Modeling of Hardware-and Systems-Related Transmission Limits: The Use of AC OPF for Relaxing Transmission Limits to Enhance Reliability and Efficiency

Marija Ilic milic@ece.cmu.edu

with contributions by

Jeffrey Lang jeffrey.lang@netssinc.com;

Sanja Cvijic sanja13@andrew.cmu.edu

Andrew Hsu andrewhs@andrew.cmu.edu

Staff Technical Conference: Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software

Docket No. AD10-12-004, Washington DC, June 24-26, 2013

Outline

- Optimization objectives in terms of real power
- Limits to optimization: grid power delivery (``congestion")
- Congestion dependent on:
  – Hardware limits (thermal, voltage; control)

  --Systems limits (solution existence and stability)
- *Implications of modeling/analysis/optimization assumptions on reliable and efficient congestion management*

Main objectives of this talk

- Inter-dependence of: 1) modeling assumptions; 2) analysis tools and 3) optimization tools.
- Optimization critical for finding physical solutions

  -Smart grid offers new control means (injections; voltage; reactances; flows; thermal limit adjustments)

  -System limits result of optimization, not an input to the problem

  -Relevance of performance objective in large systems
- Need new methods for finding combinations of control actions to

  - ensure feasible delivery

  -prioritize most effective combinations of control actions

Hardware and systems constraints

- Hard to differentiate between: 1) non-existence of a physical solution; and 2) limitations of a numerical method used.
- *Def: Physical solution ⇔ a (dynamically) stable solution within the hardware limits*
- ****Beyond thermal limits****

-Explicit differentiation between the hardware and systems limits must be made

-Hardware constraints--to ensure safe utilization of equipment

-Real power line flow constraints currently used as proxy limits to reflect systems operating problems. This needs fixing.

Modeling and tools used

- Modeling assumptions

  -load (impedance; current; real power/ power factor; real power/reactive power ratio)

  -system is dynamically stable when scheduling

  -*numerical stability of the power flow analysis/static optimization the same as existence of a physically meaningful solution*

- Analysis tools (DC power flow vs. AC power flow)
- Optimization tools (DC OPF vs. AC OPF)

The case of a two-node system

Objective: Understand existence of solution [1]

Figure 1: Two-bus system

$P_L = 1.736pu$ and $Q_L = 7.848pu$.

1. $V_2 = 4.019$ p.u and $\delta_2 = -0.04$ rad;
2. $V_2 = 0.999$ p.u and $\delta_2 = -0.17$ rad ;

Effect of numerical tools used

- DC power flow will give solution 2 for angle;
- AC power flow solution sensitive to initial conditions/method used (homotopy[6]; NR; optimization)

	Matpower PF	Homotopy PF	Matpower OPF	NETSS OPF
2-bus	$V_2 = 1$ $\delta_2 = -10°$ unstable	1 solution $V_2 = 1$ $\delta_2 = -10°$ unstable	$V_2 = 1$ $\delta_2 = -10°$ unstable	$V_2 = 1$ $\delta_2 = -10°$ unstable

Unstable=numerically unstable; J matrix has negative eigenvalues

$$Mism = -J \cdot \Delta x$$

$$\begin{bmatrix} P_{mism} \\ Q_{mism} \end{bmatrix} = - \begin{bmatrix} \frac{\partial \Delta P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial \Delta Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \cdot \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix}$$

Findings for larger systems

	$V_{min} - V_{max}$	Matpower PF	Homotopy PF	Matpower OPF	NETSS OPF
14-bus	0.94-1.06	stable	4 solutions 1 stable 3 unstable	stable	stable
30-bus	0.95-1.05	stable	2 solutions both stable	stable	stable
57-bus	0.94-1.06	stable	4 solutions 1 stable 3 unstable	stable	stable
118-bus	0.94-1.06	stable	4 solutions 1 stable 3 unstable	stable	stable
300-bus	0.94-1.06	unstable	2 solutions both unstable	unstable	unstable

Some preliminary conclusions

- *DC(O)PF--finds a solution but fails to balance reactive power and/or observe voltage/reactive power hardware limits*
- NR numerical stability (based on Jacobian) not an indicator of physical solution existence; Jacobian is not an indicator of small signal stability either; controllers using dynamic models need to be used to ensure (dynamic) stability of the solution
- *Sufficient conditions for NR to converge should not be used interchangeably for assessing whether the solution exists and/or is physically stable;* For answering the question regarding which is ``physical solution" , see [3,Chapter 7]

Analysis tools—global maximum in two node system

- *Effect of modeling assumptions* [2], [3, pp.278-283]
  - Impedance load model (maximum power transfer)-generally high voltage [4]
  - Real power/reactive power [2,3]

$$P_L = G(E_L E_G \cos\delta - E_L^2) + BE_L E_G \sin\delta \tag{5.273}$$

$$Q_L = B(E_L E_G \cos\delta - E_L^2) + GE_2 E_G \sin\delta \tag{5.274}$$

$$a = RP_L + XQ_L \tag{5.275}$$

and

$$b = XP_L - RQ_L \tag{5.276}$$

$$2E_L^2 = (E_G^2 - 2a) \pm \sqrt{E_G^4 - 4(aE_G^2 + b^2)} \tag{5.277}$$

By further normalizing power and voltage as

$$p = \frac{XP_L}{E_G^2} \tag{5.278}$$

$$e = \frac{E_L}{E_G} \tag{5.279}$$

$$q = \frac{Q_L}{P_L} \tag{5.280}$$

and

$$r = R/X \tag{5.281}$$

$$2e^2 = [1 - 2p(r+q)] \pm \sqrt{1 - 4(r+q)p + (1-rq)^2p^2} \tag{5.282}$$

For real- valued solutions of equation (5.282) to exist, it is necessary that

$$1 - 4[(r+q)p + (1-rq)^2p^2] \geq 0 \tag{5.283}$$

$$p_{min} \leq p \leq p_{max} \tag{5.284}$$

where

$$p_{max} = \frac{-(r+q) + \sqrt{(1+r^2)(1+q^2)}}{2(1-rq)^2} > 0 \tag{5.285}$$

$$p_{min} = \frac{-(r+q) - \sqrt{(1+r^2)(1+q^2)}}{(1-rq)^2} \tag{5.286}$$

- Global maximum at $\frac{dp_{max}}{dq} = 0$

$$q = -\frac{1}{r}; p_{max} = \frac{1}{4r}; e_{max} = \frac{\sqrt{1+r^2}}{2r} \tag{5.292}$$

