Simulation of MicroGrids and V2G

Sakis Meliopoulos
Professor, Georgia Institute of Technology
Email: sakis.m@gatech.edu

4th International Conference on
Integration of Renewable and Distributed Energy Resources
December 6-10, 2010
Albuquerque, NM, USA

Conference Sponsors

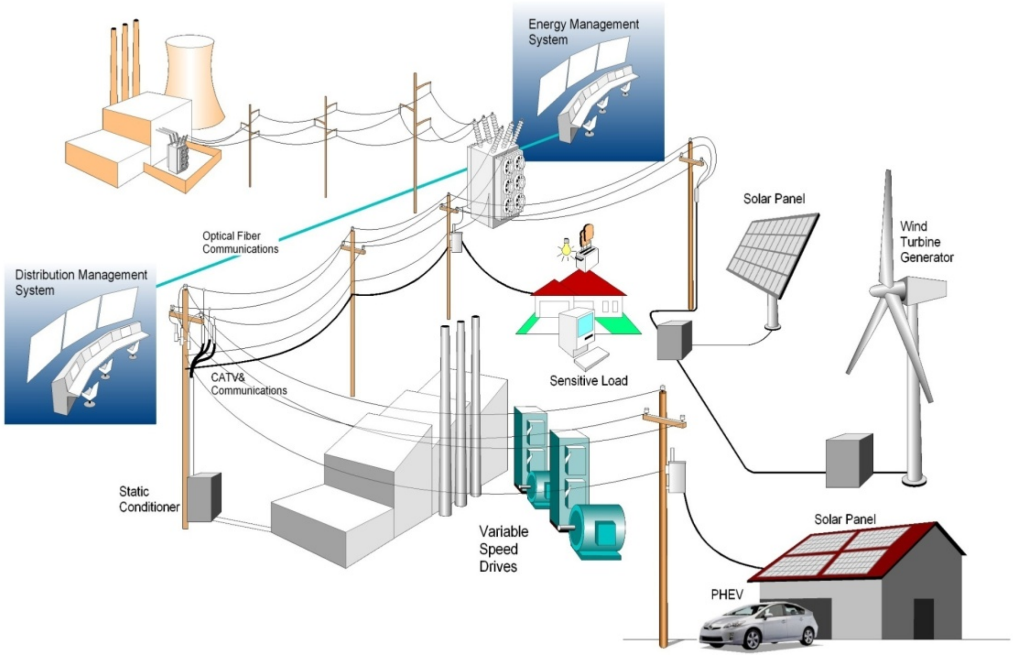
EPRI ELECTRIC POWER RESEARCH INSTITUTE
Sandia National Laboratories
Natural Resources Canada
PNM
SEPA solar electric power association

Associate Sponsors

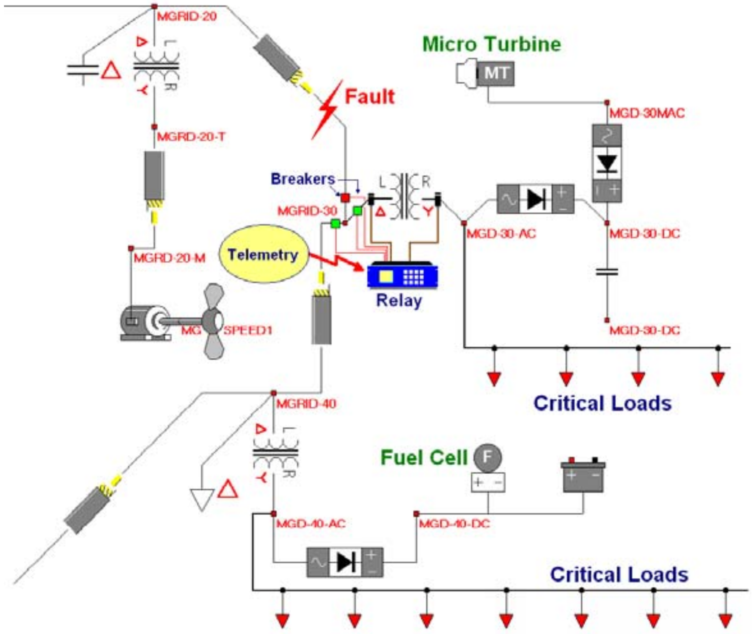
DERlab
NEDO

Introduction: What is a μGrid?

Technical and Market Forces Shape the μGrid Concept:



Initial DoE μGrid Concept:

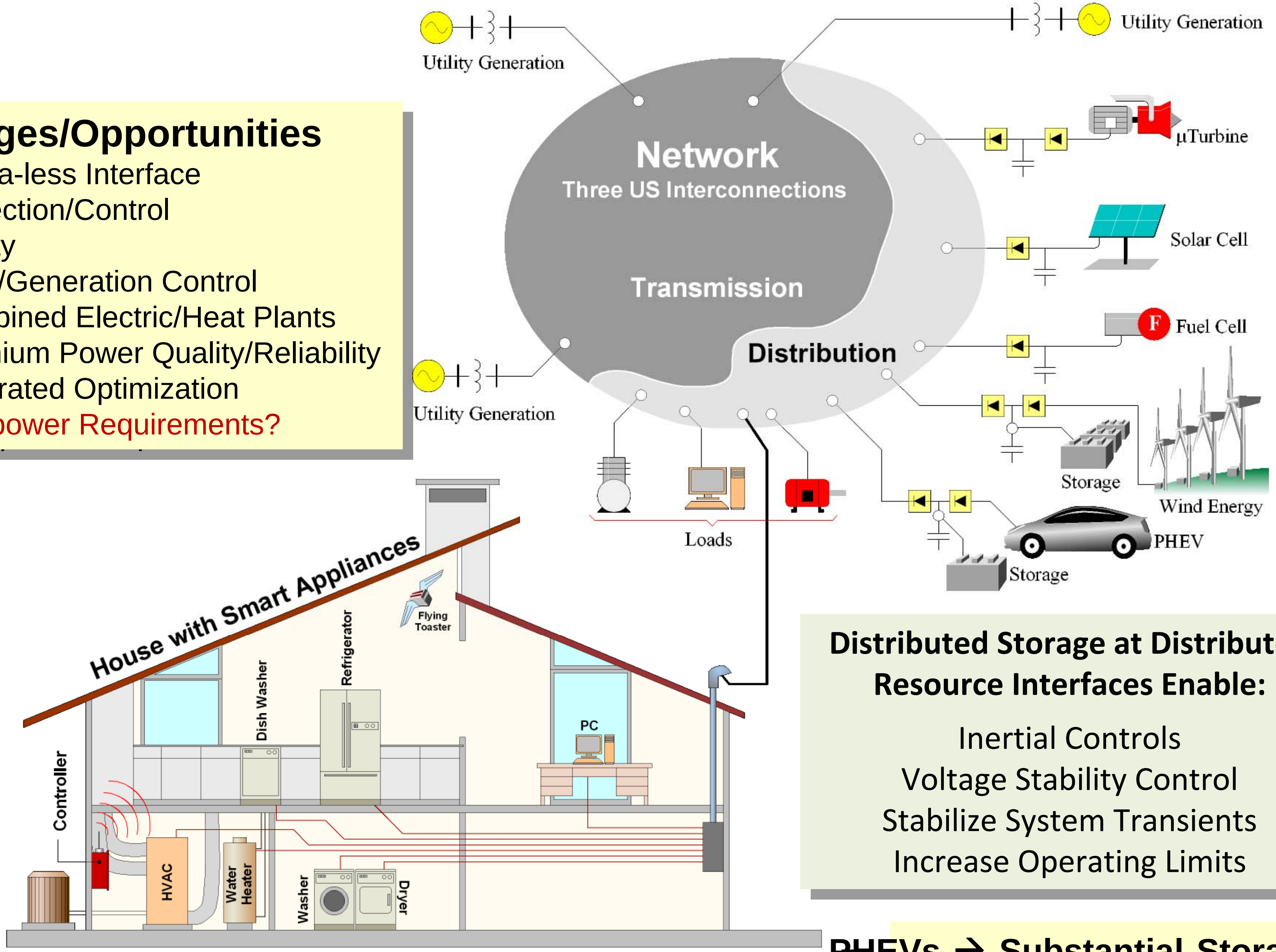


- Renewables and Storage Technologies Enable an “Active” Power Distribution System: optimization and assistance in emergencies.
- Characteristics of Renewables, PHEVs and other Resources Can Determine their Economics (and add-on value)

μGrid ← → Active Distribution Systems

Challenges/Opportunities

- Inertia-less Interface
- Protection/Control
- Safety
- Load/Generation Control
- Combined Electric/Heat Plants
- Premium Power Quality/Reliability
- Integrated Optimization
- Manpower Requirements?

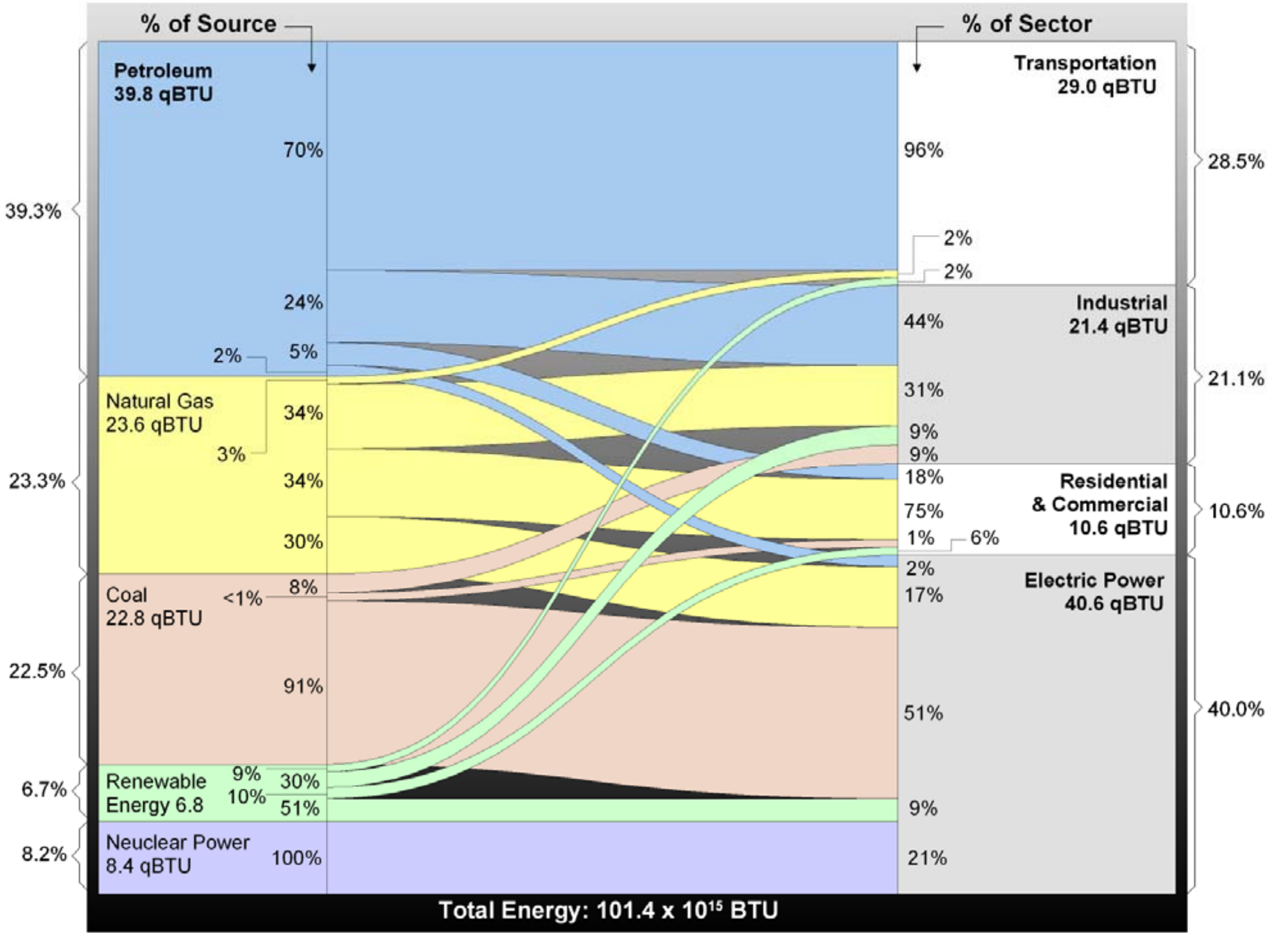


Distributed Storage at Distributed Resource Interfaces Enable:

Inertial Controls
Voltage Stability Control
Stabilize System Transients
Increase Operating Limits

PHEVs → Substantial Storage Resource

The Big Picture – Energy Utilization in 2007 (US DoE)



Observations

Twenty Years Ago the Energy Consumption in the Form of Electric Power was about 30% of total Energy Consumption.

