AC OPF and Smart Grids

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Talk outline

- Basic objectives of smart grids
- Evolution from today's grids
- Use of extended AC Optimal Power Flow (AC XOPF)
- Integration of wind, impact on LMPs; the effects of voltage optimization on LMPs
- More advanced challenges– Managing seams within control areas (TOs, DOs, ISO) and across control areas in a smart grid interconnection.

Basic Objectives of Smart Grids

- Enable sustainable energy (rel+eff+clean)
- Serve grid users-centric functions (demand-side choice, integration of new small resources)
- To meet these objectives Smart Grid must evolve to

  - perform just-in-time(JIT), just-in-place(JIP) and just-in-context(JIC) functions;

  - rely on SCADA, PMUs, AMIs, DLRs information; and,

  - coordinate most effective resources to accommodate changes as they happen (preventive no longer sustainable)

Sustainability Requires Juggling of Multiple Performance Metrics

- ***Operations =*** Managing Multiple Performance Metrics
  - Enhance reliability during normal conditions
  - Enhance reliability during non-time-critical contingencies
  - Enhance efficiency during normal operations
  - Enable the grid to adjust to initially non-feasible conditions through partial load shedding, and the adjustment of flow settings in controllable components such as PARs, OLTCs and shunts

  This is low hanging fruit for smart-grid operation

- ***Planning***: Help defer new investments by relying on JIT operations

Implementation of Corrective Actions-- AC XOPF

- AC XOPF is key to:
  - selecting the right performance metrics as needed (efficiency and reduced emission during normal conditions; managing extreme voltages and flows during abnormal conditions)
  - Computing the most effective system-wide adjustments
- Must use AC XOPF-like tools to assess feasibility and minimize total generation, or use MXV to asses feasibility and reduce voltage outliers.
- For infeasible systems, determine the minimal load shedding required for feasibility. This has to be done in coordination with the TOs and DOs if/when large amounts of load is willing to be managed when necessary.

Large Systems Examples—Meeting Different Performance Metrics

- Effects of corrective actions--- AC XOPF software effectively manages contingencies (including the demand side management help)
- Use of AC XOPF for enhancing efficiency
- Use of AC XOPF to reduce the need for reactive power reserves

Systems & Contingencies

System	Buses	Generator Buses	AC Lines	Transformers	Switched Shunts	DC Lines
I	303	53	359	85	0	0
II	1447	348	2352	507	0	0
III	5249	531	4301	1943	320	2
IV- EMS	2003	371	1921	877	31	0
IV- OPS	7678	761	6505	3221	472	0

System	Contingency Description
I	All individual 161-kV lines, and all double 400-kV line combinations
III	Loss of 5 critical lines and shunts: 5L41, 5L42, 5L81, 5L82, 5L87
IV- EMS	1026 contingencies defined by breaker settings
IV- OPS	875 contingencies involving line, transformer and machine outages

Improving Reliability by JIT, JIP Actions—A Must Do in Smart Grids

- Software-supported efficiency without threatening reliability during normal and non-time critical conditions
- CONDITIONS WILL CHANGE CONTINUOUSLY DUE TO INTERMITTENCY;
- No clear separation between normal and abnormal conditions; instead heavy reliance on JIT (corrective)

Example of Large Scale Systems—Illustrations of the Effects of Corrective Actions – System I

Contingency	NETSS Results
161-kV single-line outages (308 cases)	All contingencies are feasible except: (1) 24 cases in which radial buses become disconnected, requiring 100% load shedding; and (2) 4 cases which require partial load shedding.
400-kV double-line outages (496 cases)	All contingencies are feasible.

Results are based on variable equipment, 0.95-1.05 pu voltages, Rate A thermal limits for 161-kV outages, and 120% Rate A thermal limits for 400-kV outages.

