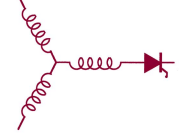
Modeling objectives

- Need to model dynamic properties
- Control input and real power flow or power angle
- Control input and reactive power flow or voltage magnitude



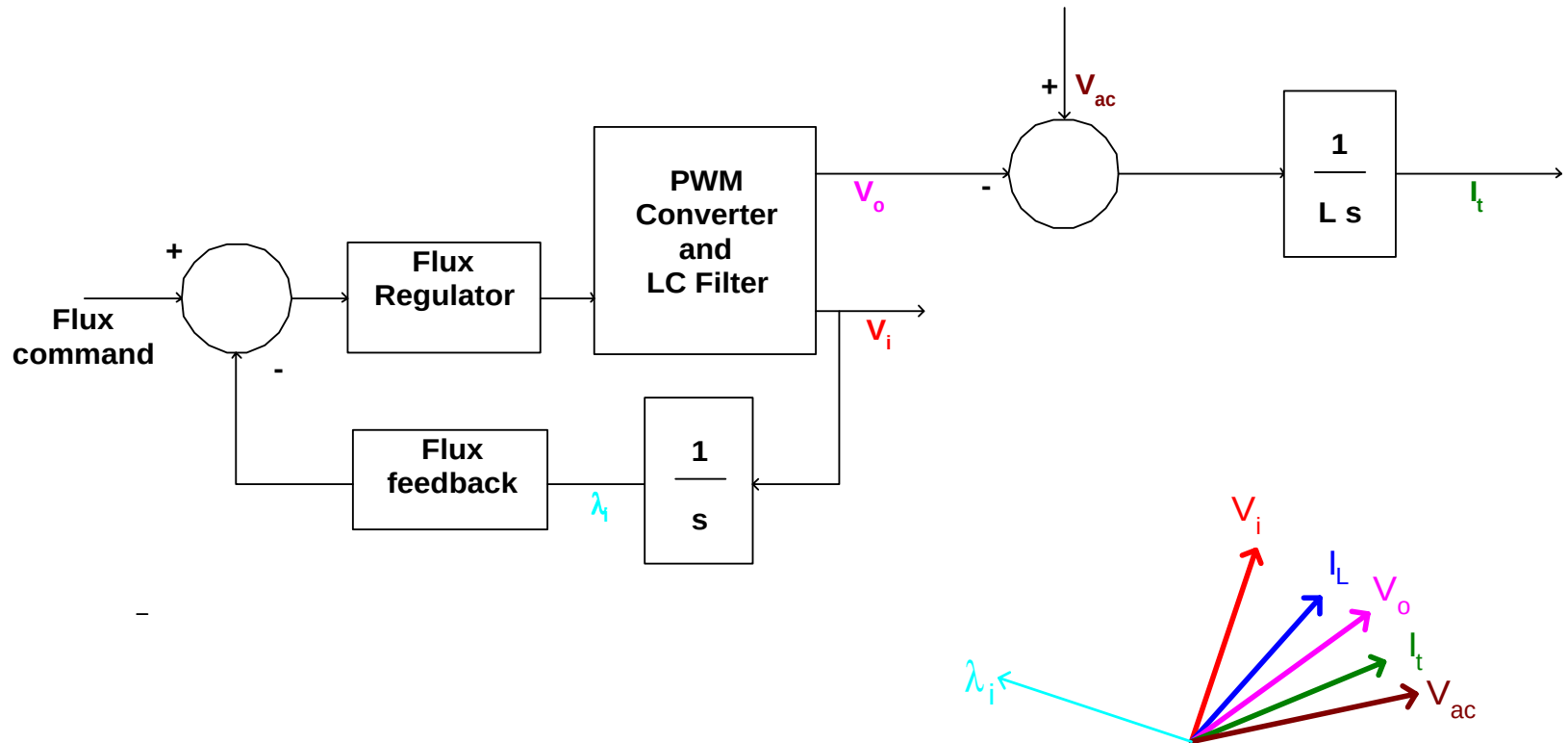
Typical controller structure (classical)

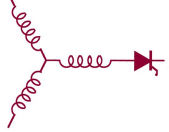




Typical controller structure

Flux vector





Key control variables

Magnitude and Phase angle

- Modulation input
- Inverter output
- Filter inductor current output
- Capacitor voltage output

Key control variables

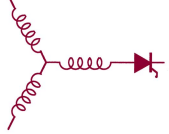
$$m(t) = |m(t)|e^{j\angle m(t)}$$

$$v_i(t) = |v_i(t)|e^{j\angle v_i(t)}$$

$$i_L(t) = |i_L(t)|e^{j\angle i_L(t)}$$

$$v_o(t) = |v_o(t)|e^{j\angle v_o(t)}$$

Instantaneous phase quantities are projections of the rotating vectors on appropriate axes



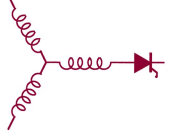
Dynamic Equations

$$L \frac{d}{dt} i_L = v_{dc} |m| \cos(\angle m - \angle i_L) - |v_o| \cos(\angle v_o - \angle i_L)$$

$$L |i_L| \frac{d}{dt} \angle i_L = v_{dc} |m| \sin(\angle m - \angle i_L) - |v_o| \sin(\angle v_o - \angle i_L)$$

$$C \frac{d}{dt} |v_o| = |i_L| \cos(\angle i_L - \angle v_o) - \frac{|v_o|}{R}$$

$$C |v_o| \frac{d}{dt} \angle v_o = |i_L| \sin(\angle i_L - \angle v_o) - \frac{|v_o|}{R}$$



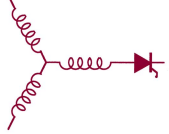
Steady state operating condition

$$0 = V_{dc} |M| \cos(\angle M - \angle I_L) - |V_o| \cos(\angle V_o - \angle I_o)$$

$$L |I_L| \omega = V_{dc} |M| \sin(\angle M - \angle I_L) - |V_o| \sin(\angle V_o - \angle I_L)$$

$$0 = |I_L| \cos(\angle I_L - \angle V_o) - \frac{|V_o|}{R}$$

$$C |V_o| \omega = |I_L| \sin(\angle I_L - \angle V_o) - \frac{|V_o|}{R}$$



Steady state operating condition

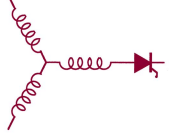
$$0 = V_{dc} |M| \cos(\phi_{mi_L}) - |V_o| \cos \phi_{v_o i_L}$$

$$L |I_L| \omega = V_{dc} |M| \sin \phi_{mi_L} - |V_o| \sin \phi_{v_o i_L}$$

$$0 = |I_L| \cos \phi_{i_L v_o} - \frac{|V_o|}{R}$$

$$C |V_o| \omega = |I_L| \sin \phi_{i_L v_o} - \frac{|V_o|}{R}$$

Classical phasor solution



Small signal model at operating point

$$\dot{x} = Ax + Bu$$

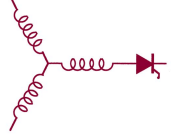
$$y = Ex + Fu$$

$$u = |\tilde{m}|$$

$$x = \begin{bmatrix} |\tilde{i}_L| \\ \angle \tilde{i}_L \\ |\tilde{v}_o| \\ \angle \tilde{v}_o \end{bmatrix}$$

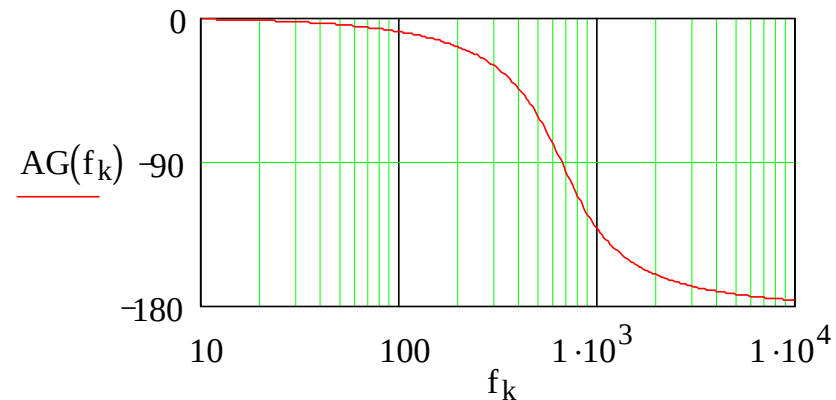
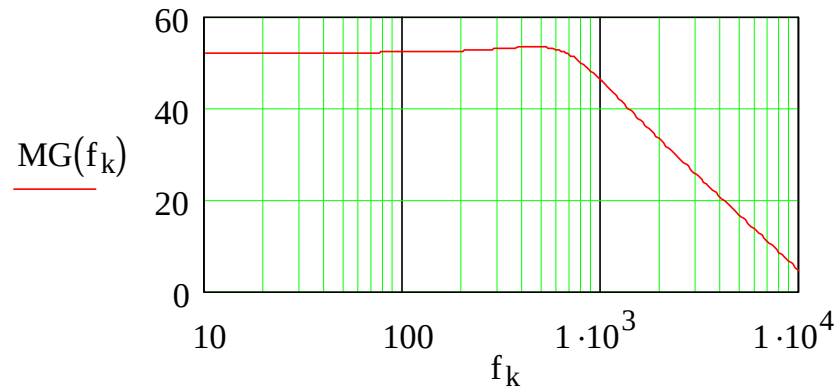
$$A = \begin{bmatrix} 0 & \omega I_L & \frac{-|V_o|}{LR|I_L|} & \frac{-\omega C|V_o|^2}{|I_L|^2 L} \\ \frac{-\omega}{|I_L|} & 0 & \frac{-\omega C|V_o|}{|I_L|^2 L} & \frac{-|V_o|^2}{LR|I_L|^2} \\ \frac{|V_o|}{RC|I_L|} & -\omega|V_o| & \frac{-1}{RC} & \omega|V_o| \\ \frac{\omega}{|I_L|} & \frac{1}{RC} & \frac{-\omega}{|V_o|} & \frac{-1}{RC} \end{bmatrix}$$

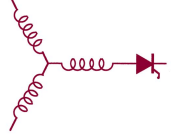
$$B = \begin{bmatrix} \frac{V_{dc} \cos \phi_{mi_L}}{L} \\ \frac{V_{dc} \sin \phi_{mi_L}}{L|I_L|} \\ 0 \\ 0 \end{bmatrix}$$