In 2007 it stood at 40%.

What will be in the Future? (50% electrification of the transportation industry will bring it to 54%)

Transportation
Overall Efficiencies:
15%

Electric Sector
Overall Efficiencies:
30%

Dependence on Oil is a National Security Issue

Analysis and Simulation Needs

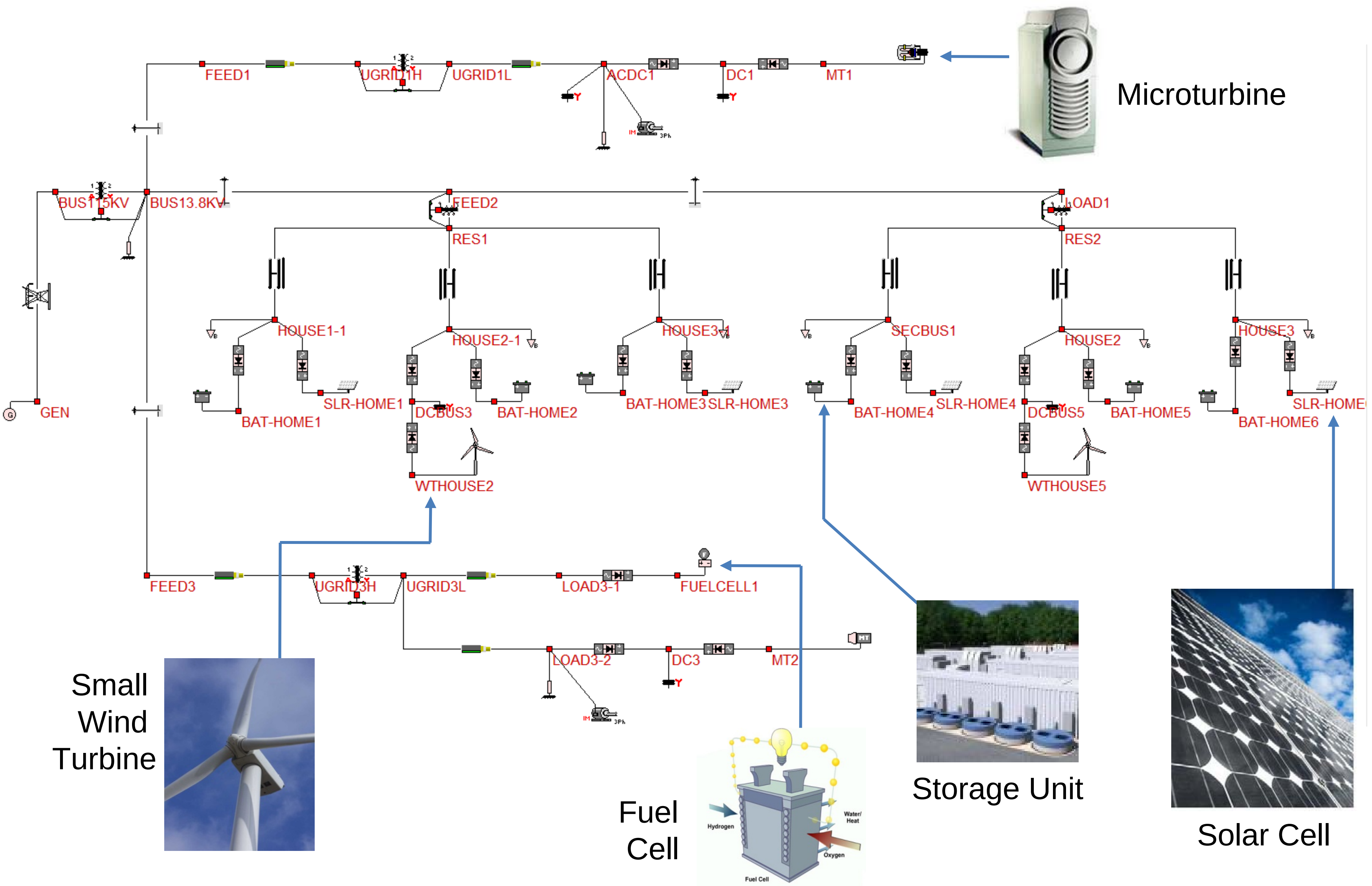
(T&D Integration Issues)

- Protection and Control
- Disturbance Ride Through Capabilities
- Safety Issues (NFPA, NEC, IEEE NESC is it enough?, WinIGS)
- Harmonics, compliance with standard 519.
- Flicker, compliance with standard 141
- Power flow, power factor, (plus/minus 98.5)
- Fault current computations
- Lightning Protection
- Reliability Issues (TRELSS Model – with Southern Co.)
    - Converting Energy Resources to Capacity Resources
    - Role of Storage
- Integrated Resource Utilization

Microgrid Analysis Tool: Needs

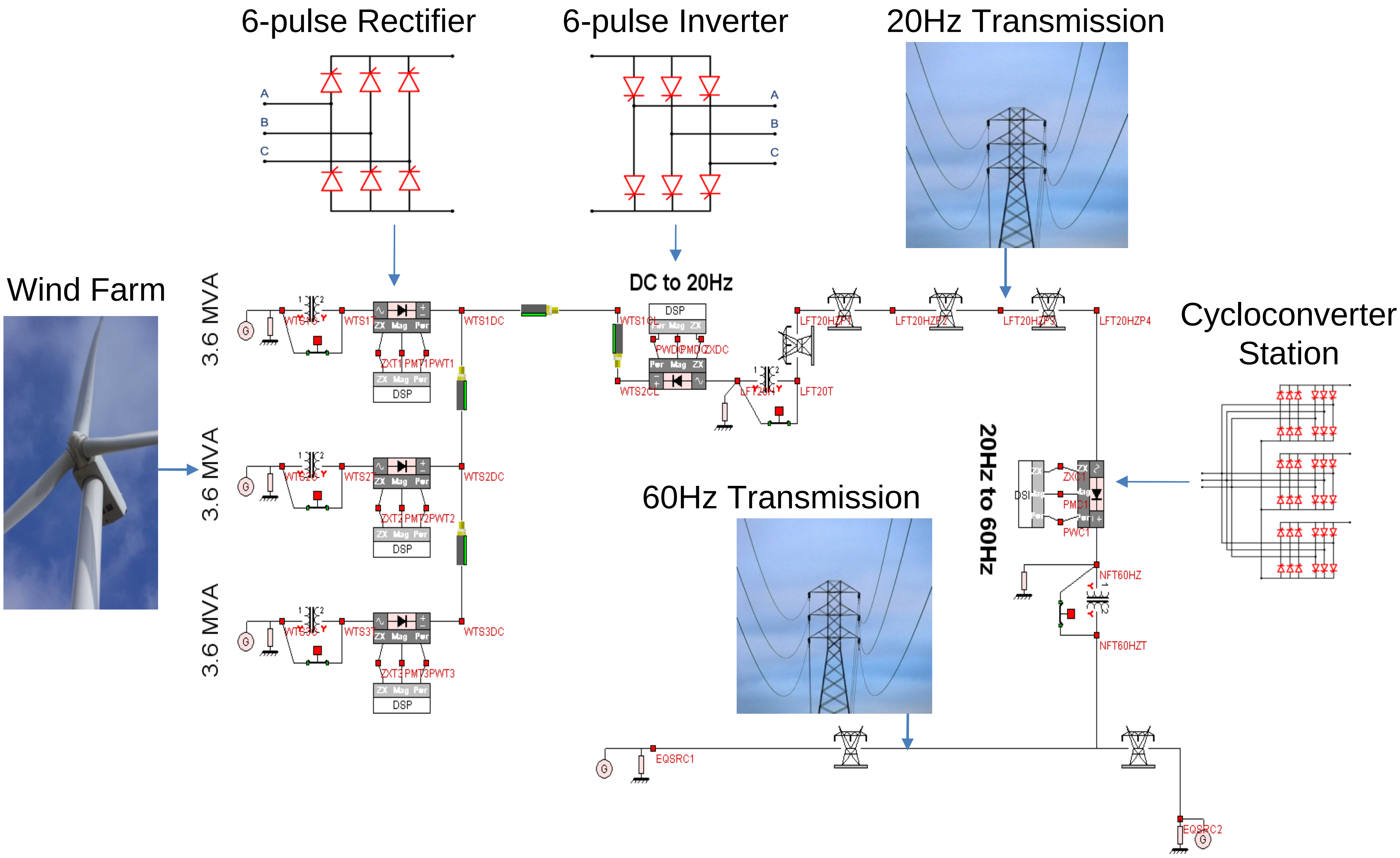
- The distribution system may contain three-wire, four-wire and five-wire circuits.
- The μGRID sources (DERs) may operate under different control laws. As a matter of fact, control functions are expected to increase as manufacturers become more sophisticated.
- The μGRID resources have characteristics that impact on system management and operations planning. Modeling of the parameters of these resources as a function of time enables more realistic simulations.
- The presence of these resources on the electric power distribution system may stress the system in ways that were not anticipated. Proper modeling of operating constraints is important to capture the limitations of the system.

