New Approaches to Balancing Security & Economy: Risk-based security-constrained economic dispatch (RB-SCED)

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Outline

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6. Effect on LMPs
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Motivation

Provide new market/security software capabilities via:

BETTER SECURITY & ECONOMIC PERFORMANCE:
Identify a more secure operating condition at lower production costs

Function		Concept		Outcome
Risk-based security-constrained economic dispatch (RB-SCED)	→	**Achieve economic objective while managing *system* security +*circuit* security instead of only the latter.**	→	**• more secure operating conditions** **• lower costs**

Motivation

This work is about how to operate power systems under steady-state contingency constraints.

It suggests two changes to the way we balance security and economy in operating power systems [1,2,3] (which is done by the SCED today).

1. Probabilistically weight the contingencies.

2. Change the nature and number of the constraints

This talk focuses mainly on #2 because it is essential.

[1] T. Dy Liacco, “Real-time Computer Control of Power Systems,” Proc. of the IEEE, Vol. 62, No. 7, July 1974,
[2] J. Carpentier, "Differential Injections Method: A General Method for Secure and Optimal Load Flows", IEEE PICA Conference Proceedings Minneapolis, MN, pp. 255-262, June 1973
[3] O. Alsac and B. Stott, “Optimal load flow with steady state security,” IEEE Trans. on Power Apparatus and Systems, Vol. PAS-93, pp. 745-751, May/June 1974

Motivation

Operating condition 1:
1 contingency having
1 post-contingency flow at
101% of its long-time emergency (LTE) limits;
all other contingencies result in post-contingency
flows<90% of their LTE

"INSECURE"

Operating condition 2:
2 different contingencies each having
2 post-contingency flows between
95% and 100% of their LTE

"SECURE"

Yet operating condition #2 is more risky than operating condition #1.
Today's approach does not capture this because it does not quantify
security level in terms of:

- "heavy" post-contingency flows <100% of LTE
- number of contingencies resulting in "heavy" post-contingency flows
- number of "heavy" post-contingency flows for each contingency

SCED and RB-SCED

Whereas SCED imposes re-dispatch control

- only for post-contingency flows exceeding its LTE
- as much as needed, to satisfy the (circuit) LTE

RB-SCED imposes re-dispatch control

- for all “heavy” flows
- weighted by flow magnitude, to satisfy a (system) risk constraint

SCED and RB-SCED

Under RB-SCED, the system is dispatched under normal conditions to:

Same as SCED	**1) Satisfy pre-contingency (normal) flow constraints**
Makes it more secure than SCED	**2) Lower post-contingency flows for circuits having post-contingency loadings above 90% of LTE flow limits**
	3) Satisfy post-contingency flow constraints **• at LTE flow limits**
Makes it more economic than SCED	**• at 105% of LTE flow limits** **• at 120% of LTE flow limits (STE)**

(2) and (3) together results in more secure & more economic operating conditions.

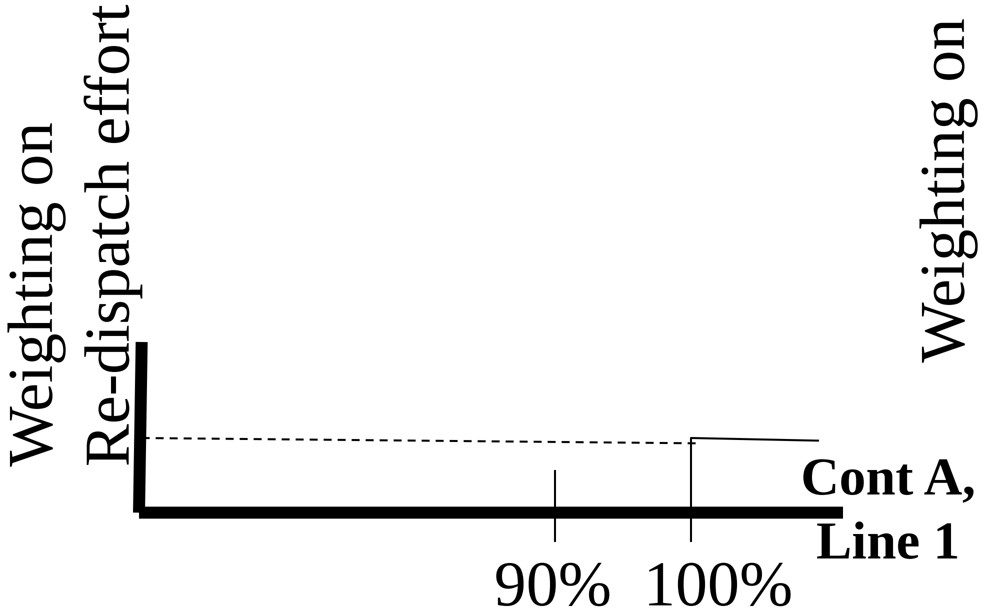
SCED and RB-SCED

Operating condition 3:

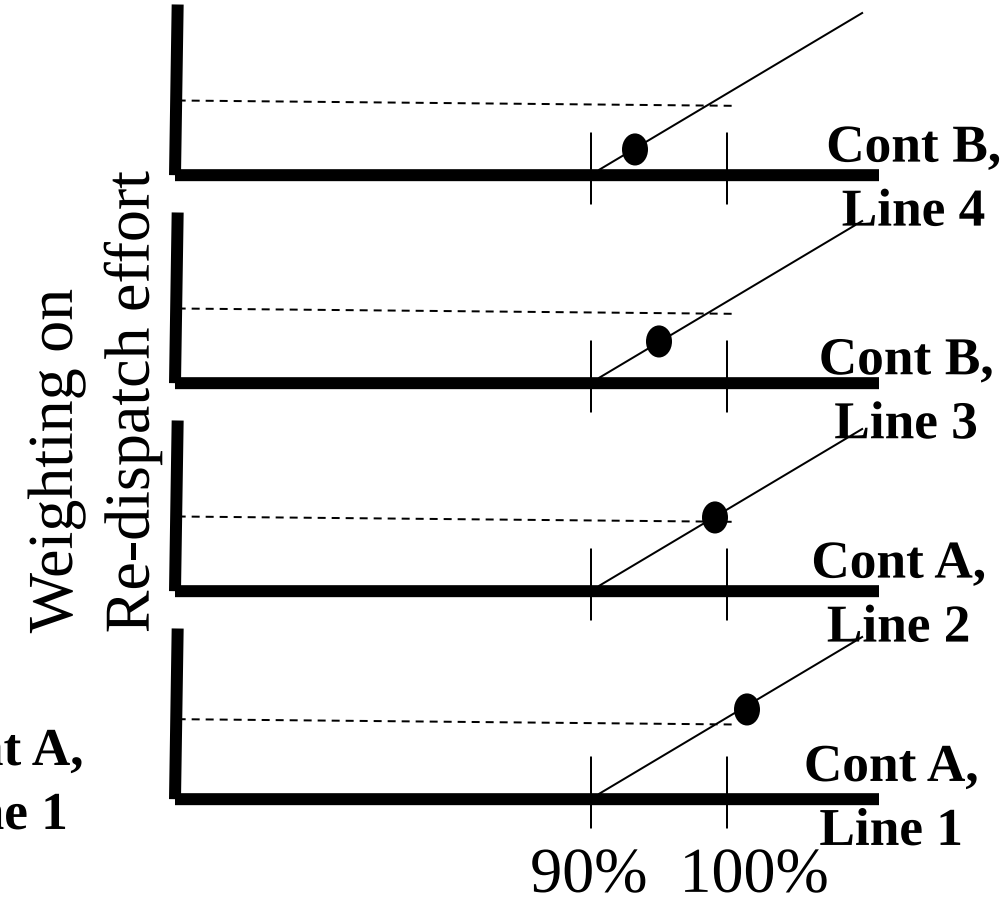
Contingency A results in post-contingency flows of 103% and 98%

Contingency B results in post-contingency flows of 95% and 93%.