and $\tan\delta = \frac{1}{r}$

At the global maximum

$$P_{loss} = G(E_G^2 + E_L^2 - 2E_G E_L \cos\delta) \tag{5.293}$$

$$Q_{loss} = B(E_G^2 + E_L^2 - 2E_G E_L \cos\delta) \tag{5.294}$$

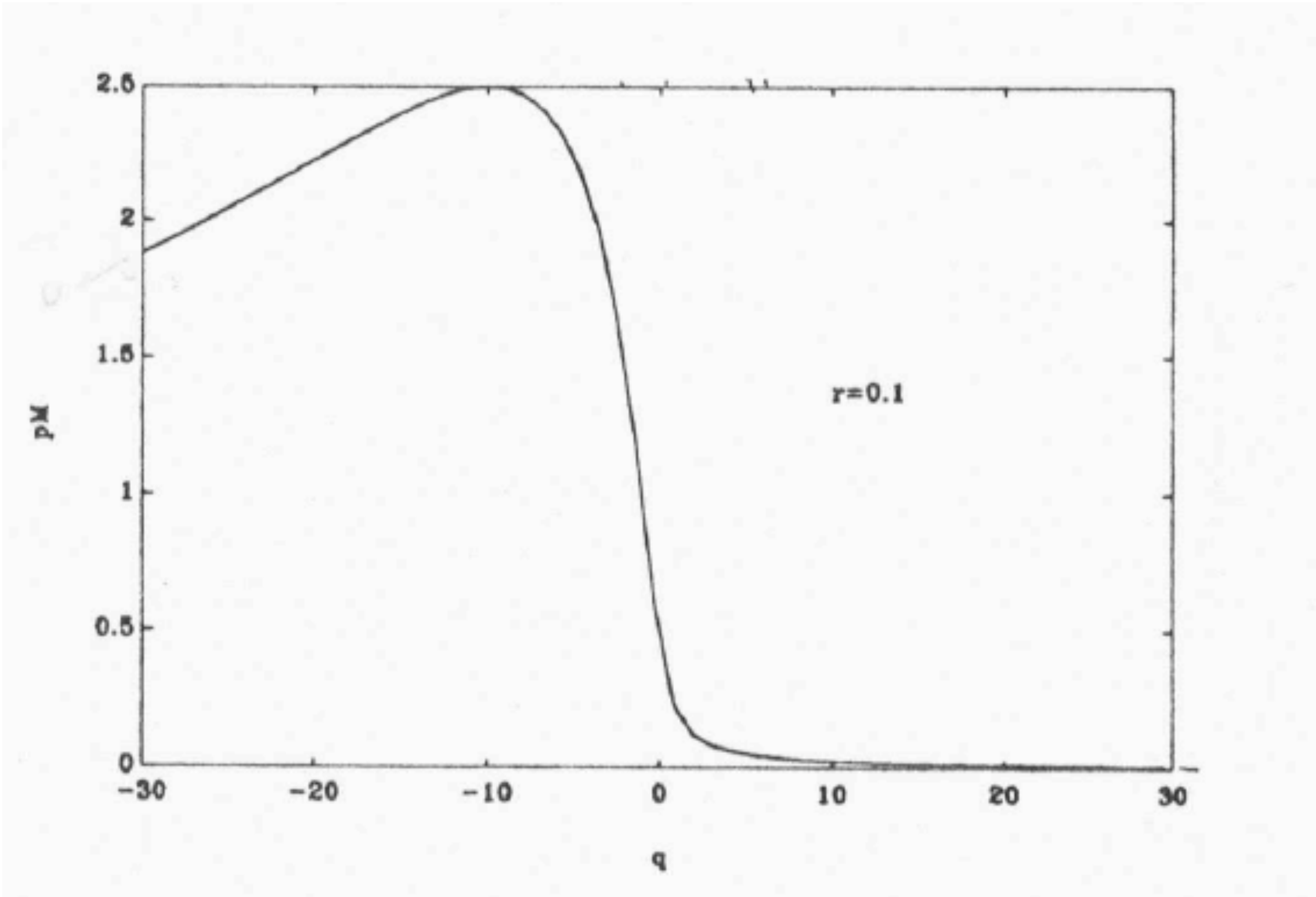
from which it follows that

$$P_{loss} = P_{max} = P_L \tag{5.295}$$

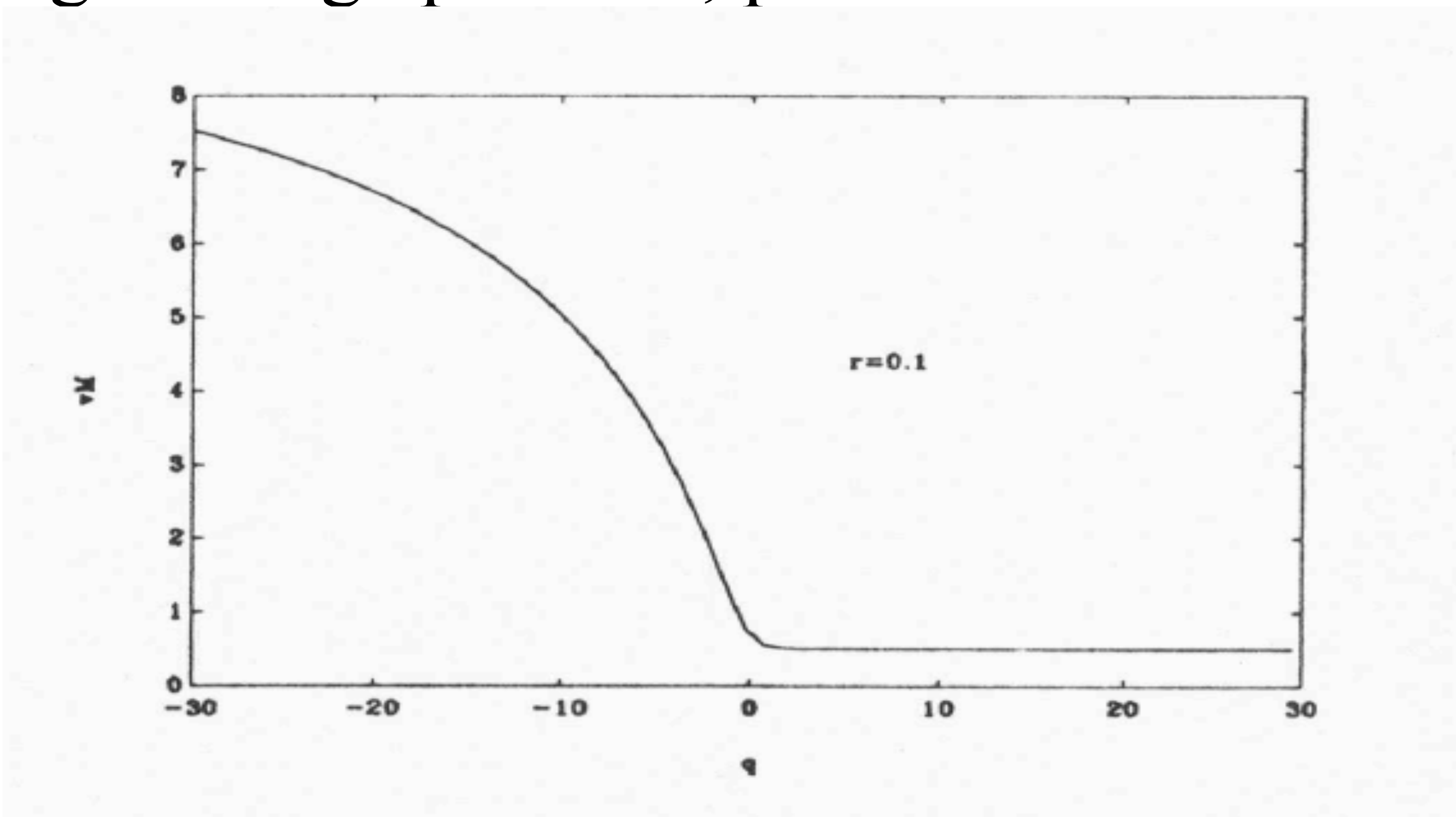
and

$$Q_{loss} = -Q_{max} = Q_L \tag{5.296}$$

Global maximum power



- High voltage problem; power factor low



$$\alpha = \frac{P_L}{\sqrt{P_L^2 + Q_L^2}} = \frac{R}{\sqrt{R^2 + X^2}}$$

Need for optimizing reactive power/voltage

- Impossible to find global optimum by running different scenarios even in the two-node system. To enhance efficiency (maximum power transfer) it is essential to run: 1) AC OPF instead of 2) DC OPF combined with AC power flow analysis.
- Non-feasible solution can be made feasible by optimizing injections, voltages, flows, reactances (smart grid)
- ****When feasible solution does not exist within the limits run families of optimization to find a feasible solution; impossible to do by analysis*