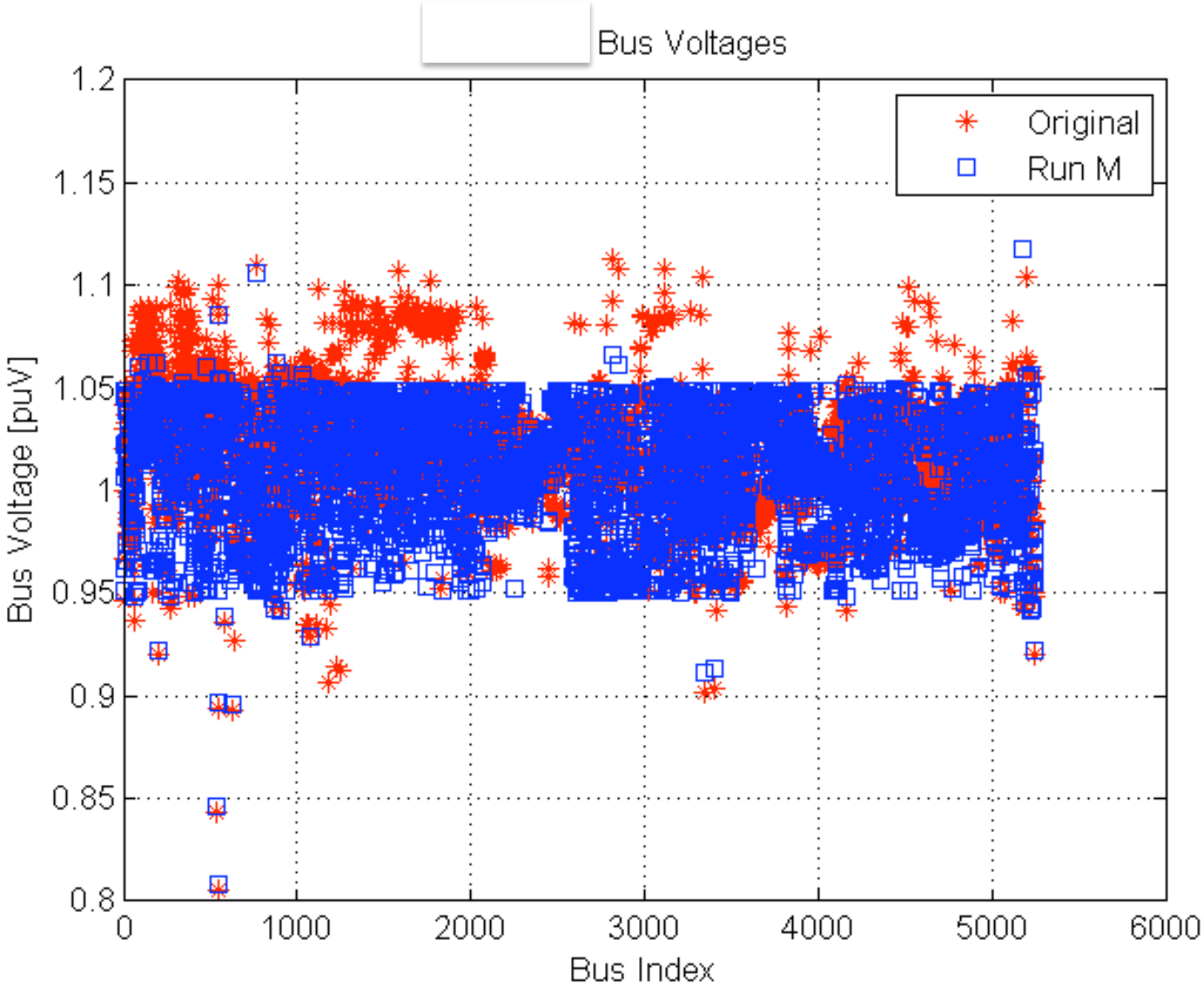
THE SAME SYSTEMS AS IN NETSS PRESENTATION JUNE 23, 2010

Results of Corrective Actions – System III

Run #	Contingency	System III Comments	NETSS Results	# Outliers
-	None	Base case		600
M	5L41	Low voltages and insufficient voltage stability	Secure voltages (0.95-1.05) excepting original outliers after optimization.	52
N	5L42	Unstable system	Secure voltages (0.95-1.05) excepting original outliers after optimization.	54
O	5L81	Low voltages and insufficient voltage stability	Secure voltages (0.95-1.05) excepting original outliers after optimization.	52
P	5L82	Low voltages and insufficient voltage stability	Secure voltages (0.95-1.05) excepting original outliers after optimization.	50
Q	5L87	Voltages too low at XXX-500	Secure voltages (0.95-1.05) excepting original outliers after optimization. Voltage at XXX-500 is 1.05.	50

Results are based on variable equipment, 0.95-1.05 pu voltages, and Rate A thermal limits, and using voltage penalty limits of 0.951-1.049 puV.