What SCED does



What RB-SCED does



Formulation - Optimization

SCED	RB-SCED	
$\text{Min}\left\{ f(\underline{P_0}) \right\}$	$\text{Min}\left\{ f(\underline{P_0}) \right\}$	
$s.t.$	$s.t.$	
$\underline{h}(\underline{P_0}) = \underline{0}$	$\underline{h}(\underline{P_0}) = \underline{0}$	**PF Eqs**
$\underline{g}_{\min} \le \underline{g}(\underline{P_0}) \le \underline{g}_{\max}$	$\underline{g}_{\min} \le \underline{g}(\underline{P_0}) \le \underline{g}_{\max}$	**normal constraints**
$\underline{g}'_{\min} \le \underline{g}_k(\underline{P_0}) \le \underline{g}'_{\max},\ k = 1, \ldots, NC$	$K_C \underline{g}'_{\min} \le \underline{g}_k(\underline{P_0}) \le K_C \underline{g}'_{\max},\quad k = 1, \ldots, NC$	
	$0 \le Risk(\underline{g}_1(P_0), \ldots \underline{g}_{NC}(P_0)) \le K_R Risk_{\max}$	**Risk constraint**

Contingency Constraints

- PF Eqs and normal constraints are identical
- $K_C<1$ tightens contingency constraints; $K_C>1$ loosens them
- Risk constraint is across all contingencies
- $K_R<1$ tightens risk constraint, $K_R>1$ loosens risk constraint
- RB-SCED becomes SCED with $K_R=\infty$, $K_C=1$
- K_R, K_C enable tradeoff between system & circuit security

Formulation - Risk Expression

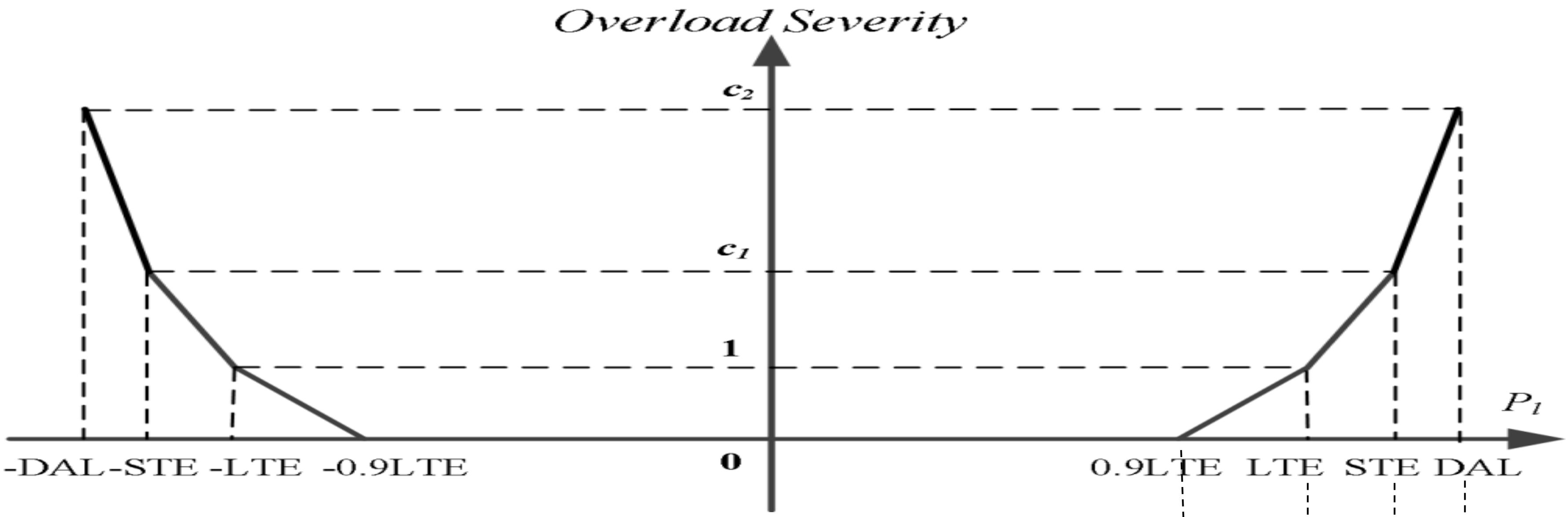
A weighted sum of normalized post-contingency flows on heavy-loaded circuits.

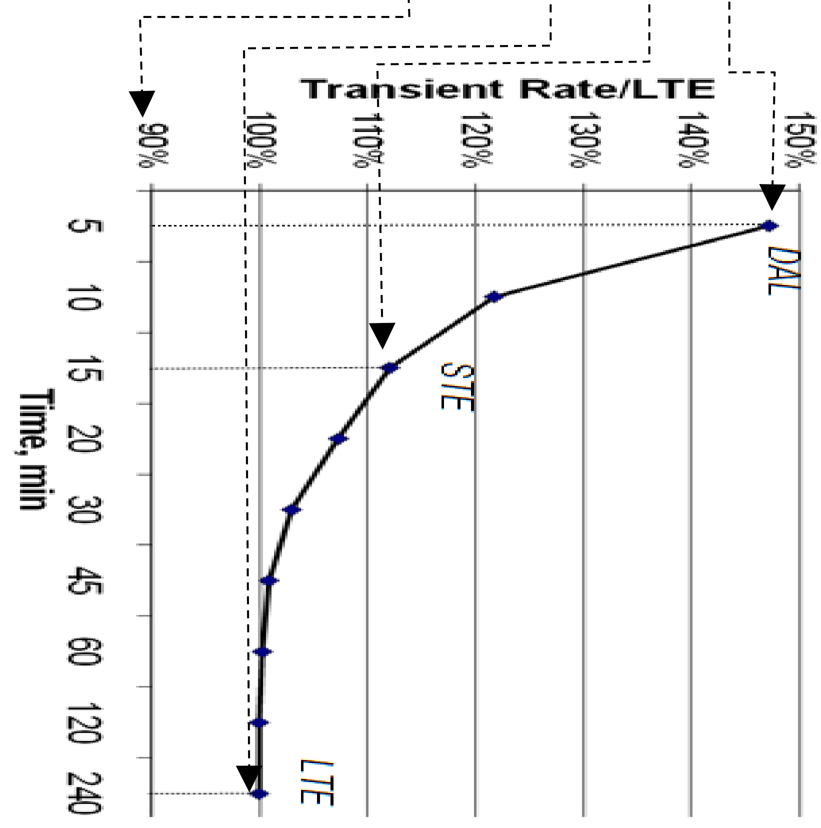
$$Risk\left(\underline{g}_1(\underline{P}_0),\ldots,\underline{g}_{NC}(\underline{P}_0)\right)=\sum_{k=1}^{N_C}\Pr_k\sum_{j=1}^{N_L}Sev_j(\underline{g}_k(\underline{P}_0))$$

Contingency probabilities:

- computed using historical data & real-time information [1]
- or assigned identical values: $Pr_k=1/(N_C+1)$ for all k.

