A Tutorial on the Flowgates versus Nodal Pricing Debate

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Objectives

1. Understand the relationship between nodal pricing and flowgate pricing as means for real time economic-based congestion management.
2. Understanding the role of property rights to the transmission system in forward energy trading and risk management and the difference between flowgate rights (FGR) and financial transmission rights (FTR) as hedging instruments for congestion.

Nodal pricing and Flowgate pricing in six easy steps

Step 1: Understanding PTDFs

Step 2: Understanding marginal units

Step 3: Understanding nodal spot pricing of energy

Step 4: Understanding flowgate spot pricing of transmission

Step 5: The relationship of the two

Step 6: Alternative approaches to congestion management

Step 1: What is a PTDF?

- Power Transfer Distribution Factor
  - Sensitivity of a flow to an injection
    - Relative to a “reference location”
    - Reference location irrelevant: to get a “bilateral PTDF” combine an injection and an extraction
- Useful to find impact of transactions on flowgates
  - A flowgate is a congested line or corridor

PTDFs the “hard” way

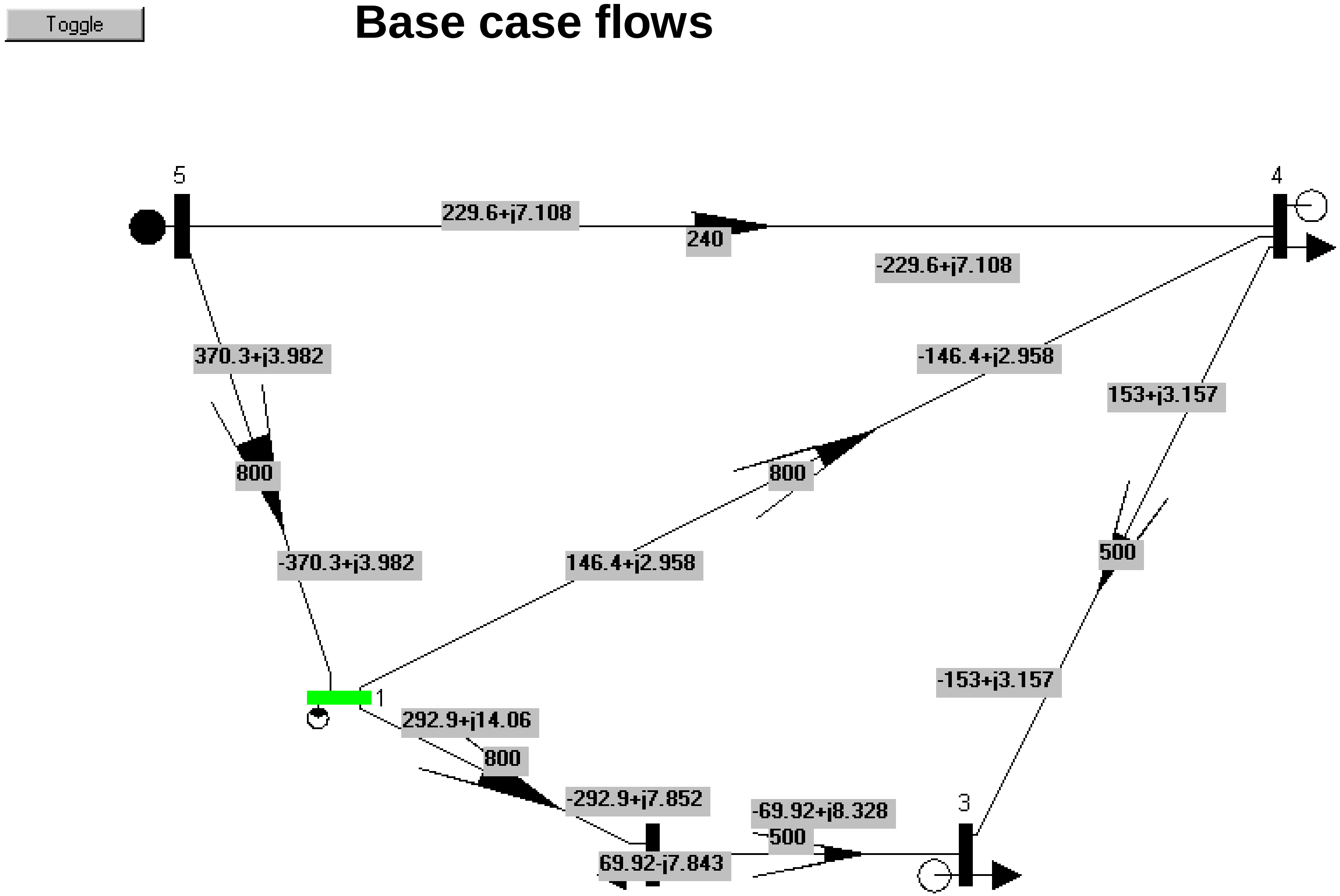
Find base power flows

Change an injection

Find new flows

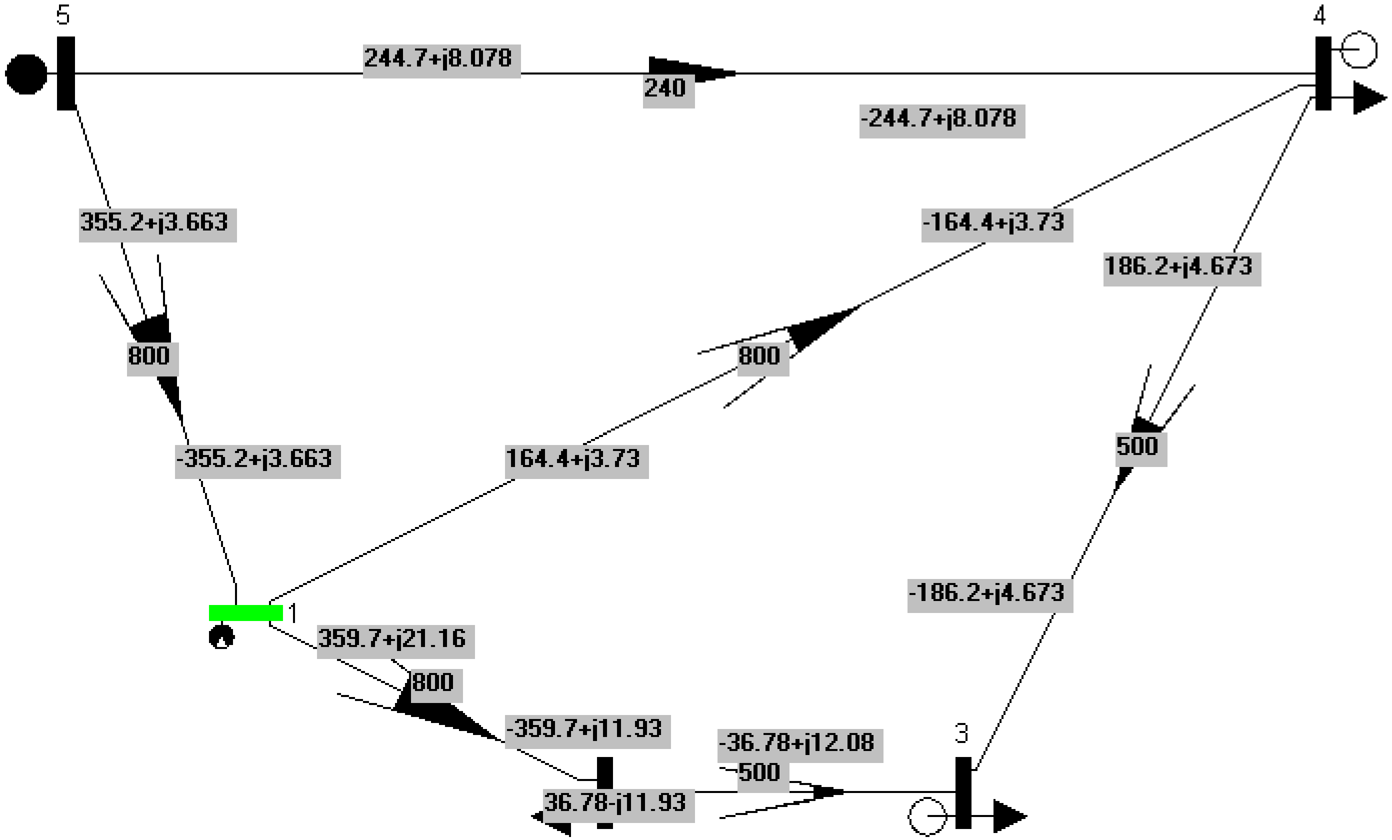
Divide change in flow by change in injection

Base case flows



Increment

Flows after increasing demand at 2 by 100 MW



Estimation of PTDFs

$$PTDF(5 \rightarrow 4,2) = \frac{\text{change in } 5 \rightarrow 4 \text{ flow}}{\text{injection at } 2}$$

$$= \frac{244 - 229}{-100}$$

$$= -0.15$$

Computing PTDFs - better way

The formula is:

$$\mathrm{PTDF} = J^{-1} J^{f}$$

where *J* is the ordinary Jacobian and J^f is the Jacobian with respect to flows

PTDFs are essential for NERC’s TLR

Computing approximate PTDFs

The formula is:

$$\text{PTDF} = B^{-1}\, B^{f}$$