Illustrative Example of a μGRID



Wind Farms/DC Transmission/Low Frequency Transmission

Quasi-Steady State and Time Domain Simulations and Studies


6-pulse Rectifier

6-pulse Inverter

20Hz Transmission

Wind Farm

DC to 20Hz

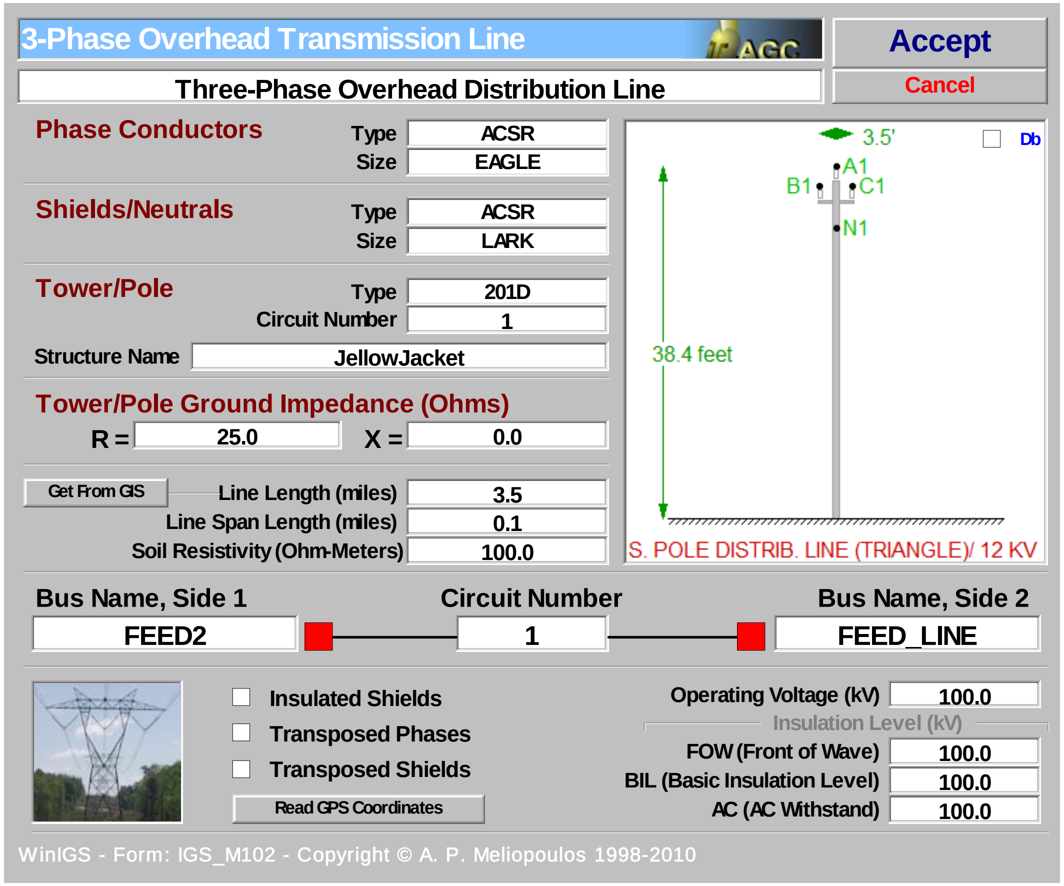
Cycloconverter Station

60Hz Transmission

20Hz to 60Hz

Physically Based Modeling Approach

Open Models: Object Orientation


3-Phase Overhead Transmission Line

Accept

Cancel

Three-Phase Overhead Distribution Line

Phase Conductors
Type ACSR
Size EAGLE

Shields/Neutrals
Type ACSR
Size LARK

Tower/Pole
Type 201D
Circuit Number 1
Structure Name JellowJacket

Tower/Pole Ground Impedance (Ohms)
R = 25.0 X = 0.0

Get From GIS
Line Length (miles) 3.5
Line Span Length (miles) 0.1
Soil Resistivity (Ohm-Meters) 100.0

S. POLE DISTRIB. LINE (TRIANGLE)/ 12 KV

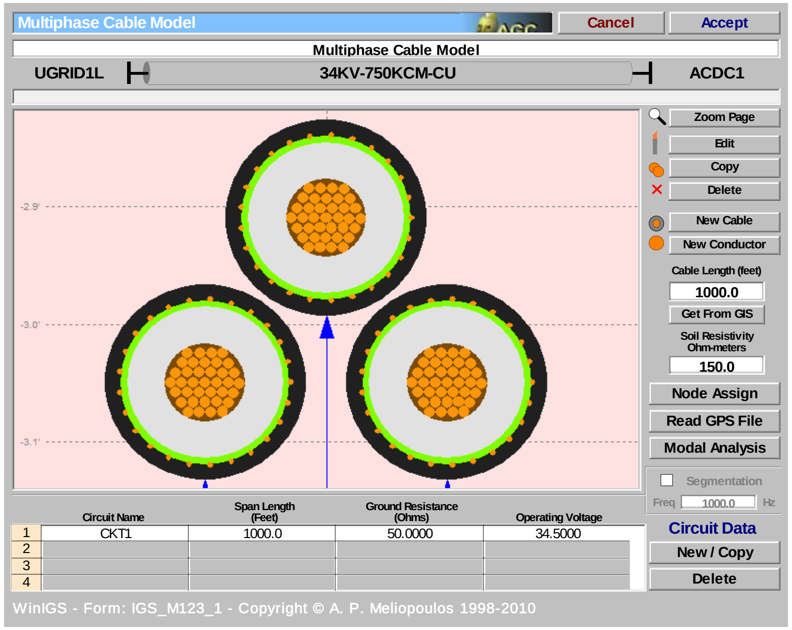
Bus Name, Side 1	Circuit Number	Bus Name, Side 2
FEED2	1	FEED_LINE

☐ Insulated Shields
☐ Transposed Phases
☐ Transposed Shields

Read GPS Coordinates

Operating Voltage (kV) 100.0
Insulation Level (kV)
FOW (Front of Wave) 100.0
BIL (Basic Insulation Level) 100.0
AC (AC Withstand) 100.0

WinIGS - Form: IGS_M102 - Copyright © A. P. Meliopoulos 1998-2010


Multiphase Cable Model

Cancel Accept

Multiphase Cable Model

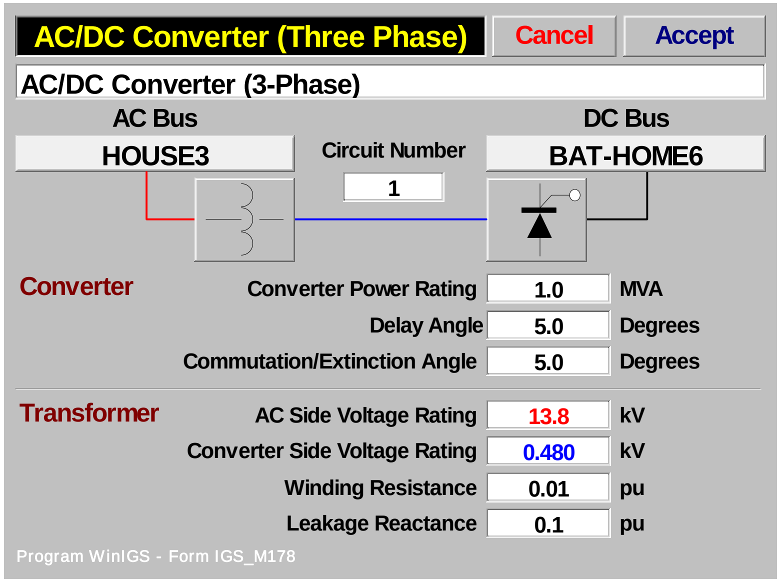
UGRID1L 34KV-750KCM-CU ACDC1

Cable Length (feet) 1000.0
Get From GIS
Soil Resistivity Ohm-meters 150.0

☐ Segmentation
Freq 1000.0 Hz

	Circuit Name	Span Length (Feet)	Ground Resistance (Ohms)	Operating Voltage
1	CKT1	1000.0	50.0000	34.5000
2				
3				
4				

WinIGS - Form: IGS_M123_1 - Copyright © A. P. Meliopoulos 1998-2010


AC/DC Converter (Three Phase)

Cancel Accept

AC/DC Converter (3-Phase)

AC Bus	Circuit Number	DC Bus
HOUSE3	1	BAT-HOME6

Converter
Converter Power Rating 1.0 MVA
Delay Angle 5.0 Degrees
Commutation/Extinction Angle 5.0 Degrees

Transformer
AC Side Voltage Rating 13.8 kV
Converter Side Voltage Rating 0.480 kV
Winding Resistance 0.01 pu
Leakage Reactance 0.1 pu

Program WinIGS - Form IGS_M178

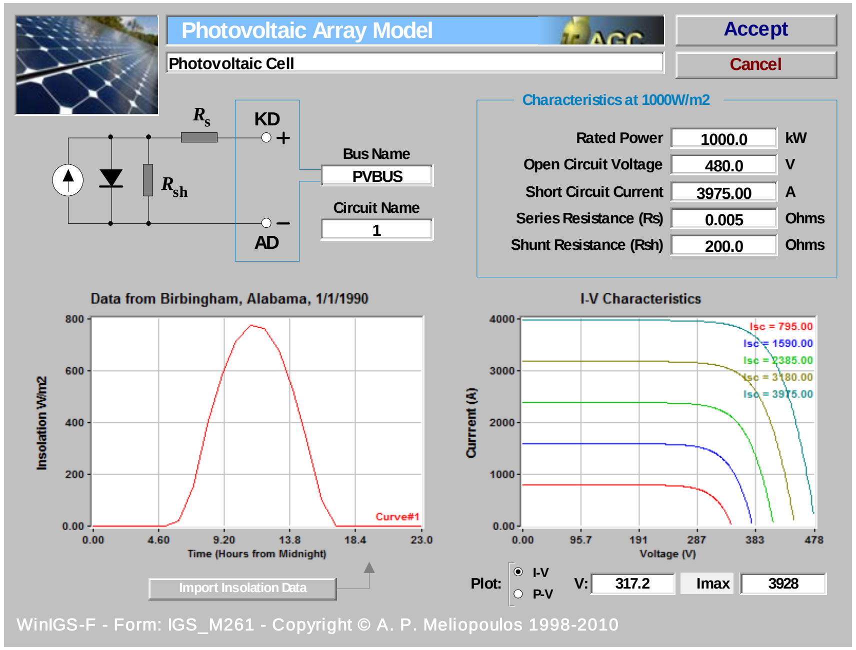
Object Oriented Models → Common Math Model

1. Steady State Models
2. Quasi-Static Models (slow dynamics)
3. Transient Models

Operational Models ← → Planning Models

Resource Management: Embedded Forecast Models

Renewables, PHEV, Distributed Resources have a “Time Component”



Photovoltaic Array Model

Photovoltaic Cell

Bus Name: PVBUS

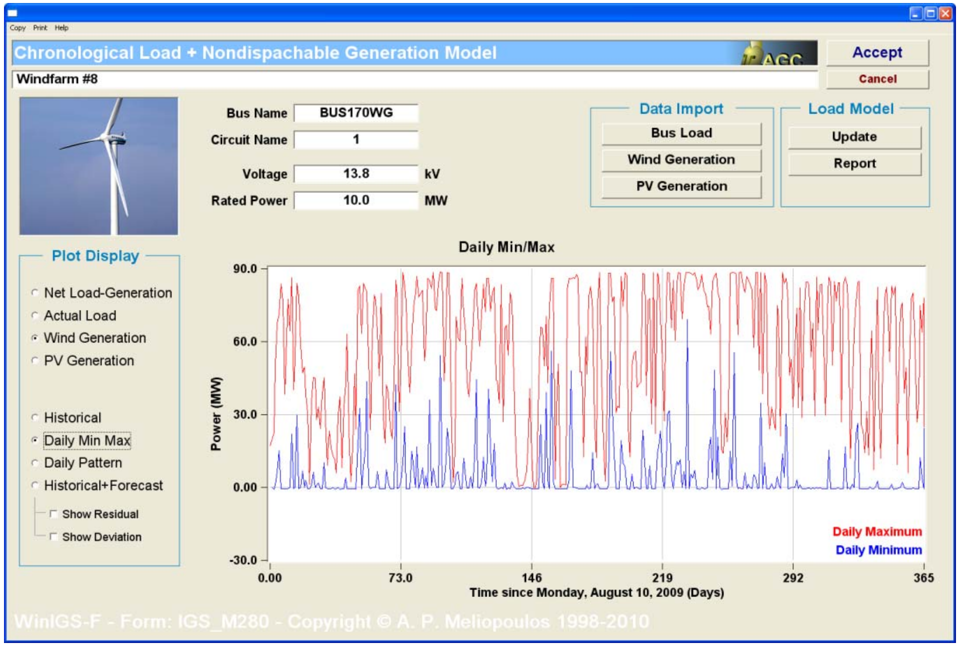
Circuit Name: 1

Characteristics at 1000W/m2

Rated Power	1000.0	kW
Open Circuit Voltage	480.0	V
Short Circuit Current	3975.00	A
Series Resistance (Rs)	0.005	Ohms
Shunt Resistance (Rsh)	200.0	Ohms

Plot: ● I-V ○ P-V   V: 317.2   Imax: 3928

WinIGS-F - Form: IGS_M261 - Copyright © A. P. Meliopoulos 1998-2010



Chronological Load + Nondispachable Generation Model

Windfarm #8

Bus Name: BUS170WG

Circuit Name: 1

Voltage: 13.8 kV

Rated Power: 10.0 MW

Plot Display

○ Net Load-Generation
○ Actual Load
● Wind Generation
○ PV Generation

○ Historical
● Daily Min Max
○ Daily Pattern
○ Historical+Forecast
☐ Show Residual
☐ Show Deviation