[1] F. Xiao, J. McCalley, Y. Ou, J. Adams, S. Myers, "Contingency Probability Estimation Using Weather and Geographical Data for On-Line Security Assessment," Proceedings of the 9th International Conference on Probabilistic Methods Applied to Power Systems, June 11-15, 2006.





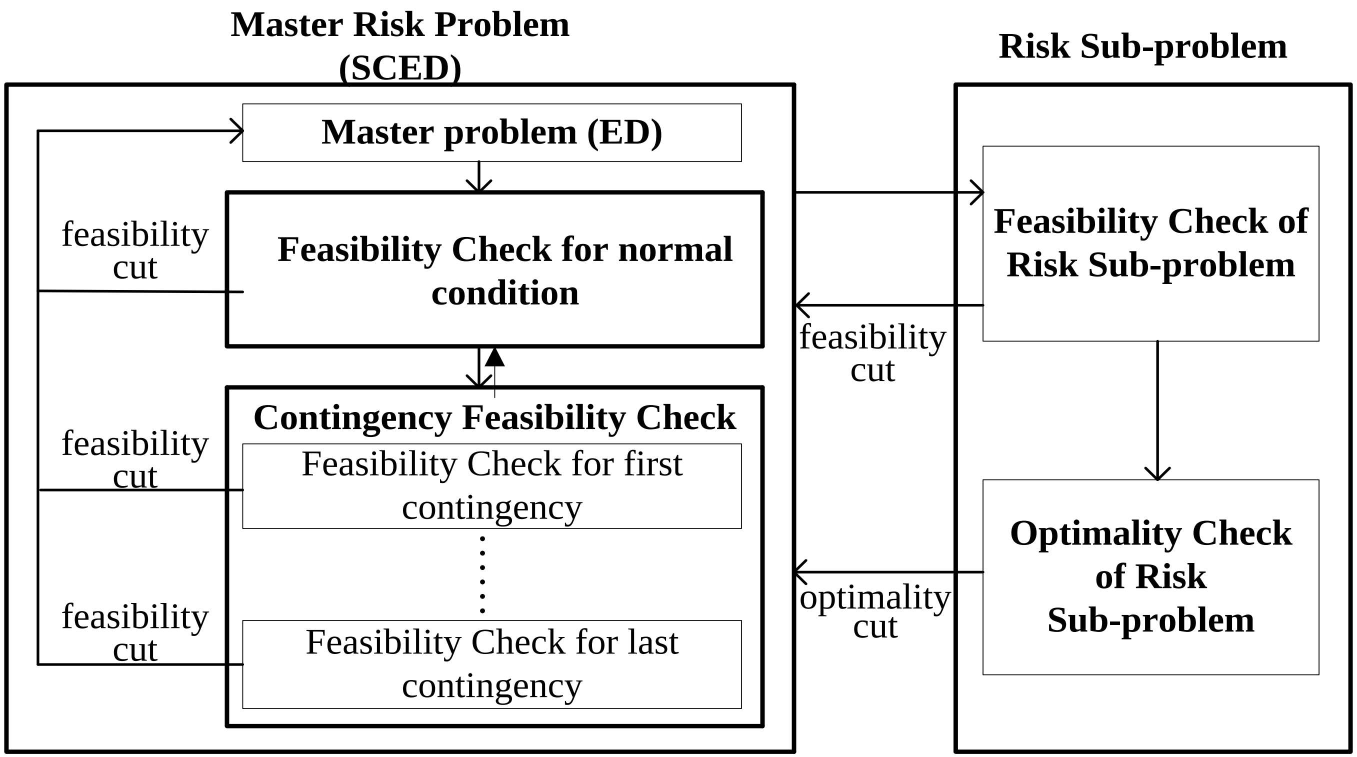
Adaptive Emergency Transm Rates [1]

- Lng-time emrgncy (LTE) rating, 4hrs
- Shrt-time emrgncy (STE) rating, 15mins
- Drastic action limit (DAL), immediate

[1] S. Maslennikov, E. Litvinov. “Adaptive Emergency Transmission Rates in Power System and Market Operation,” *IEEE Trans. Pwr Sys*, May 2009.

Formulation – Severity Evaluation

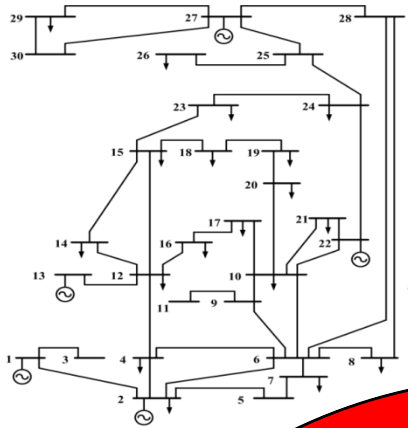
RB-SCED Solution Procedure [1]