where *B* is the *reduced* nodal susceptance matrix and B^f is a *reduced* matrix with the branch susceptances

By reduced we mean that rows (and columns) corresponding to a reference location are eliminated (results are insensitive to this choice)

For the PJM-5 example

Lines

From	To
1	2
2	3
3	4
4	5
1	4
1	5

$$X=\begin{bmatrix}0.0281\\0.0108\\0.0297\\0.0297\\0.0304\\0.0064\end{bmatrix}\qquad 1/X=\begin{bmatrix}35.59\\92.59\\33.67\\33.67\\32.89\\156.25\end{bmatrix}$$

Buses

$$B=\begin{array}{c|ccccc|}224.73 & -35.59 & 0 & -32.89 & -156.25 & \\ -35.59 & 128.18 & -92.59 & 0 & 0 & \\ 0 & -92.59 & 126.26 & -33.67 & 0 & \text{Buses}\\ -32.89 & 0 & -33.67 & 100.23 & -33.67 & \\ -156.25 & 0 & 0 & -33.67 & 188.92 & \end{array}$$

PTDF determination

Buses

$$B^f = \begin{array}{c} \\ \begin{bmatrix} -35.59 & 35.59 & 0 & 0 & 0 \\ 0 & -92.59 & 92.59 & 0 & 0 \\ 0 & 0 & -33.67 & 33.67 & 0 \\ 0 & 0 & 0 & -33.67 & 33.67 \\ -32.89 & 0 & 0 & 32.89 & 0 \\ -156.25 & 0 & 0 & 0 & 156.25 \end{bmatrix} \end{array} \text{Branches}$$

Buses

$$\text{PTDF'} = \begin{bmatrix} 0.0000 & 0.6698 & 0.5430 & 0.1940 & 0.0346 \\ 0.0000 & -0.3302 & 0.5430 & 0.1940 & 0.0346 \\ 0.0000 & -0.3302 & -0.4570 & 0.1940 & 0.0346 \\ 0.0000 & -0.1508 & -0.2088 & -0.3682 & 0.1126 \\ 0.0000 & 0.1793 & 0.2482 & 0.4378 & 0.0780 \\ 0.0000 & 0.1518 & 0.2102 & 0.3706 & 0.8931 \end{bmatrix} \text{Branches}$$

Step 2: The “marginal unit”

- With no constraints and no losses, there is one marginal unit
  - The “next MW” come from the marginal unit
  - With losses, several marginal units possible
- For one congested flowgate, there are at least two marginal units
  - There must be at least one more marginal unit than there are active constraints
  - The power for any location may come from more than one of the marginal units
    - Units on the margin can reduce their output

Step 3: Nodal spot pricing of energy

The nodal spot price is the cheapest way to deliver one MWh to a location, respecting all limits (including contingency limits)

