Carnegie Mellon

Electricity Transmission in Deregulated Markets: Challenges, Opportunities, and Necessary R&D Agenda

AUBURN

GINN COLLEGE OF ENGINEERING

PRICING TRANSMISSION CONGESTION IN ELECTRIC POWER NETWORKS

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Outline

I. Introduction

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III. Pricing Congestion under System Stability Constraints

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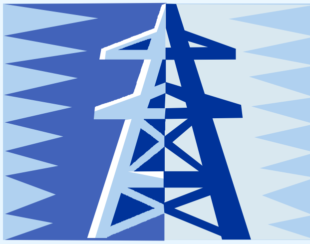
V. Conclusion

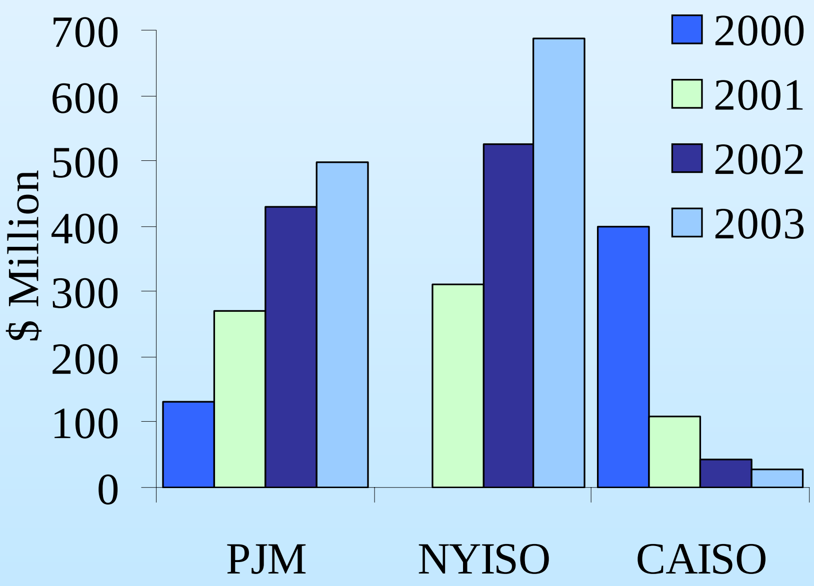


Introduction

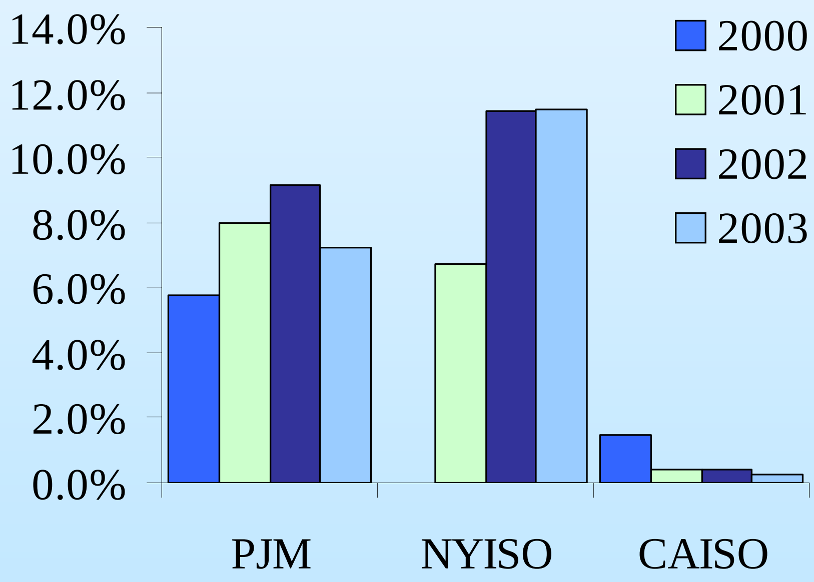
- In the PJM and NYISO markets, the cost of moving power represents between 6 to 12% of total electric costs.
- Consider that the power traded in the US wholesale market was over 800 TW-h in 2000 and rapidly increasing.
- However, relatively little money has been put into the transmission system.

Congestion Costs Statistics

Total Congestion Costs



Total Congestion Cost as a Percent of the Total Electricity Cost



Sources: PJM State of the Market Report 2003, 2002
NYISO State of the Market Report 2003, 2002
CAISO Annual Report on Market Issues and Performance 2003, 2002

Research Issues

- Objective: To include system's stability in the operation and economics of power systems
  - How should the system's stability be included in the optimal dispatch model?
  - If modeled as a flowgate constraint, how should the additional cost created by the flowgate constraint be allocated?
  - Which congestion pricing schemes send more appropriate economics signal for generation and transmission expansion that will assure system's stability?

Modeling System's Stability

- Dynamic simulations suggest that proximity to a stability limit may be predicted using flowgates
- Some companies presently manage system's stability using flowgates
- Flowgates can be related to generator outputs through Power Transfer Distribution Factors

$$\sum_{i,j}\left(\sum_{k=1}^{N} PTDF_{i,j}^{k} * P_k\right) \leq P_{flowgate,max}$$

Congestion-Pricing Approaches

Flat Rate

- Uniform price approach
- Used by pre-liberalized U.S. Markets
- Based on full cost recovery and regulated return on investment
- No proper locational economic signals

Marginal Cost

- Marginal cost pricing
- Used in restructured U.S. markets
- Based on optimum power flow models, nodal pricing, and flow-based pricing
- Appropriate locational economic signals

Market-based

- Market finds its own equilibrium.
- Requires a well-established market structure
- Based on a coordinated multilateral trading model
- Appropriate locational economic signals

Security-Stability Constrained OPF: A Nodal Pricing Model

$\text{Min } z = \sum_{k=1}^{N} c_k g_k$	Minimize Total Generation Cost
Subject to	Subject to
$\sum_{ij} S_{k,ij} \times f_{ij} + g_k = L_k \qquad (\lambda_k)$	Node balance equations for $k = 1,\ldots,N$
$f_{ij} - Y_{ij} * (\theta_i - \theta_j) = 0$	Voltage/flow equations on each line *i-j*
$-f_{ij}^{\max} \le f_{ij} \le f_{ij}^{\max} \qquad (\mu_{ij})$	Thermal flow limits for all lines *i-j*
$g_k^{\min} \le g_k \le g_k^{\max}$	Power capacities for each generator
$\sum_{ij \in FG} f_{ij} \le \mathrm{FG}^{\max}$	Security Constraint (Angular Stability)

Security-Stability Constrained OPF
A Flow-based Pricing Model

$$\text{Min } z = \sum_{k=1}^{N} c_k g_k$$

Minimize Total Generation Cost

Subject to

Subject to

$$\sum_{k=1}^{N} g_k - \sum_{k=1}^{N} L_k = 0 \qquad (\lambda)$$

Total balance equation

$$-f_{ij}^{\max} \le \sum_{k=1}^{N} PTDF_{ij}^{k} \left(g_k - L_k\right) \le f_{ij}^{\max} \qquad \left(\mu_{ij}\right)$$

Thermal flow limits for all lines *i-j*

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

Power capacities for each generator

$$\sum_{ij \in FG} \sum_{k=1}^{N} PTDF_{ij}^{k} \left(g_k - L_k\right) \le FG^{\max} \qquad \left(\mu_{FG}\right)$$

Security Constraint (Angular Stability)