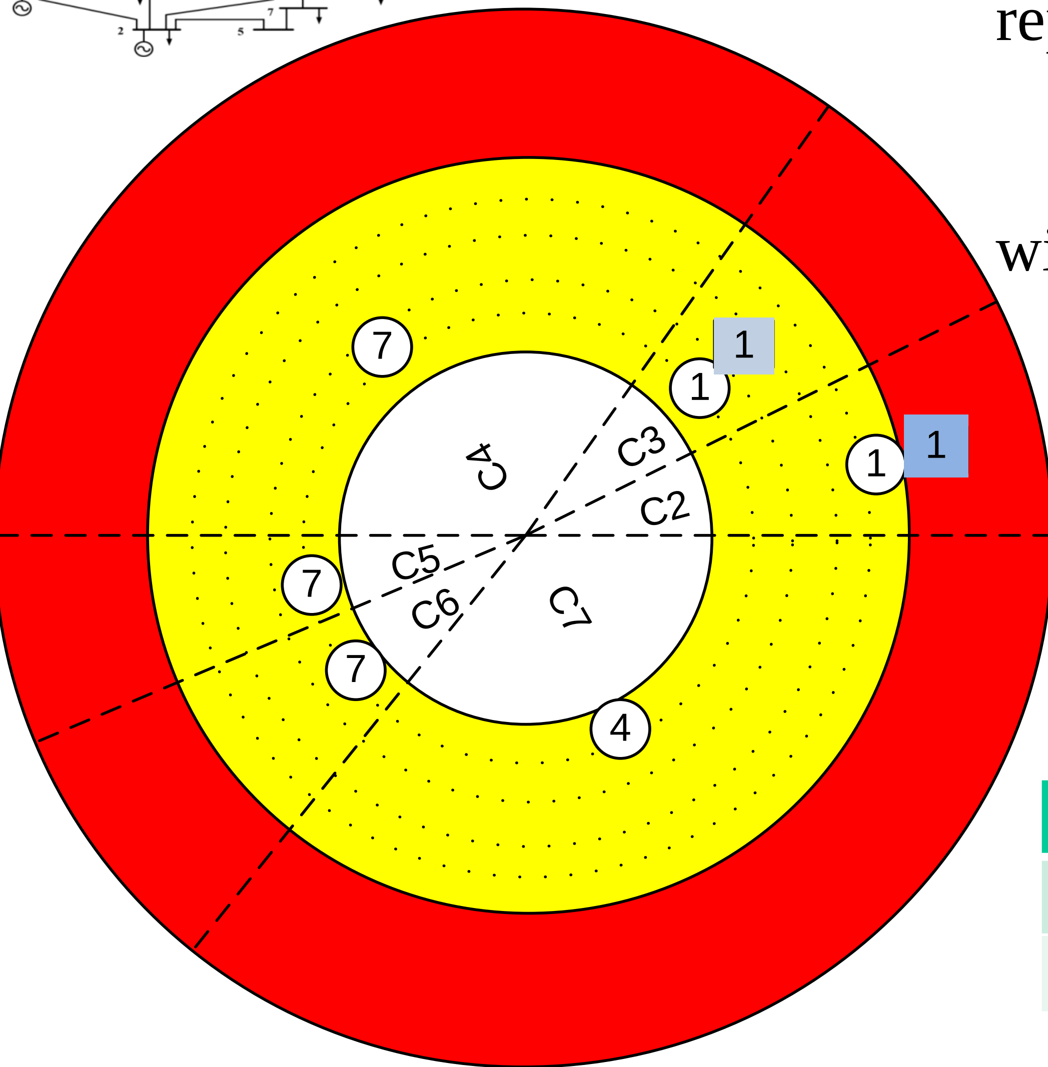
- DC power flow representation is used.
- Risk cannot be evaluated until flows are known.
- Two-level nested Benders decomposition:
  - Master risk problem is a SCED solved by Benders
  - SCED solution checked for feasibility & optimality in risk subproblem

[1] Q. Wang, J. McCalley, T. Zheng, and E. Litvinov, “A Computational Strategy to Solve Preventive Risk-based Security-Constrained Optimal Power Flow,” Digital Object Identifier: 10.1109/TPWRS.2012.2219080, *IEEE Transactions on Power Systems*, 2012.

Results: 30-bus system



IEEE 30
bus system



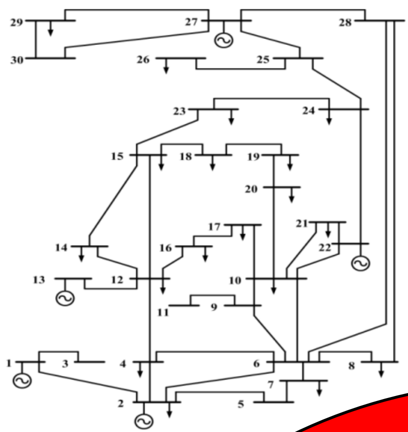
Post-contingency flows represented by
- White Circles: SCED
- Blue Squares: RB-SCED

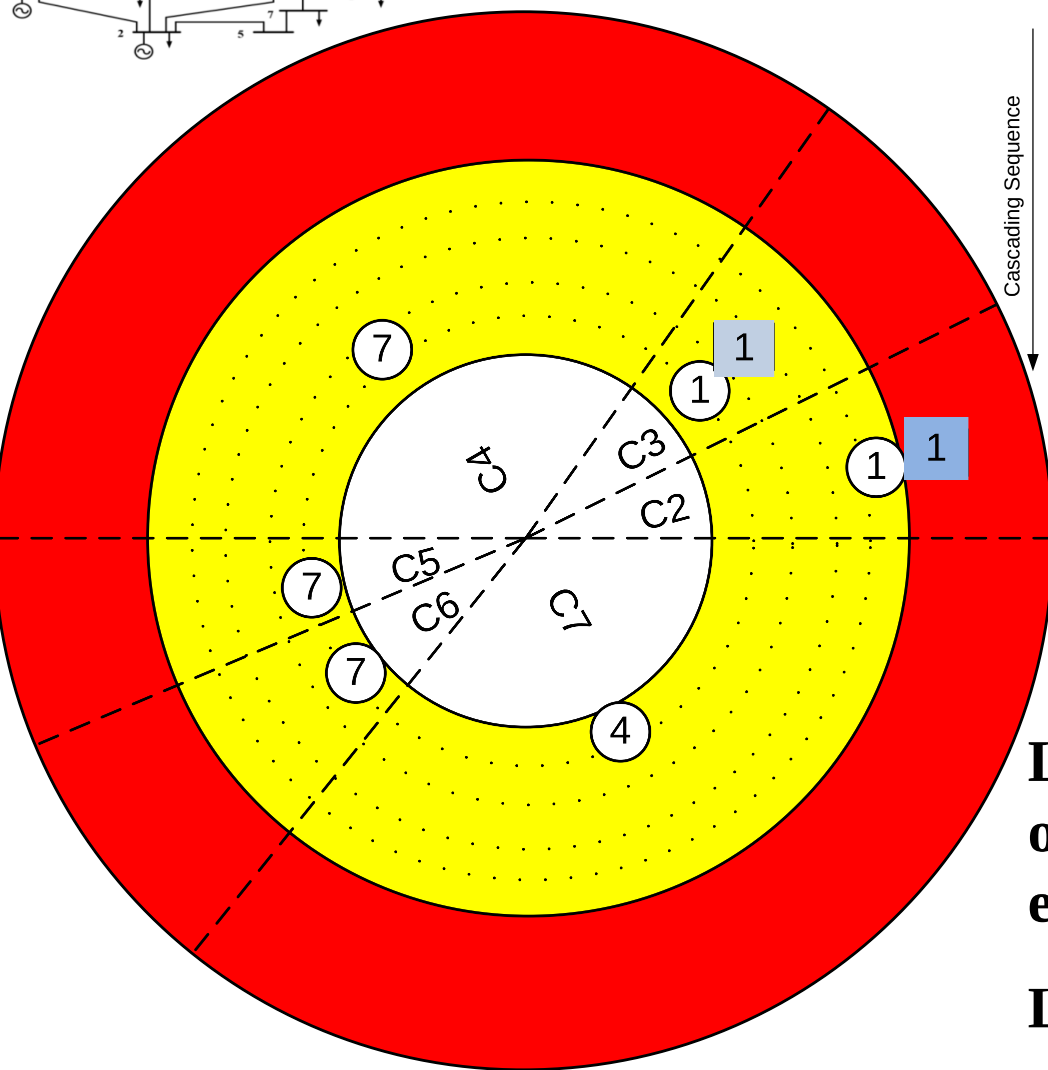
with distance to center = %flow:
- White: Safe flow, < 90%
- Yellow: Heavy flow, 90-100%
- Red: Exceeds LTE