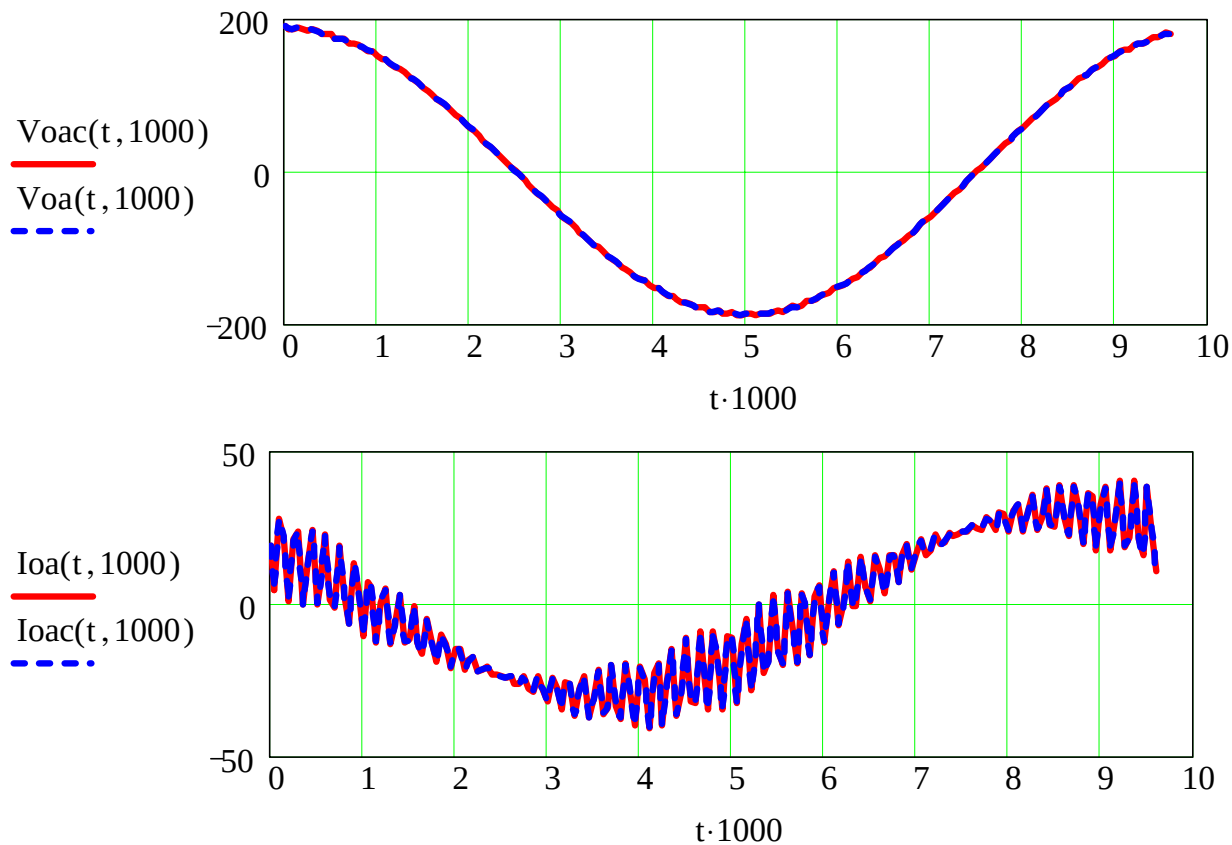
Transfer function

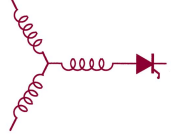
- Magnitude of modulation to output voltage



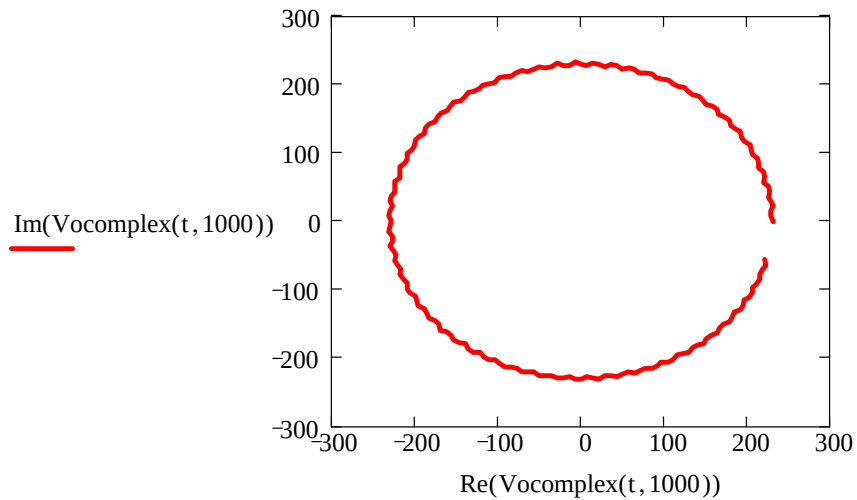


Perturbations in time domain

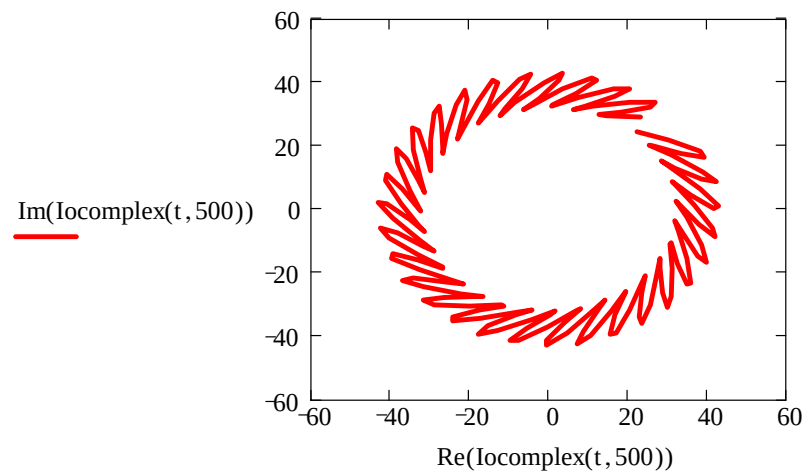


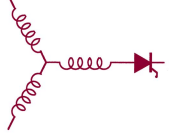


Vectors on the Complex Plane



Output current complex vector





Properties of the dynamic model

Eigen frequencies of small signal model

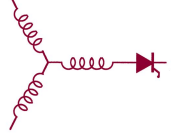
$$\begin{pmatrix} -313.396 + 629.17i \\ -313.396 - 629.17i \\ -313.396 + 509.17i \\ -313.396 - 509.17i \end{pmatrix}$$

Eigen frequencies of LC filter = 569 Hz
(incl. damping effects)

Excitation frequency = 60 Hz

Dynamic interaction issues

- Angle input to output transfer functions
- Cross coupling transfer functions
- Selection of controllers and tuning
- Outer loop effects (Real and reactive power, droop, etc.)
- Frequency synchronization
- Interactions between multiple parallel units
- EMI filter interactions



Summary

- Inverter modeling important aspect of microgrid design
- Stiff dc bus with adequate storage decouples prime mover dynamics
- Inverter dynamic model based on rotating vectors
- Model reduces to phasor model at steady state
- Small signal model properties outlined
- Various transfer functions can be determined, (esp. angle and frequency)
- Extend and integrate into system models

Operation and Control of Micro-Grids

Robert H. Lasseter
University of Wisconsin

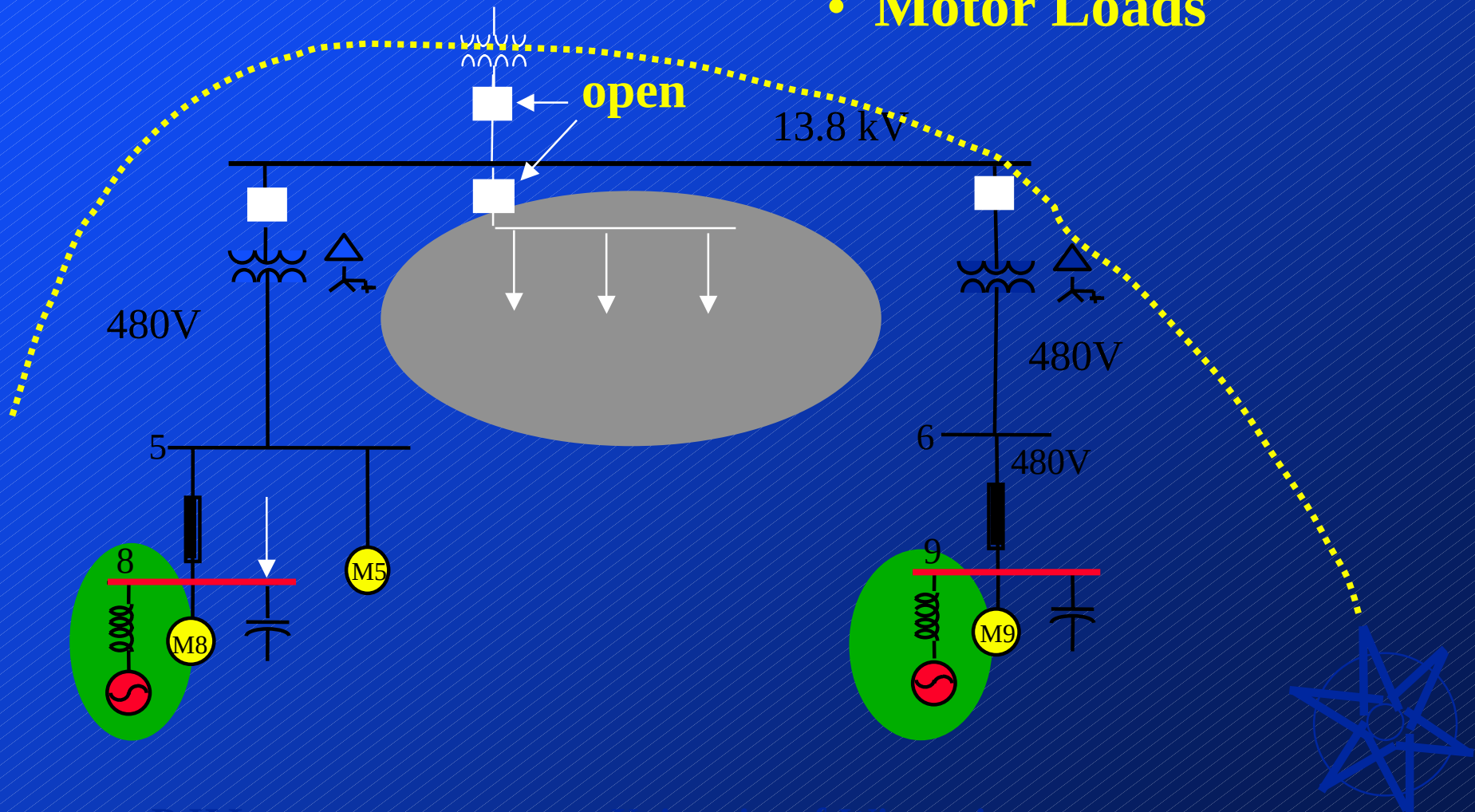


Micro-grid concept assumes:

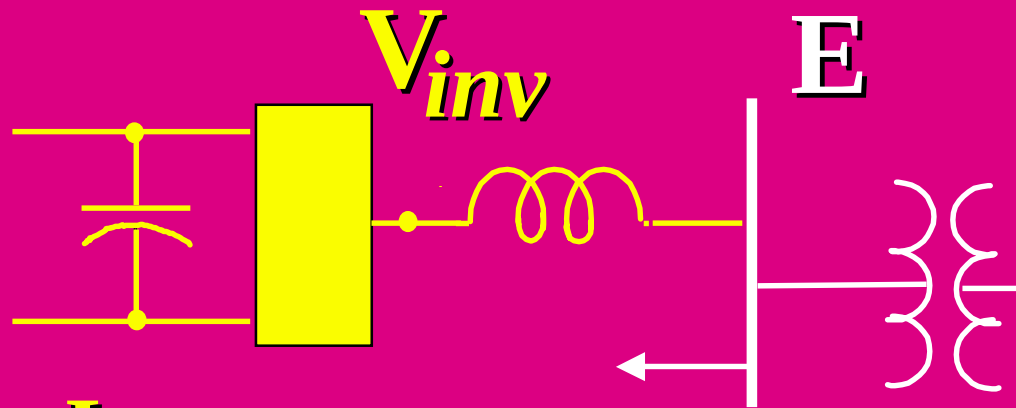
- Large clusters of micro-sources and storage systems
- Close to loads with possible CHP applications
- Customer Quality of Power
- Presented to the grid as a single controllable unit (load & source)

Micro Grid

- Solid state breaker
- **Generation & storage**
- **Motor Loads**



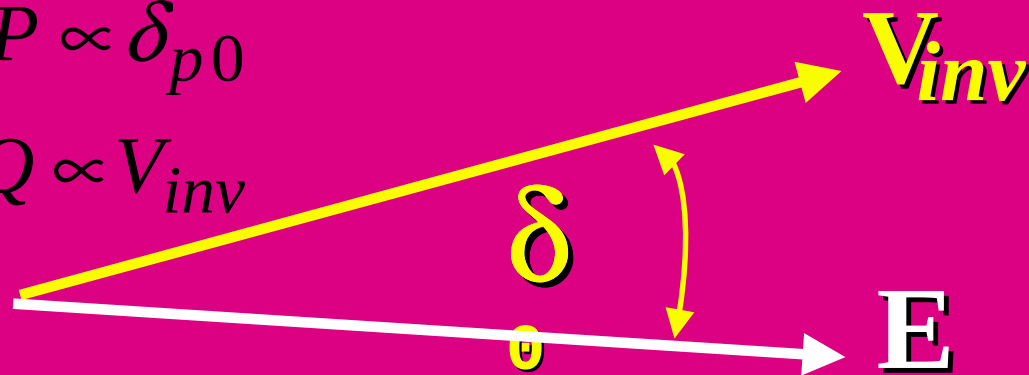
Control of P & Q using PWM Inverters



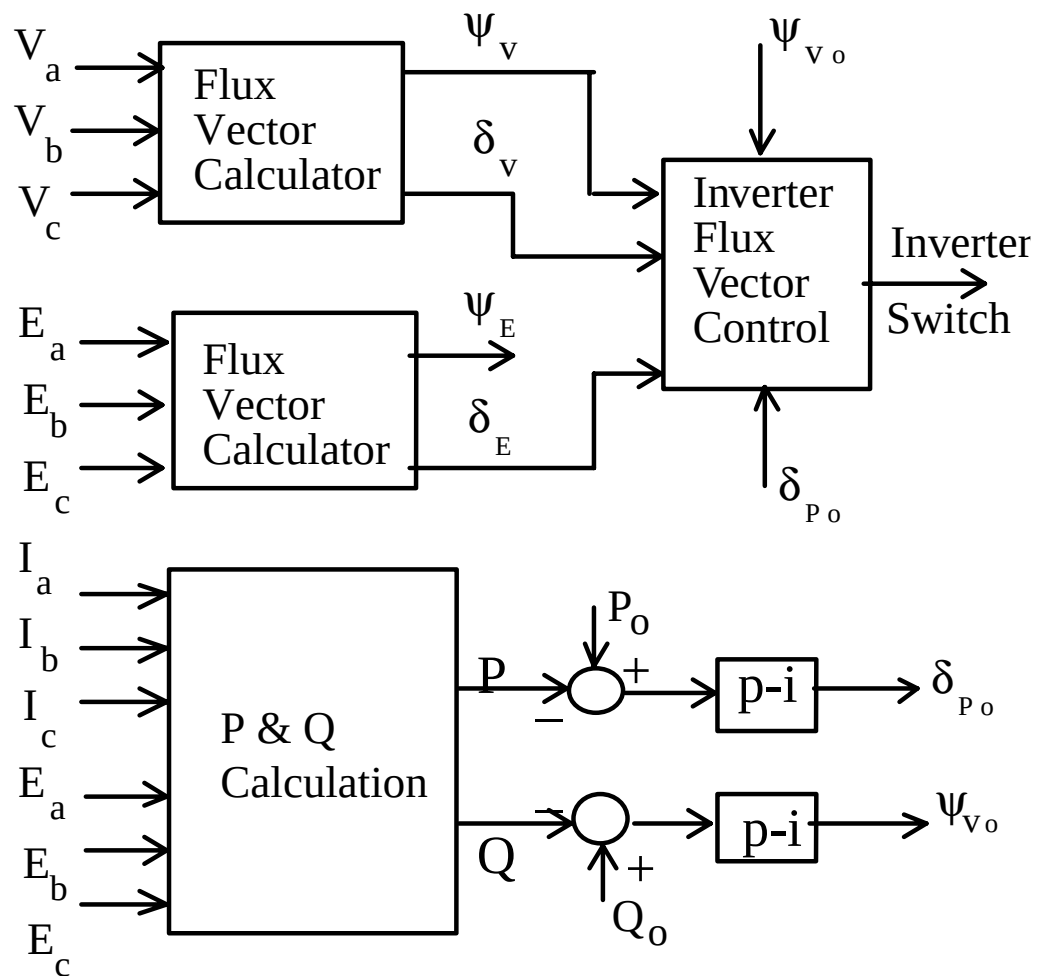
Inverter

$$P \propto \delta_{p0}$$

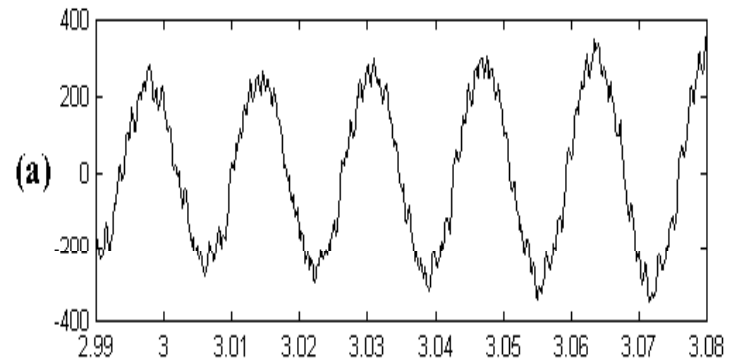
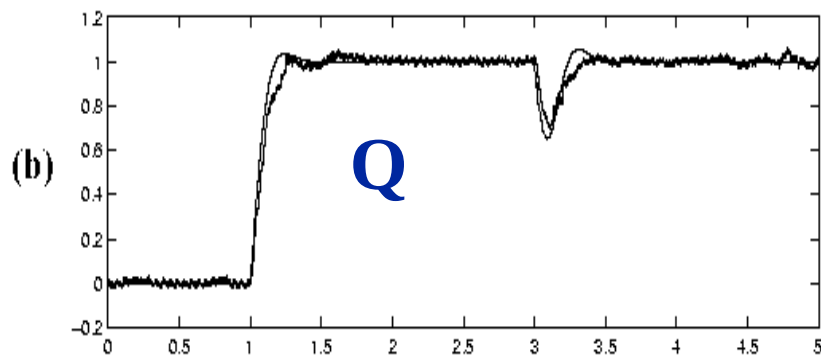
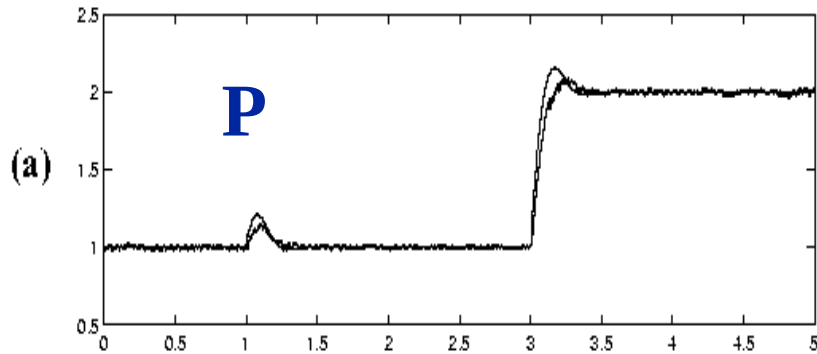
$$Q \propto V_{inv}$$