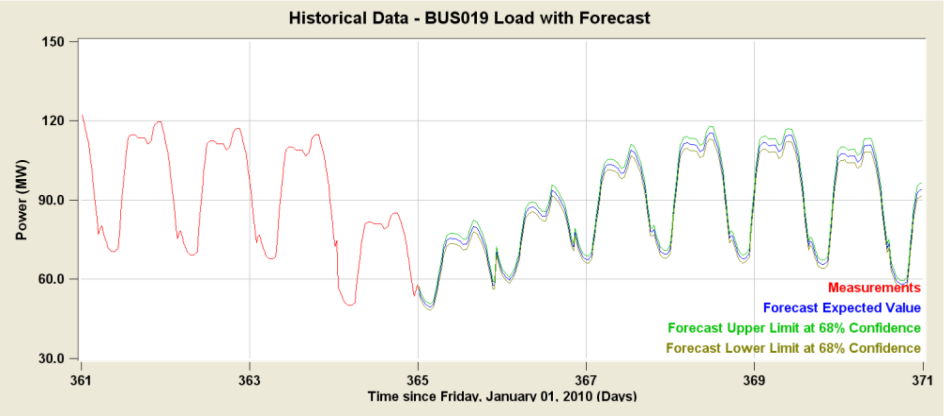
WinIGS-F - Form: IGS_M280 - Copyright © A. P. Meliopoulos 1998-2010

Modeling of Resources: Past History and Forecast of Availability

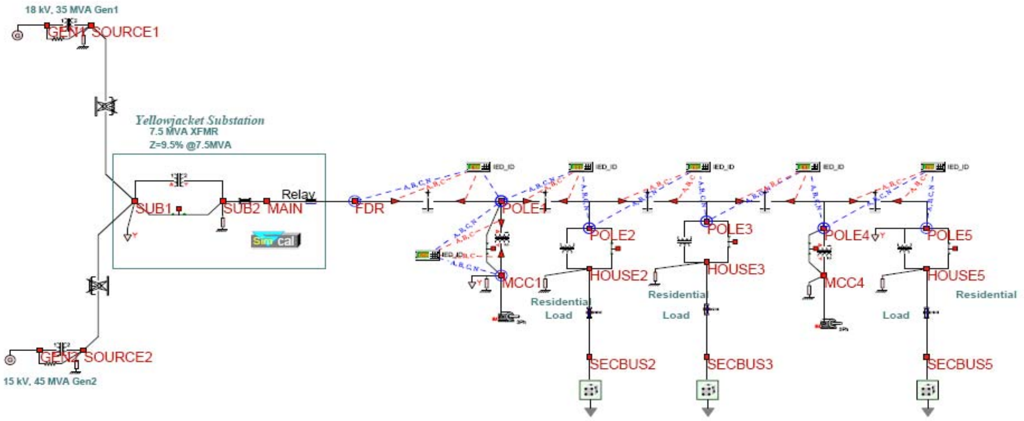
1. Example of PV Generation
2. Example of Wind Generation
3. Example of Load Forecast

Other Examples:

Movable Resources (i.e. PHEV) May Include Past History of Connection Time and Location and Forecast of Same.



Example Resource Modeling: Pluggable Hybrid Cars Coordination

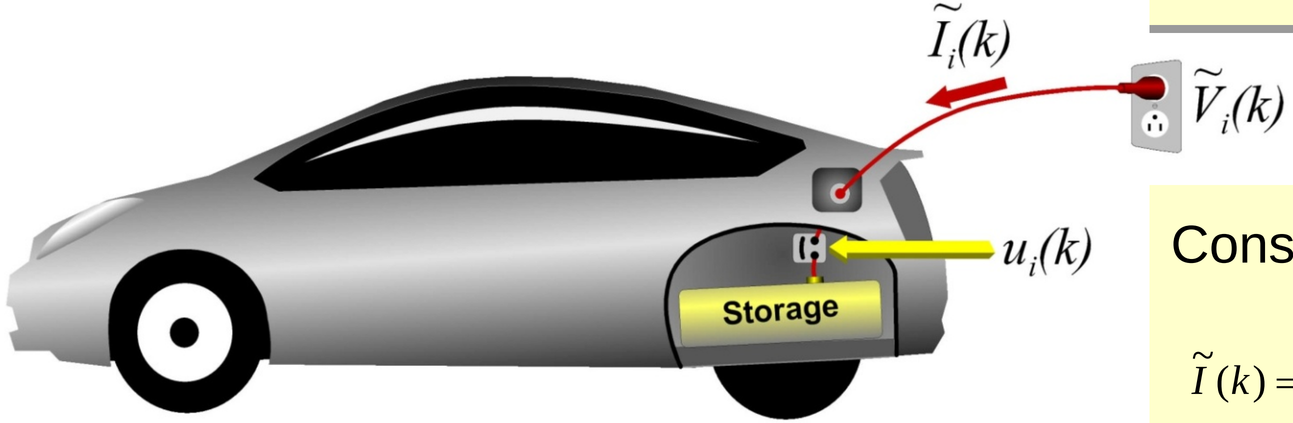


Minimize Z* subject to:

$$g\big(x(k),u(k),p(k)\big)=0;\ \ k=1,2,\ldots,N$$

$$f\big(x(k)\big)=\mathrm{Re}\left\{\tilde{V}(k)\tilde{I}^{*}(k)\right\}$$

$$z^{*}\geq f(x(k));\ \ k=1,2,\ldots,N$$



Constraints on all resources Example : PHEV

$$\tilde{I}(k)=u_i(k)\tilde{V}_i(k)a(v_i(k))$$

$$0=E_i(k)-E_i(k-1)-\mathrm{Re}\{\tilde{V}_i(k)\tilde{I}_i^{*}(k)\}$$

$$0\leq E_i(k)\leq E_{i,\max}$$

$$0=Q_i(k)-\mathrm{Im}\{\tilde{V}_i(k)\tilde{I}_i^{*}(k)\}$$

$$k=k_i,k_{i+1},\ldots K_i$$

$$0=E_i(K_i)-E_{i,\max}$$

Storage

Capacity: $E_{i,max}$

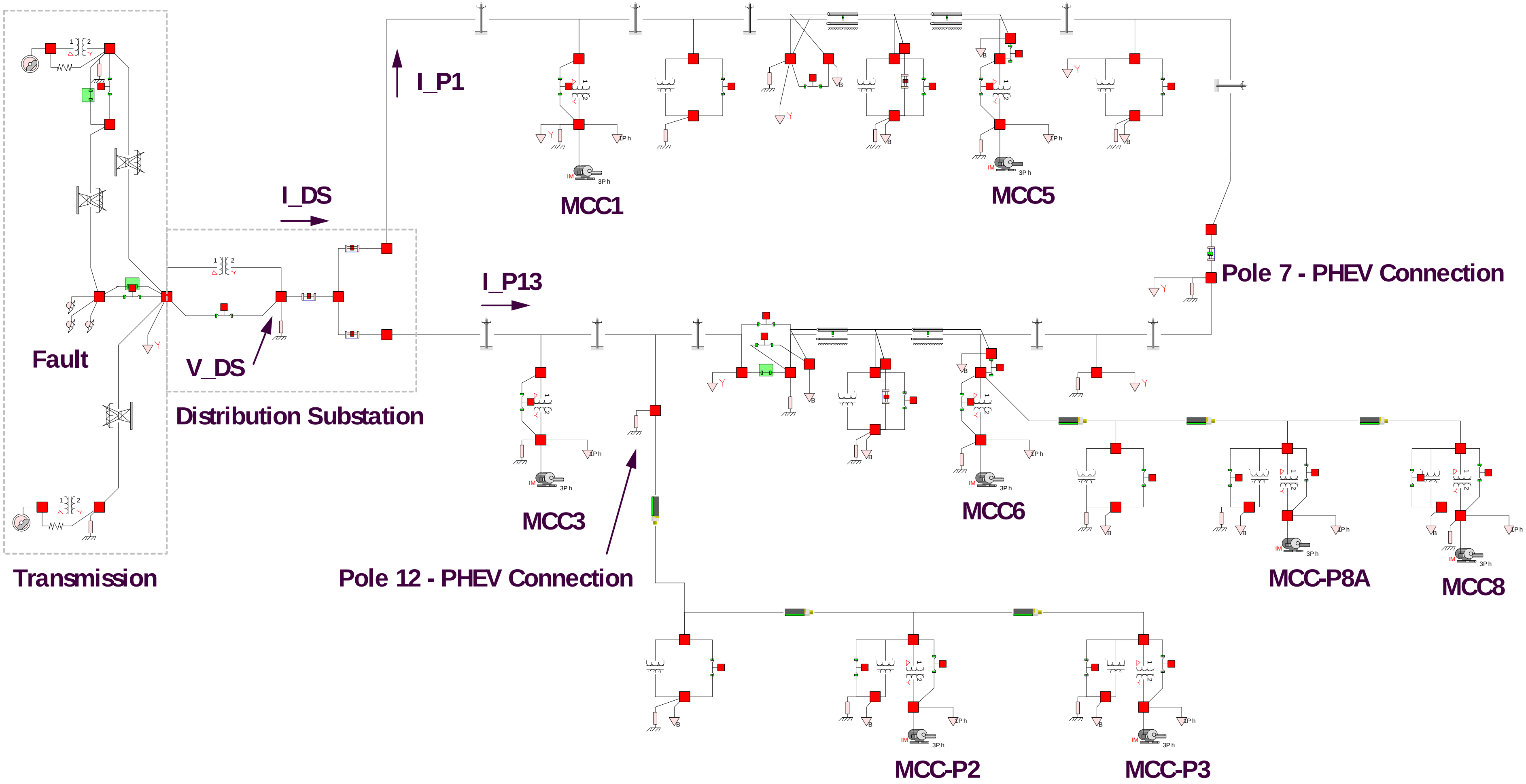
Status: E_i

$u_{i(k)}$: connectivity at time k

$v_{i(k)}$: operating mode at time k

$$v\begin{cases}=\ \ 1 & \text{charging}\\ =-1 & \text{generating}\\ =\ \ 0 & \text{VAR Source}\end{cases}$$

Important V2G Function: Mitigation of Fault Induced Delayed Voltage Recovery - Example