PTDFs + Constraints + Marginal Units ⇒ Spot Prices

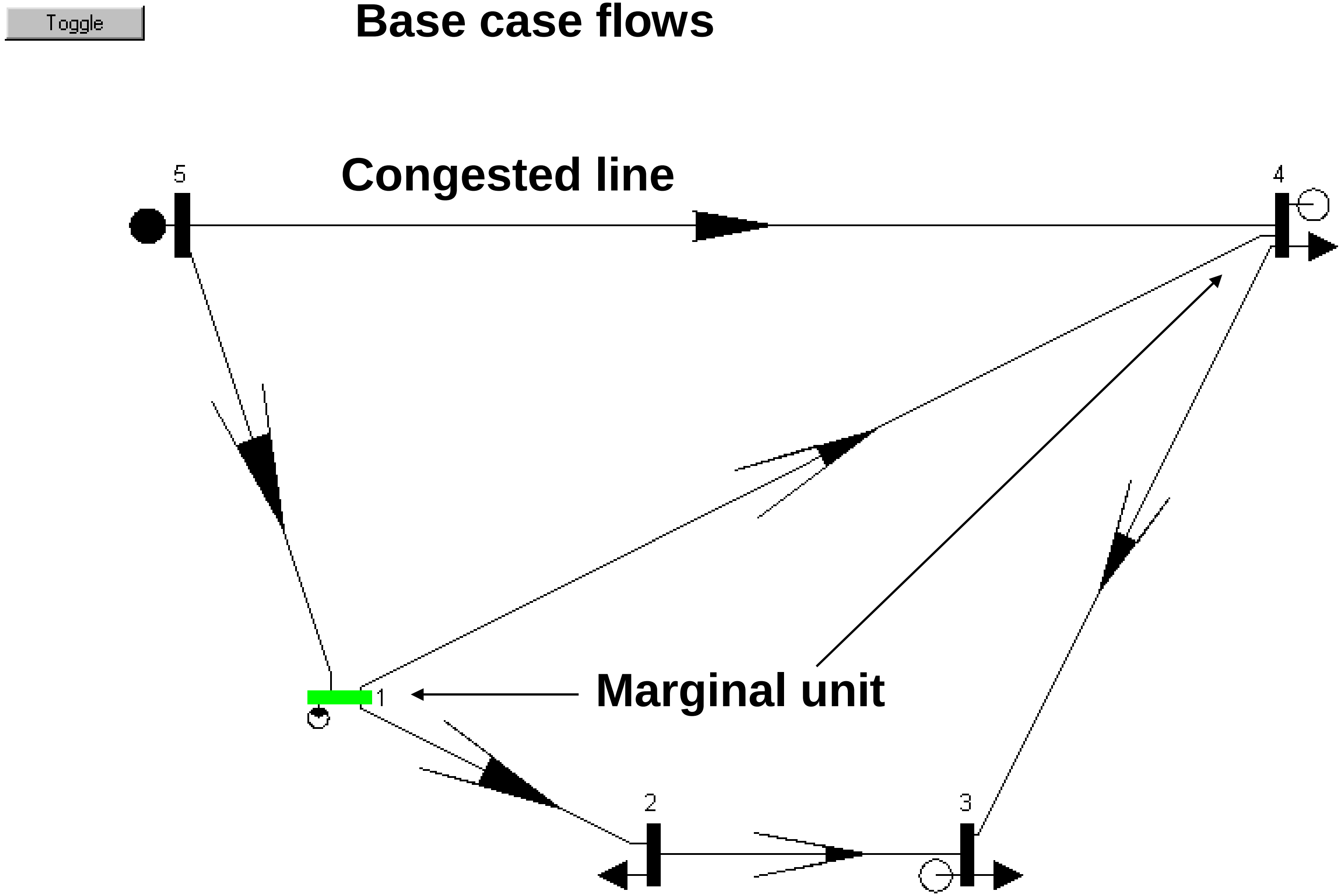
Identify constraining conditions

Identify marginal units

Solve simple optimization problem

- How cheaply can power be delivered to a location from these units respecting all constraints?
- What is the shadow price (marginal value) of the capacity on the congested flowgates?

Base case flows



Congested line

Marginal unit

Delivery point of interest

Computation specifics

Buses

$$\mathrm{PTDF}' = \begin{array}{|rrrrr|}\hline 0.0000 & 0.6698 & 0.5430 & 0.1940 & 0.0346 \\ 0.0000 & -0.3302 & 0.5430 & 0.1940 & 0.0346 \\ 0.0000 & -0.3302 & -0.4570 & 0.1940 & 0.0346 \\ 0.0000 & -0.1508 & -0.2088 & -0.3682 & 0.1126 \\ 0.0000 & 0.1793 & 0.2482 & 0.4378 & 0.0780 \\ 0.0000 & 0.1518 & 0.2102 & 0.3706 & 0.8931 \\ \hline \end{array}$$

Branches

Sending 1 MW from 1 to 2 increases the flow on 5-4 by 0.1508 MW

Sending 1 MW from 4 to 2 increases the flow by –0.3682+0.1508=–0.2174

We do not want the 5-4 flow to increase

We want the total delivered to be 1 MW

$$\begin{bmatrix} 0.1504 & -0.2174 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} P_1 \\ P_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Doing the computation

Two equations in two unknowns:

$$\begin{bmatrix} 0.1504 & -0.2174 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} P_1 \\ P_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Their solution is:

P_1=0.5904 P_4=0.4096

The energy spot price at bus 2 is thus

15*0.59+30*0.41= 21.15

(Spot prices at bus 1 and 4 are 15 and 30)

Step 4: Flowgate spot pricing of transmission capacity

- The flowgate spot price is the incremental value to the system (reduction in dispatch cost) resulting from increasing the ATC on a flowgate by 1 MW under least cost security constrained dispatch.
  - Only congested flowgates have positive incremental value, i.e, are commercially significant.
- The flowgate spot price is also the value of 1 MW counterflow (produced trough redispatch) on the flowgate

Computing Flowgate spot prices

As before:
Sending 1 MW from 1 to 2 increases the flow on 5-4 by 0.1508 MW
Sending 1 MW from 4 to 2 increases the flow by –0.3682+0.1508=–0.2174

Now we want the 5-4 flow to increase by 1 MW while the net injection is zero

$$\begin{bmatrix} 0.1504 & -0.2174 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} P_1 \\ P_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