Results of Corrective Actions – System III



Improving efficiency by JIT, JIP Actions

- Continuously adapt what is available to improve efficiency during normal operation.

  -A. Requires that local controllers/protection on power plants, transmission lines and consumer consumption act quickly and in coordination

  -B. Requires on-line coordinated exchange between utilities and larger regions

  -C. This requires use of tools like AC XOPF

Improved Efficiency (OPF) – System IV OPS

Minimum total real generation under normal conditions. Controls include generator voltages and real power, and transformer settings in System IV alone.

Run #	Solution	Controls	Generation [MW]	Losses [MW]	Losses [%]
-	Original	Original	70298	1986	100
5	NETSS	Fixed except for real-power generation	70264	1952	98
6	NETSS	Variable	70181	1107	56

Improved Efficiency (OQF) – System IV OPS

Minimum total reactive generation under normal conditions. Controls include generator voltages and real power, and transformer settings in System IV alone.

Run #	Solution	Controls	RSS Reactive Generation [MVAR]	Real Generation [MW]
-	Original	Original	1492	30567
13	NETSS	Fixed except for real power generation	1418	30500
14	NETSS	Same as Run 13 except for voltage adjustments at buses 72692, 72694, 73110 and 73216	1368	30502
15	NETSS	Same as Run 14 except for additional voltage adjustments at buses 73116 and 73276	1342	30502
16	NETSS	Variable	1152	30492

Power is totaled across System IV alone.

Maintaining System Security

- First, optimize system performance during contingency

  - primary objective is to determine whether a feasible control space exists (real and reactive power are balanced at all buses, all bus voltages are within their limits, and all controls are within their limits)

  - secondary objective examines the cost of the contingency

    System III → extreme voltage management

    System I & System IV → minimize transmission losses

- Second, if a feasible control space does not exist, employ minimal load shedding to determine a feasible control space

  - restrict load shedding to the same zones as the contingency

System I

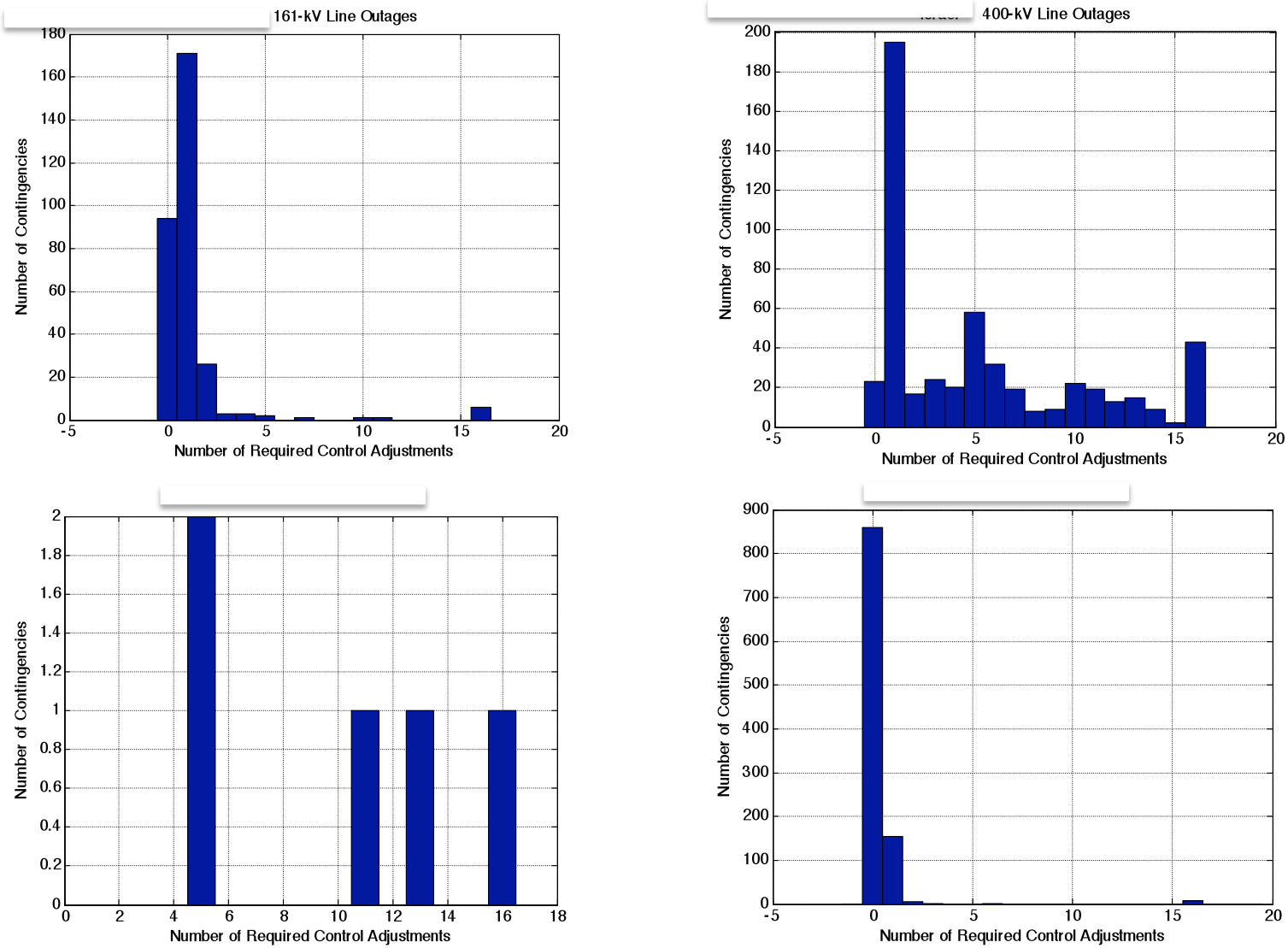
- All 400-kV single-line and double-line outages result in a secure system using all available controls
- All but 4 161-kV single-line outages result in a secure system using all available controls
- Minimal localized load shedding restores system security in all four exceptional cases