I_P1

I_DS

I_P13

MCC1

MCC5

Pole 7 - PHEV Connection

Fault

V_DS

Distribution Substation

MCC3

MCC6

Transmission

Pole 12 - PHEV Connection

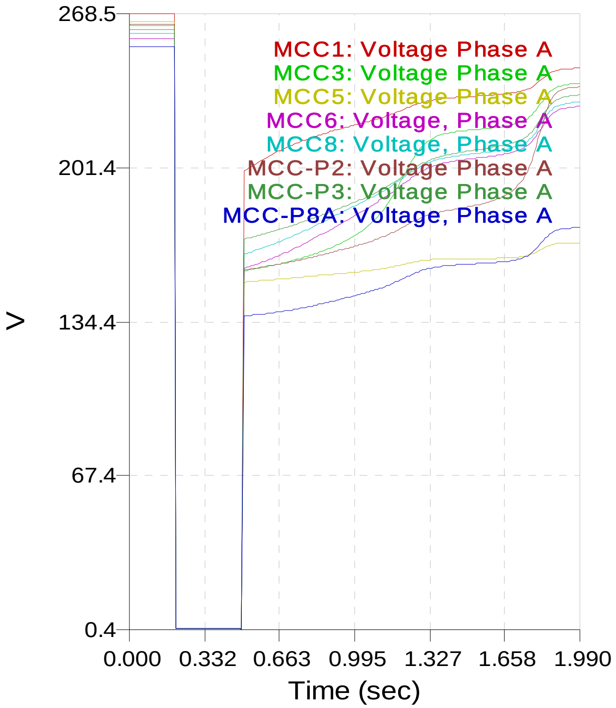
MCC-P8A

MCC8

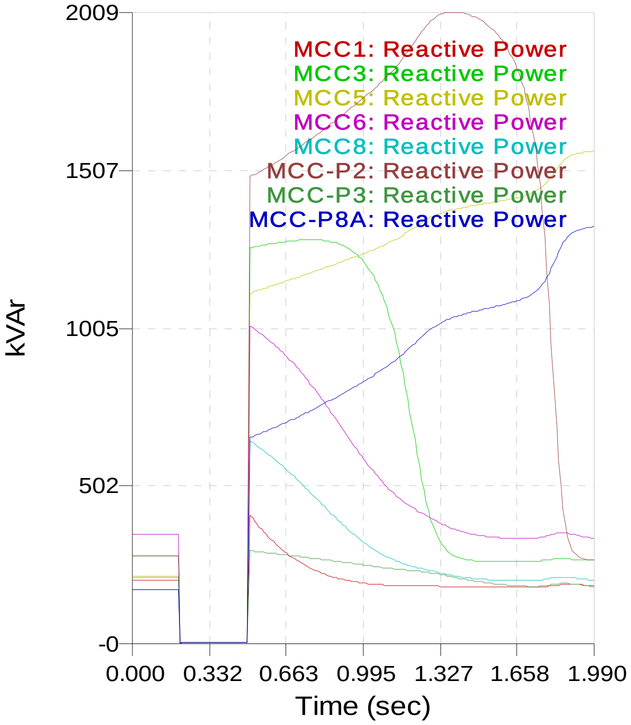
MCC-P2

MCC-P3

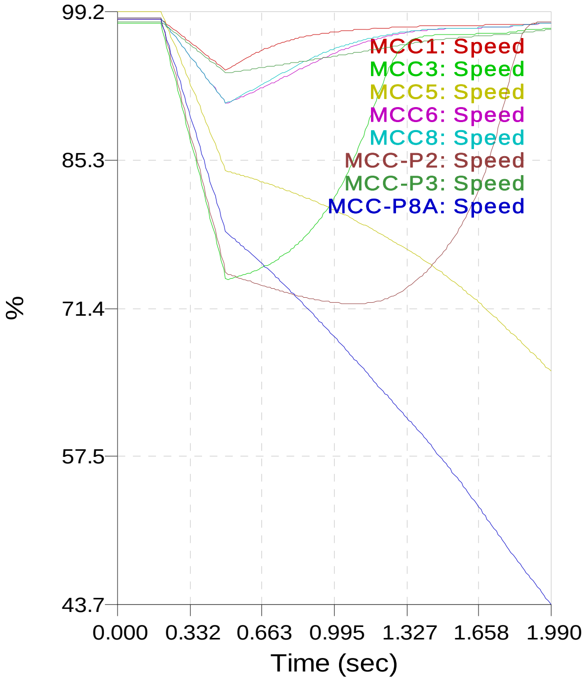
Voltage Recovery at Eight Electric Motors Locations



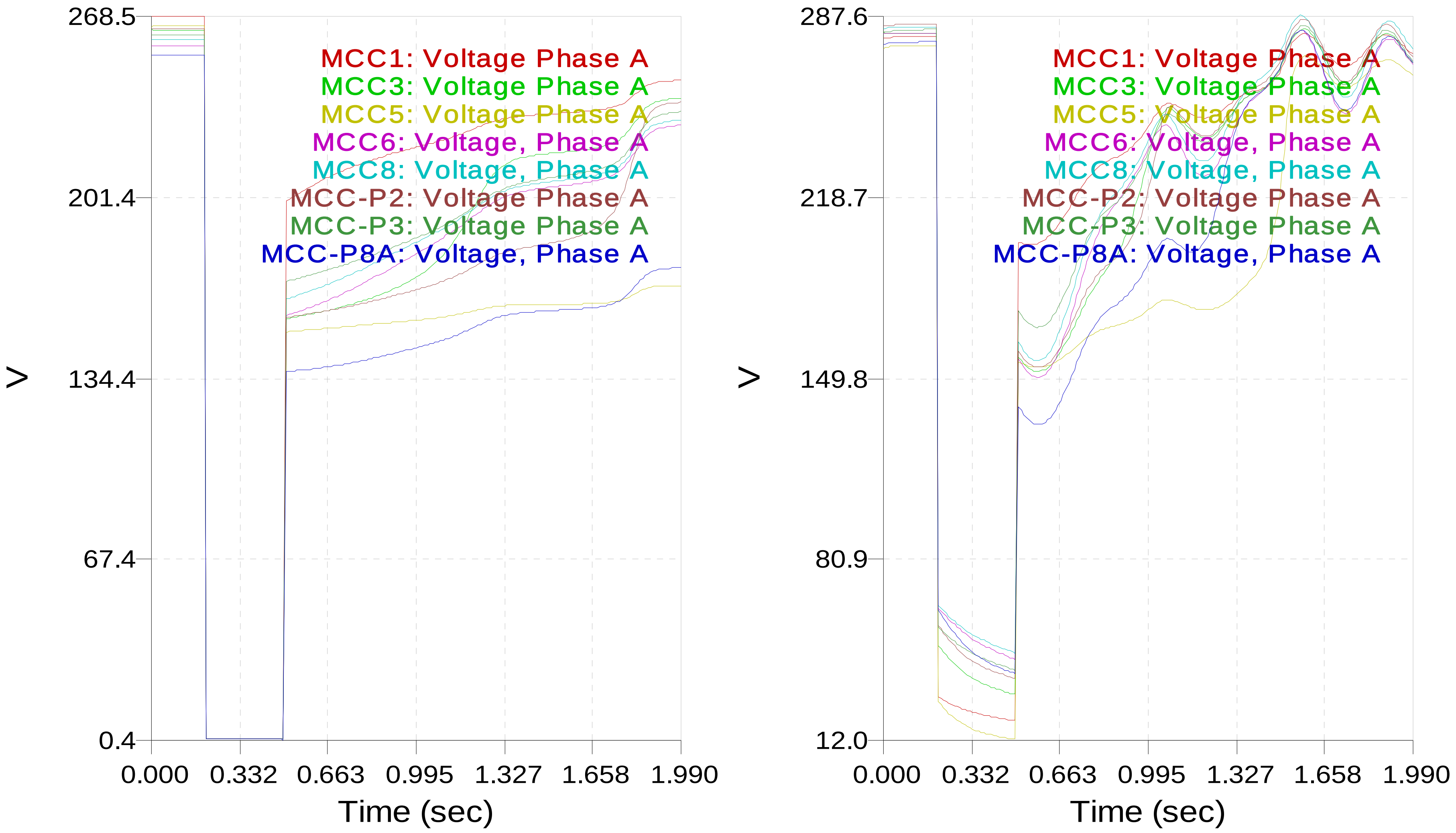
Reactive Power Absorption of Eight Electric Motors