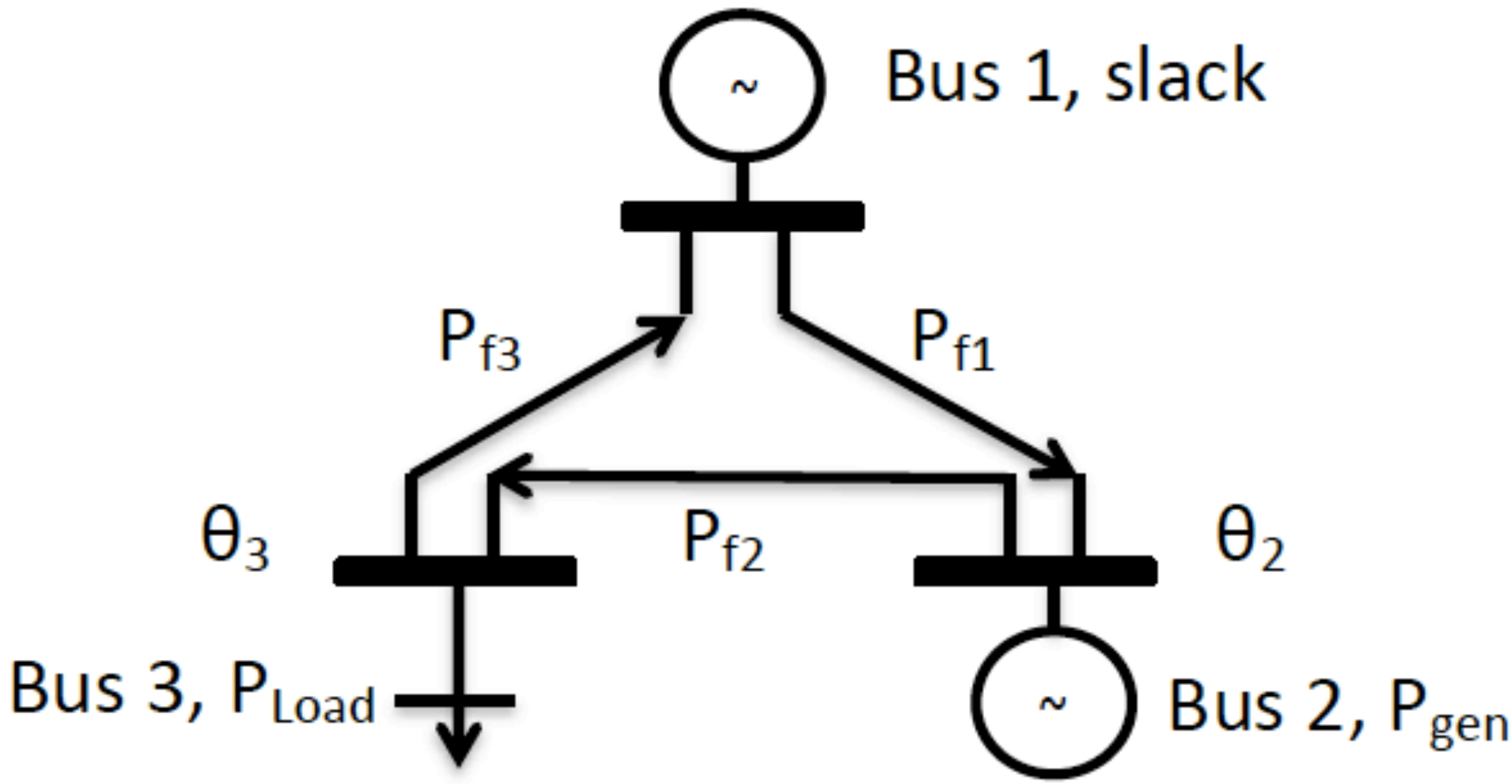
Open questions-Choice of decision variables

- Injections; voltages; flows; network parameters???
- Reactance control particularly interesting
- For direct power flow control

-in two node systems has an easy interpretation of maximum power transfer;

-large systems require completely new formulations: (1) new power flow solvers, including distributed power flow calculator [7]; (2) distributed power flow solution as an optimization problem, with reactance adjustments [10]

Reactance control for ensuring feasible delivery [7]-[10]



Already feasible solutions

P_{gen}	P_{Load}	$G_{1,2}$	$G_{2,3}$	$G_{3,1}$	$B_{1,2}$	$B_{2,3}$	$B_{3,1}$
2	-2	0	0	0	-10	-10	-10

The solution reached by the Newton Raphson solver is:

Newton Raphson solution	
θ_2 (degrees)	θ_3 (degrees)
3.8283	-3.8283

For reference: $\theta_1 = 0$ (slack bus),

$\delta_1 = \theta_1 - \theta_2$, $\delta_2 = \theta_2 - \theta_3$, $\delta_3 = \theta_3 - \theta_1$

Optimization w.r.t. flows gives the same answer

Optimization based method solution (feasible)					
$P_{f,1}$	$P_{f,2}$	$P_{f,3}$	$P_{L,1}$	$P_{L,2}$	$P_{L,3}$
-0.66768	1.3323	-0.66764	1.1592e-006	5.8516e-007	-5.7402e-007

δ_1 (degrees)	δ_2 (degrees)	δ_3 (degrees)	λ_2	λ_3	μ
-3.8283	7.6564	-3.8283	-4.6367e-006	2.2961e-006	-1.548e-007

Controlling NR non-convergent power flow

The infeasible case for this 3 bus system has the following parameters:

P_{gen}	P_{Load}	$G_{1,2}$	$G_{2,3}$	$G_{3,1}$	$B_{1,2}$	$B_{2,3}$	$B_{3,1}$
2	-2	0	0	0	-0.1	-0.1	-0.1

The optimization based algorithm returns the following results:

Optimization based method solution (infeasible)					
$P_{f,1}$	$P_{f,2}$	$P_{f,3}$	$P_{L,1}$	$P_{L,2}$	$P_{L,3}$
-0.64175	1.218	-0.64173	0.28062	9.7009e-006	-0.28061

δ_1 (degrees)	δ_2 (degrees)	δ_3 (degrees)	λ_2	λ_3	μ
306.3745	107.2496	306.3759	-1.1225	1.1224	0.066569

Ensuring feasibility by optimizing injections

The solution as a result of Newton Raphson method is now:

Newton Raphson solution	
θ_2 (degrees)	θ_3 (degrees)
53.1301	- 53.1301

And the optimization based solution is:

Optimization based method solution (adjusted injections)					
$P_{f,1}$	$P_{f,2}$	$P_{f,3}$	$P_{L,1}$	$P_{L,2}$	$P_{L,3}$
-0.079369	0.096643	-0.079335	1.1231e-005	7.42e-009	-1.1223e-005

δ_1 (degrees)	δ_2 (degrees)	δ_3 (degrees)	λ_2	λ_3	μ
-52.5129	104.9935	-52.4806	-4.4923e-005	4.4894e-005	2.4325e-006

Feasible solutions with line reactance adjustments

The optimization based method, with line adjustments, results in the following solution:

Optimization based method solution (adjusted line reactances)					
$P_{f,1}$	$P_{f,2}$	$P_{f,3}$	$P_{L,1}$	$P_{L,2}$	$P_{L,3}$
-0.46123	1.5388	-0.46117	0	0	0