Contingency	Required Load Shedding
Line 2210-2250	40% at Bus 3020
Line 3010-3020	23% at Bus 2250
Line 4140-4500	60% at Bus 4500
Line 4200-4330	28% at Bus 4300 and 3% at Bus 4310

System IV-EMS

Contingency	Transformer Controls	Required Load Shedding
129N	Fixed	27% at Bus 3818
240C	Fixed	11% at Bus 1120
C129	Fixed	14% at Bus 3818
E131	Fixed	100% at Bus 4061 3% at Bus 4089 100% at Bus 4638
ZC36	Fixed	38% at Bus 8732
ZC37	Fixed	14% at Bus 7255
129N	Variable	27% at Bus 3818
240C	Variable	11% at Bus 1120
C129	Variable	14% at Bus 3818
E131	Variable	100% at Bus 4061 97% at Bus 4638

Minimal-Control-Action Results



Estimated efficiency savings through corrective actions apporach

- 10%-20% of $200B is $20B-$40B savings each year in the United States!!!

- Imagine how much more sustainable the Earth could be
- Grossly under-estimated assessments of Smart Grid potential (it is NOT delivery losses only)

The Future Role of AC OPF in Integrating wind—NPCC example

- Study the impact of integrating large scale wind power on system operations and costs
- Compare DCOPF vs. ACOPF in terms of LMP and generation schedules.
- Valuing operational parameters (voltage and reactive power support) of power grid under different optimization scenarios
- Simulations done by NETSS, in support of PhD work of Noha-Abdel Karim (CMU)