Speed of Eight Electric Motors



Voltage Recovery at Eight Electric Motors Locations

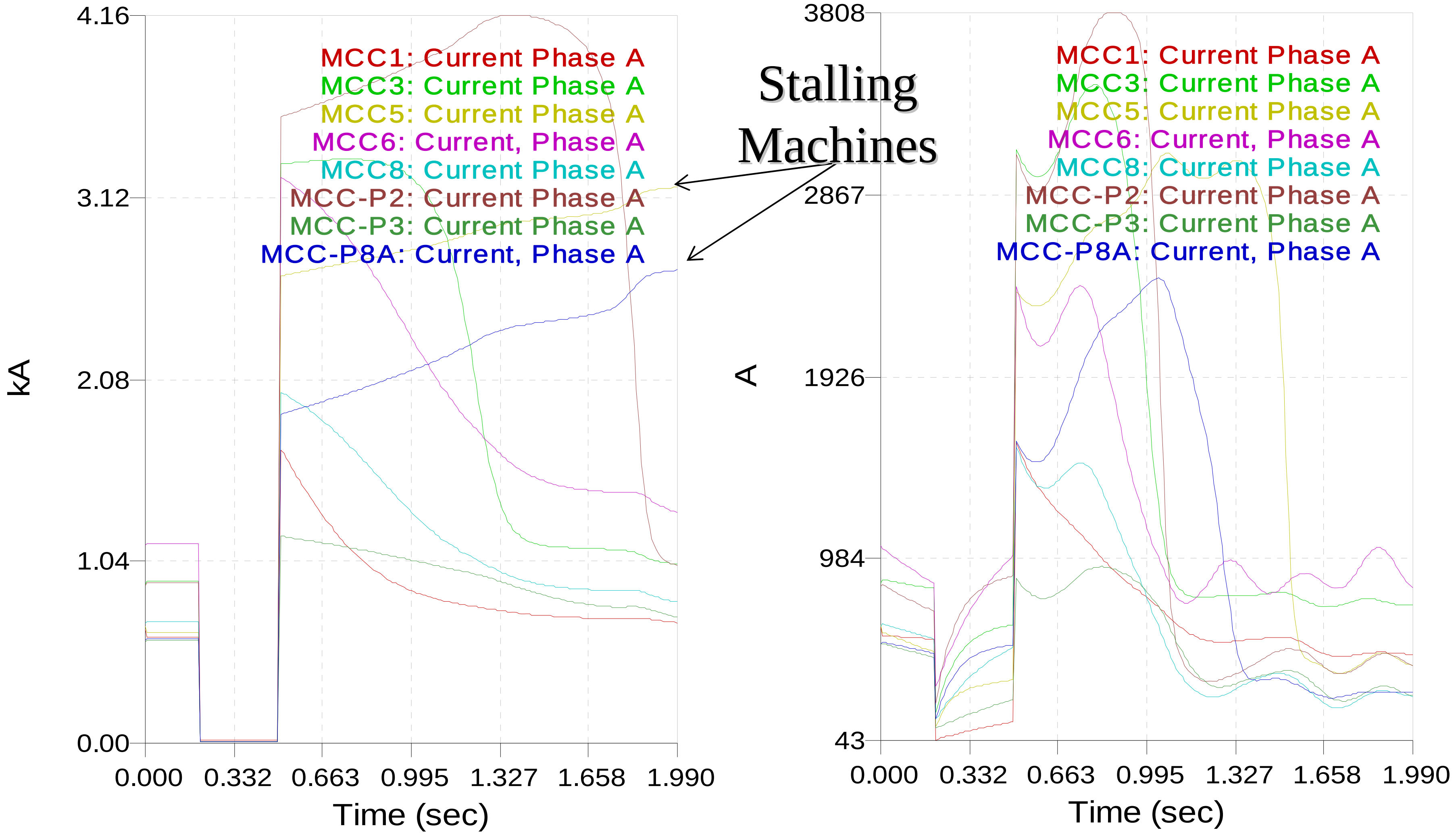


Without PHEVs

With PHEVs

PHEVs provide reactive power to speed-up voltage recovery and avoid stalling

Reactive Power Absorption of Eight Electric Motors



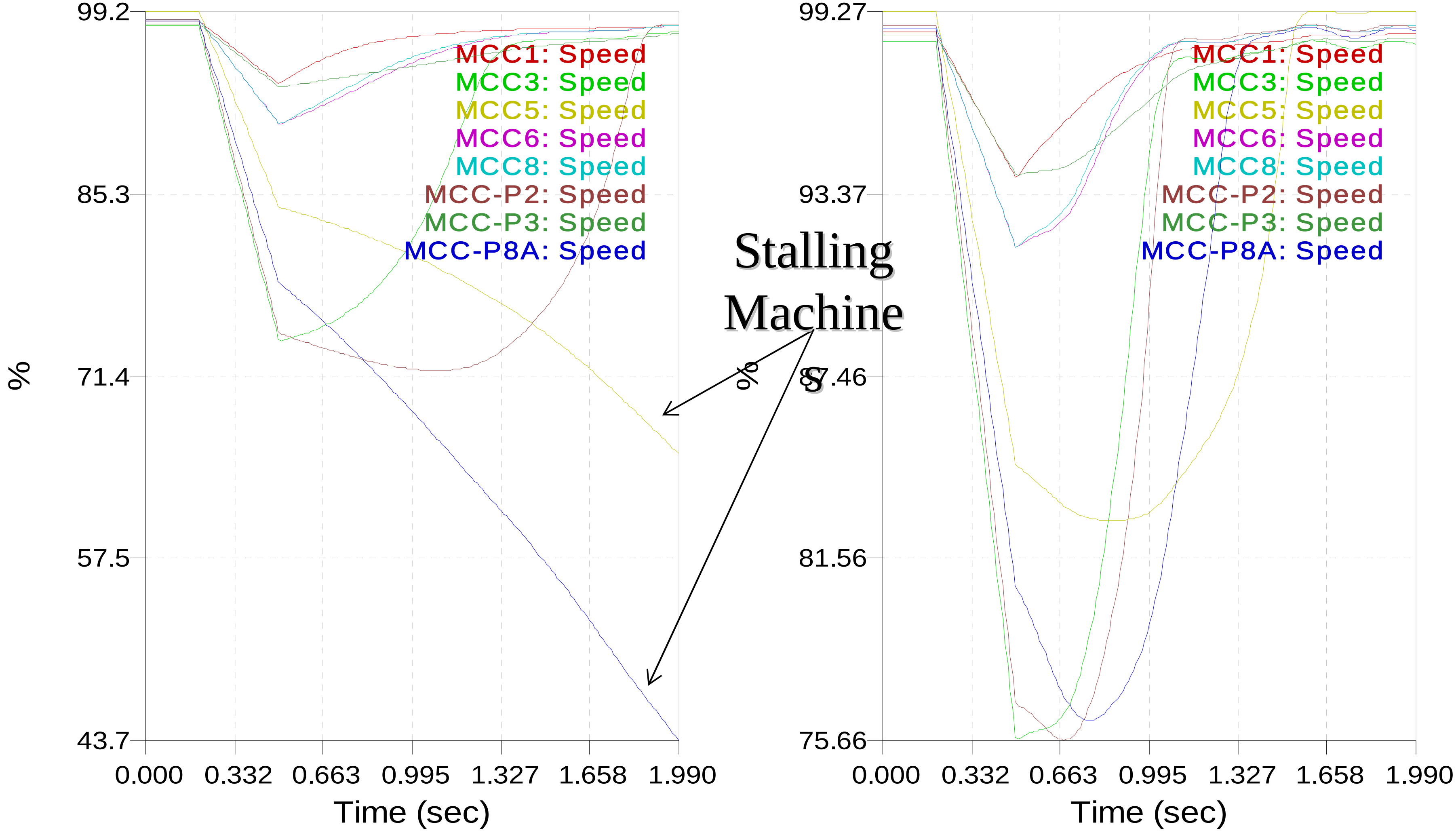
Stalling Machines

Without PHEVs

With PHEVs

PHEVs provide reactive power to speed-up voltage recovery and avoid stalling

Speed of Eight Electric Motors



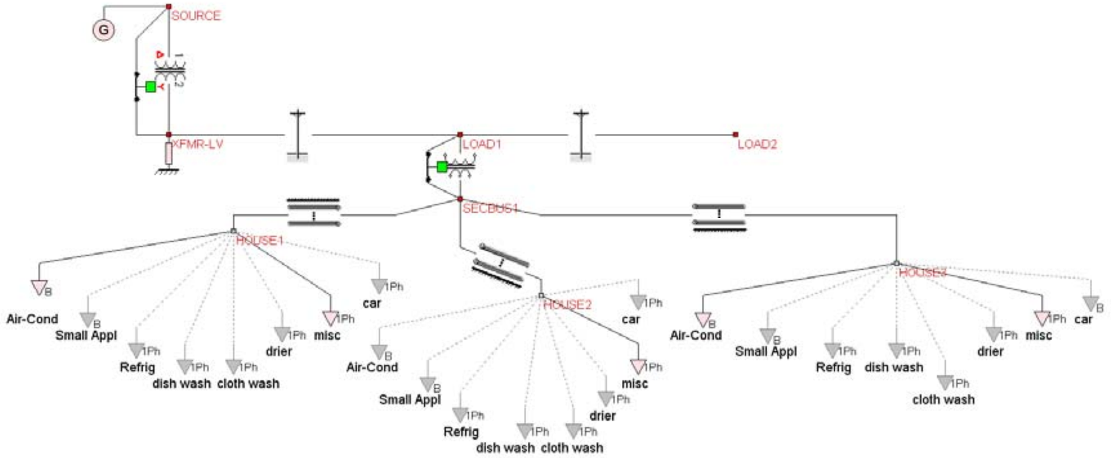
Stalling Machines

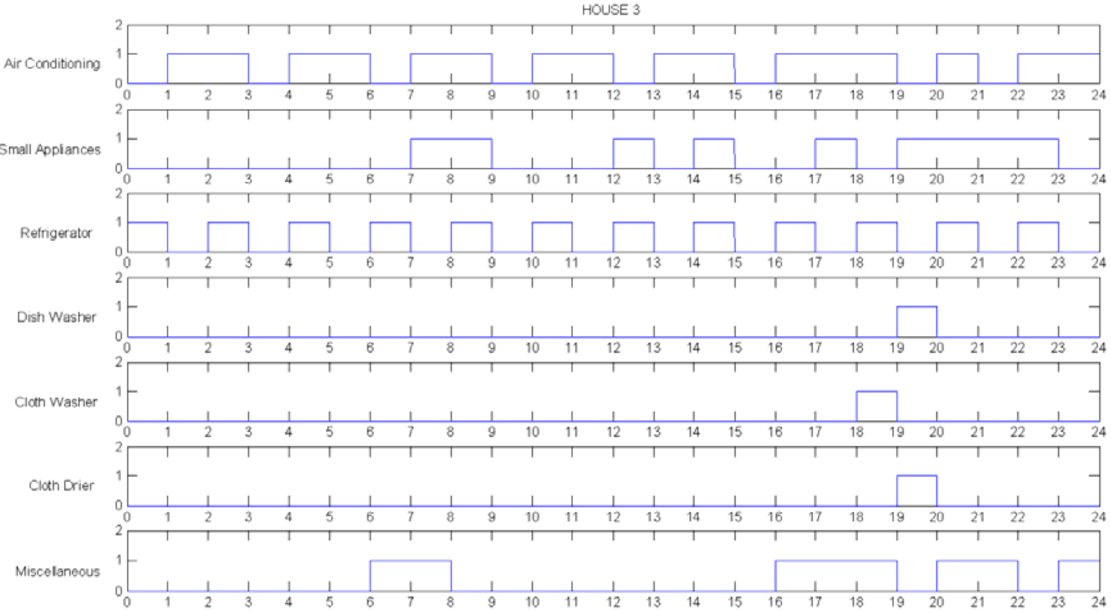
Without PHEVs

With PHEVs

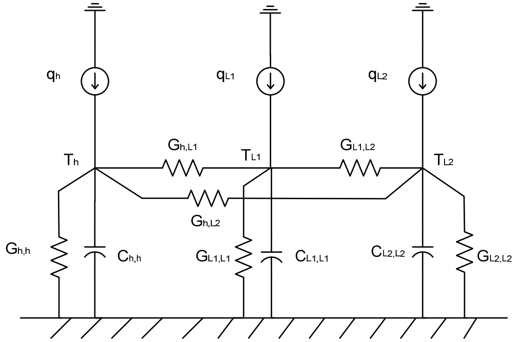
PHEVs provide reactive power to speed-up voltage recovery and avoid stalling

Impacts of PHEV on Infrastructure





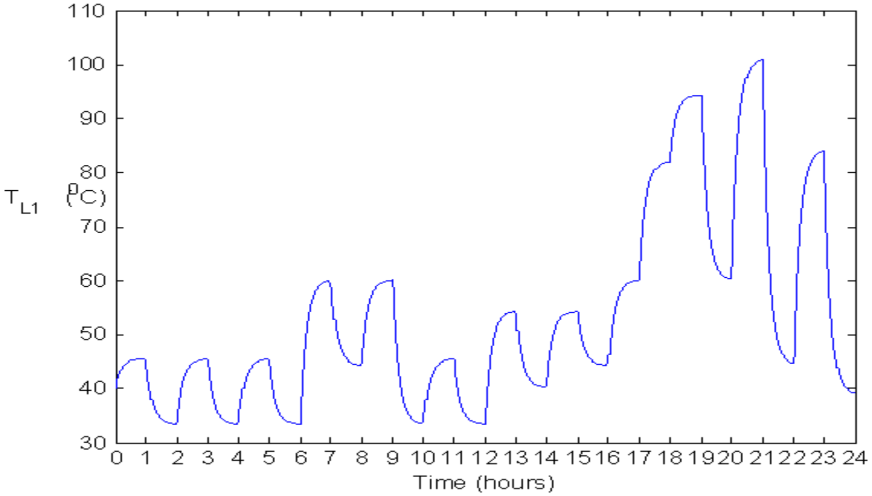
- Integrated electro-thermal models of distribution systems and distribution transformers that include houses, commercial buildings, loads, etc. can be used to investigate impact.
- Probabilistic models of electric power demand superimposed to demand for PHEV charging drive the integrated model.
- Simulation of the integrated system provides the operating temperature of distribution transformers as a function of time and loss of transformer life.



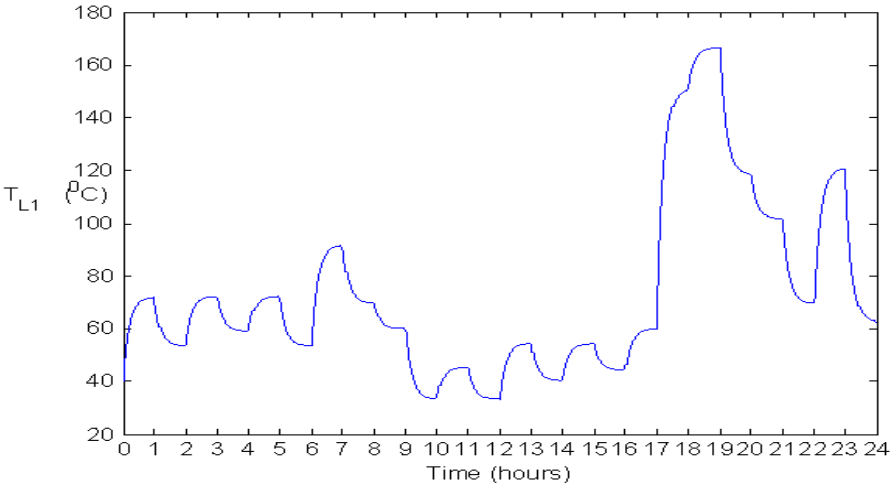
$$C\frac{dT}{dt} = -GT + q$$

Impacts of PHEV on Infrastructure

Example of 15 kVA Distribution Transformer Feeding Three Houses



Sample simulation without PHEV.
Computed expected life of transformer = 353 years



Sample simulation with PHEV40.
Computed expected life of transformer = 1.85 years

$$LOL = \sum_{h=1}^{24} h \cdot e^{(-(A+\frac{B}{\tilde{T}}))}$$

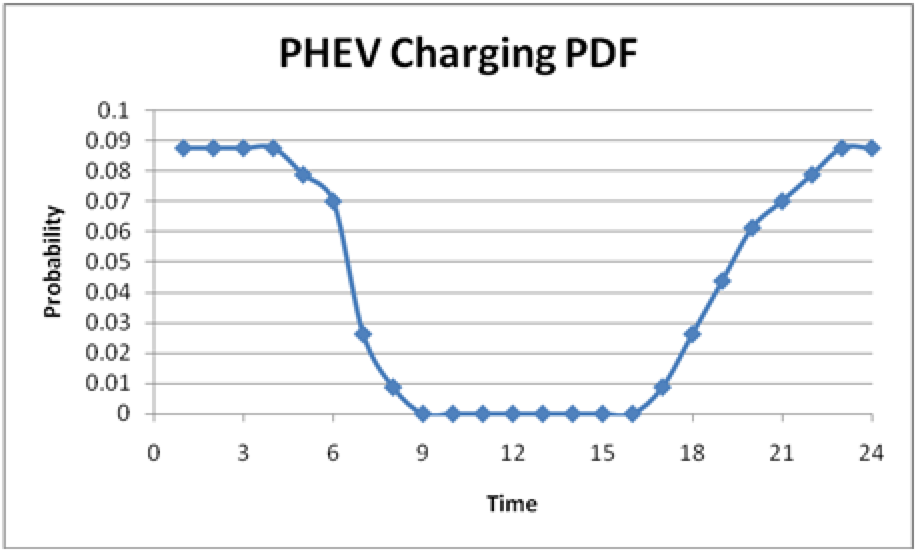
	LOL (normalized)	Expected Life (years)
Without PHEVs, 20 ^{0}C	$7.7588 \cdot 10^{-6}$	353.11
With PHEVs, 20 ^{0}C	$10.6 \cdot 10^{-5}$	25.85
Without PHEVs, 30 ^{0}C	$2.2 \cdot 10^{-5}$	124.3
With PHEVs, 30 ^{0}C	$2.67 \cdot 10^{-4}$	10.25