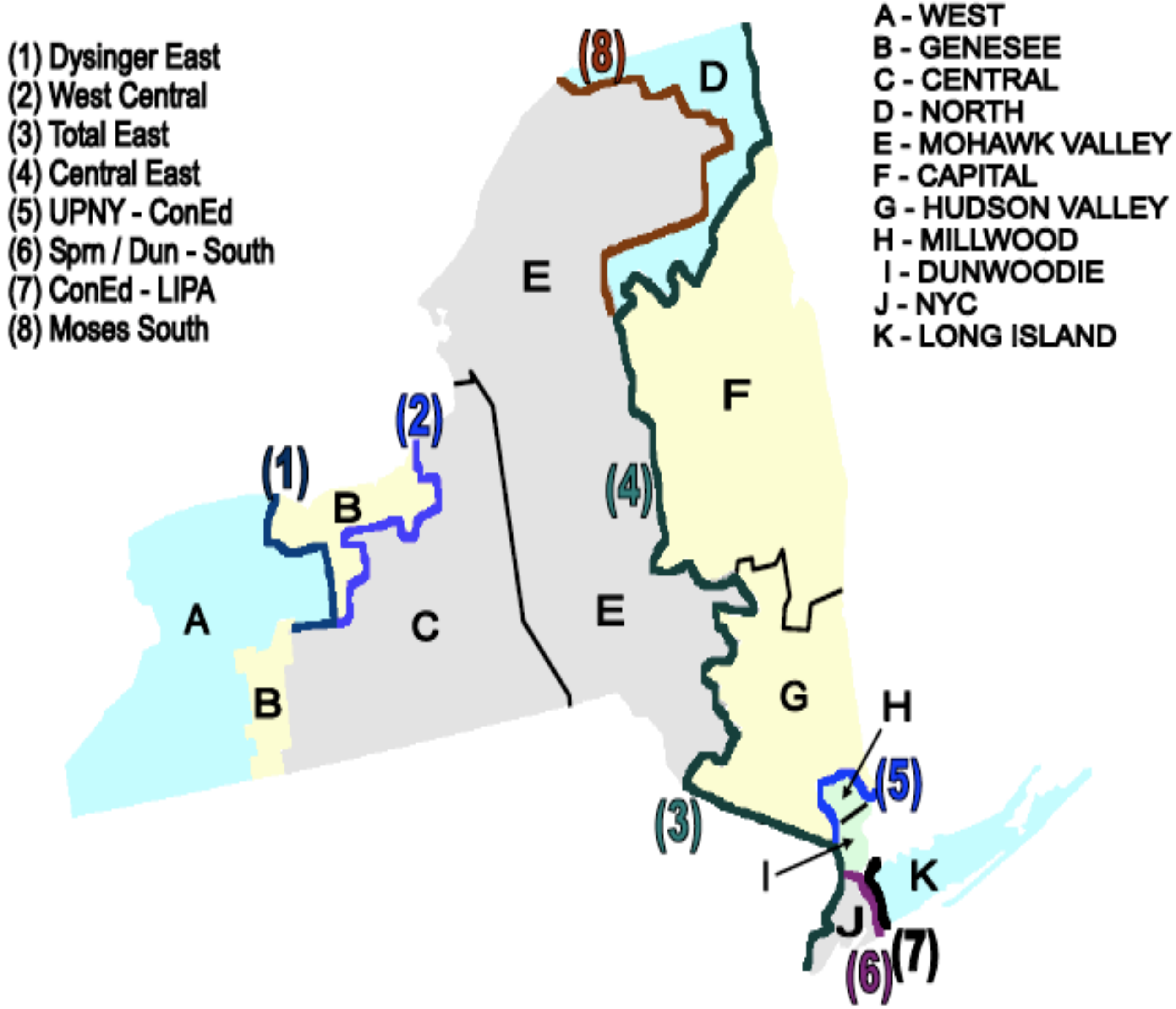
δ_1 (degrees)	δ_2 (degrees)	δ_3 (degrees)	λ_2	λ_3	μ
25.4026	-50.8021	25.3995	2.1376e-008	-2.1325e-008	2.807e-009

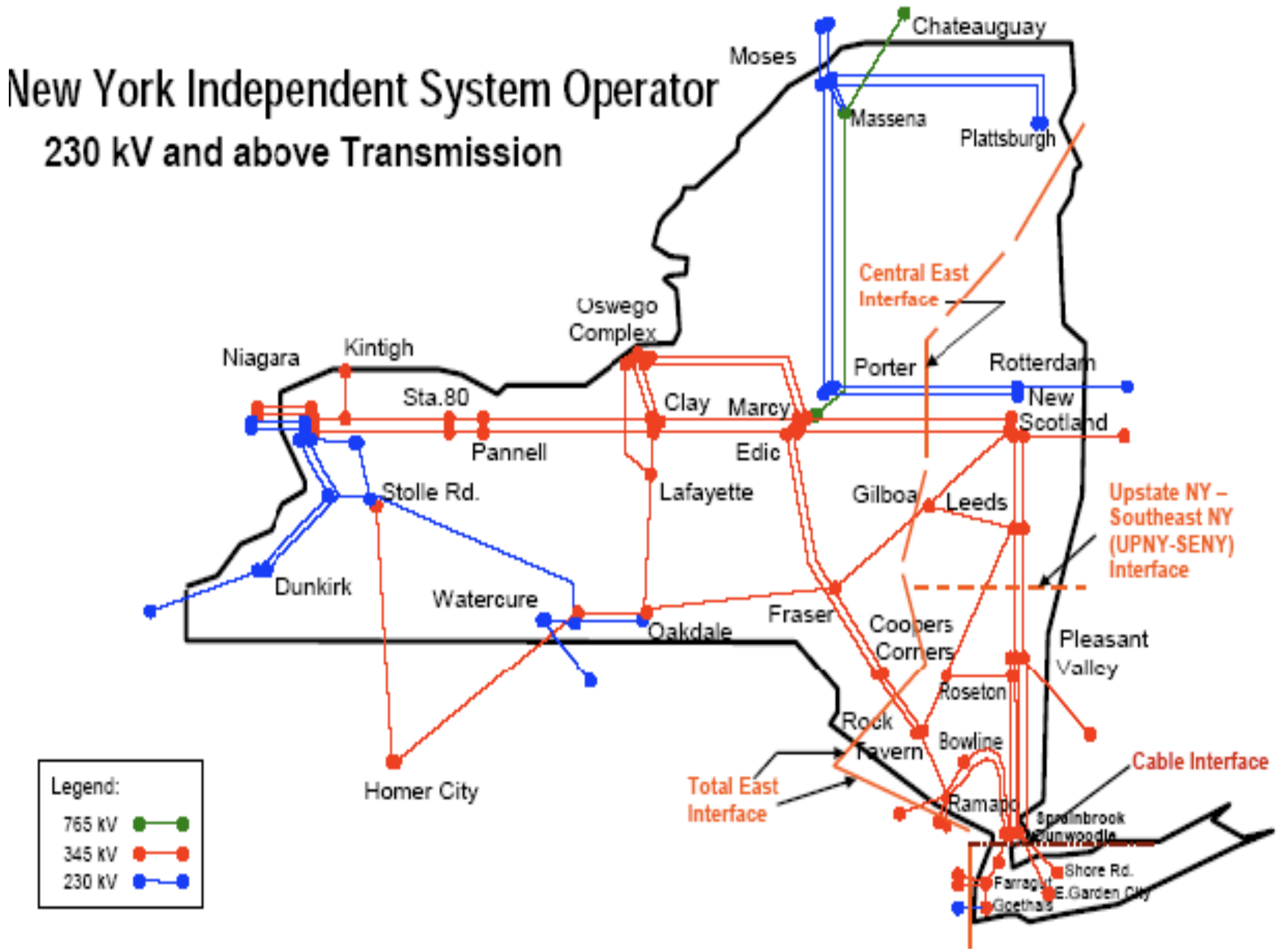
$B_{1,2}$	$B_{2,3}$	$B_{3,1}$
-1.0752	-1.9856	-1.0752

Relevance for general systems- Optimizations objectives considered

- (1) points-to-points transfer optimizations;
- (2) optimizations designed to maximize interface flows;
- (3) loadability optimizations as an alternative to both interface studies;
- (4) economic dispatch, and
- (5) loss minimization

- ***In two bus system under certain assumptions (1)-(5) are the same objectives; not true in general****