LMPs are calculated by $LMP_k = \lambda + \sum_{ij} (PTDF_{ij}^{k} \times \mu_{ij}) + \sum_{ij \in FG} (PTDF_{ij}^{k} \times \mu_{FG})$

Congestion Cost Calculation

Nodal Pricing Model

- Total congestion cost

$$CR = \sum_{ij} \left(LMP_j - LMP_i \right) f_{ij}$$

- Congestion cost allocated to line *ij*

$$CR_{ij} = \left(LMP_j - LMP_i \right) f_{ij}$$

Flow-based Pricing Model

- Total Congestion cost

$$CR = \sum_{ij} (\mu_{ij} \times f_{ij}) + \mu_{ij} \times FG^{\max}$$

- Congestion cost allocated to line *ij*

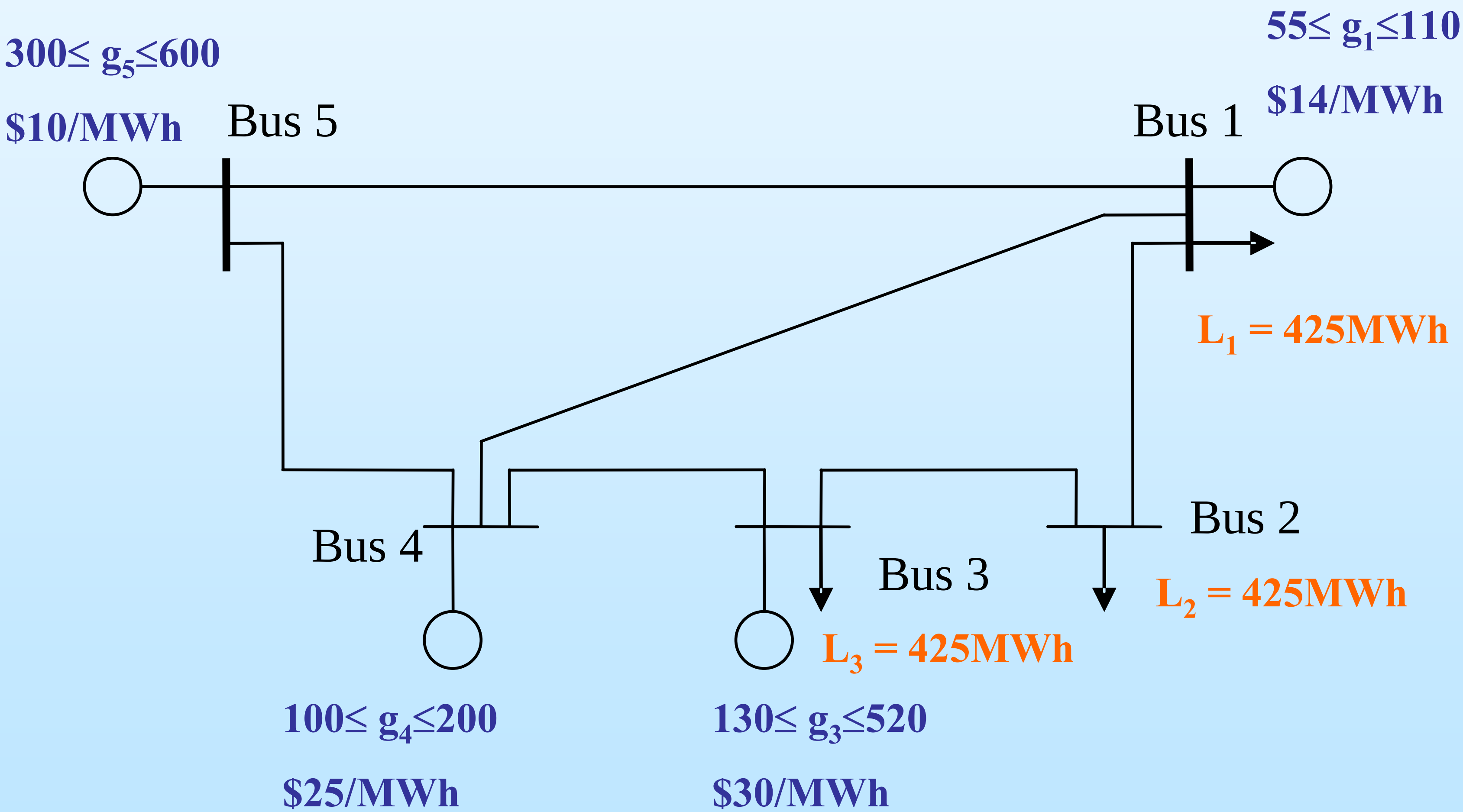
$$CR_{ij} = \mu_{ij} \times f_{ij}$$

$$CR_{FG} = \mu_{ij} \times FG^{\max}$$

Nodal vs. Flow-based Model

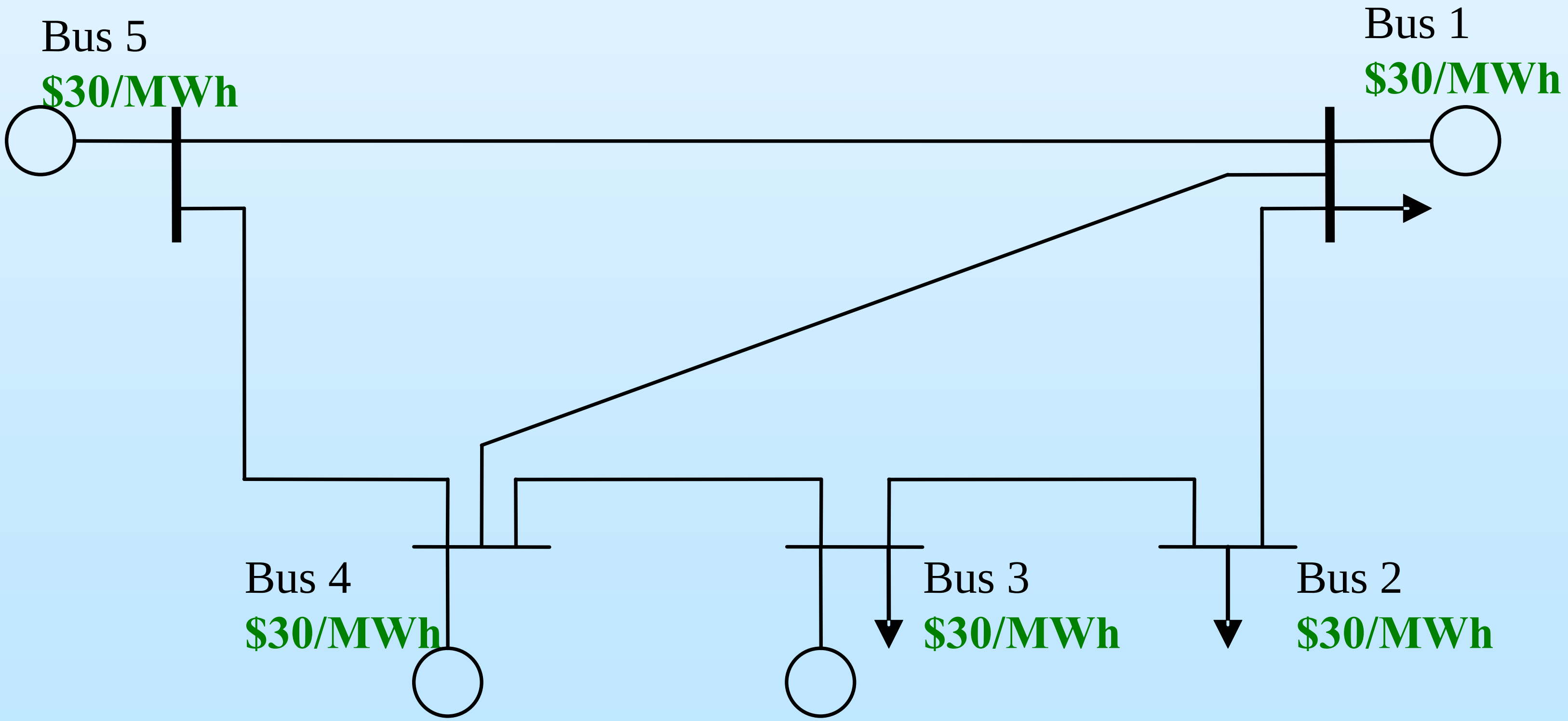
	Nodal Model	Flow-based Model
Generation Expansion Incentives	Provides correct incentives.	Provides correct incentives.
Transmission Expansion Incentives	Little incentive provided.	Correct signals available for transmission investment.
Market Experience	PJM (1998) NY ISO (1999) ISO-NE (2003)	CAISO (Zonal) ERCOT (proposed flowgate-zonal)