Impacts of PHEV on Fuel Utilization

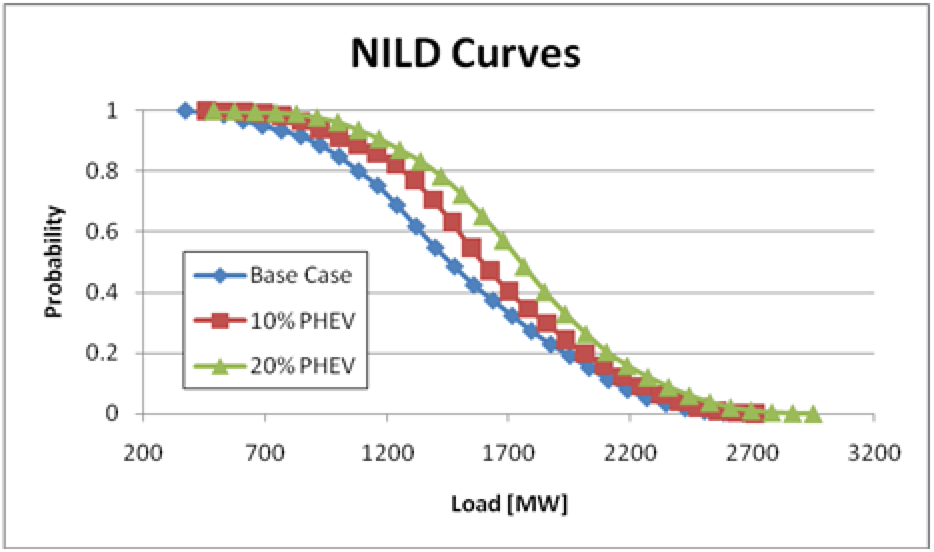
Methodology

Probabilistic Production Costing method. Generation is subject to outages and each unit has specific economics. The dispatch procedure is simulated while a probabilistic model of unit availability is used. Model computes expected operational time, expected production (MWh), expected cost by each unit and total. Different scenarios are considered: (a) segregated electric power system operation and gasoline powered cars, and (b) electric power operation with a certain penetration percentage of PHEV.

PHEV Charging Scenario



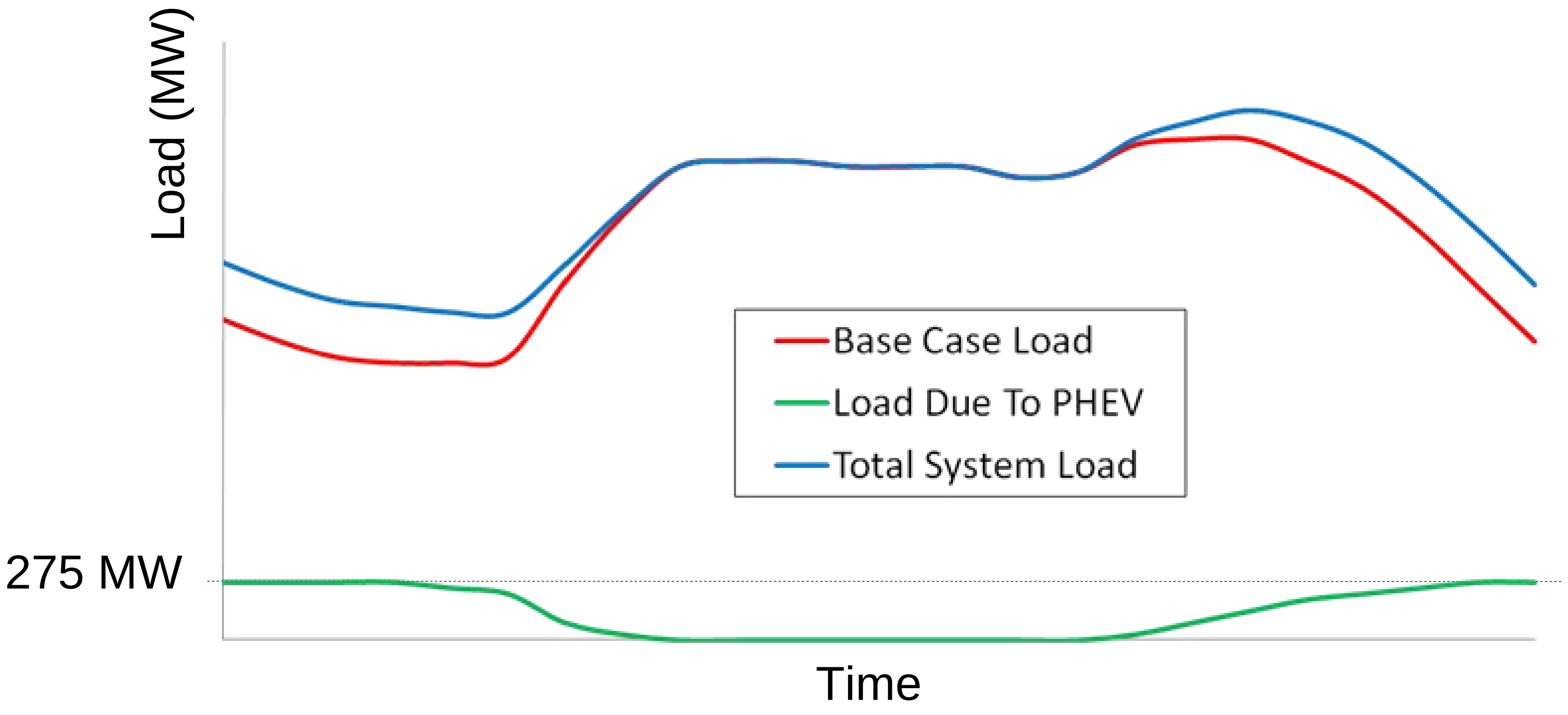
Effective Load Model (PDF of Load)



Primary Energy Source Utilization

PHEV Load

Additional load due to PHEV shown for the first simulated day



The minimum increased 22.10% and 30.66% for the 10% and 20% PHEV penetration scenarios, respectively. And the maximum load increased only 1.75% and 10.78% increase for the 10% and 20% PHEV penetration, respectively. This load leveling is a potential benefit of the semi-controllable load that PHEVs present.

Example of Probabilistic Production Costing

Costing/Reliability Analysis and Outcomes – Example Test System

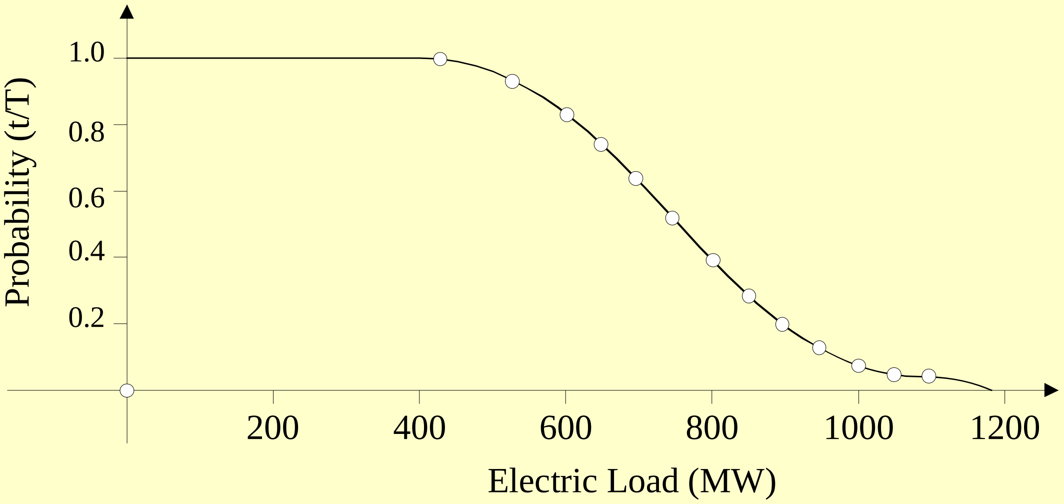
Generating Units and Primary Fuel

Fuel	Size [MW]		Num. Units	FOR
	Max. Cap.	Min. Cap.		
#6 Oil	12	2.4	5	0.02
#2 Oil	20	16	4	0.10
#6 Oil	50	15.2	4	0.04
Coal	76	12.5	3	0.02
Nat. Gas	125	31.25	4	0.08
Nuclear	155	54.25	3	0.10
Coal	197	68.95	1	0.05
Coal	350	140	2	0.08
Nuclear	400	100	1	0.12

Primary Fuel Data

Fuel	Heat Content Kcal/Kg	Price $/Kg
Nuclear	$19.069 * 10^{13}$	60,000
Coal	6,000.0	0.05
Petroleum	12,000.0	0.65
Natural Gas	12,800.0	0.35

Example Load Model Converted to a "Load Duration Curve"



Probabilistic Production Costing

Example Test System

Generating Units Heat Rates

Size [MW]	a_h	b_h	c_h
12	3,330,369	2,550,425	15,047
20	10,080,000	3,150,000	0
50	21,092,334	2,550,425	2,376
76	31,362,044	1,963,834	2,413
100	26,227,189	2,257,130	2,395
155	43,407,948	1,946,828	1,401
197	33,003,505	2,193,793	329
350	81,532,894	1,873,123	822
400	90,962,133	2,244,962	116

Generating Units Emissions

	NO_x		CO_2	
Size [MW]	a_p	b_p	a_p	b_p
12	20	0.5	6,459	158
20	8	3.8	1,252	626
50	46	0.2	4,733	151
76	180	0.7	37,417	145
100	283	0.9	52	0.2
155	548	1.1	92,849	183
197	374	0.9	123,204	309
350	1,604	3.2	270,004	335
400	0	0	0	0

$$\text{Heat Rate} = A + B \cdot P + C \cdot P^2$$

Probabilistic Production Costing

Example Results

Primary Energy Source:		#6 Oil	#2 Oil	Coal	Nuclear	Natural Gas
Total Energy [GWh/year]	Base Case	62.81	8.14	9171.00	3083.00	665.40
	10%PHEV	72.08	9.51	9591.00	3083.00	736.80
	20%PHEV	84.56	11.42	9990.00	3084.00	824.00
Percent Change	10%PHEV	0.07%	0.01%	3.11%	0.00%	0.53%
	20%PHEV	0.16%	0.02%	5.85%	0.01%	1.13%