The solution to the two equations with two unknowns is: P_1= 2.7189 P_4= - 2.7189

An extra 1MW capacity on 5-4 enable us to reduce injection at bus 4 by 2.7189 MW and increase injection at bus 2 by the same amount

The Flowgate spot price = reduction in system cost = 2.7189*(30 - 15) = $40.78/MW/h (shadow price on 5-4)

Step 5: The relationship between nodal spot energy prices and flowgate spot transmission prices

Let:

N_i = Energy nodal spot price at bus i

F_j = ATC shadow price at flowgate j (flowgate spot price)

$$N_{reference} - N_i = \sum_{\text{all flowgates j}} F_j * PTDF_{ij}$$

$$N_k - N_i = \sum_{\text{all flowgates j}} F_j * (PTDF_{ij} - PTDF_{kj})$$

Only congested flowgate need to be counted

In our example:

$N_1 - N_2 = 15 - 21.15 = - 6.15 = - 0.1508 * 40.78$

$N_4 - N_2 = 30 - 21.15 = 8.85 = (- 0.1508 + 0.3682) * 40.78$

Step 6: Alternative approaches to congestion management and transmission service settlement

- RTO Dispatches all scheduled transactions based on security constrained OPF
  - Bilateral transactions from node A to B pay (or get paid) ex-post opportunity cost = Nodal price difference times total MW transacted.
  - Bilateral transactions pay shadow prices on congested flowgates times the flow they induce on each flowgate or collect shadow prices times the counterflow they produce.
- RTO publishes PTDF and bilateral transactions must support their schedules with ATC rights on congested flowgate they impact.
  - Flowgate rights are auctioned off (or endowed for grand fathered rights or transmission investment) and subsequently traded in secondary markets where their prices are set by supply and demand (in equilibrium these pries should converge to shadow price).

(Most researchers and practitioner agree that for real time congestion management and settlement the first approach is preferable.)

Tradable Property Rights

Purpose:

- Facilitates efficient use of scarce resources (Coase)
- Mechanism to reward investment
- Enable risk management (hedging, forward markets)

Aspects of Property rights:

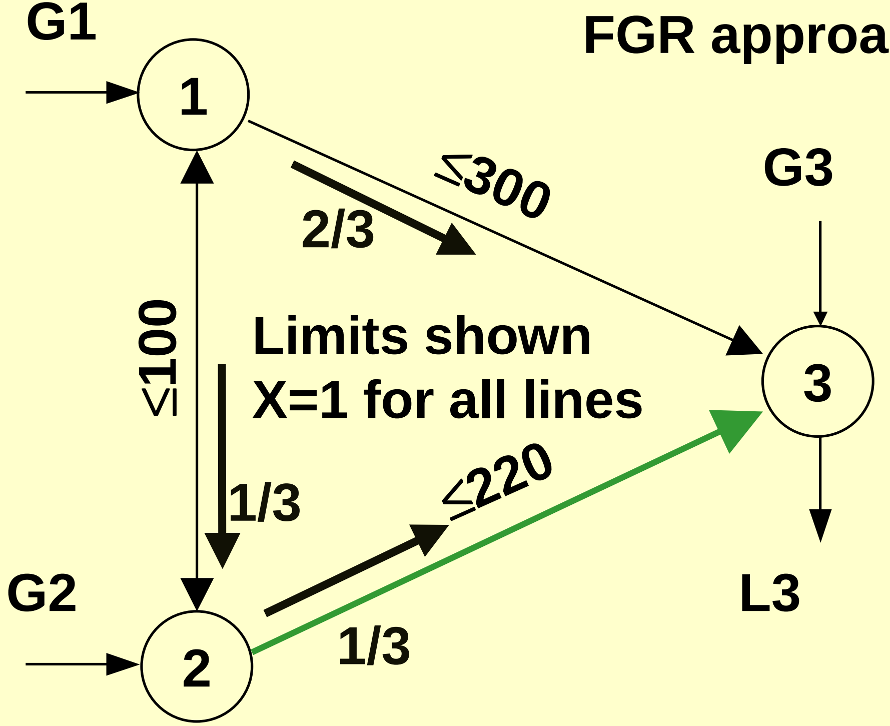
- Right to financial gain from asset
- Right to use asset (weak physical)
- Right to exclude others from using the asset (strong physical)

Types of property rights in power transmission systems

- FTR – Financial Right (PJM)
  - Right or obligation to the difference of nodal prices on 1 MW of balanced transaction between two specific nodes or between a node and a hub (two sided contract can be positive or negative).
- FGR – Financial + Weak Physical (CA)
  - Right to shadow prices on 1 MW ATC on a specific flowgate (constrained element or line) in a specific direction - one sided contract always nonnegative payoff - option to the buyer obligation to the seller)
  - Right to scheduling priority for flow on flowgate whenever curtailment is employed (if redispatch market doesn’t clear or in case of ties)
  - No right to withhold - scheduling right reverts to the RTO if not used (retention of financial right ?)

Hedging forward transactions with FTRs and FGRs

G1 has a bilateral contract with L3 to deliver 150 MW and wants to hedge congestion charges:



Limits shown
X=1 for all lines

FTR approach: Buy 150MW of FTR 1→ 3
FGR approach: Buy 100MW of FGR 1→3
50MW of FGR 1→2
50MW of FGR 2→3
(FGR portfolio emulates the distribution of flow according to the PTDFs published by the RTO)

Real time settlements

Suppose real time dispatch is based on security constrained OPF and the flow constraint on link 2 → 3 with corresponding shadow price F_{23} (shadow prices on uncongested links are zero) and nodal prices N_1 , N_2, N_3

Nodal pricing based congestion charges paid by the generator for the 150MW transaction from node 1 to 3 are $150*(N_3 - N_1)$

Settlement for 150MW FTR 1 → 3 paid to the generator is $100*(N_3 - N_1)$

Settlement for 50MW FGR 2 → 3 is $50* F_{23.}$. But $N_3 - N_1 = 1/3* F_{23}$ (relation of nodal and shadow prices)

Both the FTR and FGR settlements offset the real time congestion charges (full hedging)

So what is the difference?