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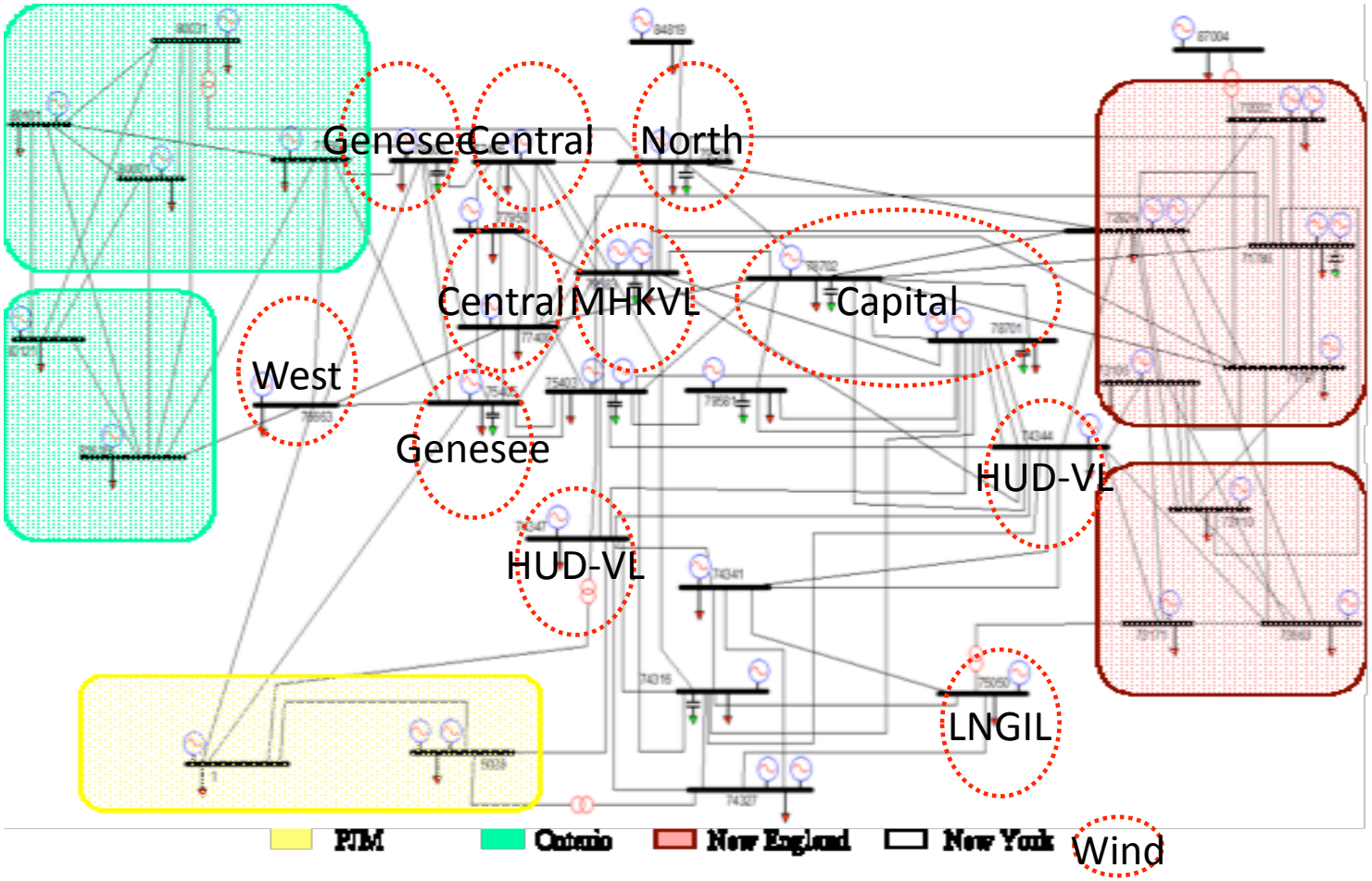
NPCC System



One line diagram of the reduced NPCC equivalent model

Marginal Cost Formula Used in 2008 $

	Fuel Cost $/ MBTU	*Heat rate BTU/KWh*	*MC $/MWh*
Coal	2.31	8,844	20.43
Gas	8.82	7,196	63.47
Uranium	0.52	10,400	5.41
Oil	14.51	10,842	157.32

Installed and projected MW zonal Wind penetration levels of NYISO

	Potential MW wind power			
Area	**Base wind**	**10%**	**50%**	**100%**
West	156.6	401.6	2008	4016
Genesee	10	51.5	257.5	515
Central	36	92.2	461	922
North	8.5	43.3	216.5	433
MHK– VL	35	268.3	1341.5	2683
Capital	27.4	70.3	351.5	703
HUD –VL	6	15.4	77	154
LG – IL	11.7	60	300	600
Total	**391**	**1,002.6**	**5,013**	**1,0026**

NPCC Equivalent Generation Mix[1]