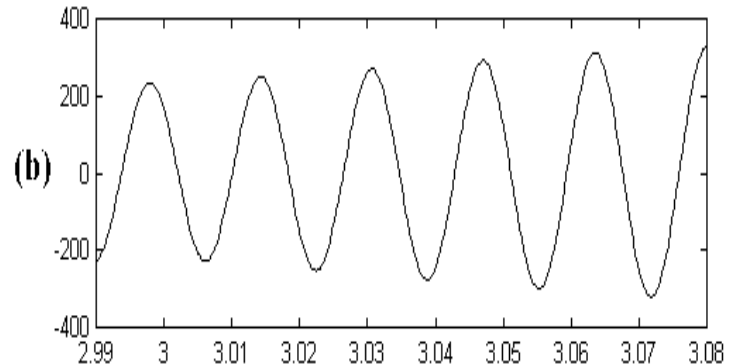
Basic P Q Controller



Basic P & Q Response



Current



Micro Grid connected to T/D Grid

Micro-Sources Provide

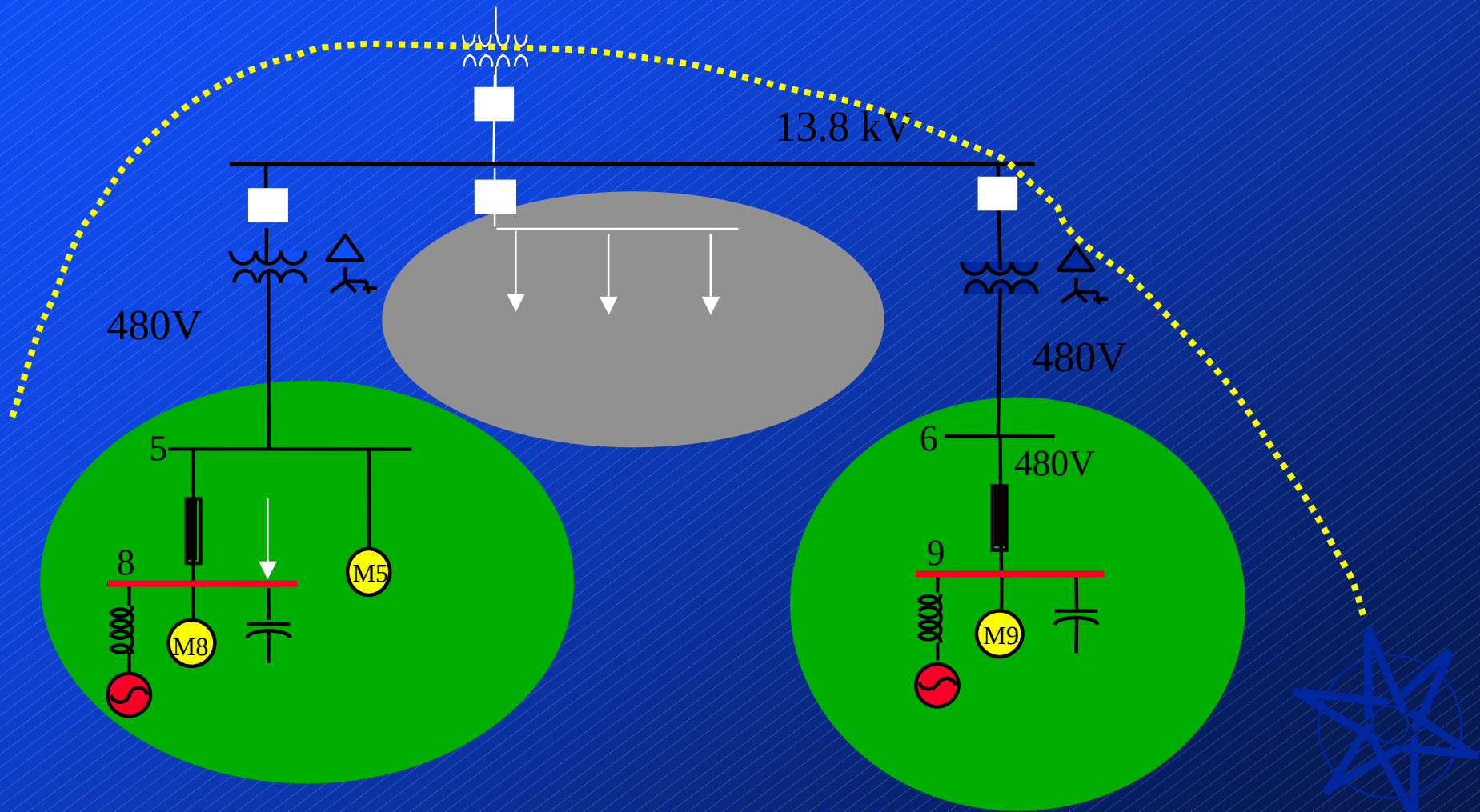
- Control of local bus voltage
- Control of base power flow

Fast Load tracking is provided by the grid

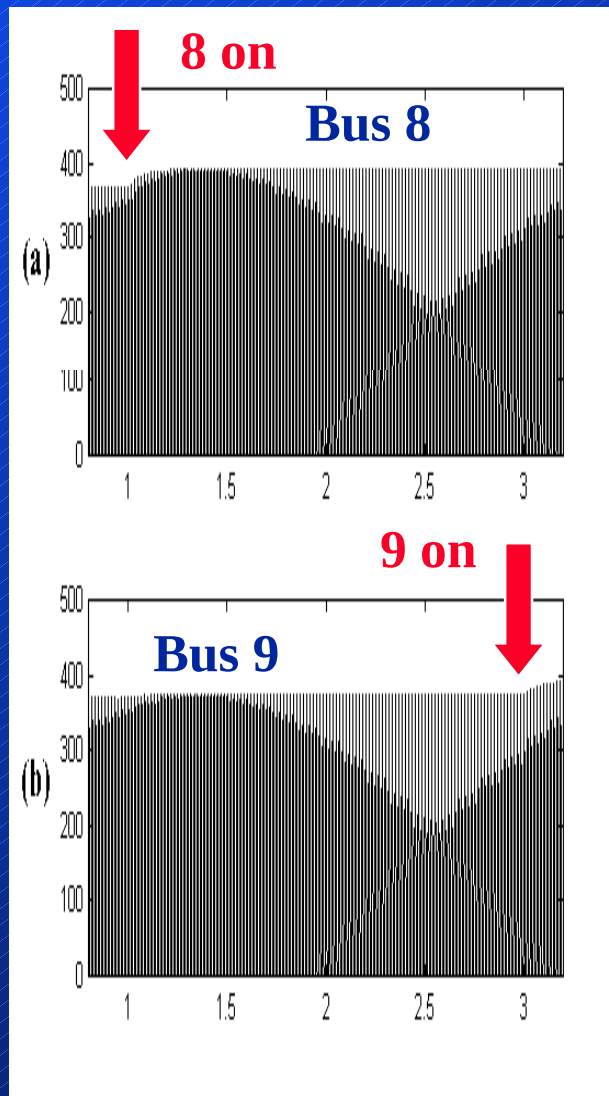
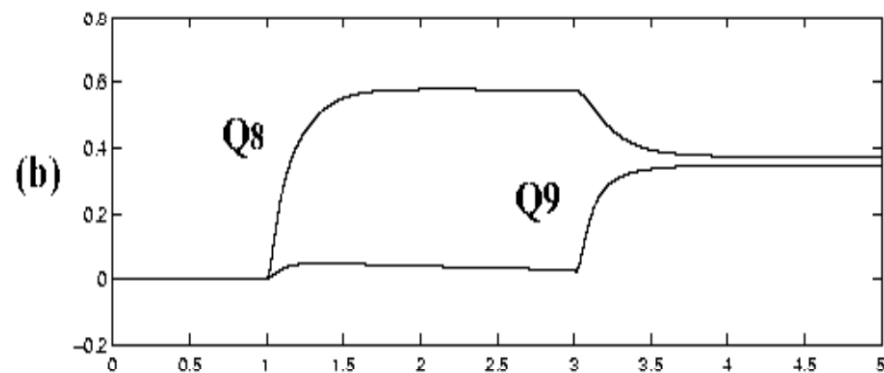
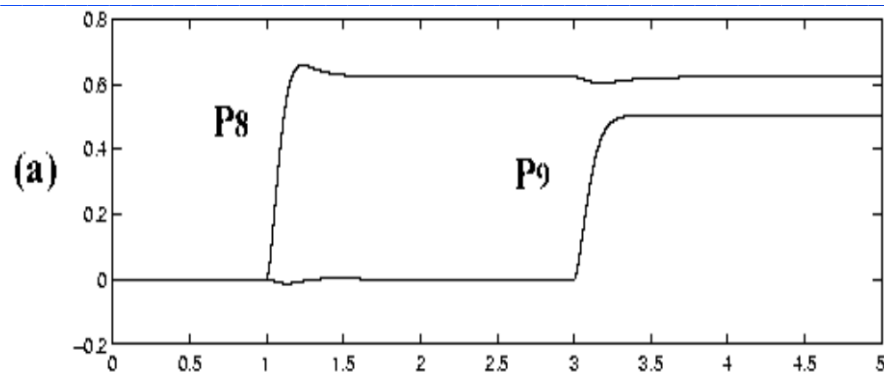
Micro Grid: Dispatchable load to the grid

Micro Grid

- P control
- V control of 8 & 9



P V controller



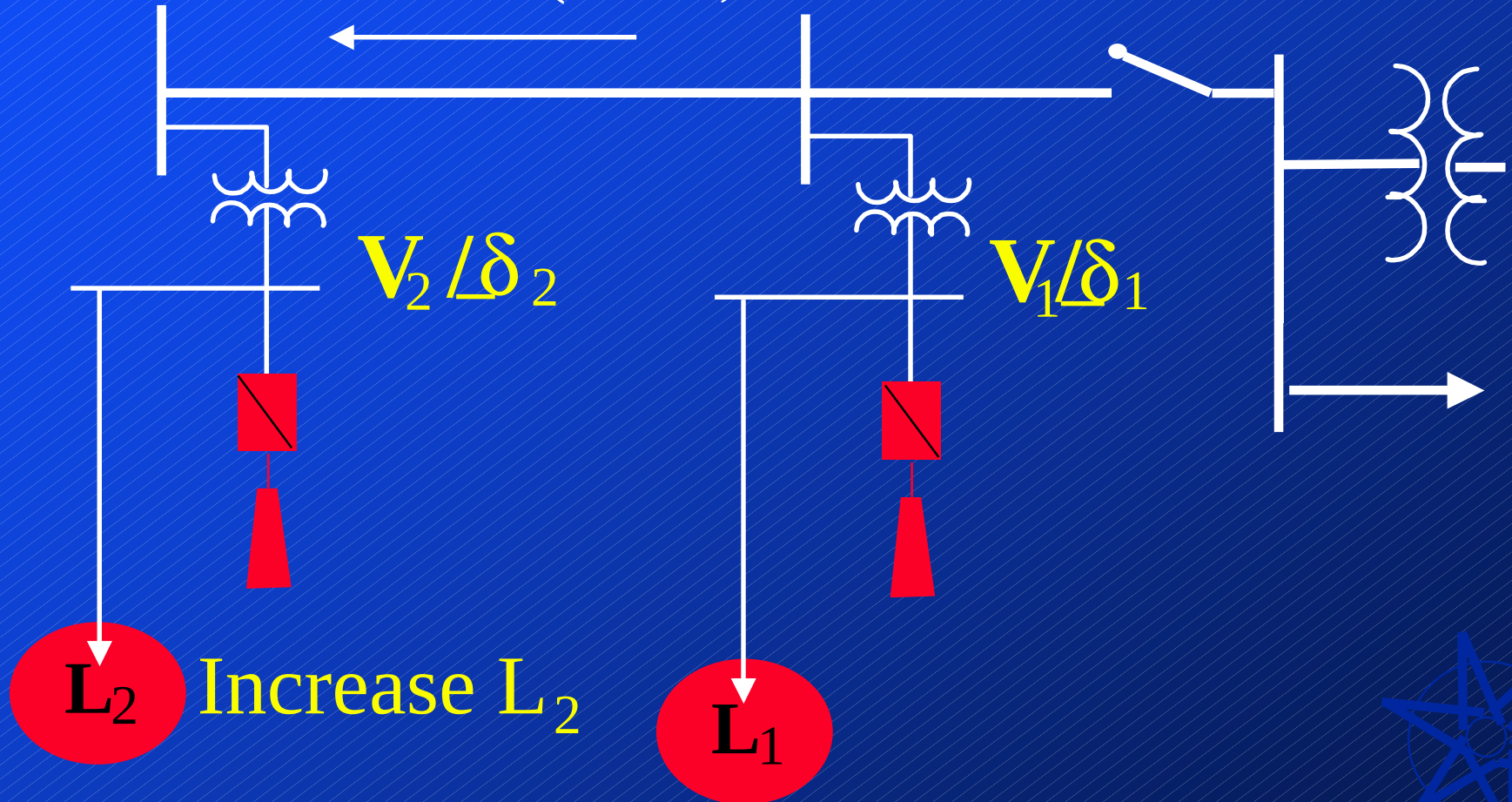
Isolated Micro Grid

Issues

- **Instantaneous power balance**
 - **Use storage on dc bus**
 - Storage on the ac bus
 - Include rotating machines in Micro-grid
- **Load Sharing**
- **Frequency Control**