- FTRs guarantee a perfect hedge
  - Insurance against congestion on flowgates
  - Insurance against changes in PTDFs
  - Insurance against changes in ATC on flowgate
  - Solvency conditions necessitates limiting the FTR offering
- FGRs only provides insurance against congestion on flowgates
  - Holder is responsible to maintain proper mix
  - PTDF tracking services or insurance against deviation can be offered as a service by private commercial entities
  - Socialization of changes in congestion cost due to PTDF changes proposed (e.g. MISO) but is a bad idea

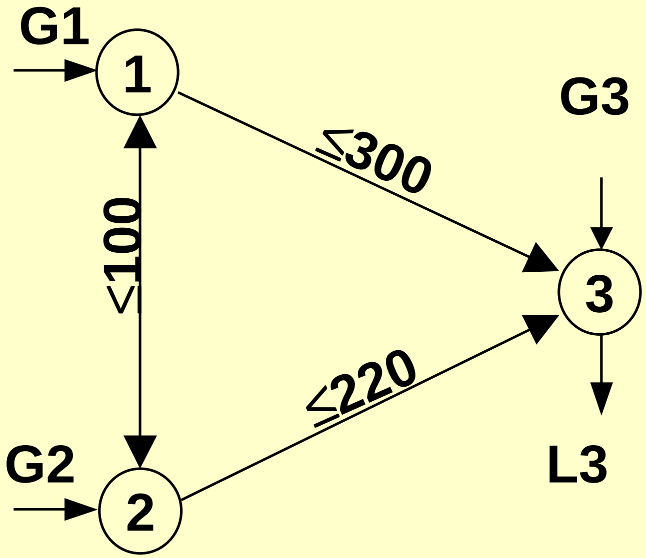
Issuing and trading FTRs

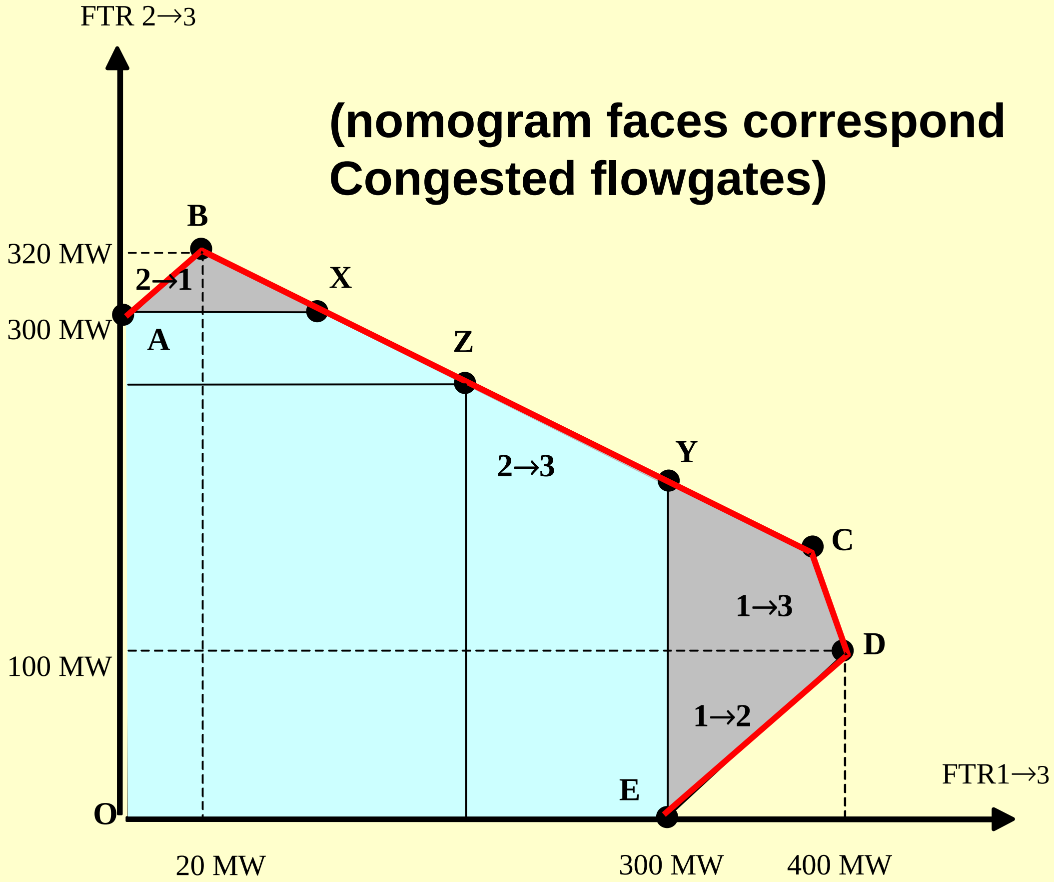
- FTRs representing financial property rights to the transmission system must be issued centrally by the RTO (Speculative FTRs “off track betting” can be issued by anyone but have no physical cover)
- To insure that congestion revenues can cover FTR settlements FTRs must meet a “simultaneous feasibility condition”
- The FTR “operating point” corresponding to simultaneous bilateral schedules replicating all outstanding FTRs must meet all security and flow constraints.
- In an FTR auction (PJM) bidders submit bids for specific FTRs, RTO selects winning bids by treating FTR bids as proposed schedules using a security constraint OPF that maximizes FTR revenue

Issuing and trading FTRs (cont'd)

- When the operating point differs from the FTR operating point congestion charges will exceed FTR settlement. The difference represents unhedged congestion.
- Reconfiguration of simultaneously feasible FTRs to track the operating point must be done centrally (monthly at PJM).
- Low liquidity due to large number of FTRs coordination requirement makes secondary trading virtually impossible.
- FTRs must be issued as two sided instruments (that can have negative value) in order to provide adequate hedging capability.
- Issuing FTRs as options while meeting simultaneous feasibility severely restricts FTR offering and hedging capability.