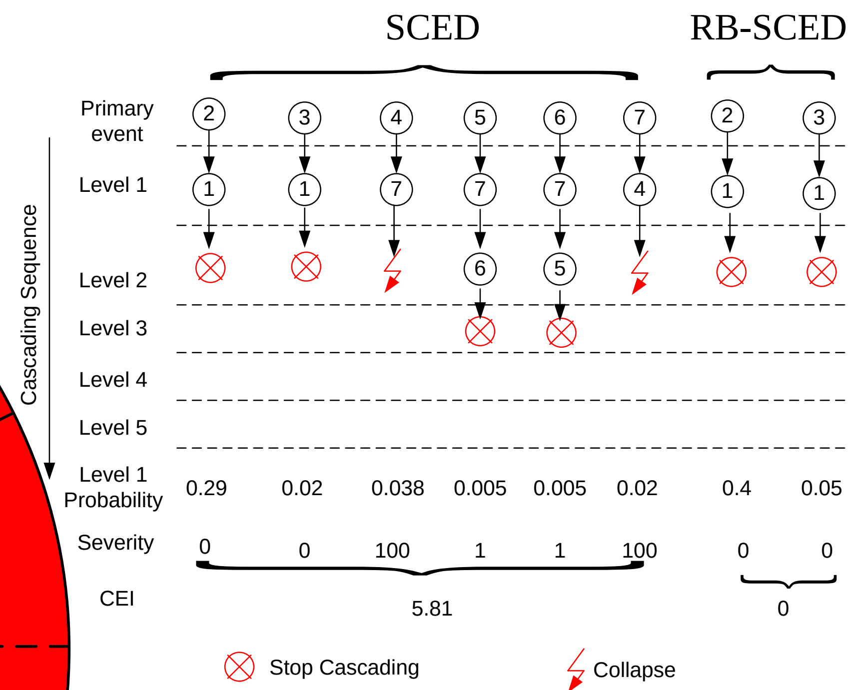
Sectors: contingencies

	SCED	RB-SCED
Cost	$451,383	$446,420
Risk	1.51	0.84

Results: 30-bus system Is it more secure?





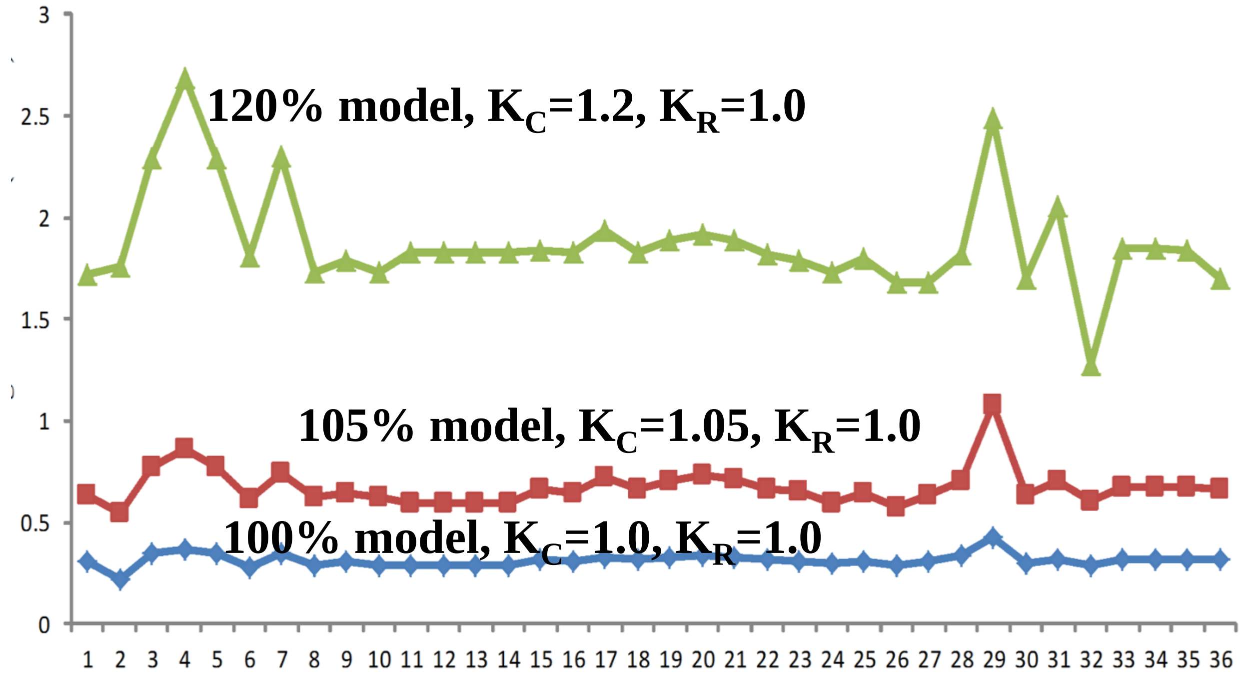


Level 1 is a second trip after initial outage, for circuits w/ flows exceeding 90%.

Levels 2, 3, … occur if flow>125%

Results: 30-bus system
Is it more secure?

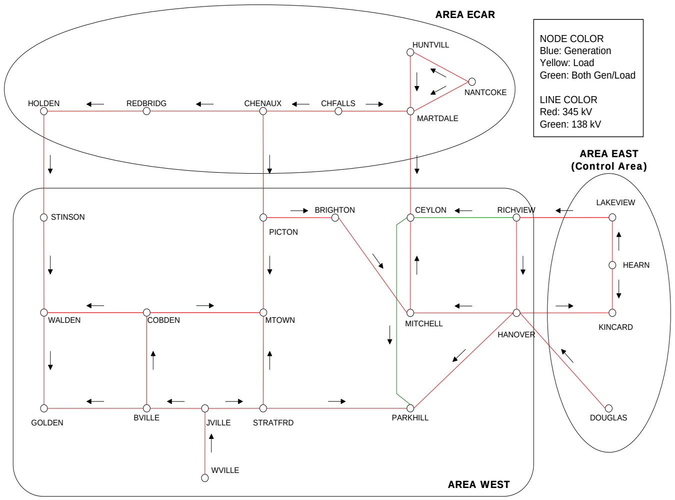
[Qmargin of RB-SCED]
-[Qmargin of SCED]
(MVARS)