Numerical Example



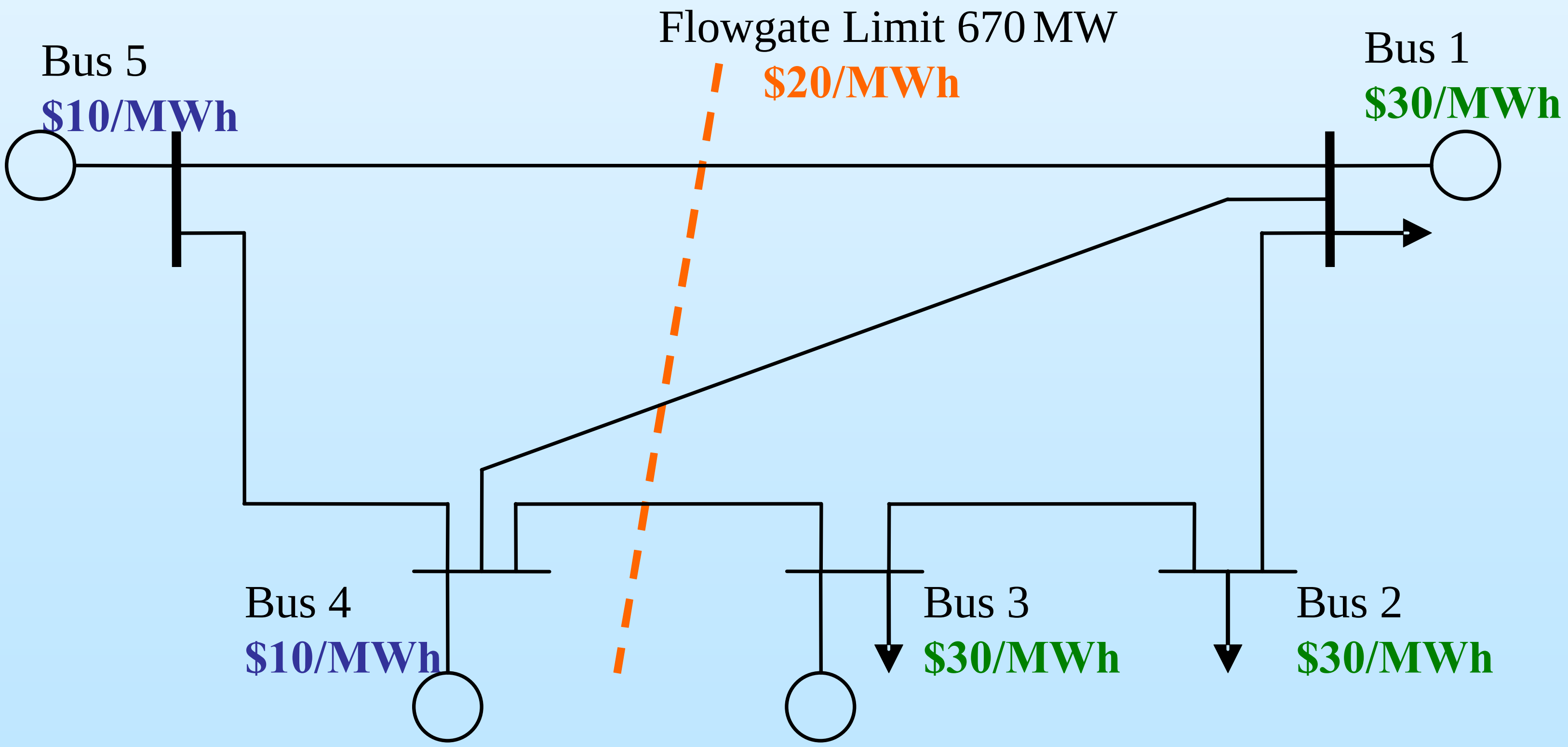
Effects of the Stability Constraint Alone

Assuming ***no flowgate*** and ***no thermal limits*** on the lines:



Effects of the Stability Constraint Alone

Assuming ***no thermal limits*** on the lines:



Effects of the Stability Constraint Alone

	Without FG	With FG	Redispacth Cost
Total Revenue to Gen	$38,250	$24,850	-$13,400
Total Production Cost	$23,490	$24,590	$1,100
Net Income to Gen	$14,760	$260	
Congestion Cost	$0	$13,400	
Total Cost to Load	$38,250	$38,250	$0

- Revenue to generators decreases significantly.
- Total cost to load remains unchanged.
- Although redispatch cost for the production cost is $1,100, congestion cost is $13,400.