(1) Dysinger East
(2) West Central
(3) Total East
(4) Central East
(5) UPNY - ConEd
(6) Spm / Dun - South
(7) ConEd - LIPA
(8) Moses South
A - WEST
B - GENESEE
C - CENTRAL
D - NORTH
E - MOHAWK VALLEY
F - CAPITAL
G - HUDSON VALLEY
H - MILLWOOD
I - DUNWOODIE
J - NYC
K - LONG ISLAND
A
B
B
C
D
E
E
F
G
H
I
J
K
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)


New York Independent System Operator
230 kV and above Transmission
Chateauguay
Moses
Massena
Plattsburgh
Central East
Interface
Oswego
Complex
Niagara
Kintigh
Sta.80
Clay
Marcy
Porter
Rotterdam
New
Scotland
Pannell
Edic
Stolle Rd.
Lafayette
Gilboa
Leeds
Upstate NY –
Southeast NY
(UPNY-SENY)
Interface
Dunkirk
Watercure
Oakdale
Fraser
Coopers
Corners
Pleasant
Valley
Roseton
Rock
Tavern
Bowline
Cable Interface
Homer City
Total East
Interface
Ramapo
Shore Rd.
Farragut
E.Garden City
Goethals
Legend:
765 kV
345 kV
230 kV

Conflicting optimization objectives [5]

- Objectives (1)-(5) often conflict and are best served with control dispatches specific to each objective
- For example, the greatest possible large power transfer from Canada to NYC does not result in the maximum possible flow across many of the interfaces along the way.
- Similarly, economic dispatch does not result in the stress of any single interface over another.
- Interface flows should not be a goal in itself.
- Instead, the objectives should be targeted toward enabling system-wide objectives such as reliable generation cost minimization and/or maximization of power delivered to the large load centers.

Combinatorial aspects of control solutions

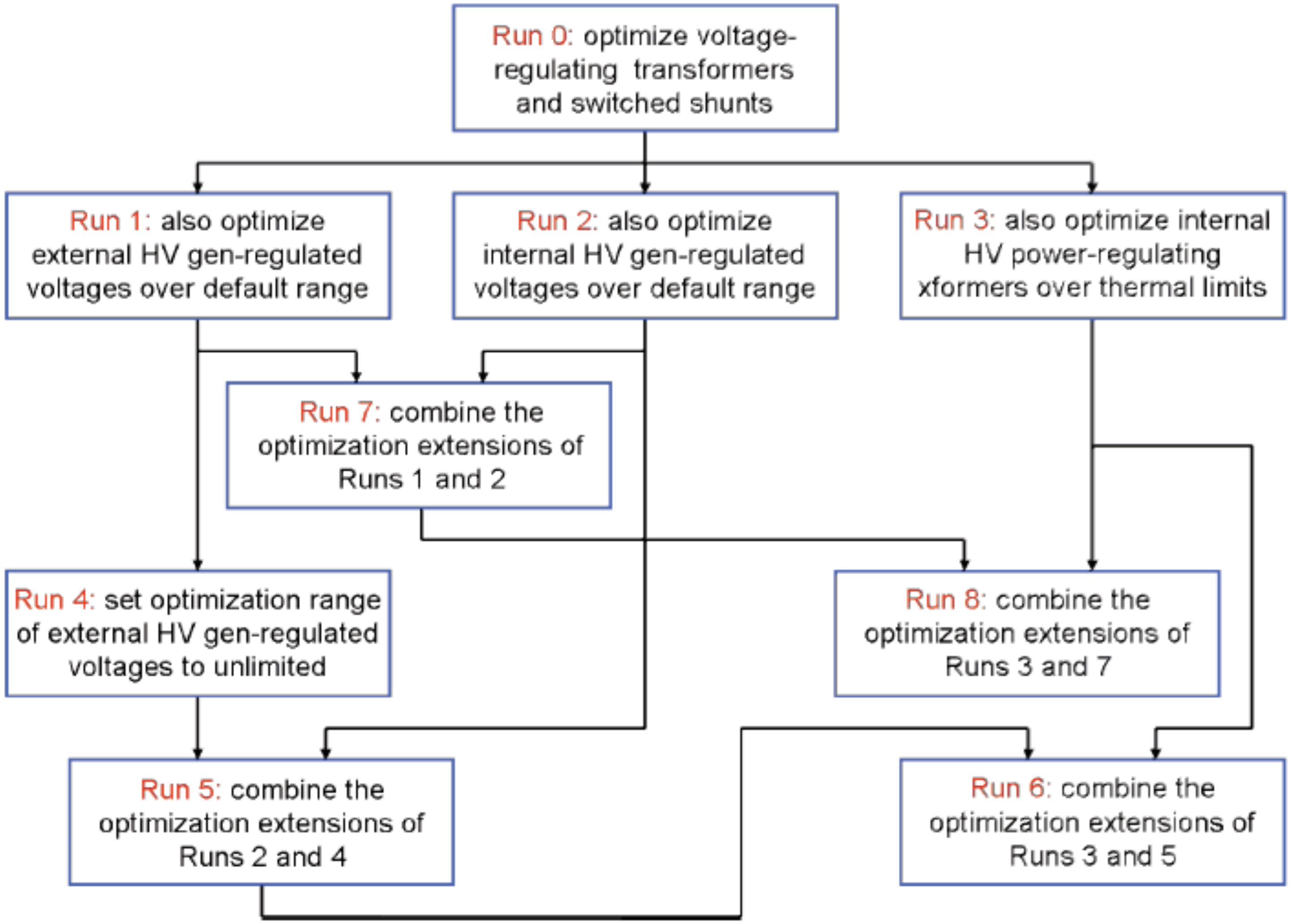


Figure 1-1: ***Flow Charts of Optimization Runs***

Conflicting optimization objectives

Run Set		Run 0		Run 2		Run 7	
		NYC Load [MW]	Int. Flow [MW]	NYC Load [MW]	Int. Flow [MW]	NYC Load [MW]	Int. Flow [MW]
DE/WC	L2	21156	DE: 2285 WC: 966	21542	DE: 2798 WC: 1438	21594	DE: 2800 WC: 1441
	PP[DEWC]3	20122	DE: 2154 WC: 846	20175	DE: 2203 WC: 900	20242	DE: 2203 WC: 902
	IF[DE]1	20546	2388	20867	2812	20553	2812
	IF[WC]1	20581	1059	21016	1453	20630	1457
CE	L5	21381	3109	21509	3207	21538	3209
	PP[CE]2	20762	3027	21114	3248	21332	3292
	IF[CE]1	21116	3398	21235	3482	21193	3515
TE	L6	20870	5759	21041	5995	21082	6016
	PP[TE]2	20461	5395	20733	5721	20968	5939
	IF[TE]0	20665	5884	20841	6071	20813	6101

Table 9: *Comparison of NYC load and interface flows across various optimizations*

Maximizing Loadability

- As an alternative to interface flow optimizations, it is of interest to determine how much real power can be transferred from one region to another through the NYCA bulk transmission system independent of concerns over individual interfaces.
- As an example, the loadability optimization considered here seeks to maximize the load served in NYISO Areas 9, 10 and 11 (Dunwoodie, NY City and Long Island) using additional power generated in IESO and HQ.