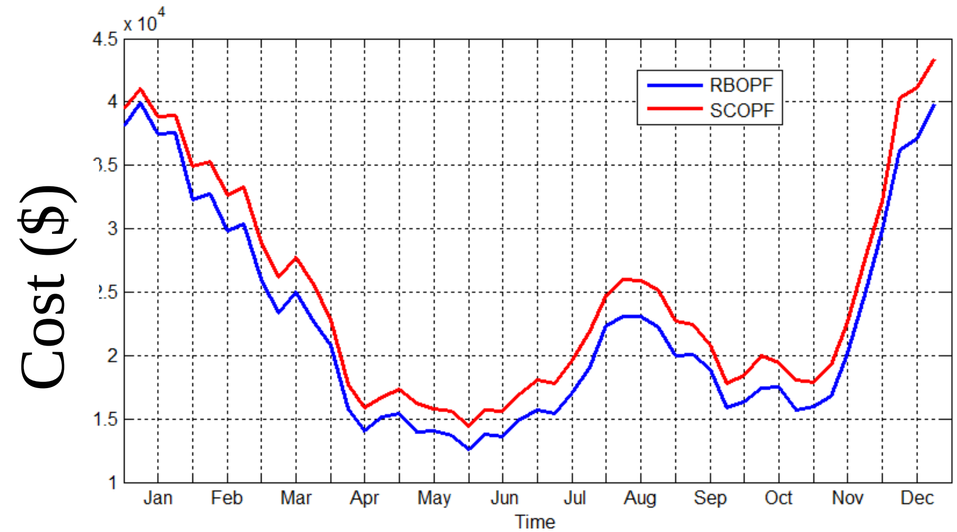


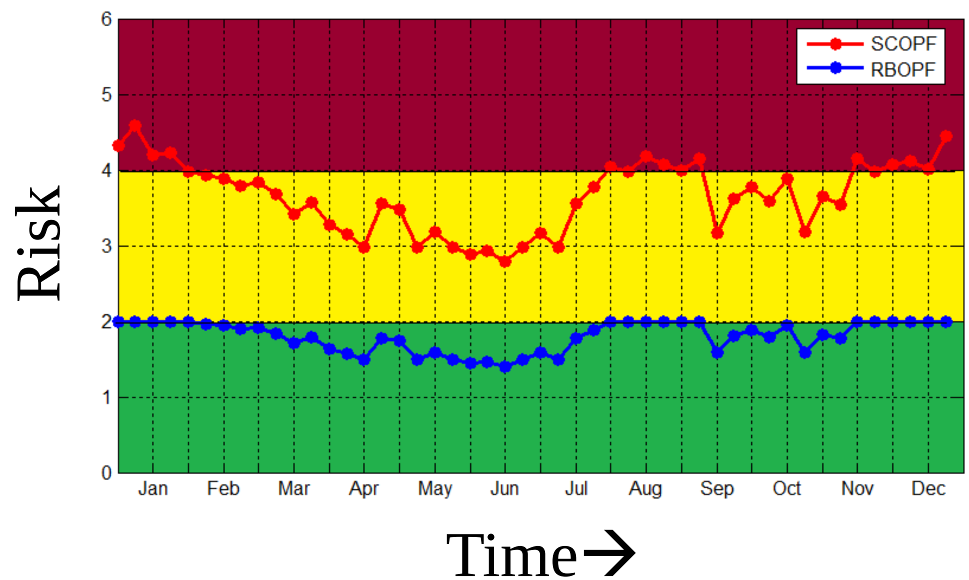
Contingency #

Post-contingency flows are more uniformly loaded, reactive losses are lower, so Qmargin is greater.
AC power flow analysis indicates SCED model has more reactive losses than RB-SCED model.

Results: 85-bus system





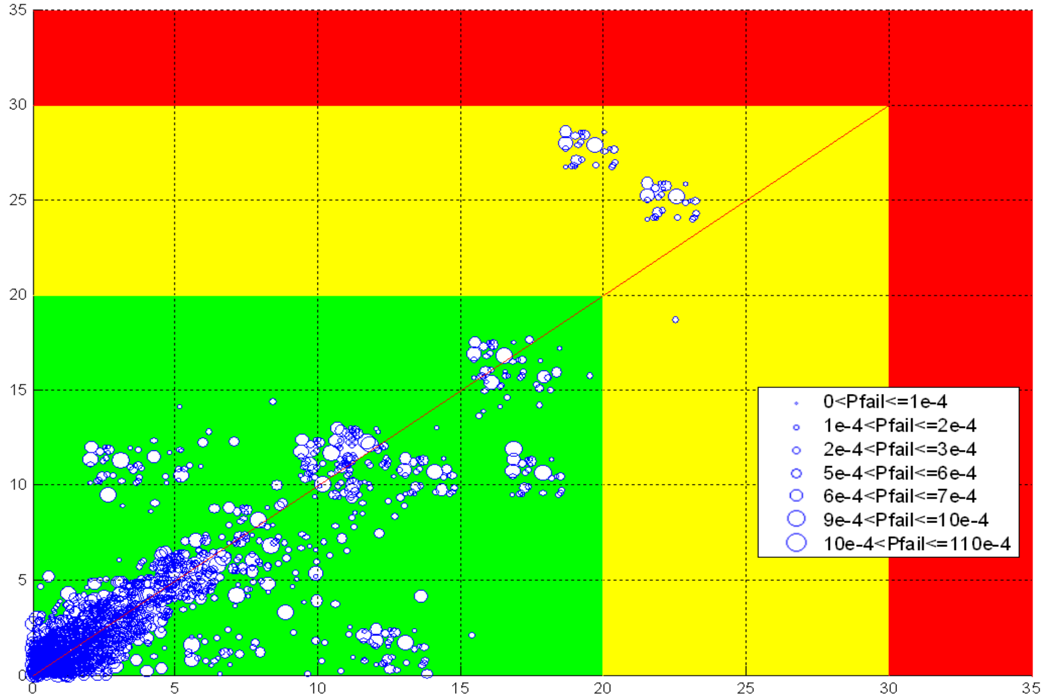


R. Dai, H. Pham, Y. Wang, and J. McCalley, “Long term benefits of online risk-based optimal power flow,” *Journal of Risk and Reliability* (Part O of the Proceedings of the Institution of Mechanical Engineers): Special Issue on "Risk and reliability modeling of energy systems,” Vol. 226, Issue 1, Feb, 2012.

Results: 85-bus system
Is it more secure?

Post-contingency angle separations

SCED



RB-SCED

R. Dai, H. Pham, Y. Wang, and J. McCalley, “Long term benefits of online risk-based optimal power flow,” *Journal of Risk and Reliability* (Part O of the Proceedings of the Institution of Mechanical Engineers): Special Issue on "Risk and reliability modeling of energy systems,” Vol. 226, Issue 1, Feb, 2012.