EXAMPLE



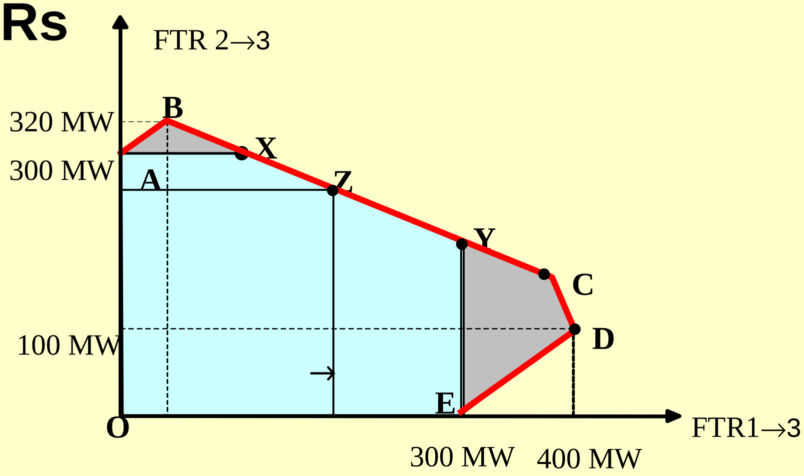


(nomogram faces correspond Congested flowgates)

- **Two sided FTRs must stay within the outer nomogram (if operating point is on face AB or ED FTR 2→3 must pay)**
- **One sided FTRs (options) must stay within inner nomogram**

EXAMPLE (cont’d)

- Negative valued 2 → 3 FTRs at D represents a counterflow obligation (needed to offset settlement of extra 1 → 3 FTRs)
- If FTR point matches operating point FTR settlements equals congestion revenues, RTO breaks even and all transactions can be perfectly hedged.
- If FTR point is Z and operating point is Y then there are too many 2 → 3 FTRs and not enough 1 → 3 FTRs
  - RTO has excess congestion revenue
  - Not all transactions can be hedged (those that are have perfect hedges)



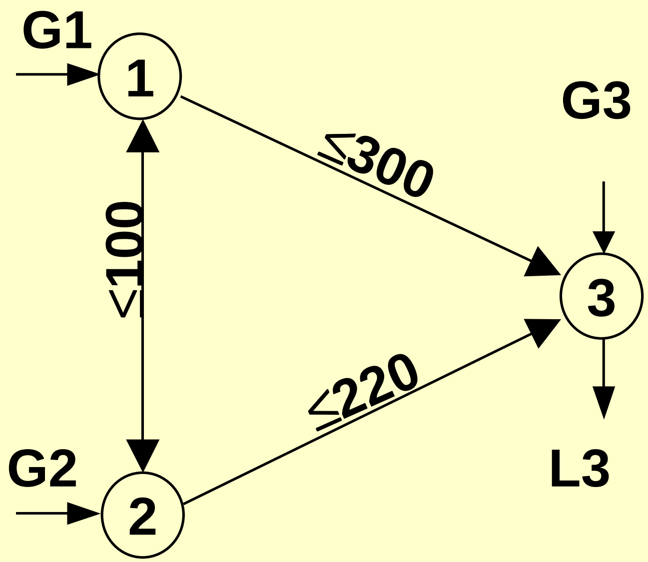
Issuing and trading FGRs

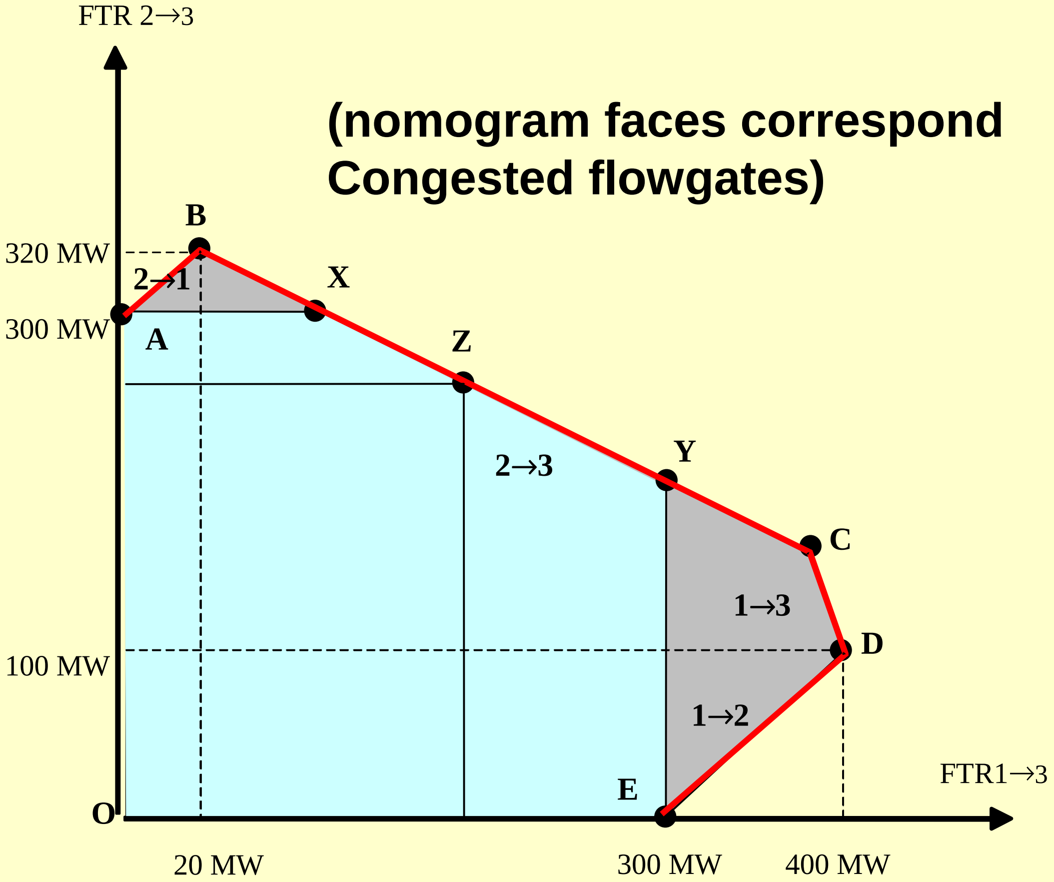
- **RTO auctions FGRs (financial with or without scheduling priority) as property rights to the directional flowgates' physical capacity**
- **Only commercially significant flowgates (those likely to congest) need to be included in auction**
- **FGRs are issued as options since settlement (based on shadow prices) can only be positive or zero**
- **Number of FGRs on each flowgate determined independently of others (no simultaneous feasibility condition)**
- **RTO publishes current PTDFs informing traders FGR mix needed to hedge point to point transactions**