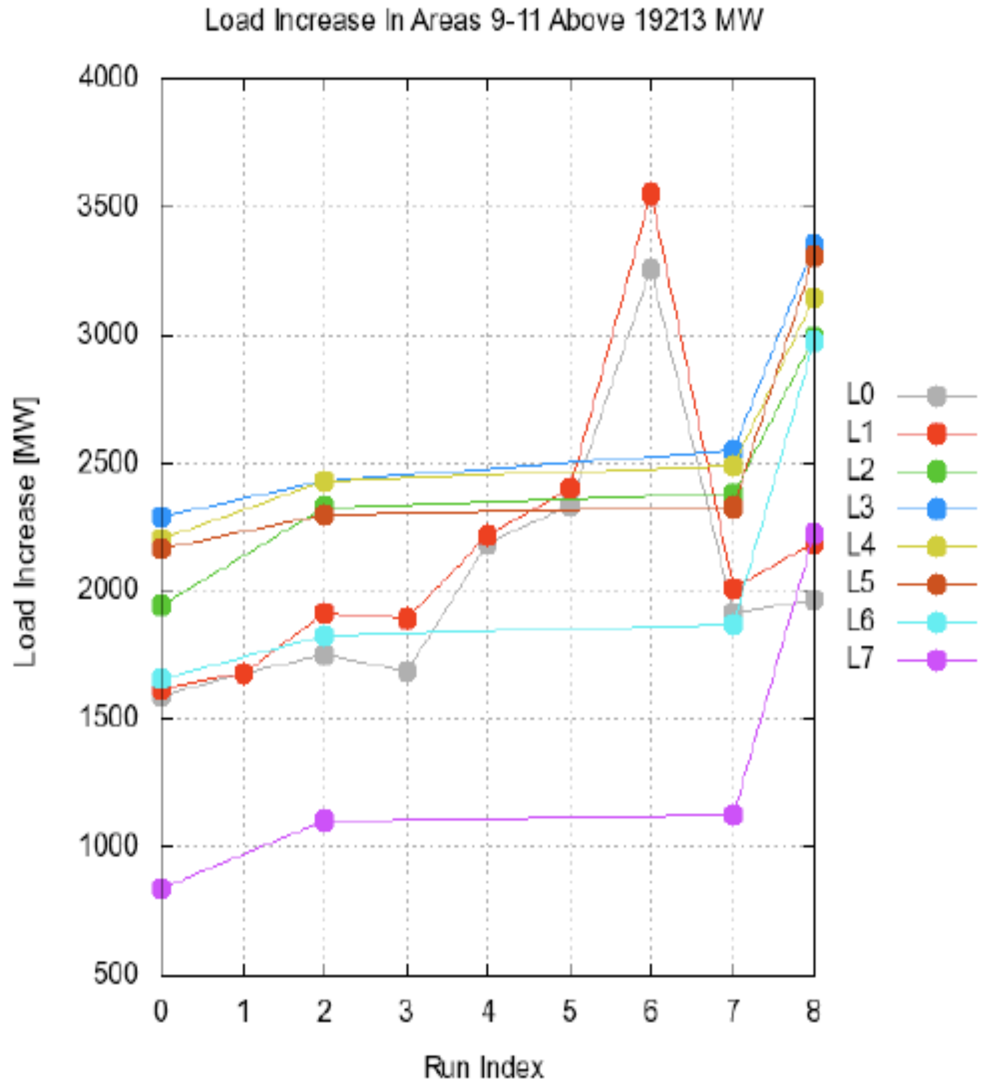
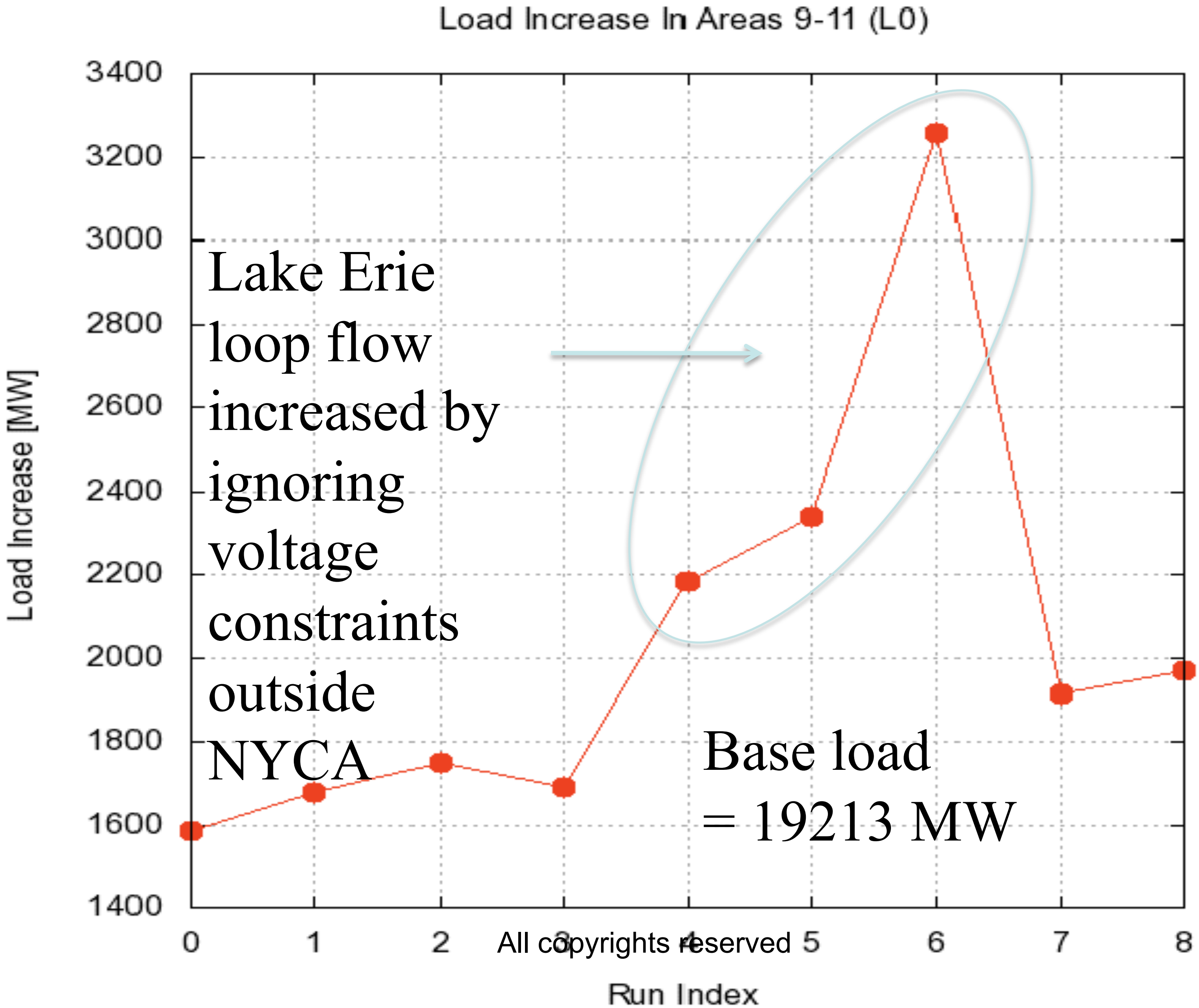


Figure 1-2: *Load served in NYISO Areas 9-11 above the base load of 19213 MW for various combinations of contingencies and control dispatch.*

Load Increase in NYC



Potential for economic dispatch savings

Case	Generation Cost [$/Hr]	Annual Savings
A No voltage control	1205958	Benchmark
B NYCA x-former dispatch	1133203	$637M
00	1115321	$794M
01	1110705	$834M
02	1115025	$796M
03	1098848	$941M
04	1068956	
05	1063000	
06	1018623	
07	1110290	$838M
08	1094488	$980M