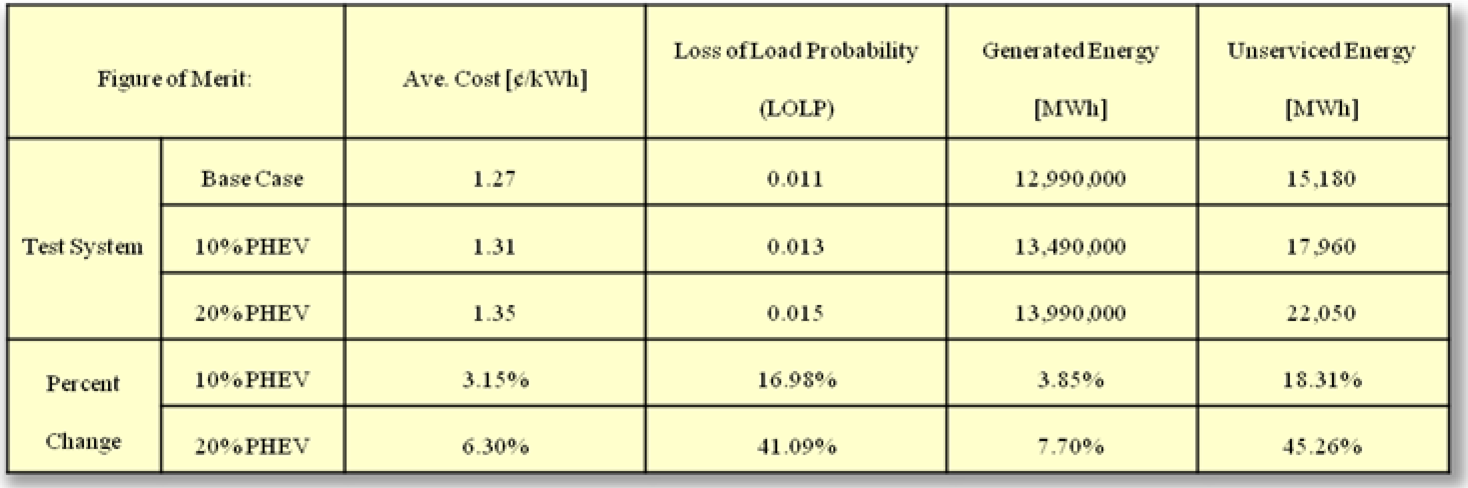


Figure of Merit:		Ave. Cost [¢/kWh]	Loss of Load Probability (LOLP)	Generated Energy [MWh]	Unserviced Energy [MWh]
Test System	Base Case	1.27	0.011	12,990,000	15,180
	10%PHEV	1.31	0.013	13,490,000	17,960
	20%PHEV	1.35	0.015	13,990,000	22,050
Percent Change	10%PHEV	3.15%	16.98%	3.85%	18.31%
	20%PHEV	6.30%	41.09%	7.70%	45.26%

Probabilistic Production Costing

Example Results (Pollutants)

		NO_x	CO_2
Power System EAP [kg]	Base Case	47,269,504	7,878,934,800
	10% PHEV	48,105,359	8,004,246,500
	20% PHEV	49,887,315	8,113,374,100
Percent Change	10% PHEV	1.77%	1.59%
	20% PHEV	3.36%	2.98%

Energy Normalized EAP [kg/MWh]	NO_x	CO_2
Base Case	3.7856	856.5478
10% PHEV	3.6936	811.1942
20% PHEV	3.6022	767.9256

Probabilistic Production Costing

Example Results

NO_x [kg]	IC Vehicles	PHEVs	Total Vehicles	Power System	Total	Total Generated Energy [MWh]
Base Case	1,905,700	0	1,905,700	4.727E+07	4.918E+07	12,990,000
90% IC Vehicles, 10% PHEV	1,715,130	6,717	1,721,847	4.811E+07	4.983E+07	13,490,000
80% IC Vehicles, 20% PHEV	1,524,560	13,435	1,537,995	4.886E+07	5.039E+07	13,990,000

CO_2 [kg]	IC Vehicles	PHEVs	Total Vehicles	Power System	Total	Total Generated Energy [MWh]
Base Case	3.248E+09	0	3.248E+09	7.879E+09	1.113E+10	12,990,000
90% IC Vehicles, 10% PHEV	2.923E+09	1.590E+07	2.939E+09	8.004E+09	1.094E+10	13,490,000
80% IC Vehicles, 20% PHEV	2.598E+09	3.181E+07	2.630E+09	8.113E+09	1.074E+10	13,990,000

μGRIDs and Smart Grids

The Smart Grid is an Effort to Develop Enabling Technologies for:

- Increased Efficiency
- Increased Reliability
- Friendly Infrastructure for Renewable Resources

The Smart Grid is Expected to create manpower requirements of highly trained engineers and technicians

Smart Distribution System Technologies

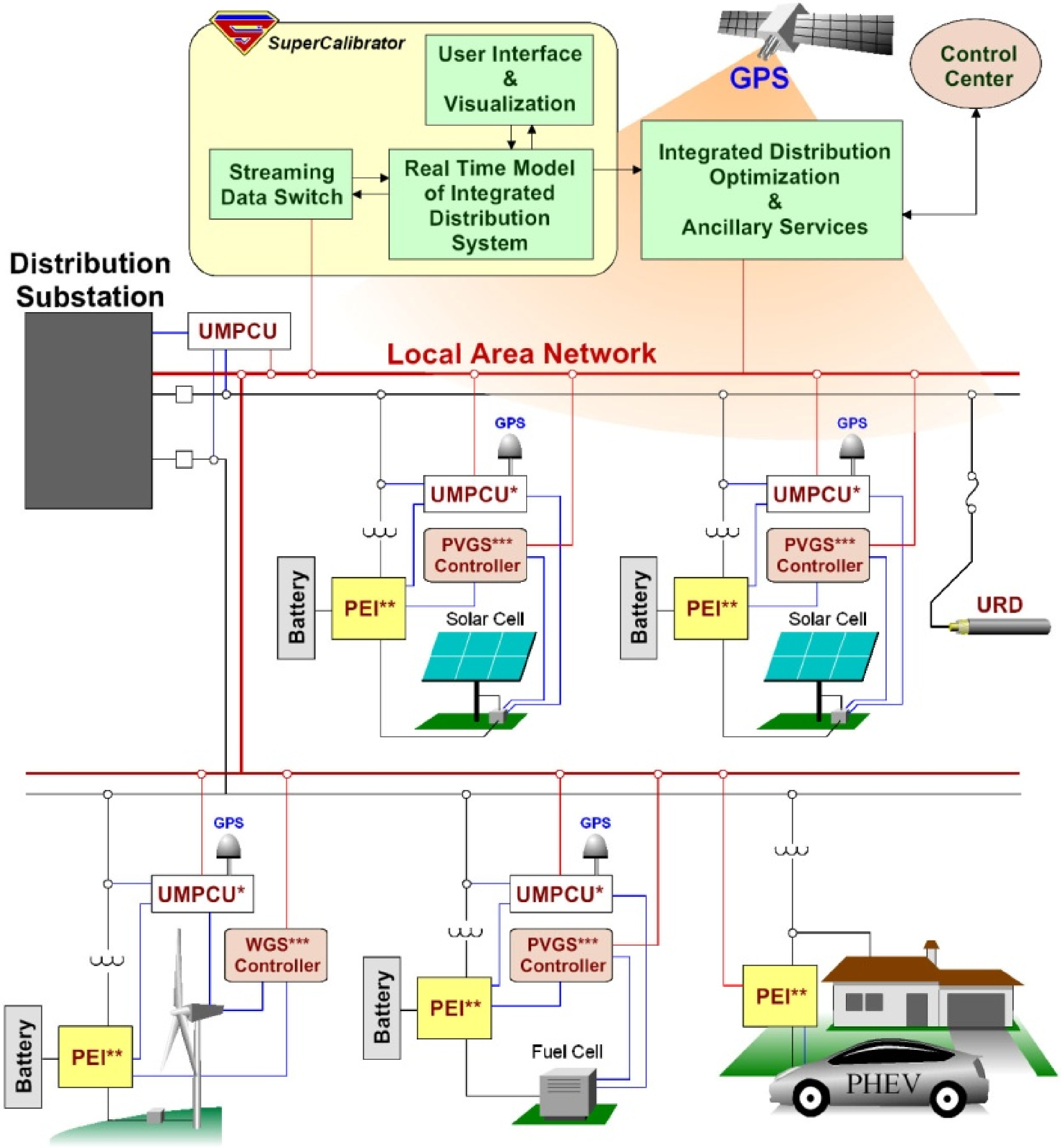
Distribution Management System – New Approach

Real Time Monitoring:

- GPS-Synched Metering
- 3-Phase State Estimation

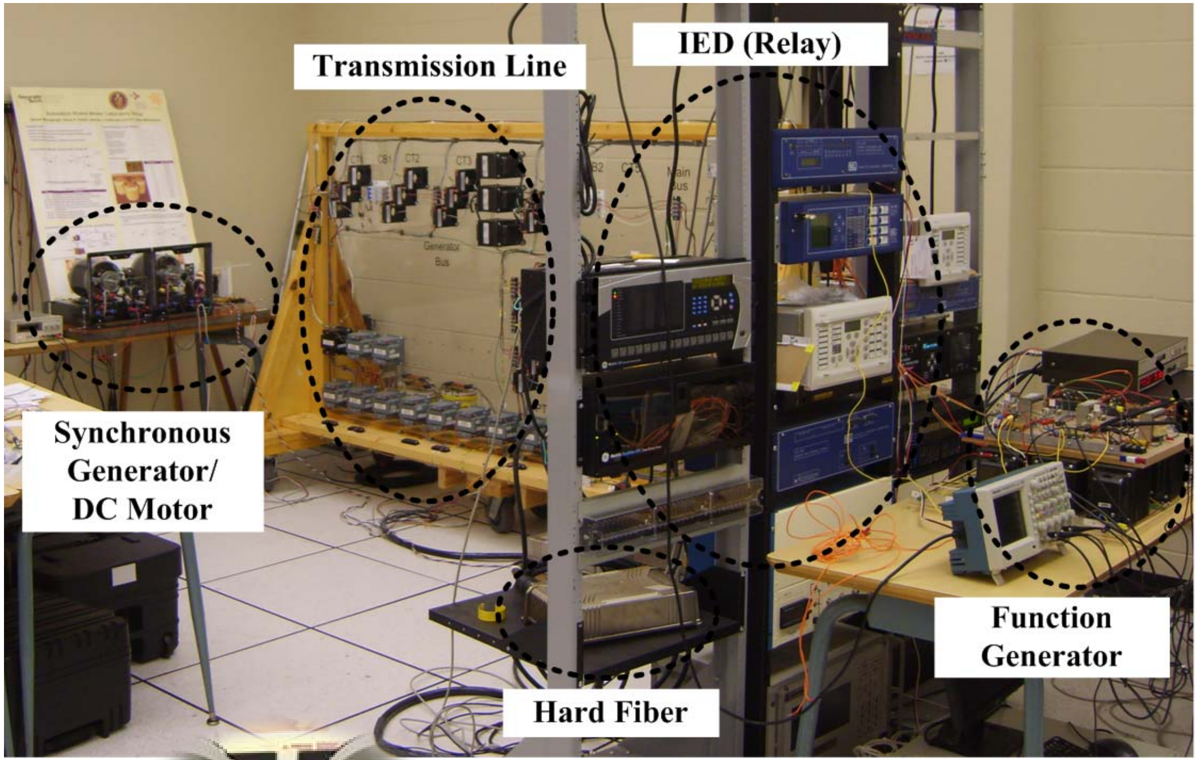
Real Time Controls:

- Loss Minimization
- Voltage Profile Control
- Emergency Management
- Inertial Controls
- Voltage Stability Control
- Stabilize System transients
- System Reliability
- Increase Operating Limits



Robotic Operation of Active Distribution Systems

Test Bed at Georgia Tech



Robotics: Automation of the Process,
Elimination of Human Involvement and Error

Approach: Provide Additional Intelligence to Relays and in General IED to Transmit:
(a) Data,
(b) Connectivity and
(c) Model

Infrastructure: Distributed Centers (Computers) Collect Info and Construct the Real Time Model of the System which Provides the Basis for Protection, Control and Operation

Applications: Feeder Balancing, Load Leveling, Voltage Control, Plug and Play, etc., etc.

Summary

- μGRIDS or Active Distribution Systems Can Become Technically and Economically Attractive to Utilities.

- Simulation of Active Distribution Systems Requires New Approaches to Modeling and Analysis.

- Electric and Plug-In Hybrids can become a valuable resource

- Local infrastructure issues are manageable

- The environmental impact is favorable.

- The impact of system security is favorable.

- Smart Grid Technologies will get us there.

- Technology is ready today to enable Robotic Operation of the Active Distribution System with Plug and Play capability as well as islanding operation.