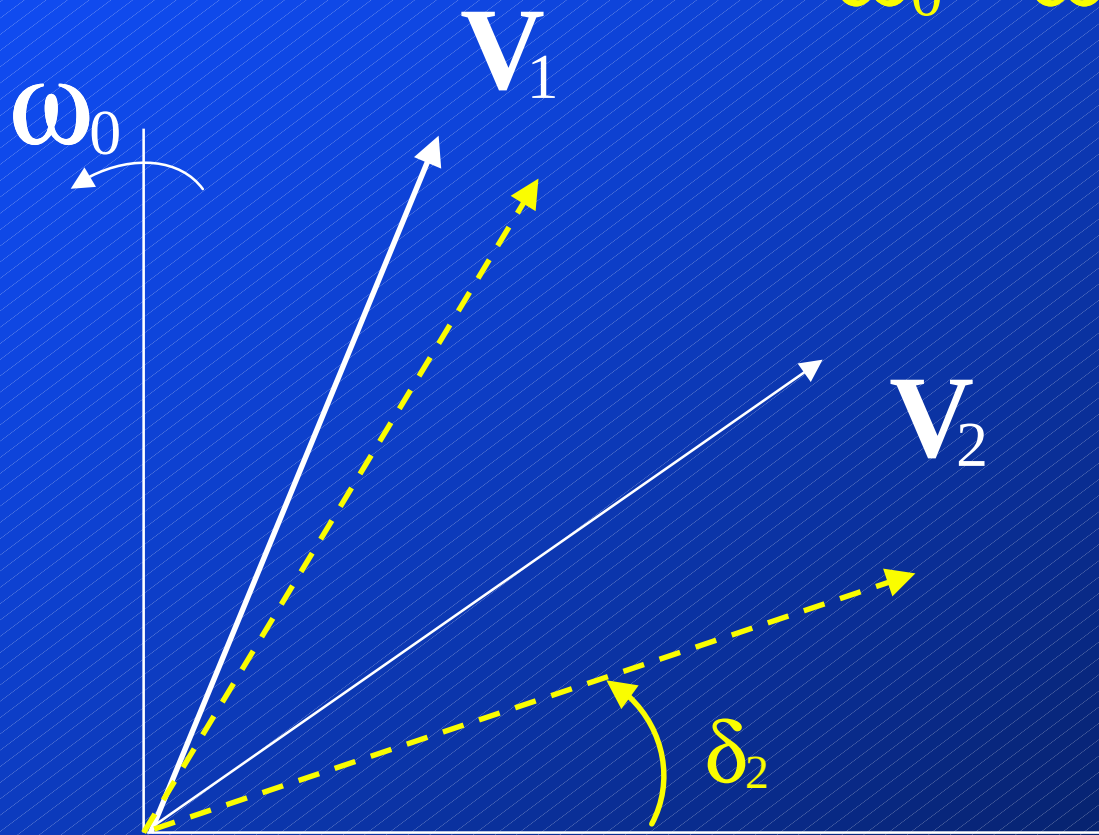
Island System

$$P \sim \sin(\delta_1 - \delta_2)$$

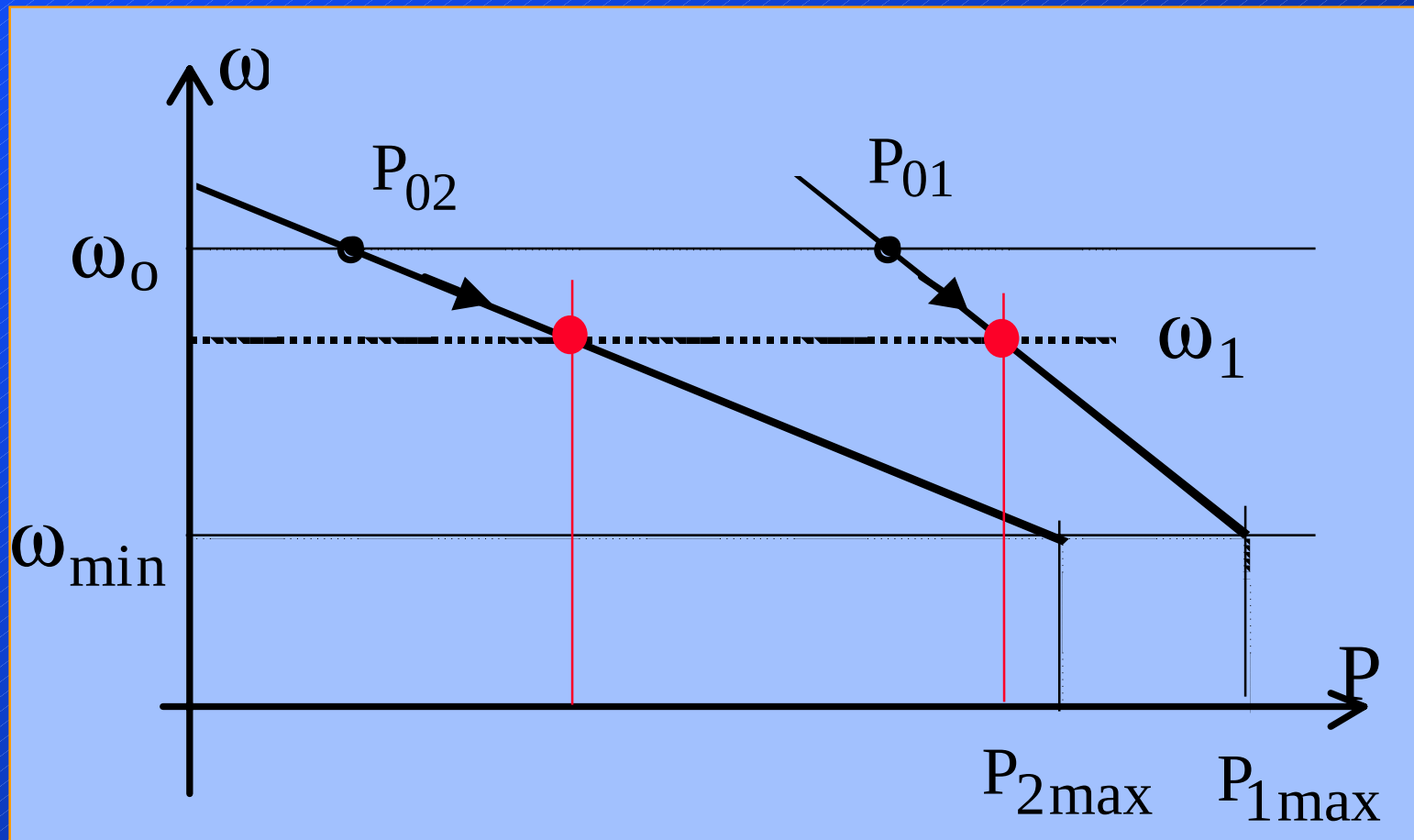


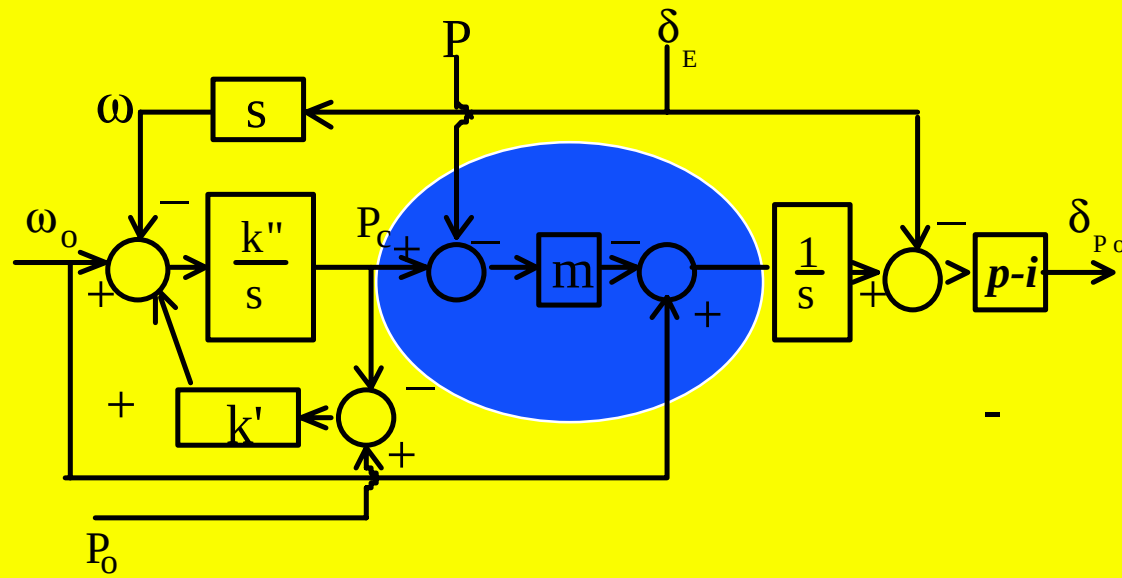
$$P \sim \sin(\delta_1 - \delta_2)$$

$$\omega_0 > \omega_1 > \omega_2$$

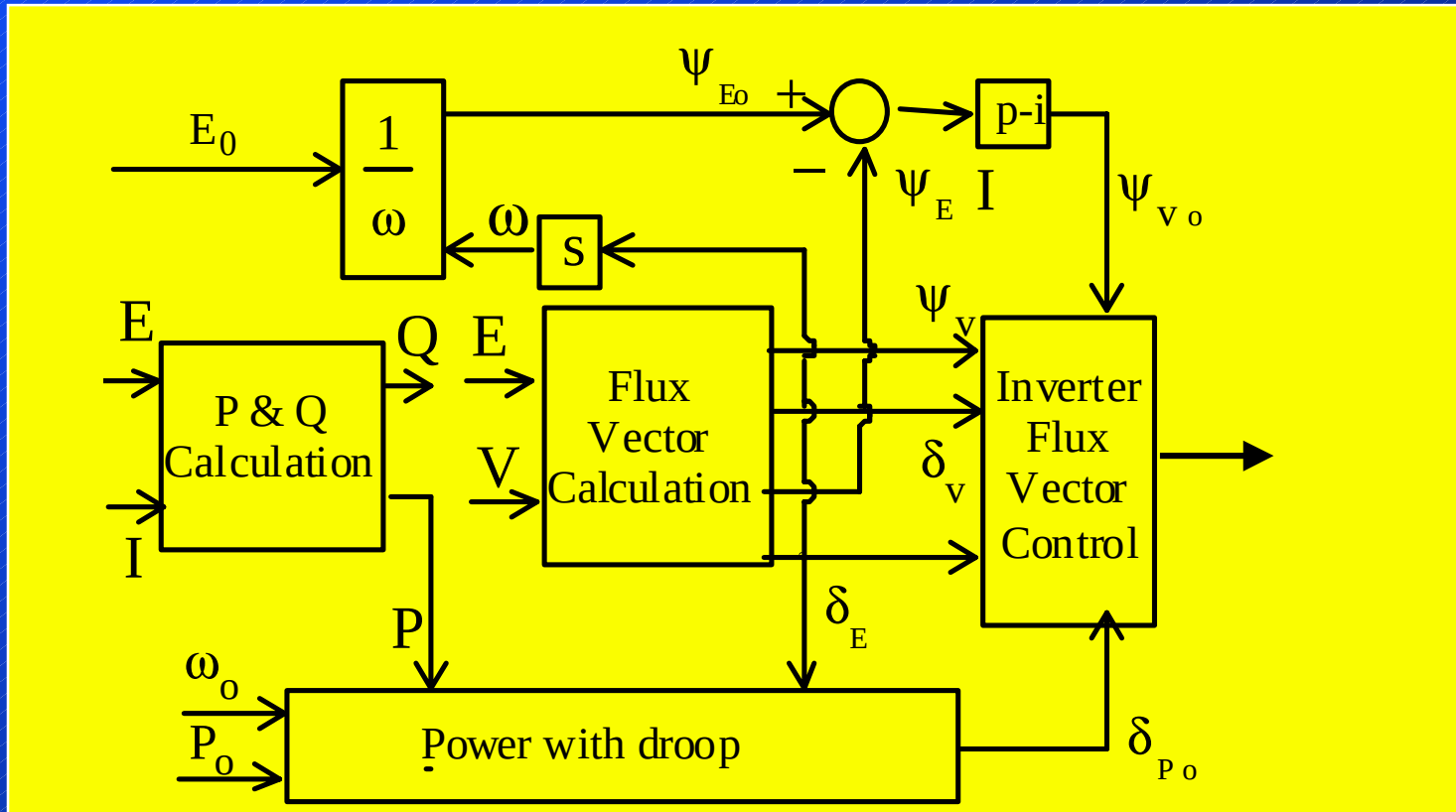