Results: ISONE System

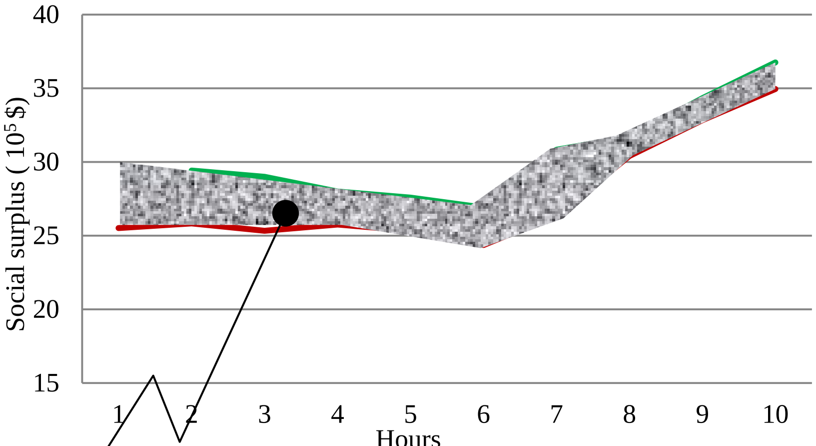
ISO New England system

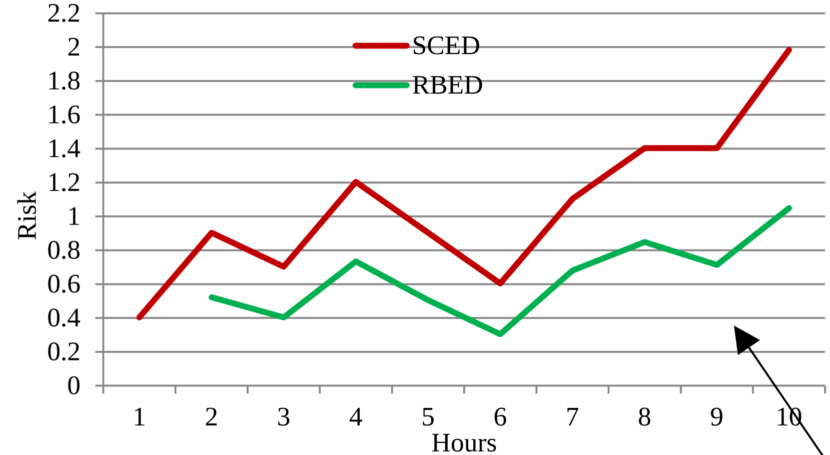
- 2351 buses, 3189 circuits, 250 contingencies
- 802,150 decision variables, 4,001,196 constraints
- $Risk_{max}$ = Risk from SCED so reference risk is no higher than what has been acceptable in the past, then, K_R=0.5
- Solved in CPLEX on a PC laptop with inter Core 2 Duo 2.50 GHz and 3GB memory; solution time is ~20 min.

	SCED	RB-SCED		
		100% Model (K_C=1, K_R = 0.5)	105% Model (K_C =1.05, K_R = 0.5)	120% Model (K_C =1.20, K_R = 0.5)
Cost ($/hr)	684,642	728,899	610,611	605,542
Risk	18.27	9.13	9.13	9.13

Results: ISONE System

Comparing SCED & RB-SCED on ISO-NE system for 10 sequential hrs (Different cases from previous slide).





- Area=ISO-NE savings over 10 hrs=$2M (assume 0 during other 14 hrs)
- Annual cost saving: $2.0M×5×52=$520M/yr (assume 0 for weekend)

And it is more secure!

Results: ISONE System
Is it more secure?

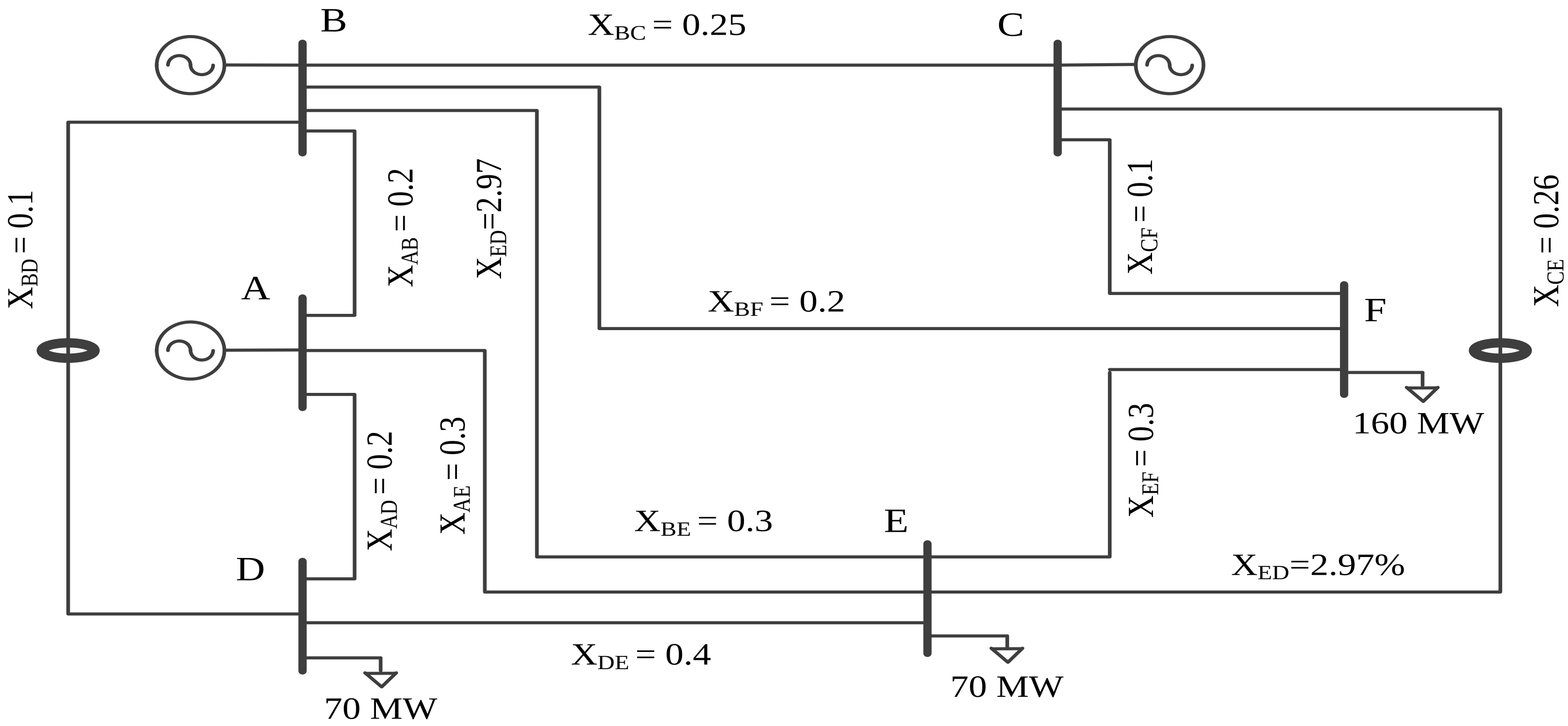
		Number of circuits with flows exceeding 90% of continuous limit in the *normal state*	Number of circuits with flows exceeding 90% of LTE in *all post-contingency states*
SCED		33	8183
RB-SCED	100% model	28	6819
	105% model	22	5388
	120% model	23	5678

Effect on LMPs

Traditional LMPs=	Risk-based LMPs
$LMP_i^{Energy} = \lambda_1$	$RLMP_i^{Energy} = \lambda_2$
+ $LMP_i^{Loss} = -\frac{\partial Loss}{\partial P_i}\lambda_1$	+ $RLMP_i^{Loss} = -\frac{\partial Loss}{\partial P_i}\lambda_2$
+ $LMP_i^{Congestion} = -(\sum_{l=1}^{NL}\mu_{1l}^0 GSF_{l-i}^0 + \sum_{k=1}^{NC}\sum_{l=1}^{NL}\mu_{1l}^k GSF_{l-i}^k)$	+ $RLMP_i^{Congestion} = -(\sum_{l=1}^{NL}\mu_{2l}^0 GSF_{l-i}^0 + \sum_{k=1}^{NC}\sum_{l=1}^{NL}\mu_{2l}^k GSF_{l-i}^k)$
	+ $RLMP_i^{Risk}\Big\|_{S_1} = -\sum_{k=1}^{NC}\sum_{l=1}^{NL} r_l^k Pr_k GSF_{l-i}^k \tau$

The risk component of the LMP provides a price signal that incentivizes market participants to improve system risk.