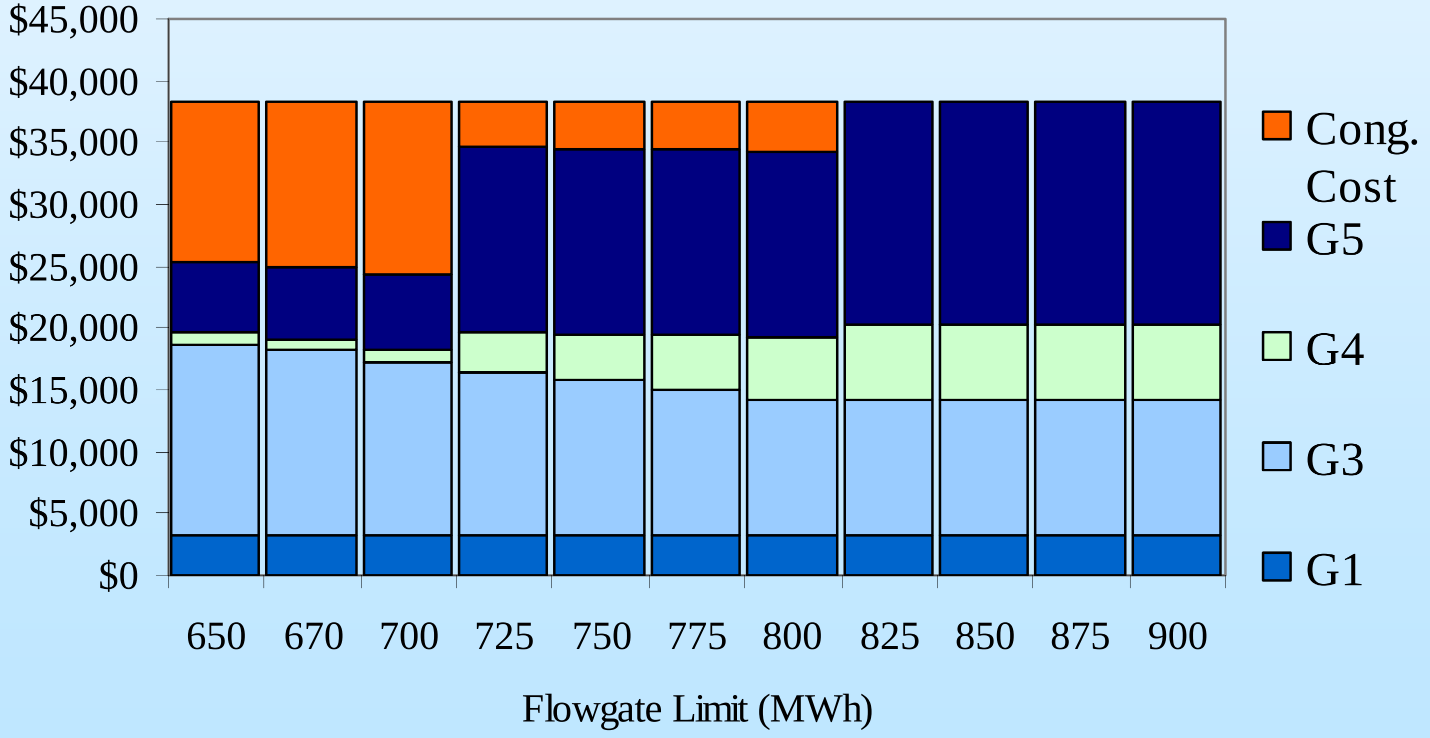
Allocation of Congestion Costs

Line	12	23	43*	54	41*	51*	FG
Flow-b. App	$0	$0	$0	$0	$0	$0	$13,400
Nodal App.	$0	$0	$5,300	$0	$2,550	$5,550	$0

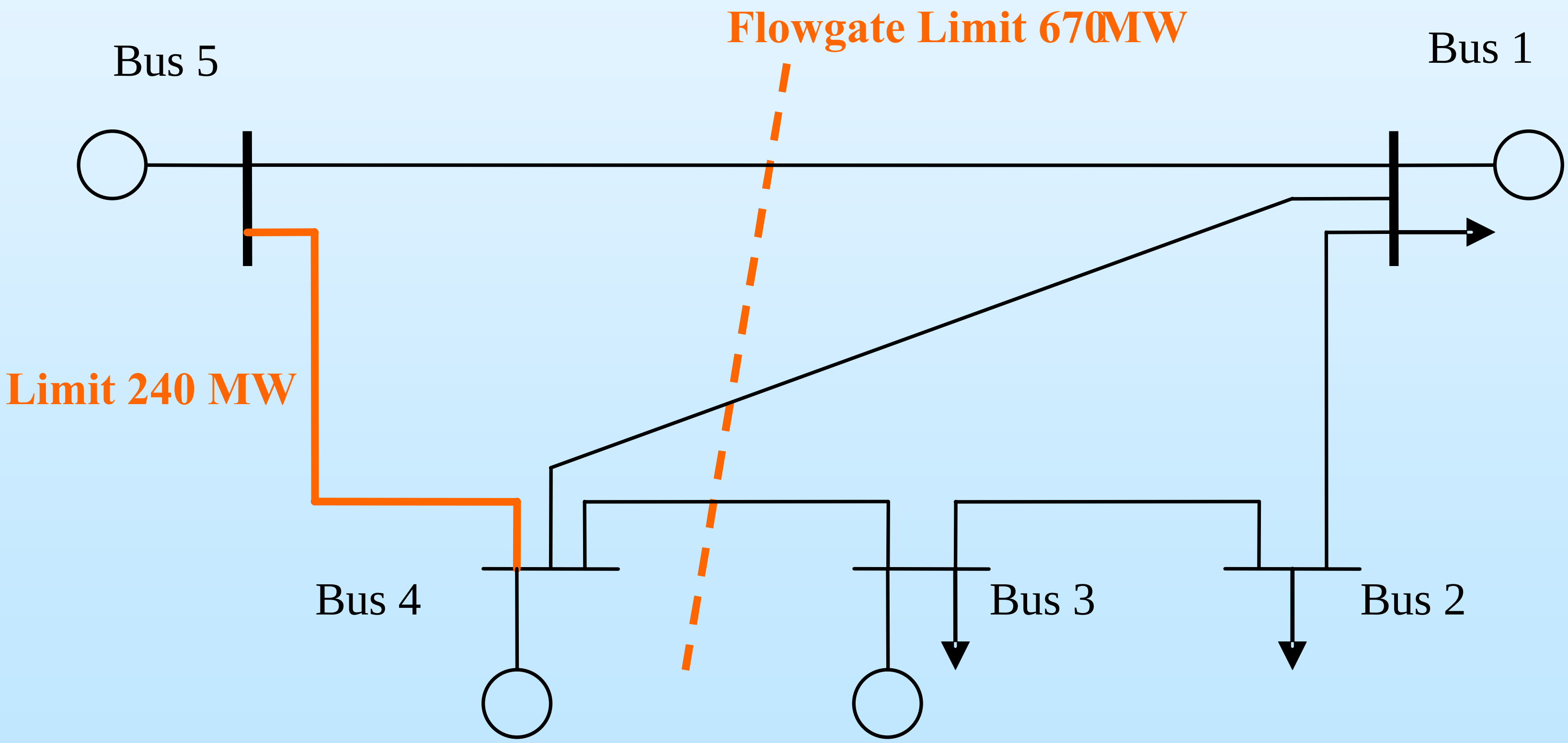
Note that under the nodal congestion pricing scheme, no congestion cost is ever assigned directly to the flowgate constraint.