Frequency Droop



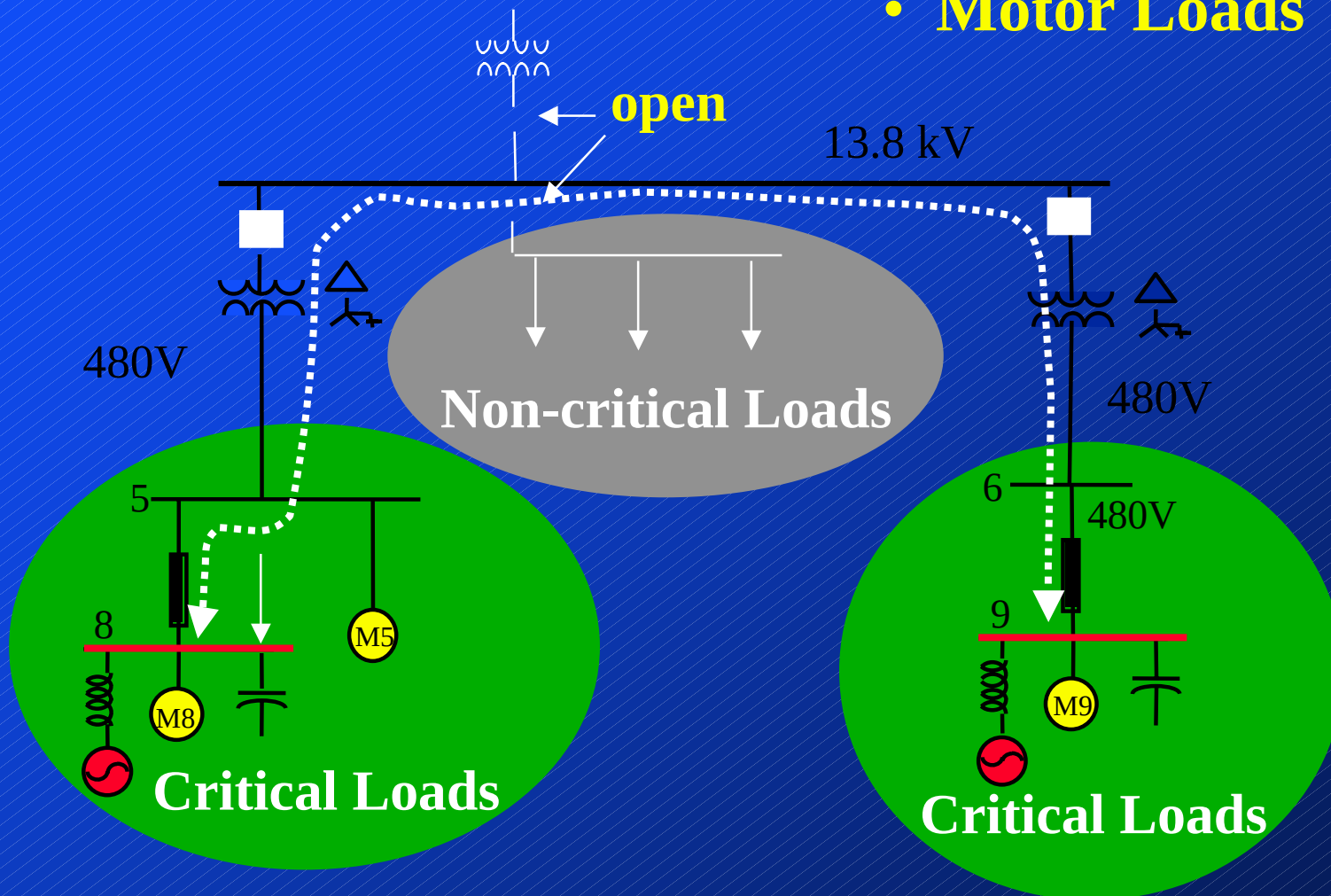


P V Controller with Droop

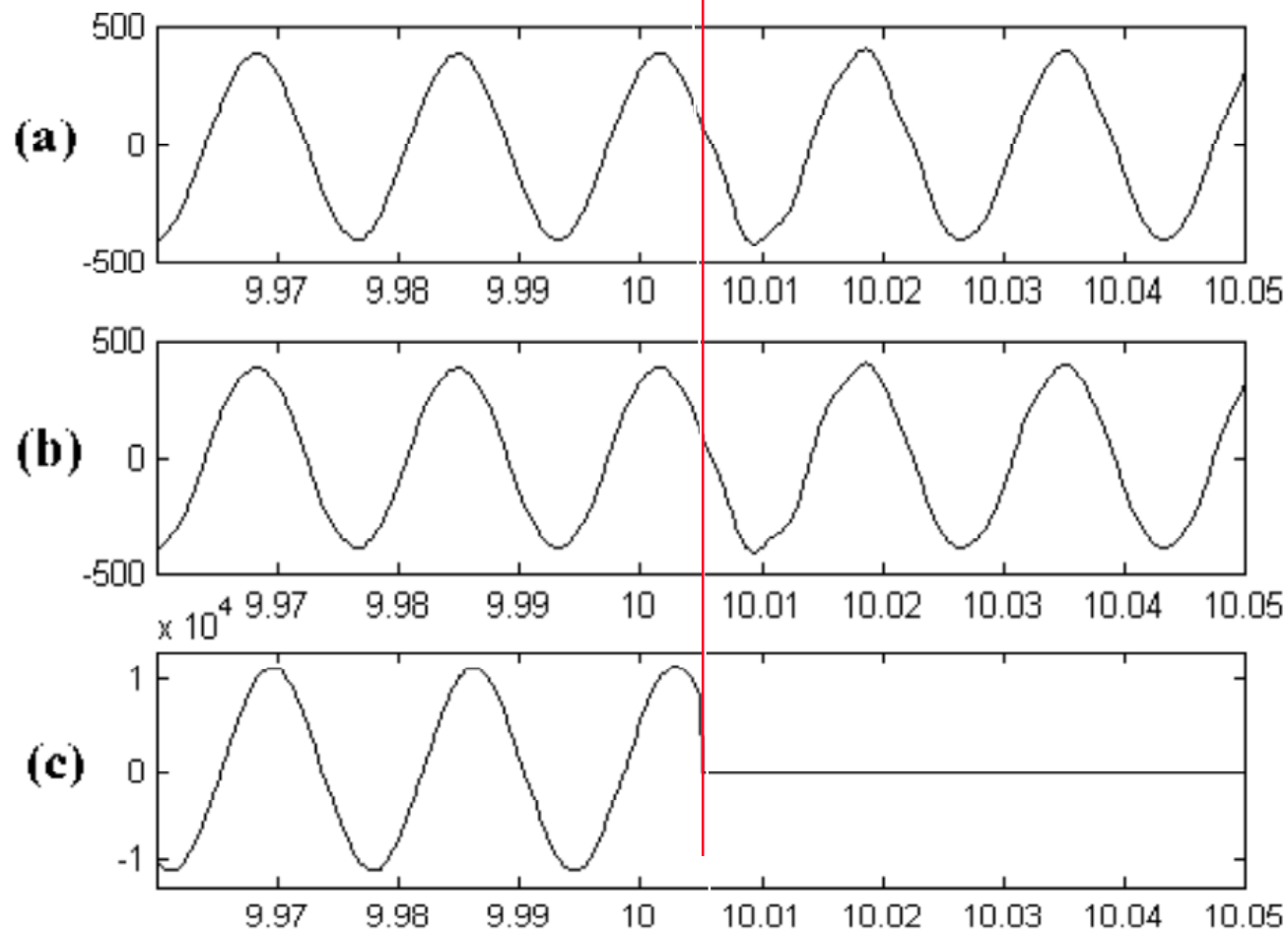


Island Micro Grid

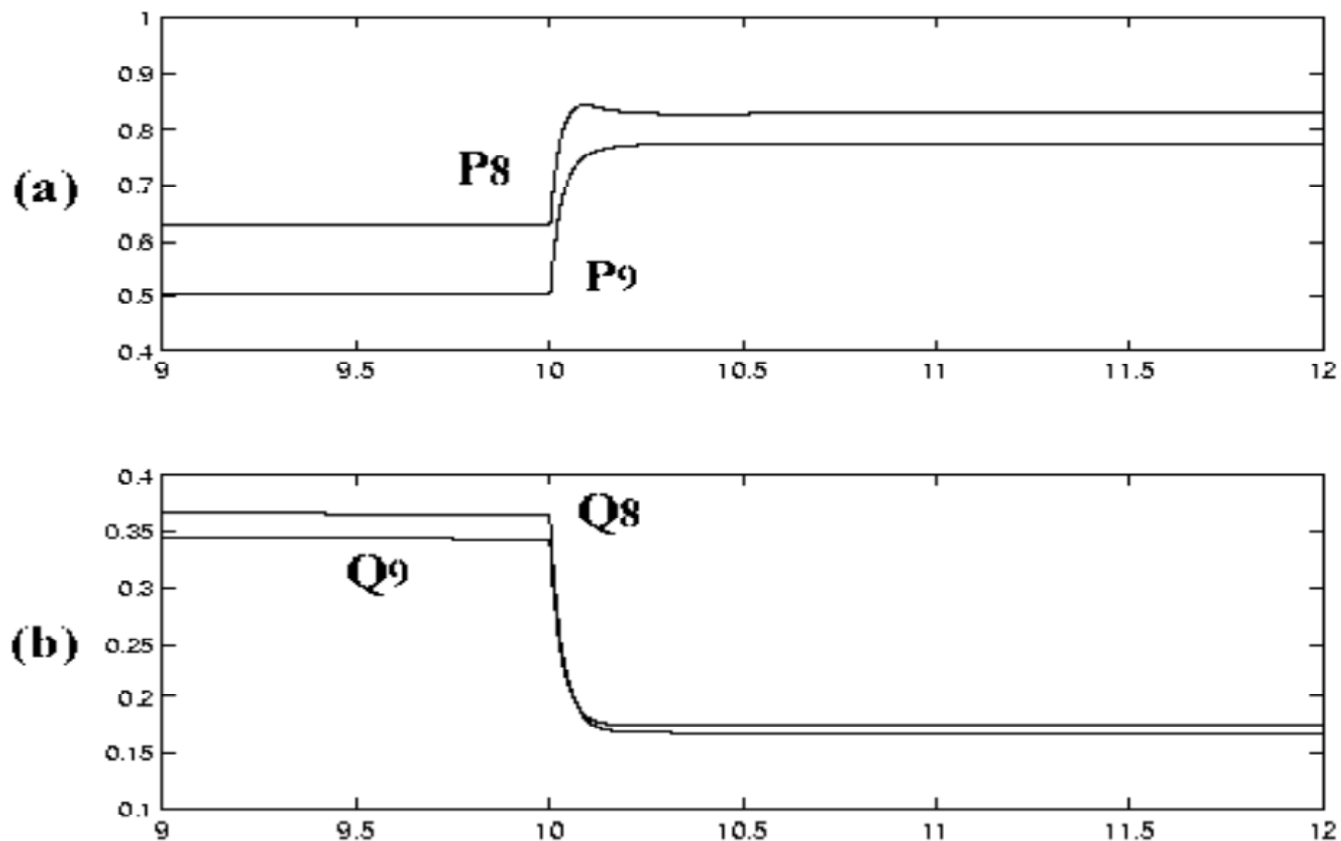
- Solid state breaker
- **Generation & storage**
- **Motor Loads**