Bus #	Market Zone	Generation Mix
1	PJM	34% Coal, 24% Nuclear, 15% Gas, 23% Oil, 5% Hydro
5028	PJM	33.3% Coal, 33.3% Gas, 33.3% Oil
70002	New England	100% Gas
71786	New England	20% Nuclear, 35% Gas, 35% Oil, 10% Hydro
71797	New England	30% Nuclear, 50% Gas, 20% Oil
72926	New England	25% Nuclear, 75% Hydro
73106	New England	66.6% Oil, 33.4% Gas
73110	New England	75% Nuclear, 15% Oil, 10% Gas
73171	New England	66.6% Oil, 33.4% Gas
73663	New England	66.6% Oil, 33.4% Gas
74316	NY - Dunwoodie	100% Nuclear
74327	NY - NY City	66.6% Gas, 33.4% Oil
74341	NY - Millwood	100% Refuse
74344	NY - Hudson Valley	100% Gas
74347	NY - Hudson Valley	10% Coal, 5% Hydro, 85% Gas
75050	NY - Long Island	66.6% Gas, 33.4% Oil
75403	NY - Mohawk Valley	100% Hydro
75405	NY - Central	50% Gas, 50% Oil
76663	NY - West	66.6% Oil, 33.4% Gas
77400	NY - Central	100% Gas
77406	NY - Central	50% Nuclear, 50% Gas
77950	NY - Central	100% Nuclear
78701	NY - Capital	100% Gas
78702	NY - Capital	75% Gas, 25% Hydro
79578	NY - North	20% Gas, 80% Hydro
79581	NY - Capital	100% Hydro
79583	NY - Mohawk Valley	20% Wind, 20% Hydro, 60% Gas
79584	NY - West	100% Hydro
79800	NY - Genesee	70% Nuclear, 30% Coal

[1] *Source*: Eric H. Allen, *Jeffrey H. Lang, and Marija D. Ili´c,* "A Combined Equivalenced-Electric, Economic & Market Representation of the Northeastern Power Coordinating Council US Electric Power System," *IEEE Power System Transaction, Feb. 2008*

2. LMP Sensitivities to Wind: ACOPF vs. DCOPF

ACOPF

$$Min \sum_{i=1}^{N} C_{Gi} P_{Gi}$$

$$P_{Gi} - P_{Li} - P(V,\theta) = 0$$

$$Q_{Gi} - Q_{Li} - Q(V,\theta) = 0$$

$$Pg_i^{\min} \le Pg_i \le Pg_i^{\max}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}$$

$$\begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_B \end{bmatrix} \le \begin{bmatrix} F_1^{\max} \\ F_2^{\max} \\ \vdots \\ F_B^{\max} \end{bmatrix}$$

$$V_i^{\min} \le V_i \le V_i^{\max}$$

DCOPF

$$Min \sum_{i=1}^{N} C_{Gi} P_{Gi}$$

$$\sum_{i=1}^{N} P_{Gi} - \sum_{i=1}^{N} P_{Di} = 0$$

$$Q_{Gi} - Q_{Li} - Q(V,\theta) = 0$$

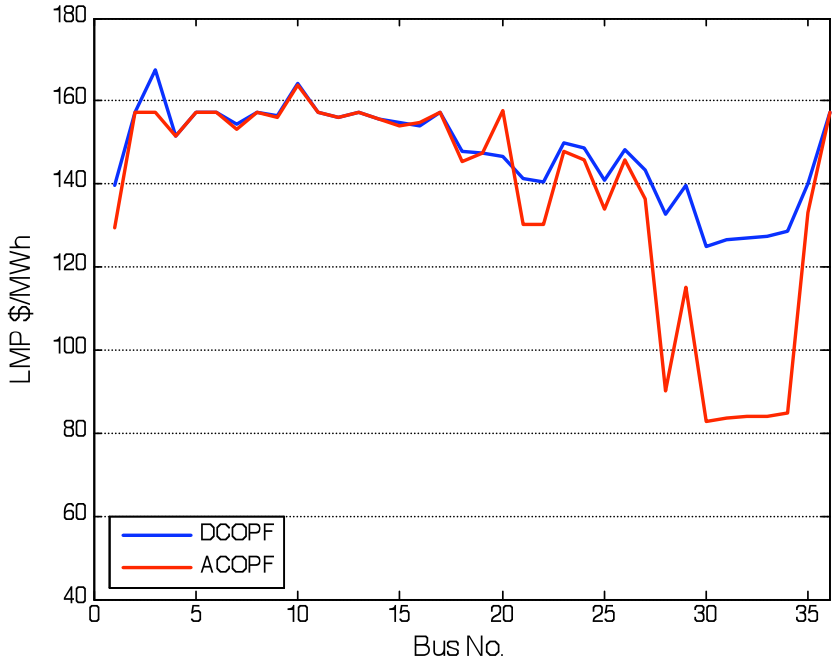
$$Pg_i^{\min} \le Pg_i \le Pg_i^{\max}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}$$