Issuing and trading FGRs (cont’d)

- All congestion revenues paid as settlements of FGRs issued by RTO or as real time negative congestion payments to counterflow producers
- FGRs traded on secondary markets
- Traders or private commercial entities update FGR portfolio to maintain point to point hedges
- Producers of counterflow on commercially significant flowgates can sell private FGRs (covered by their expected real time counterflow revenues from RTO) on secondary market (these will command the same prices and settlement as RTO issued FGRs but will be settled privately)
- Sellers of counterflow FGRs undertake an obligation. Such obligations are necessary to enable full hegdging cover for all transactions
- RTO issued FGRs for physical capacity + private FGRs for counterflow => All transactions can be fully hedged for any operating point (but it is up to the market to get the FGRs into the right hands)

EXAMPLE




(nomogram faces correspond Congested flowgates)

- RTO can sell 100MW 2→1 FGRs, 100MW 1→2 FGRs, 300MW 1→3 FGRs, 300MW 3→1 FGRs, 220MW 2→3 FGRs, 220MW 3→2 FGRs (all covered by physical capacity of system)
- G1 can sell up to 6.3MW counterflow 1→2 FGRs (covered by an obligation to generate 20MW)
- G2 can sell up to 33.3MW counterflow 2→1 FGR (covered by an obligation to generate 100MW)

Efficient Forward Trading with FTRs

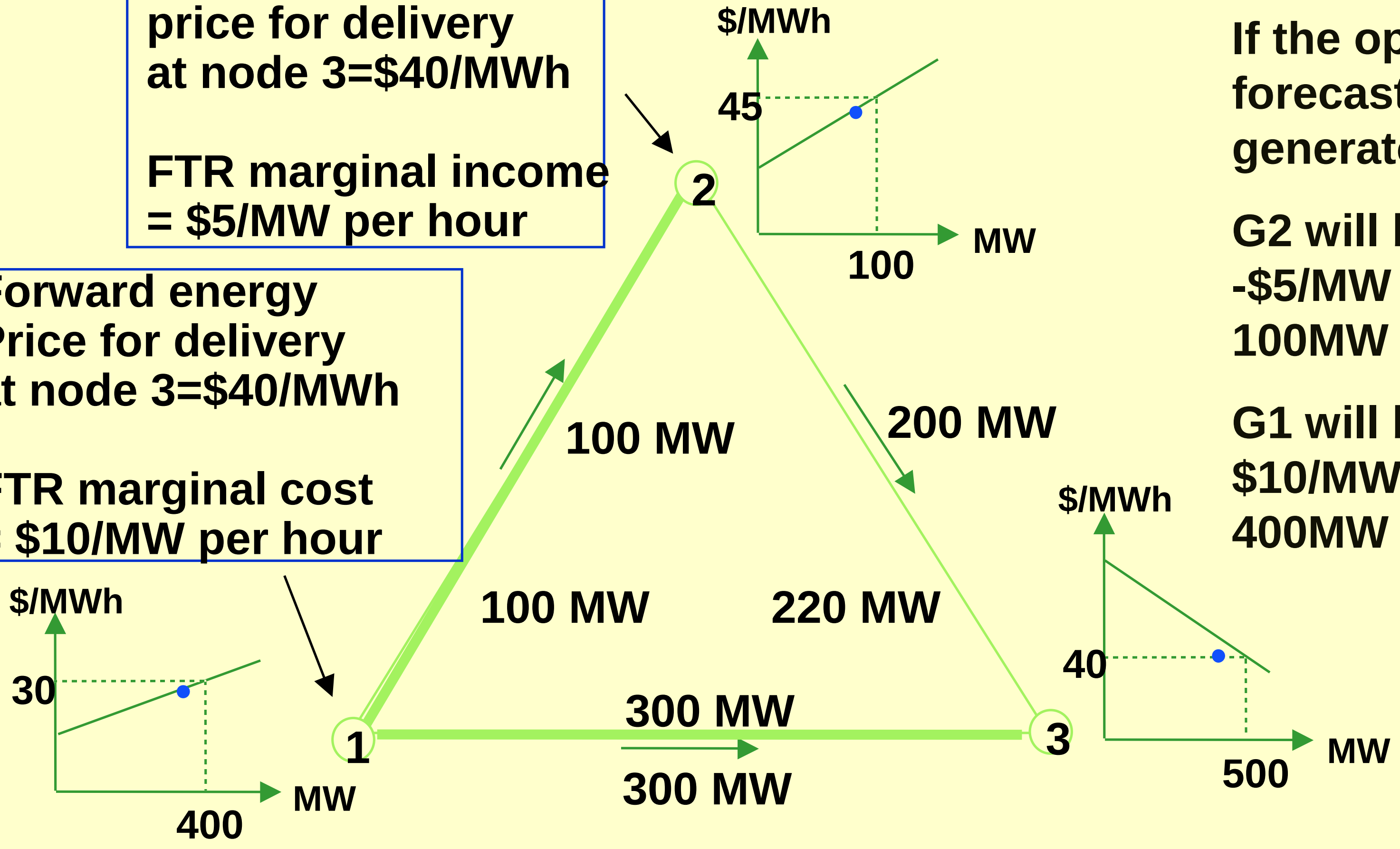
OPF solution = point D on nomogram)