Effects of the Flowgate Constraint Alone

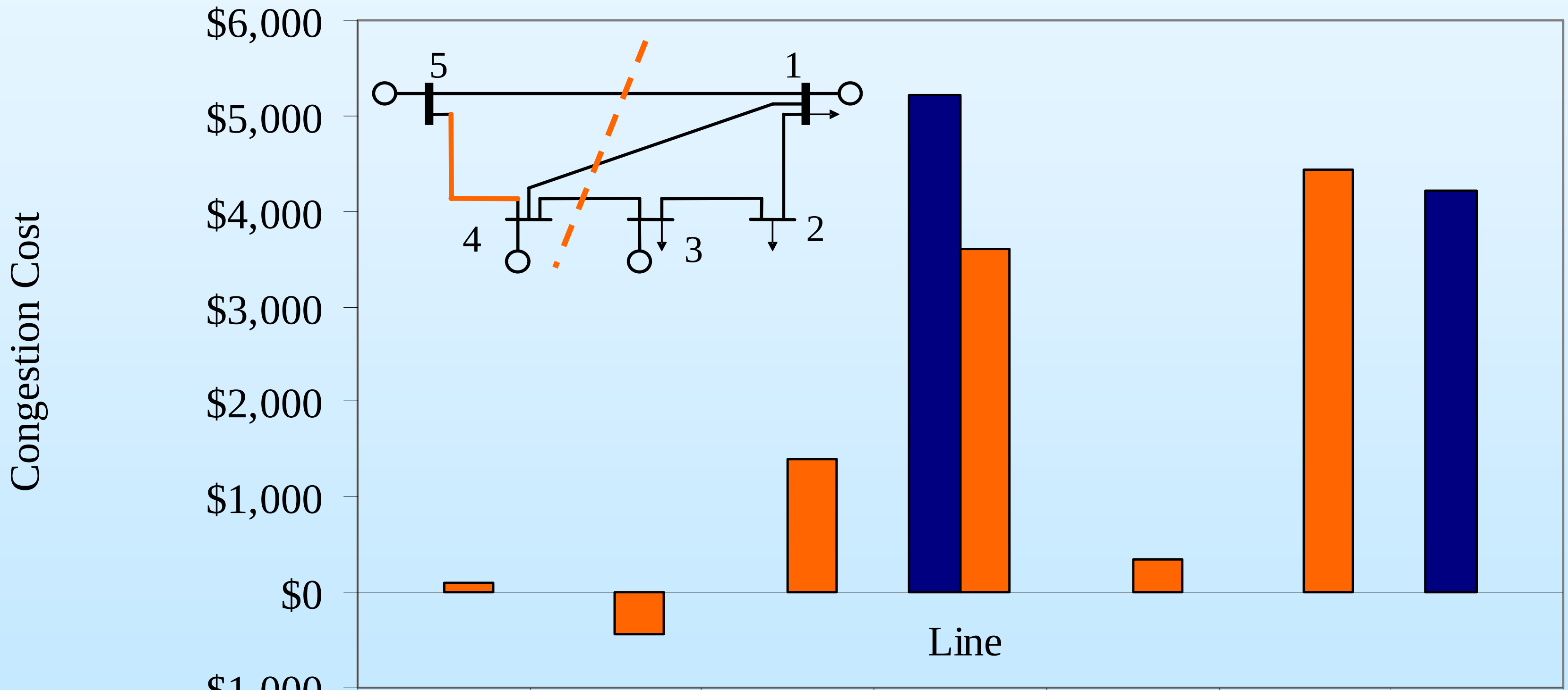
Partition of the *Total Cost to Load* in terms of ***total generation revenues*** and ***congestion costs*** when there are ***no thermal limits*** on the transmission lines.



Effects of the Flowgate Constraint with Thermal Limits



Allocating congestion costs



	12	23	43*	54	41*	51*	FG
Flow-b. App.	$0.00	$0.00	$0.00	$5,208.5	$0.00	$0.00	$4,205.3
Nodal App.	$97.78	-$444.77	$1,392.0	$3,600.0	$336.57	$4,432.2	$0.00

Allocating Congestion Costs to Transmission Lines

Flow-based Allocation

- The price of the flowgate is used to assign values by

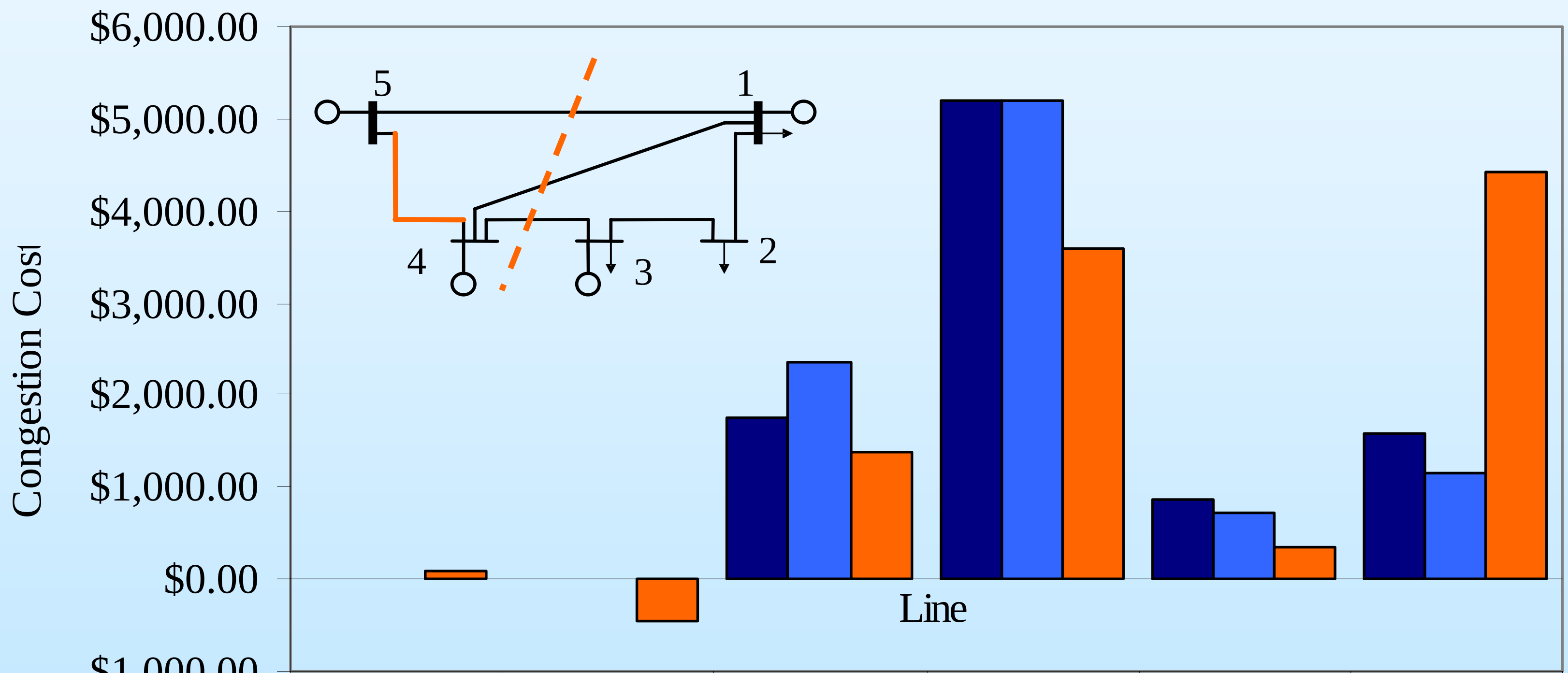
$$CR_{ij} = p_{FG} \times f_{ij} \quad \left(\forall ij \in FG\right)$$

PTDF-based Allocation

- Assumes equal flow sent from generators.
- Constant coefficients used every time.

	Flow-based Allocation		PTDF-based Allocation	
Line	**Flow**	**Cong. Cost**	**ΣPTDFij**	**Cong. Cost**
43	278.40	$1,747.43	1.1177	$2,350.14
41	137.55	$863.37	0.3382	$711.12
51	254.04	$1,594.52	0.5441	$1,144.06
Total	**670**	**$4,205.32**	**2.0000**	**$4,205.32**

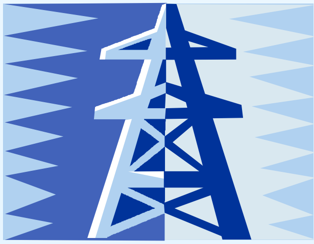
Comparison of the Congestion Allocation Schemes



	12	23	43*	54	41*	51*
Flow-b. Alloc.	$0.00	$0.00	$1,747.40	$5,208.51	$863.35	$1,594.51
PTDF-b. Alloc.	$0.00	$0.00	$2,350.14	$5,208.51	$711.12	$1,144.06
Nodal App.	$97.78	-$444.77	$1,392.02	$3,600.00	$336.57	$4,432.23

Comparison of Congestion Cost Allocation Schemes

- Nodal Approach
  - Provides little incentive for transmission expansion. Prices can't give you which constraints are binding.
  - Assigns value to uncongested lines.
  - Does not assign a direct cost to the flowgate
- Flow-based Approach
  - Assigns costs to only congested lines.
  - Assigns a cost to the flowgate.
  - ***Flow-based allocation*** uses flowgate price to assign congestion due to stability to the lines.
  - ***PTDF-based allocation*** uses fixed coefficients to assign congestion to flowgate lines but assumes equal dispatched flows from generators.