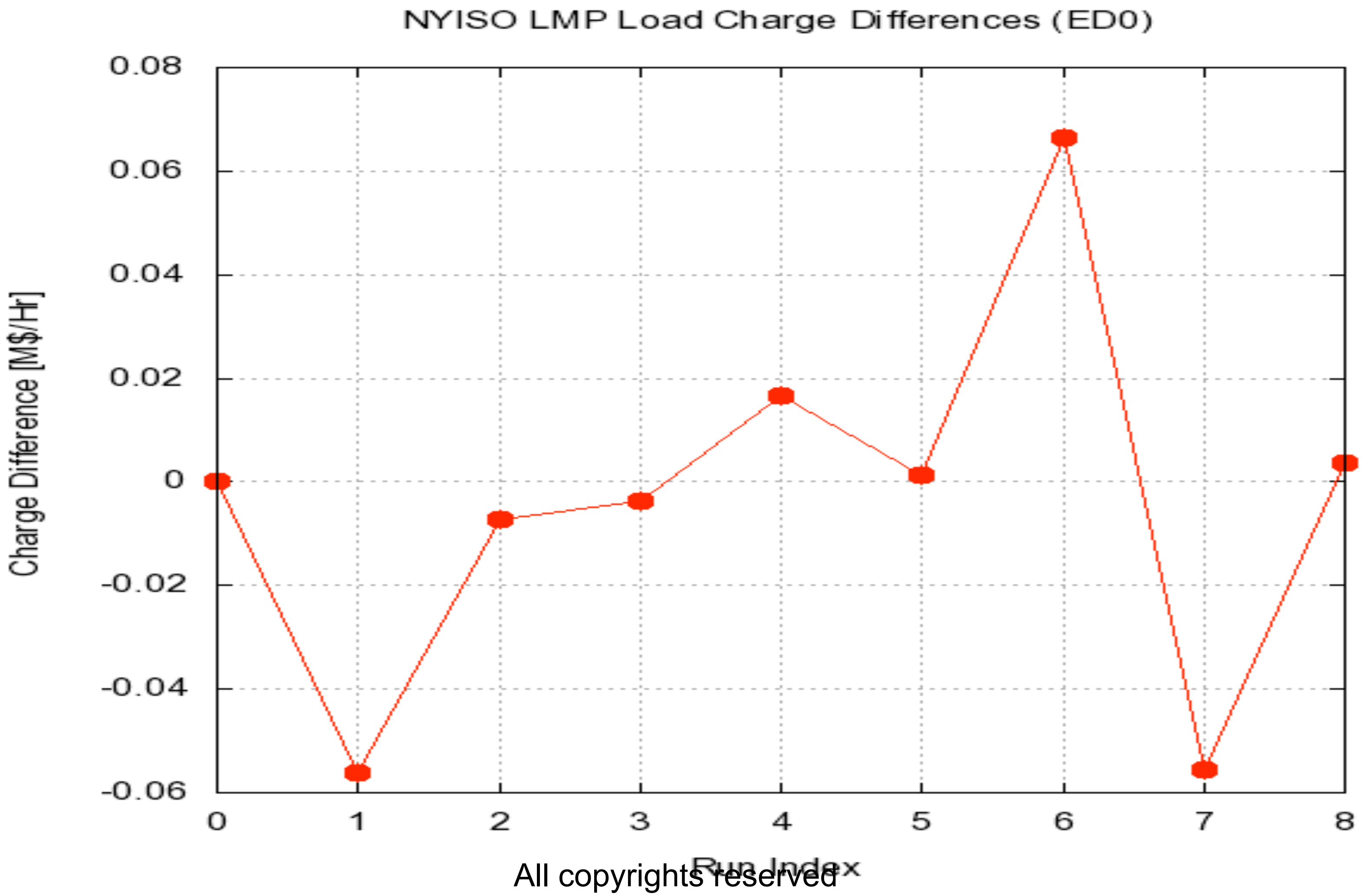
Contingency?	Voltage Range	Thermal Limit	Generation Cost [$/Hr.]	Generation Cost Increase
No	0.98-1.02	Rate A (Normal)	1,110,290	Benchmark
Yes	0.98-1.02	Rate A	1,145,554	3.2%
Yes	0.95-1.05	Rate A	1,120,197	0.9%
Yes	0.98-1.02	Rate B (LTE)	1,114,792	0.4%
Yes	0.95-1.05	Rate B	1,080,022	-2.7%

Table 11: *Effects of varying limits on generation cost; (LEEDS_3-PLTVLLEY) postcontingency*

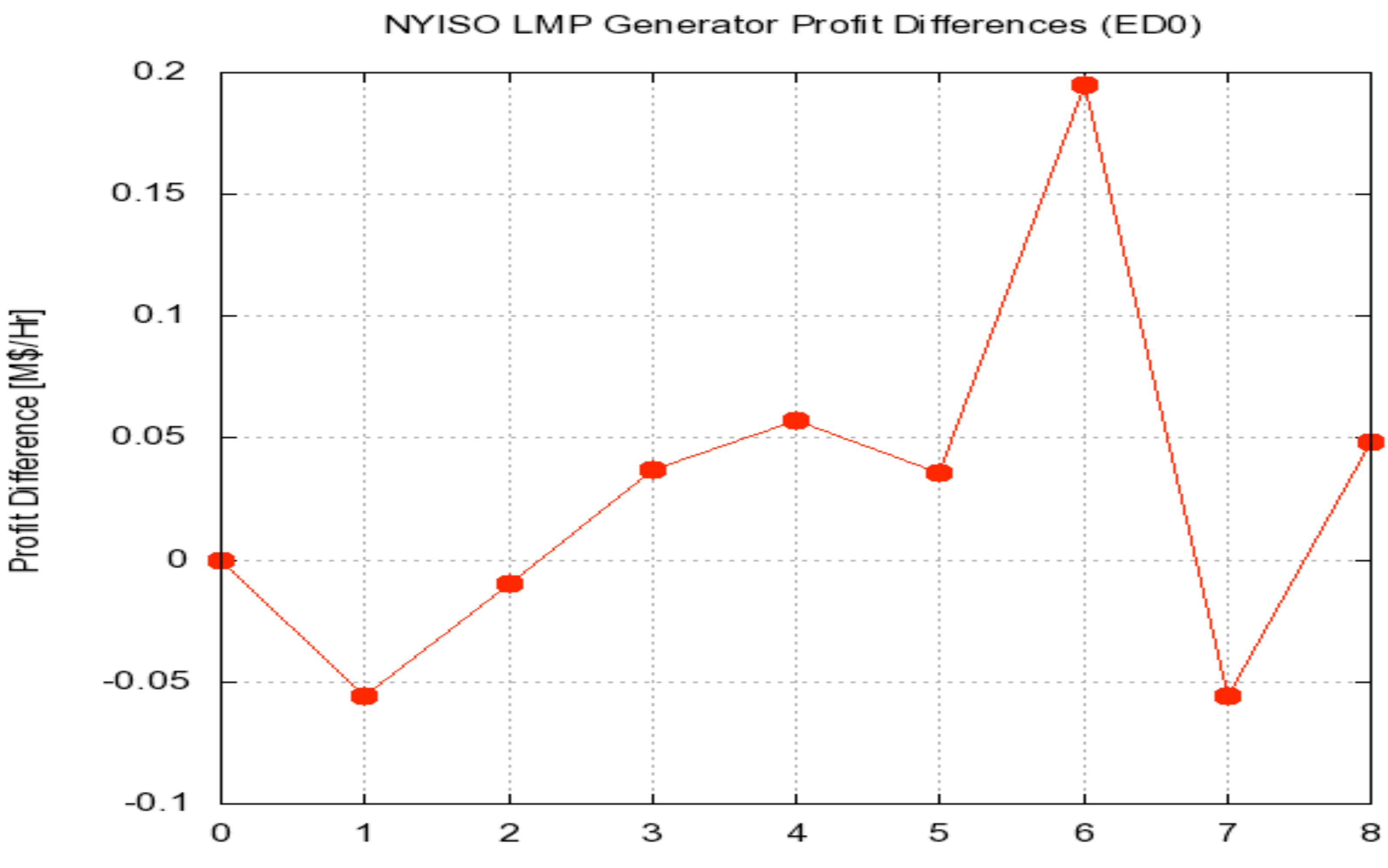
Potential Economic Dispatch Benefits from Corrective Actions