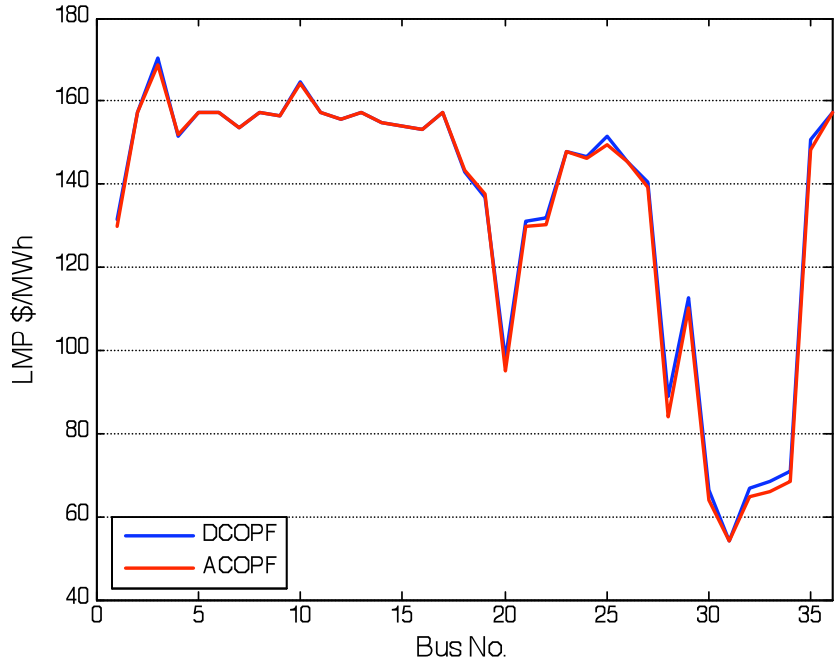
$$\begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_B \end{bmatrix} \le \begin{bmatrix} F_1^{\max} \\ F_2^{\max} \\ \vdots \\ F_B^{\max} \end{bmatrix}$$