Conclusion

- This paper examined transmission congestion pricing on power networks with flowgate-based stability constraints.
- The difference of these pricing models is the allocation of the total congestion costs to the lines on the network.
- Effects of the stability constraint on the total cost of generator dispatch, total cost to load, and total congestion cost were analyzed.

Thank you!

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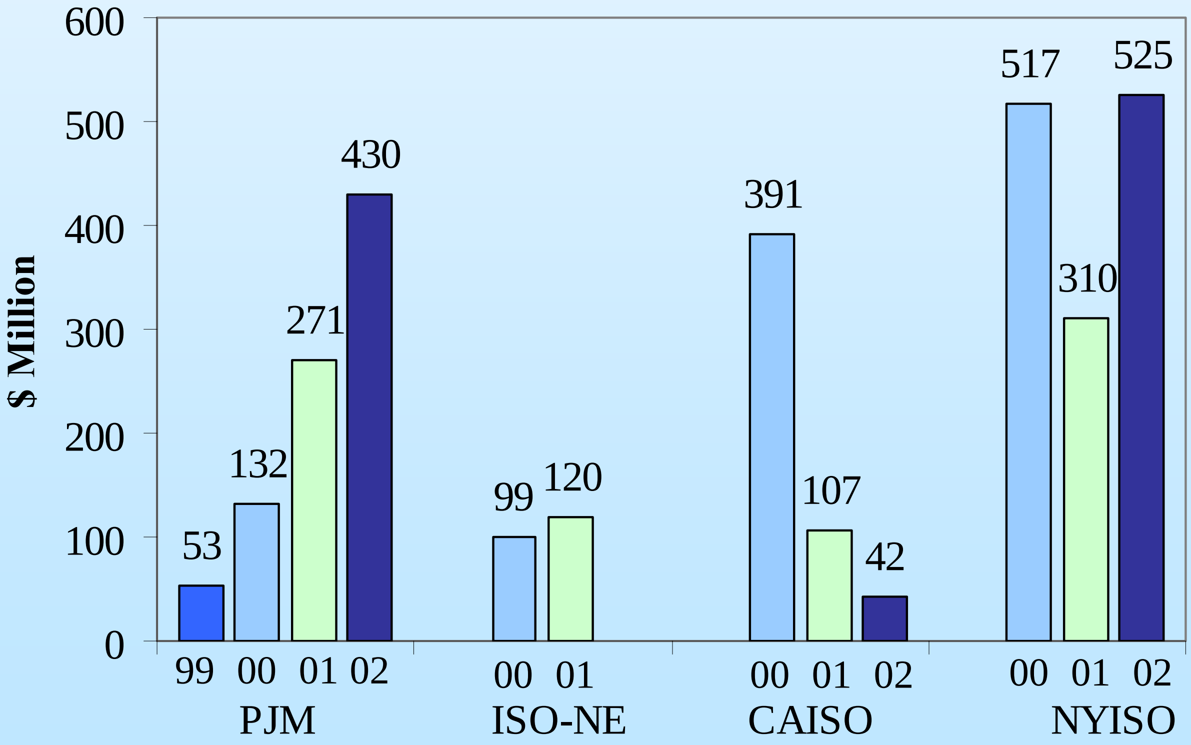
Congestion Costs Reported from ISOs

- Transmission congestions and investment have become an emergent problem.



Source: Lesieutre and Eto 2004

Optimum Dispatch Without any Congestion

- Optimum dispatch ***without the stability constraint*** and ***without transmission thermal limits***

No Flowgate limit	1	2	3	4	5	Total
LMP	$30	$30	$30	$30	$30	
Generation (MW)	110	0	365	200	600	1275
Total Production Cost	$1,540	$0	$10,950	$5,000	$6,000	$23,490
Total Revenue to Gen	$3,300	$0	$10,950	$6,000	$18,000	$38,250
Net Income to Gen	**$1,760**	**$0**	**$0**	**$1,000**	**$12,000**	**$14,760**
Load (MW)	425	425	425	0	0	1275
Total Cost to Load	$12,750	$12,750	$12,750	$0	$0	$38,250
	FGR Price	**MW**	**Tot FG Cong.**	**Gen Redisp.**	**Cong. Cost**	
	$0	0	**$0**	$0	$0	

Optimum Dispatch with Stability Constraint

- Optimum dispatch ***with the stability constraint*** and ***without transmission thermal limits***

Flowgate limit 670	1	2	3	4	5	Total
LMP	$30	$30	$30	$10	$10	
Generation (MW)	110	0	495	100[1]	570	1275
Total Production Cost	$1,540	$0	$14,850	$2,500	$5,700	$24,590
Total Revenue to Gen	$3,300	$0	$14,850	$1,000	$5,700	$24,850
Net Income to Gen	**$1,760**	**$0**	**$0**	**-$1,500[1]**	**$0**	**$260**
Load (MW)	425	425	425	0	0	1275
Total Cost to Load	$12,750	$12,750	$12,750	$0	$0	$38,250
	FGR Price	**MW**	**Tot FG Cong.**	**Gen Redisp.**	**Cong. Cost**	
	$20	670	**$13,400**	$1,100	$13,400	

[1] Minimum generation for generator 4 is 100MW.