- It is shown that contingencies, when supported by corrective T&D equipment and generation voltage dispatch, can often be managed well without any additional reserve requirements; there is enough capacity on the system [5].
- The bigger problem is enabling delivery of power to the right place. Currently, during normal conditions, the dispatch of additional expensive and/or polluting generation is required up front to reliably prepare for contingencies.
- It would be more efficient to use a corrective approach to managing non-time critical contingencies, and the indirect savings from moving to the corrective approach would reduce the currently required reserves by 10-15%. This cumulatively leads to major efficiency improvements during normal conditions.
- *DC OPF with AC power flow (PV curve) suboptimal*

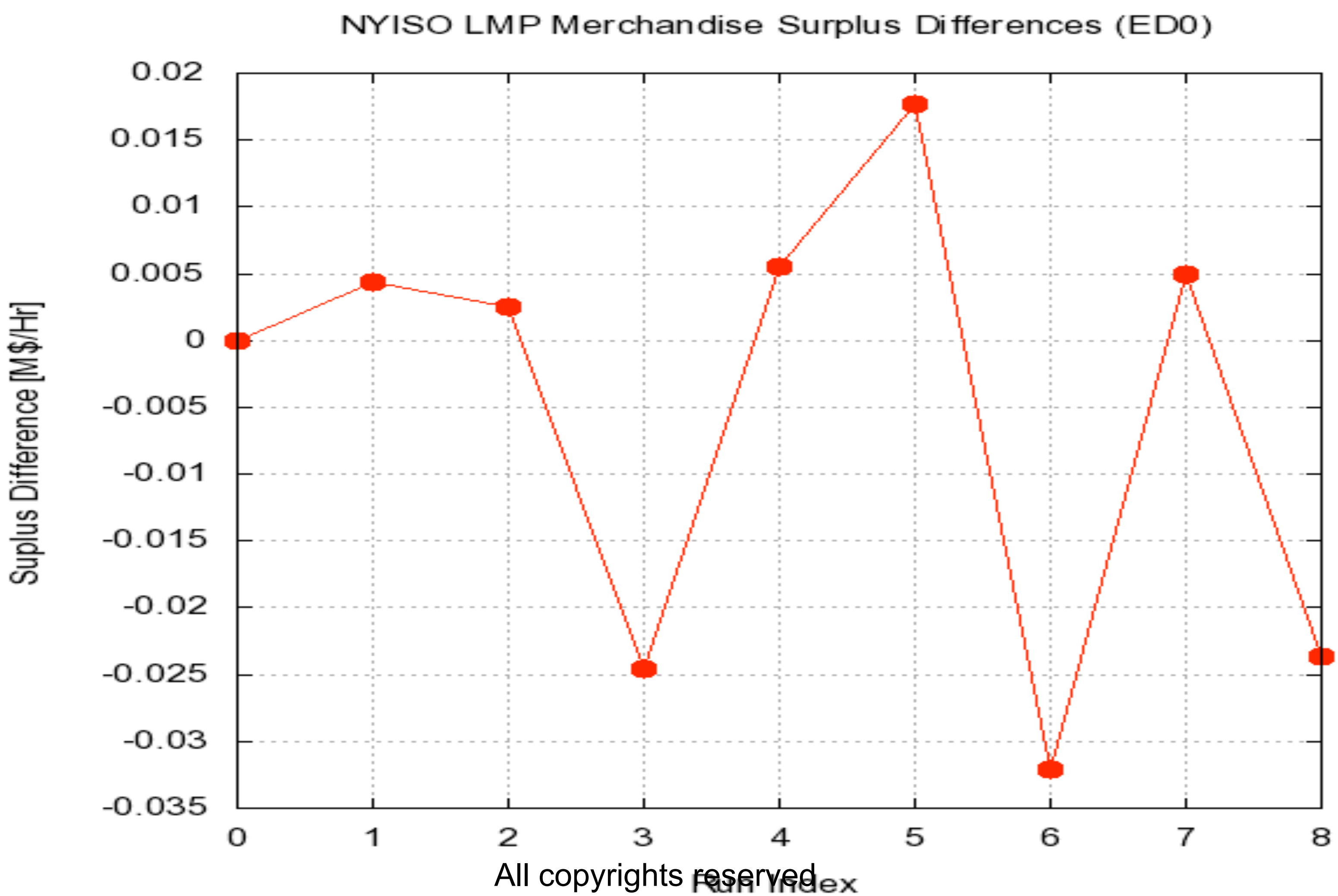
Effects of optimization on markets-Load Charge Differences



Generation Profit Differences



Merchandise Surplus Differences



Critical role of optimization

- Optimization with respect to many available decision variable very beneficial to minimizing cost and serving greater loads all the time.
- *Voltage constraints sometimes hide thermal constraints until voltage is optimized (use of DLRs dependent on optimization used)*
- Multiple optimization are useful in managing resources; still, maximizing import into large loads and minimizing generation cost the key
- Good software gives priorities as part of its output

Importance of voltage optimization

- Many resources (generators, FACTS, transformers, shunts) can control voltage requiring AC OPF for their optimization
- *Without voltage optimization some assets can not be utilized up to their thermal limits*
- Voltage optimization enables serving a greater number of users at a lower cost and with less pollution without adding more assets, all the time.
- Market design needed to support voltage optimization at value

Conclusions

- Based on our findings and the availability of the robust NETSSWorks software used throughout the NYSERDA study [5], we recommend that the most effective dispatch of controllable T&D and generation equipment be implemented.
- This would ensure that the system remains within its hardware constraints as conditions vary. One must screen for voltage excursions at all buses as well as for thermal limits of all lines.
- Without this, the result could be an unreliable system. Critical contingencies should not be inputs, but rather outputs of optimization tools which continuously attempt to find the best adjustments to keep the system within the hardware constraints (ensured reliability) while attempting an efficient (inexpensive and clean) utilization of available resources.
- This way, one could begin to manage reliability and efficiency in a coordinated way.

References

[1] Sanja Cvijic, Marija Ilic, Jeffrey Lang, Report on Numerical Stability of Multiple Power Flow Solutions, NETSS WP 2012, July 2012.

[2] Ilic. M.D., Liu, X., Some optimality notions pf voltage profile for the steady state operation of the electric power systems, Proc. of the Workshop on Bulk Power System Voltage Phenomena, III, Davos, Switzerland, 1994.

[3] Ilic, M.D, Zaborszky, J., Dynamics and Control of Large Scale Electric Power Systems, Willey&Sons, 2000.

[4] Calvaer, A.J., On the maximum loading of active linear electric multiports, Proc. IEEE, pp. 282-283, 1983.

[5] Ilic, M., Lang, J., "Voltage Dispatch and Pricing in Support of Efficient Real Power Dispatch", Final Report, NYSERDA Project 10476, 2012.

[6] Sanja Cvijic, Peter Feldmann and Marija Ilic, "Applications of Homotopy for Solving AC Power Flow and AC Optimal Power Flow", PES General Meeting in San Diego, July 2012

[7] Ilić, M. and Hsu, A. "Toward Distributed Contingency Screening Using Line Flow Calculators and Dynamic Line Rating Units (DLRs)" , Hawaiian International Conference of System Sciences (HICSS). Maui, Hawaii, January 2012.

[8]Hsu, A. and Ilić, M. "Distributed Newton Method For Computing Real Decoupled Power Flow In Lossy Electric Energy Networks" , North American Power Symposium (NAPS), 2012 , vol., no., pp.1-7, 9-11 Sept. 2012.

[9]Ilić, M. and Hsu, A. "General Method For Distributed Line Flow Computing With Local Communications In Meshed Electric Networks", Patent application 20130024168, January 24, 2013

[10]]Ilić, M. and Hsu, A., A Method for Adjusting Generation. Demand and/or Line Flows/Reactances to Ensure Feasible AC Power Flow, Carnegie Mellon Univ. Provisional Patent Filing, June 7, 2013.