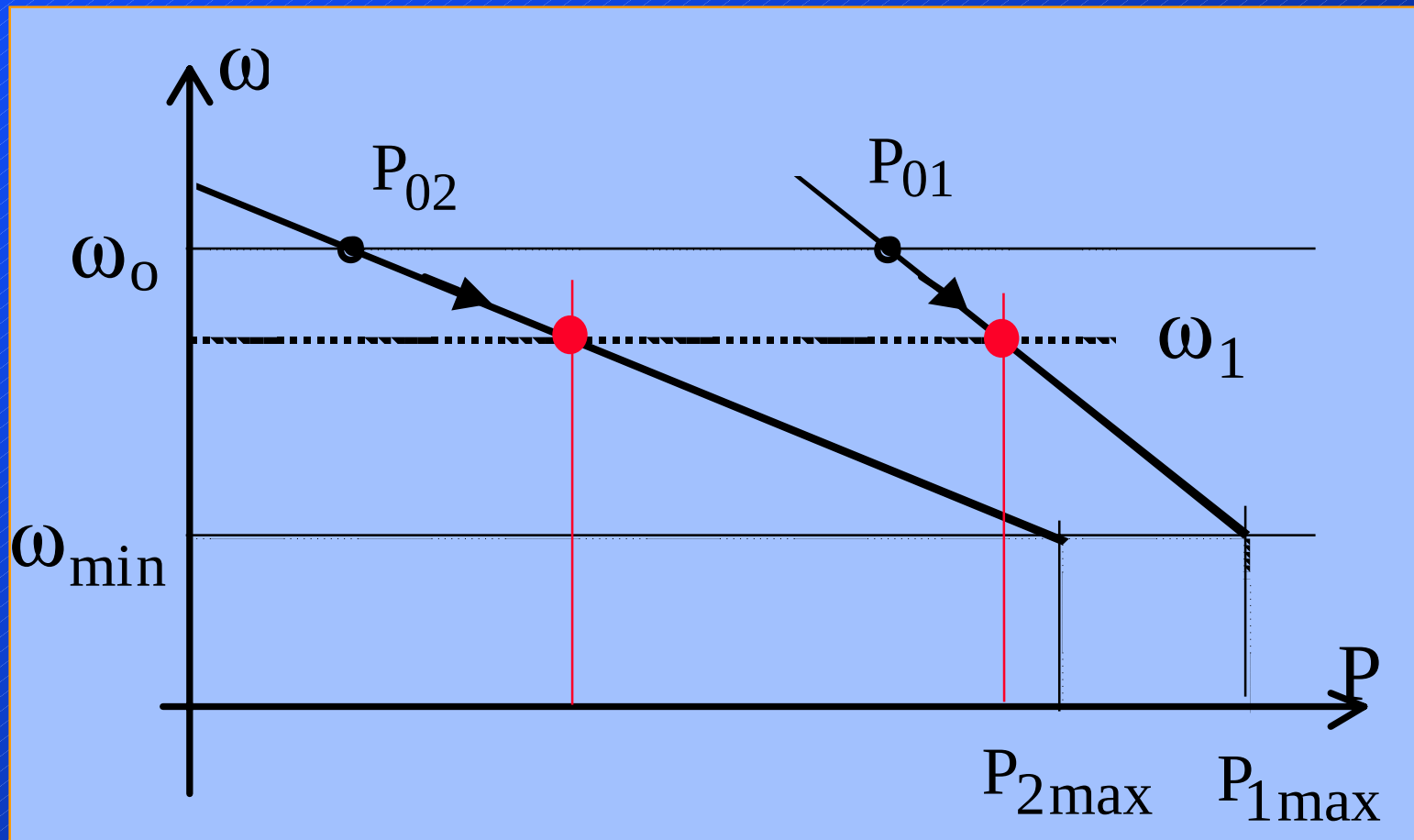
Voltage on Buses 8 & 9



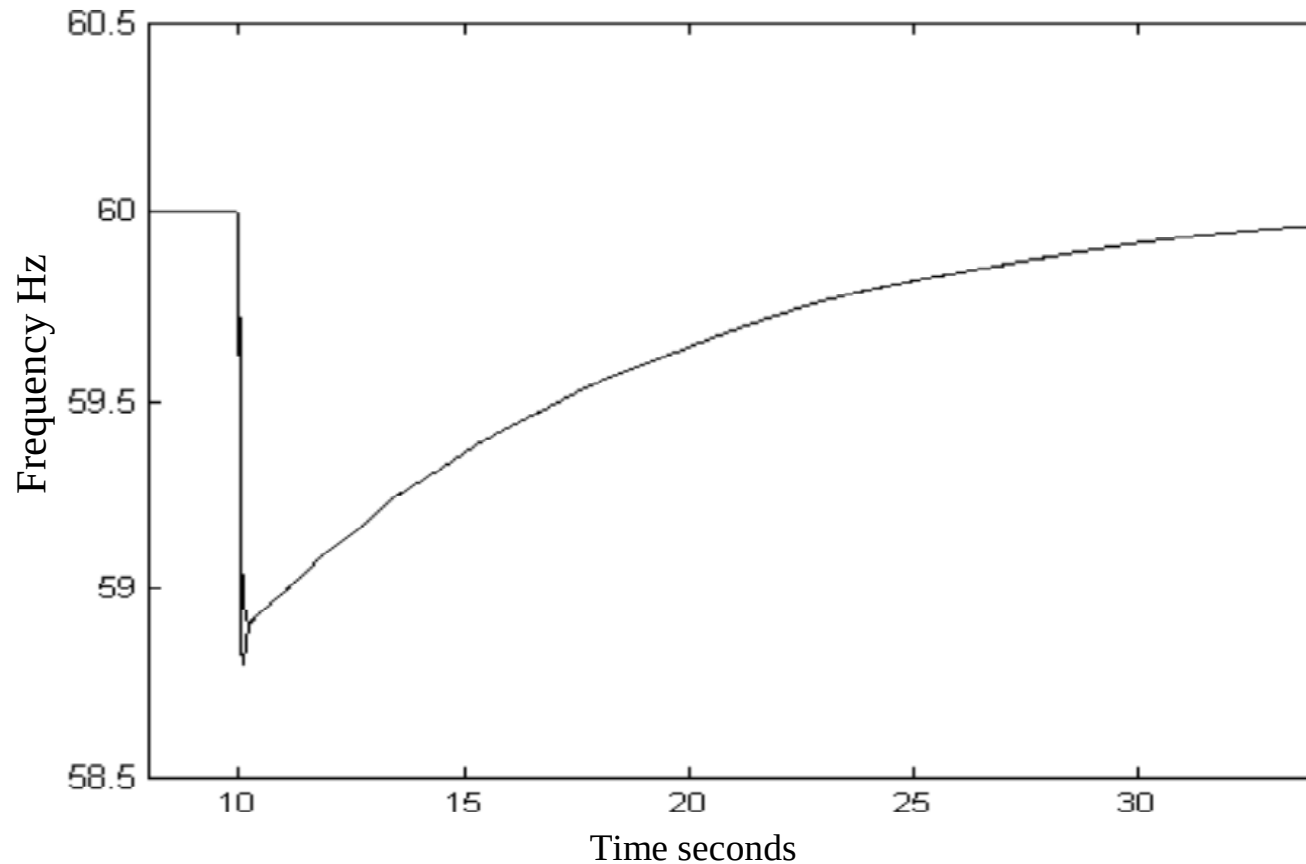
Injected P & Q Buses 8 & 9



Frequency Droop



Frequency at bus 8



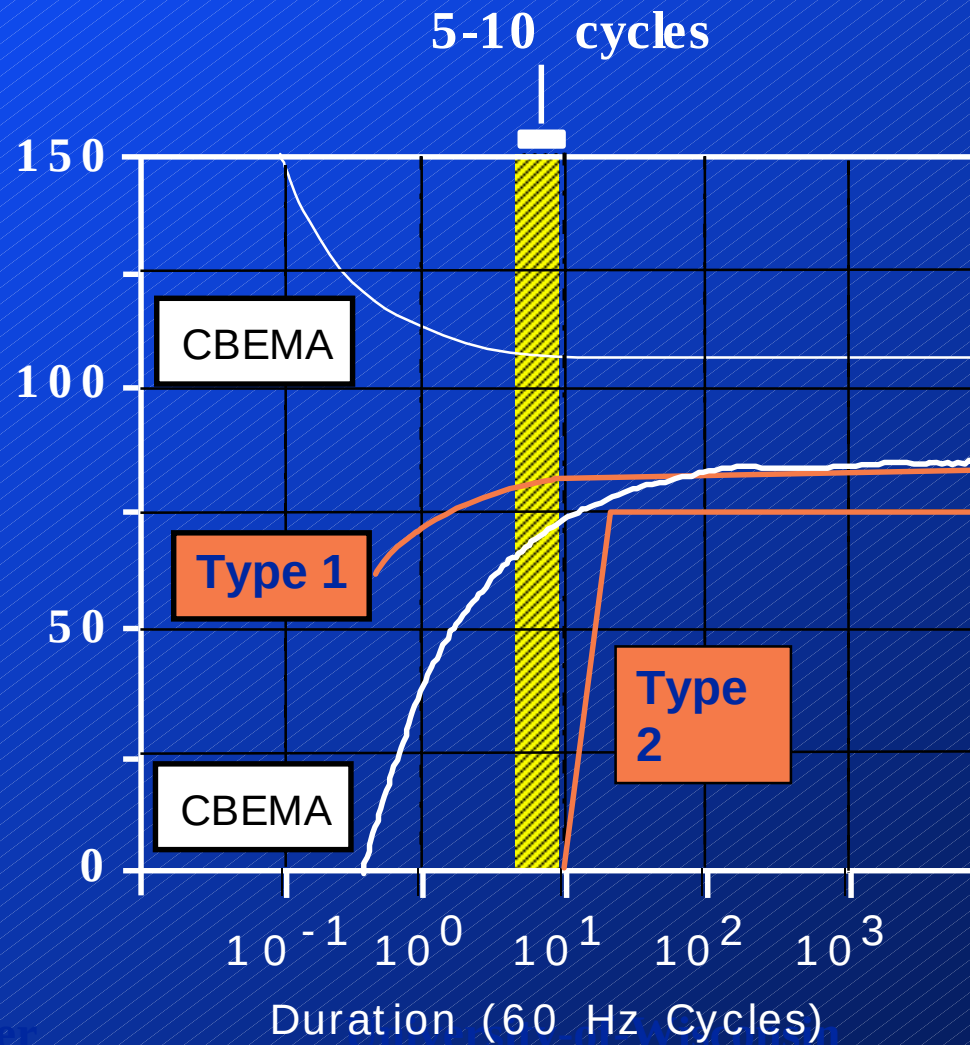
Sensitive loads

(Quality & Service)