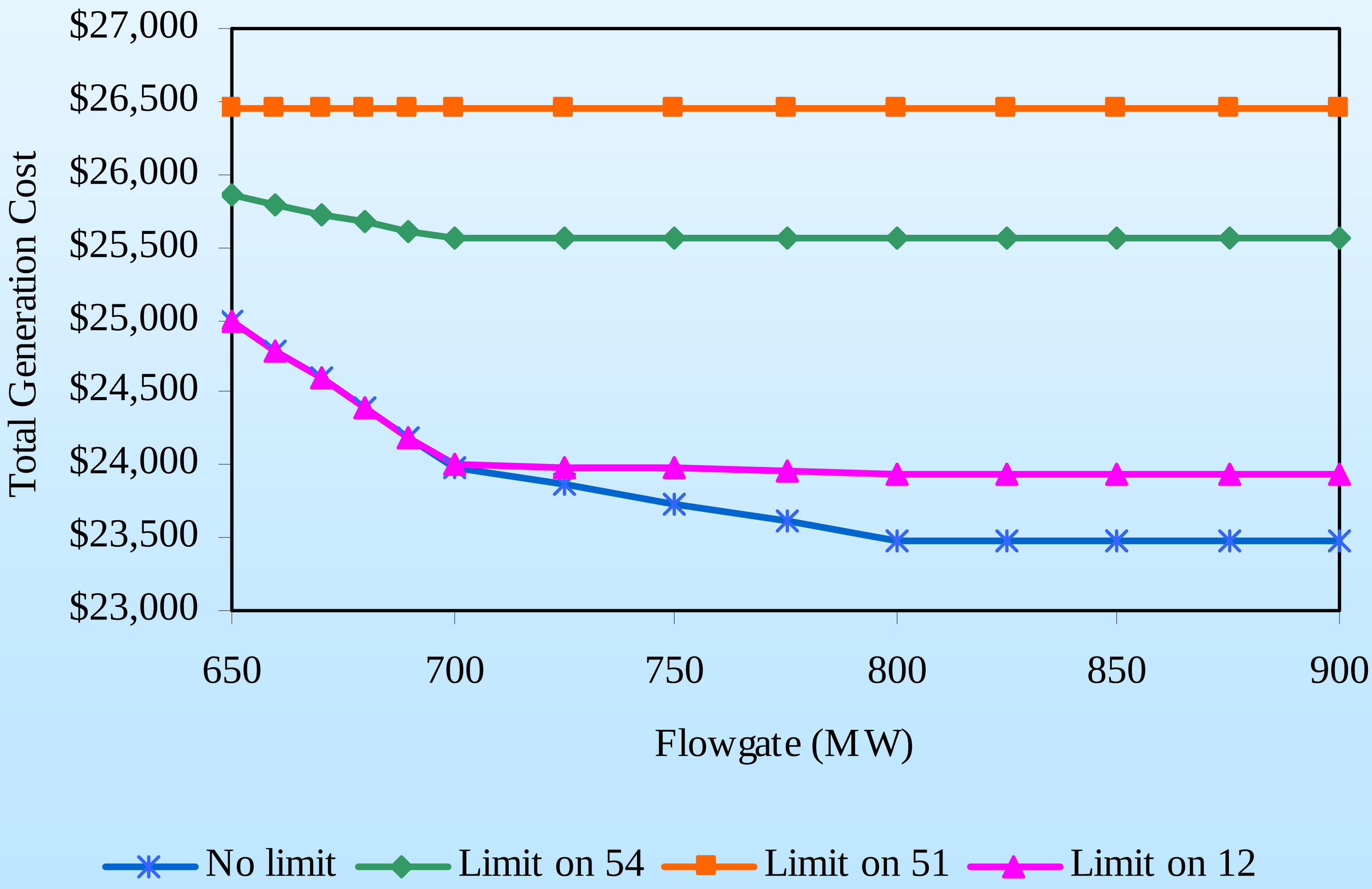
Allocating congestion costs due to stability constraint

Allocation of congestion costs under flow-based and nodal approaches in the case of optimum dispatch ***with thermal limit on line 54*** (= 240MW) and ***with flowgate limit*** (= 670MW)

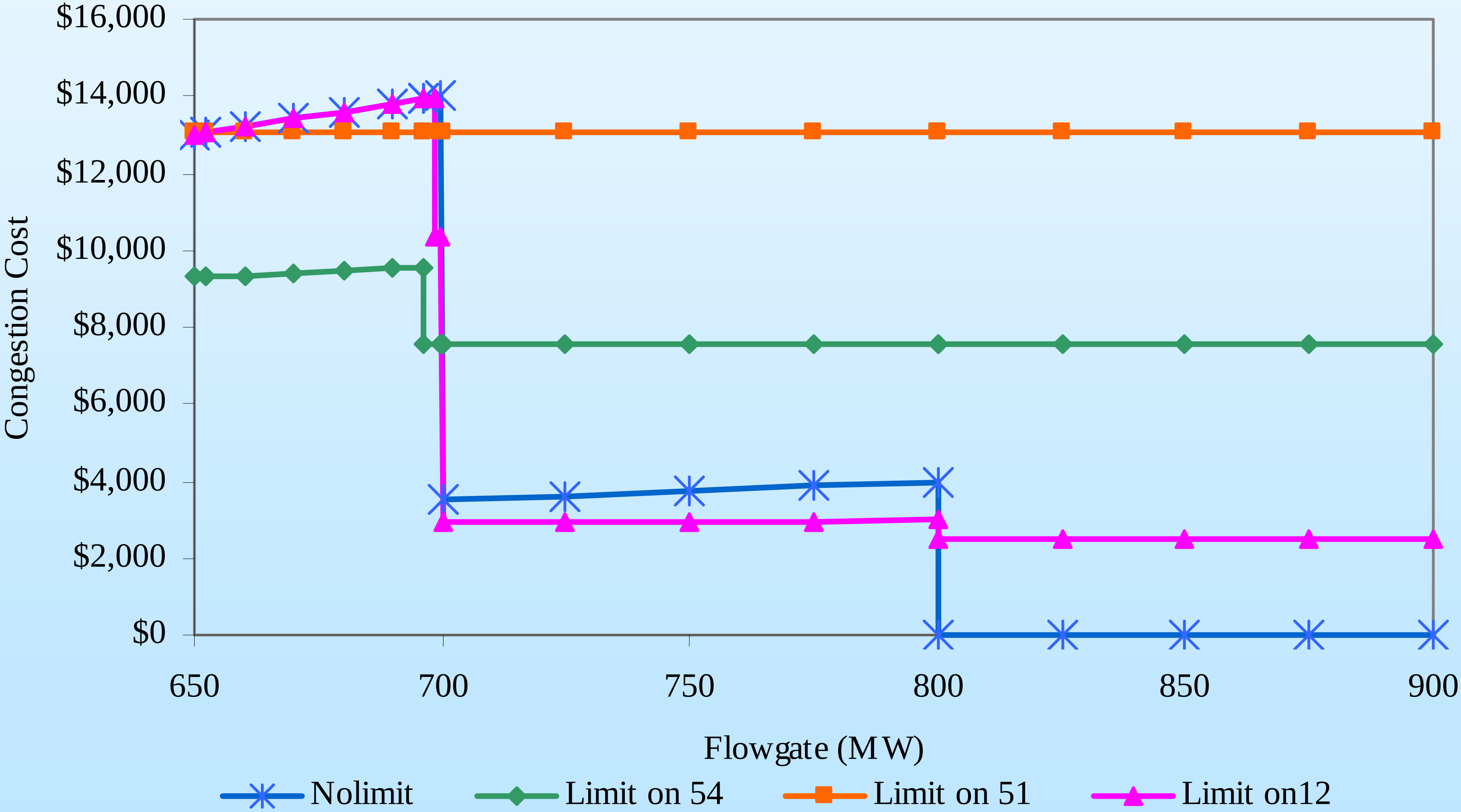
		Flow-based Approach		Nodal Approach	
Line	**Flow**	**FGR**	**Cong. Cost**	**LMP$_j$-LMP**	**Cong. Cost**
12	76.60	\$0.00	\$0.00	\$1.28	\$97.78
23	-348.40	\$0.00	\$0.00	\$1.28	-\$444.77
43*	278.40	\$0.00	\$0.00	\$5.00	\$1,392.02
54	240.00	\$21.70	\$5,208.51	\$15.00	\$3,600.00
41*	137.55	\$0.00	\$0.00	\$2.45	\$336.57
51*	254.04	\$0.00	\$0.00	\$17.45	\$4,432.23
FG	670.00	\$6.28	\$4,205.32	\$0.00	\$0.00
Total			\$9,413.83		\$9,413.83

Significant differences exist in allocating the congestion costs.