$$V_i^{\min} \le V_i \le V_i^{\max}$$

LMP Sensitivities to Wind: ACOPF vs. DCOPF

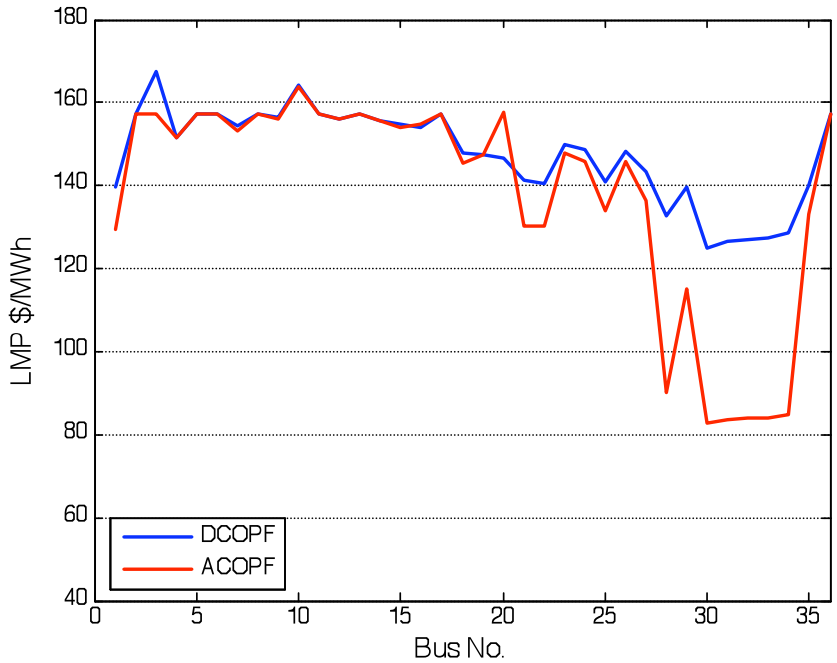


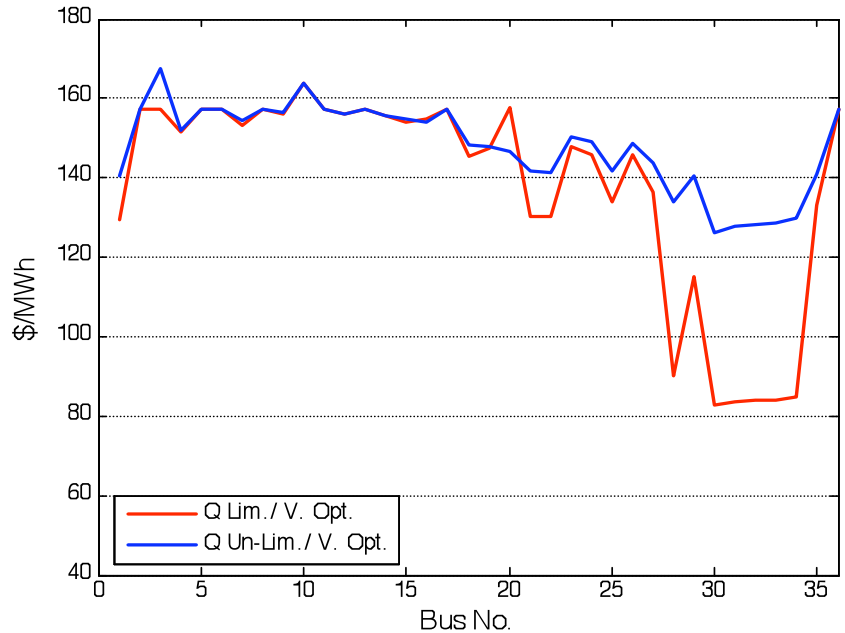
LMP values NO wind & No load scale



LMP values at 10GW wind & 1.3 load scale

The Value of Voltage Dispatch





Preliminary observations

- The results show greater LMP sensitivity to net power injections at nodes with minimum LMP values, which happen to be the nodes with hydro, nuclear and wind installed capacities
- A negligible LMP sensitivity effect almost occurs at nodes with high LMP and expensive generations
- DCOPF is then performed to compare LMP sensitivities to ACOPF, the results show an over LMP estimation using DCOPF for No wind/load scale scenario
- Different optimization scenarios have been applied to show the benefit of voltage optimization and Q support on LMP, and it has been shown an under estimation of LMP when voltage is not optimized and an over-estimation when Q support is unlimited.

Smart Grid Enabled by AC XOPF—Coordinated Voltage Support (CVC)

A smart grid involves two-way information exchange between ISO, TOs and DOs

- TOs and DOs propose ranges of equipment settings to the ISO
- ISO coordinates optimal settings of generators, T&D equipment and demand served
- TOs and DOs control settings of their equipment based on ISO advisory computations; this could become automated (need for remote monitoring and control of key OLTCs and CBs, for example)

Important observations

- ISO will optimize system-wide objective depending on the overall conditions as they evolve.
- It is key to make sure that the load is served, according to the demand functions given by the DOs.

Summary---Toward JIT,JIP,JIC in Smart Grids

- Preventive action: one control set for normal operation as well as all for contingencies

  - relatively risk-free and simple to implement

  - large operating margins during normal operation results in conservative, expensive and environmentally unfriendly operation, and probable over-construction with associated increased maintenance

- Corrective action: separate control set for normal operation and for each contingency

  - smaller operating margins during all operation resulting in reduced financial and environmental costs

  - requires more complex control algorithms and infrastructure

  - appropriate only for non-time-critical contingencies

Summary- Toward the Smart Grids

- The grid is challenged to support many unconventional users.
- Impossible to build new infrastructure for the "worst case" scenario. Must rely on JIT corrective instead of on preventive actions.
- Meeting sustainability objectives will require adaptively targeted performance metrics.
- The number and diversity of system users will require all possible in terms of on-line decision making.
- Key role of information and software.