Results: Six bus system



Model	Bus Name	(R)LMP	(R)LMP Energy	(R)LMP Congestion	RLMP Risk
SCED	A	13.53	13.53	0.00	-
	B	11.33	13.53	-2.20	-
	C	11.83	13.53	-1.70	-
	D	34.58	13.53	21.04	-
	E	16.95	13.53	3.41	-
	F	13.73	13.53	0.20	-
100% model (K_C =1; K_R =0.9)	A	13.53	13.53	0.00	0.00
	B	12.11	13.53	-1.80	0.37
	C	14.99	13.53	0.26	1.19
	D	33.13	13.53	19.48	0.11
	E	15.51	13.53	2.70	-0.73
	F	14.30	13.53	0.14	0.62
105% model (K_C=1.05; K_R =0.9)	A	13.53	13.53	0	0.00
	B	14.66	13.53	0	1.13
	C	17.13	13.53	0	3.60
	D	13.87	13.53	0	0.33
	E	11.35	13.53	0	-2.19
	F	15.41	13.53	0	1.87

Some buses have higher RLMPs; some have lower, due to

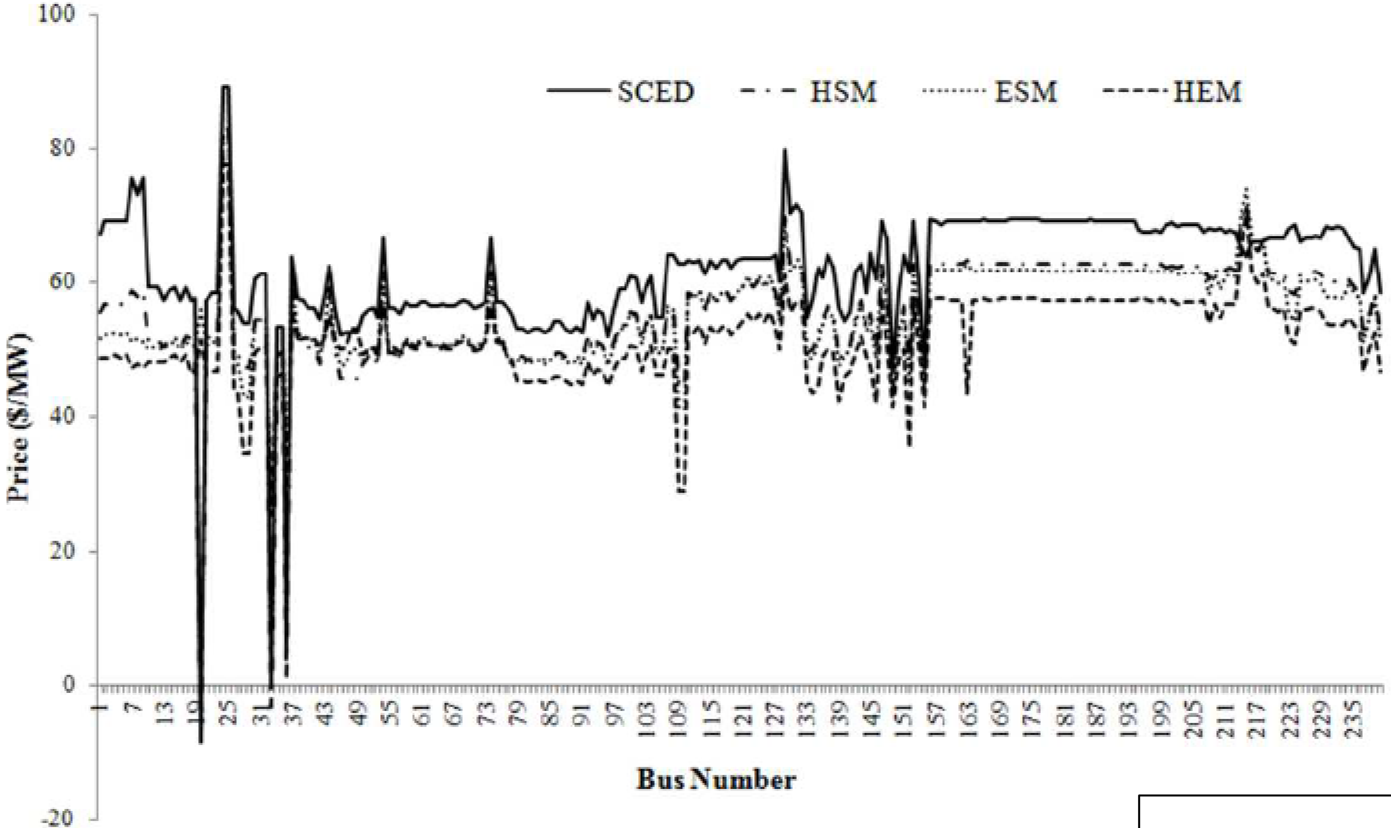
- Risk constraint causes increase
- Relaxed post-contingency limits causes decrease

For SCED & 100% model, investment incentives are on B-D. For 105% model, investment incentives are on C-E.

Difference is due to RLMP's ability to distinguish between

- line C-E's carrying heavy post-contingency flow for 2 contingencies, with post-contingency loadings of 97.5% and 101.8%, respectively,
- line B-D's carrying heavy post-contingency flow for only 1 contingency, with post-contingency loadings of 100%.

Results: 240 bus WECC system



	SCED	RB-SCED 100% model	RB-SCED 105% model	RB-SCED 120% model
Average ($)	60.85	61.60	55.42	51.73
Standard Dev.	9.75	9.27	6.82	6.45

R-LMP's are more uniform over space and, we think, less volatile.

Corrective RB-SCED [1]

- Corrective RB-SCED allows post-contingency corrective action to relieve loadings;
- Formulated, coded, and tested it on 30-bus system and on ISO-NE system;
- Results from ISO-NE system are below.

Constraints	CSCOPF	CRB-SCOPF		
		HSM (K_C=1, K_R = 0.5)	ESM (K_C =1.05, K_R = 0.5)	HEM (K_C =1.20, K_R = 0.5)
Risk	18.24	9.12	9.12	9.12
Cost ($)	616172.1	678654.3	608672.2	593676.6

approach		no. of circuits with flow over 90% *limit*	
		normal state	*contingency states*
CSCOPF		30	7201
CRB-SCOPF	HSM	21	5876
	ESM	19	5019
	EESM	18	4963

[1] *Q. Wang, J. McCalley, T. Zheng, and E. Litvinov, "Solving Corrective Risk-based Security-Constrained OPF with Lagrangian Relaxation and Benders Decomposition," under review by *IEEE Transactions on Power Systems*.

Conclusions

- RB-SCED: potential to significantly enhance efficiencies of real-time electricity markets;
- while simultaneously increasing security levels and providing operators with a “system lever” for more effective control.
- Offers basis for identifying prices when “unmanageable constraints” are relaxed;
- No changes in market structure are required.
- Next step: commercialize into market SW; then gain experience side-by-side with SCED

References

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