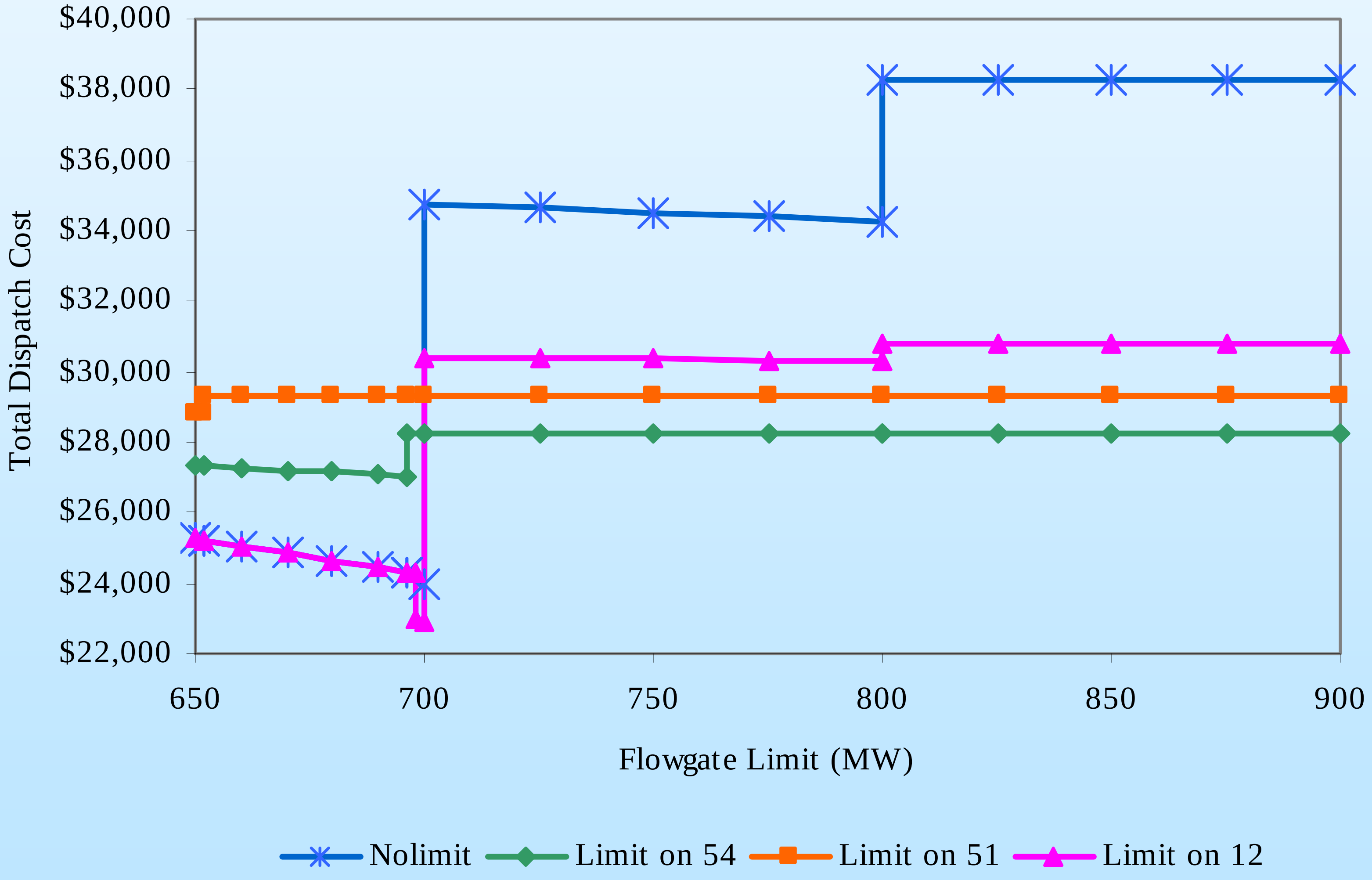
Total Production Cost



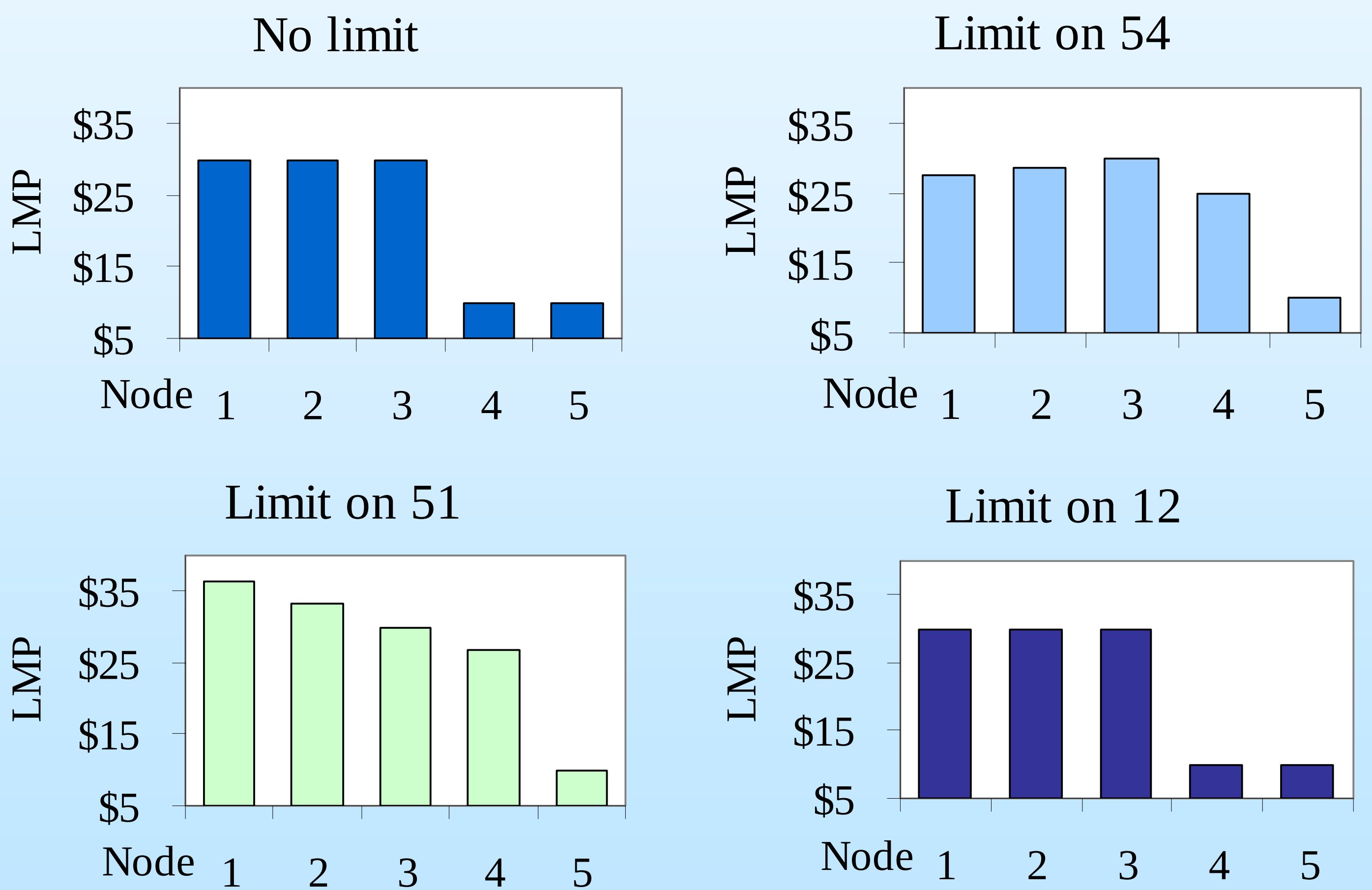
Total Congestion Cost



Total Dispatch Cost



*Changes in **LMPs** with Different Transmission Thermal Limits*



Flowgate Limit 670MW