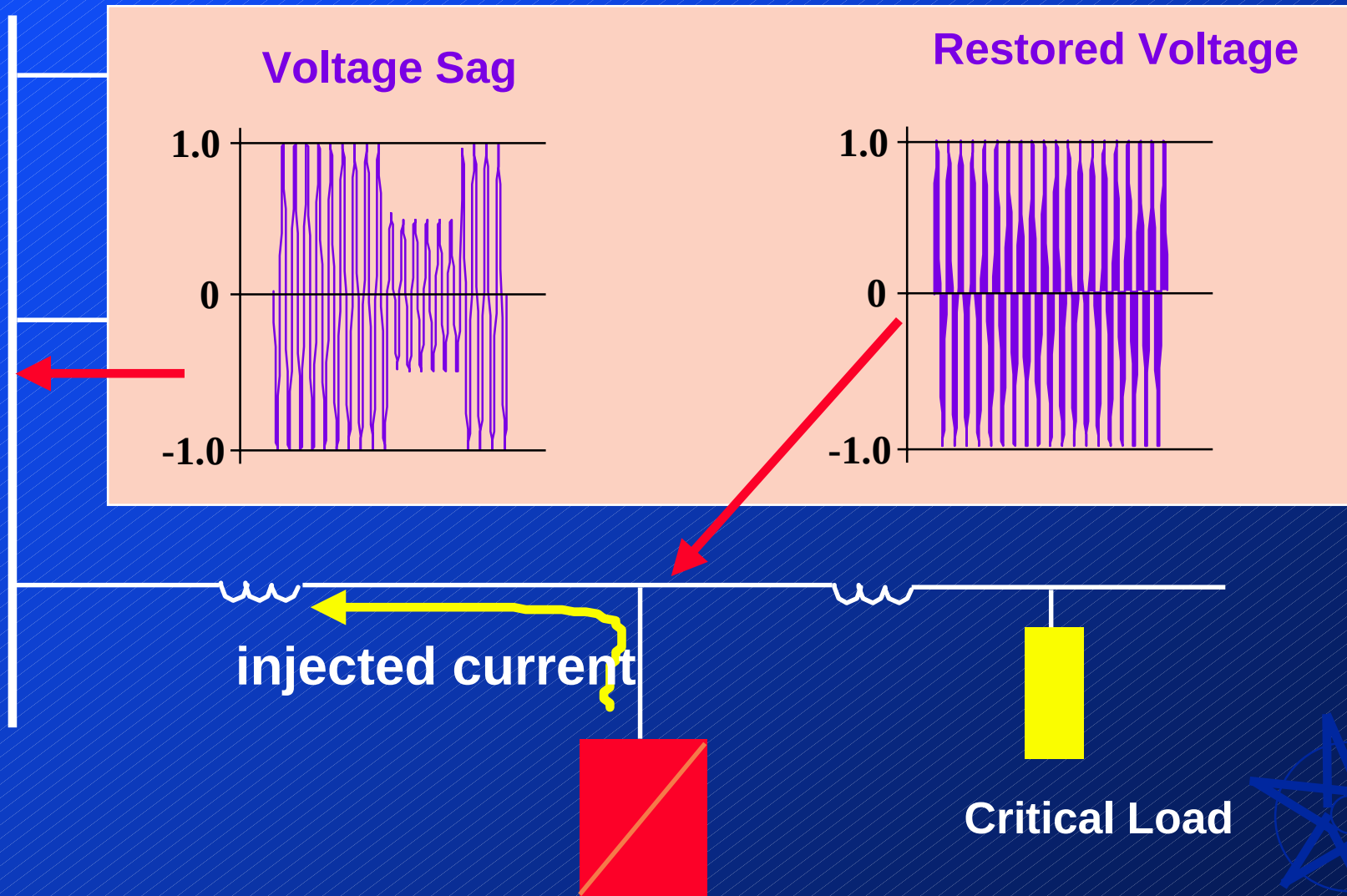
Power Quality is the attribute of electric power which enables utility customers' electrical and electronic equipment to operate as intended



Voltage Sensitivity

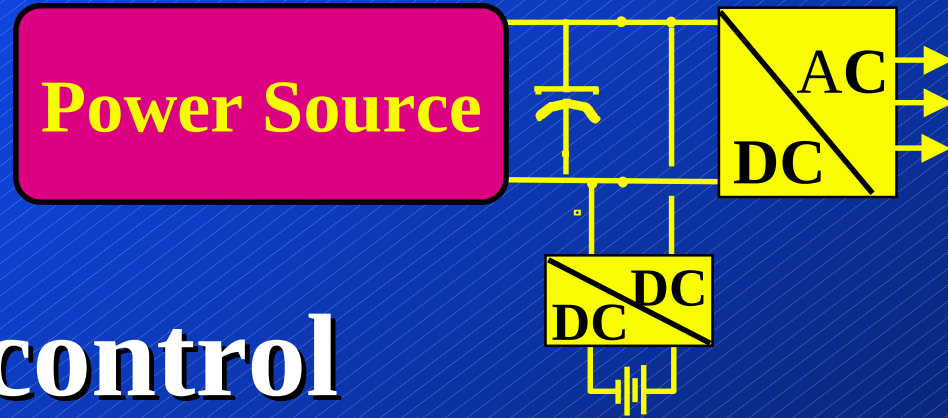


Shunt current injection

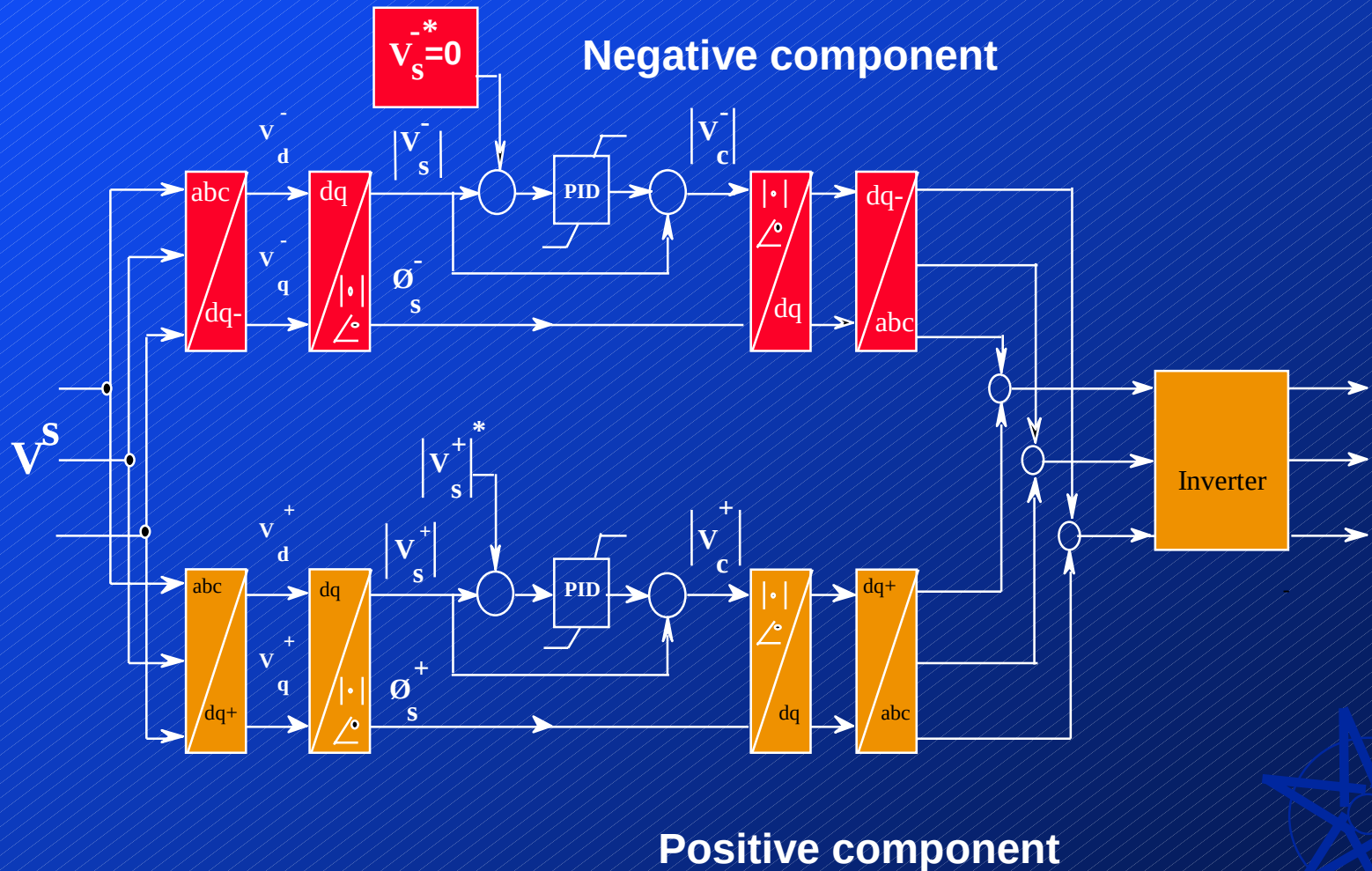


Premium Power Micro Source

- Power
- UPS
- Voltage control
unbalance
frequency



Voltage Sag Regulator



Inverter Response to SLG



Micro Grids & Premium Power

- **Generation Close to loads**
 - Local reliability
 - Possible CHP applications
- **Premium Power**
 - UPS functions
 - Back-up service
 - Custom Power functions

Research Needs

1. Clear interfaces/functions to the Grid
2. Micro-Grid protection
3. Plug & play controls
4. Placement tools including CHP.