Forward energy
price for delivery
at node 3=$40/MWh

FTR marginal income
= $5/MW per hour

Forward energy
Price for delivery
at node 3=$40/MWh

FTR marginal cost
= $10/MW per hour



If the operating point is forecasted correctly by generators

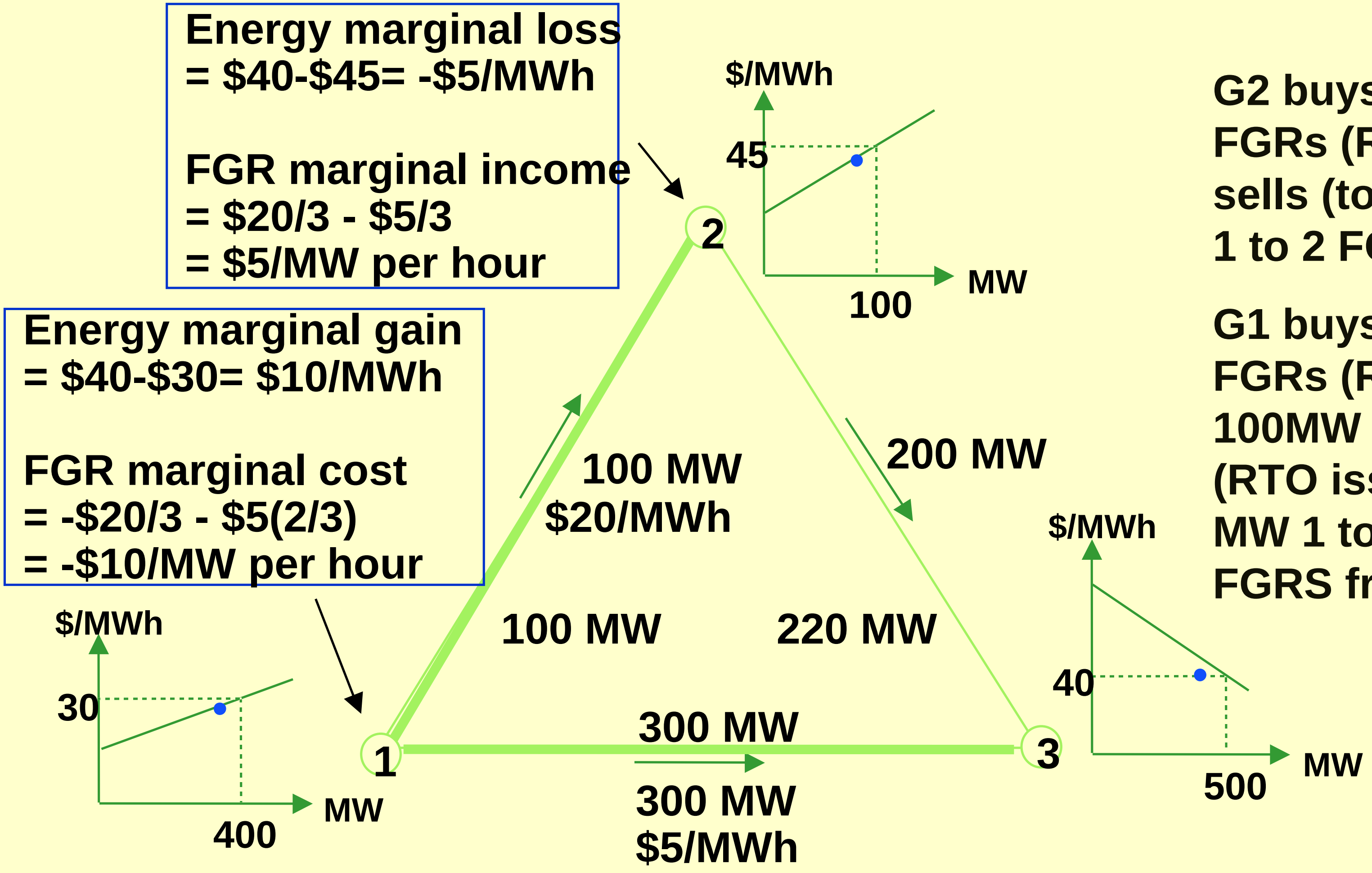
G2 will bid up to -$5/MW per hour for 100MW 2 to 3 FTRs

G1 will bid up to $10/MW per hour for 400MW 1 to 3 FTRs

In real time congestion charges=FTR settlements

Efficient Forward Trading with FGRs

Market equilibrium=OPF solution (point D on nomogram)



Energy marginal loss
= $40-$45= -$5/MWh

FGR marginal income
= $20/3 - $5/3
= $5/MW per hour

Energy marginal gain
= $40-$30= $10/MWh

FGR marginal cost
= -$20/3 - $5(2/3)
= -$10/MW per hour

G2 buys 33.3 MW 1 to 3 FGRs (RTO issued) and sells (to G1) 33.3 MW 1 to 2 FGRs

G1 buys 267MW 1 to 3 FGRs (RTO issued), 100MW 1 to 2 FGRs (RTO issued) and 33.3 MW 1 to 2 counterflow FGRS from G2

In real time congestion charges=FGR settlements

Pros and Cons of FTR

- Offers full hedges that account for security constraint dispatch
- If Operating point differs from FTR point not all transaction can be hedged
- Centrally managed frequent reconfiguration auctions needed
- FTRs must be defined as two sided instruments (otherwise feasibility condition is too strict)
- Not conducive to secondary trading

Assumptions underlying FGR approach

- Flowgates can be defined
- Number of commercially significant flowgates is small and predictable
- PTDFs are relatively stable
- Flowgate capacities are stable and known

Pros and cons of FGRs

- Amenable to secondary trading
  - No simultaneous feasibility required
  - Requires less central coordination
  - Small number facilitates liquidity
- FGR can be issued for long periods
  - Effective property rights for investment or grandfathered rights
- All the grid capacity is sold (all congestion charges are distributed as FGR settlements)
- FGRs are one sided instruments (holder has no obligation but issuer does)
- Reliance on market to assemble hedges for point to point transactions
- Hedges are not perfect unless the cost of PTDF variation is socialized (can create gaming incentives)
- Underlying assumptions may not be valid

Best of Both Worlds

- Real time congestion settlement based on locational marginal cost
- RTO can offer both FTRs and FGRs so that combination of FTRs is within the nomogram but remaining capacity on flowgates (not fully utilized at FTR point) can also be sold
- FGRs settled based on flowgates shadow prices. FTR settled as portfolio of FGRs or based on nodal price differences (who underwrites the difference?)
- Secondary FGR markets enable traders to reconfigure their hedges so as to track changes in operating point