Slides taken from:

EEE 598
Electric Energy Markets

School of ECEE, ASU

Professor Kory W. Hedman

Locational Marginal Prices

Locational Marginal Prices (LMPs)

- Typical Definition:
  - Cost for the operator to deliver 1 additional MW (or a small increment) to a bus/node in the network

Note: some market entities only recognize a subset of nodes within their system when running their market. Gens, loads not at the nodes they represent must then be approximated at a nearby node (i.e., a form of network reduction occurs). The subset of nodes represented in the market that get an LMP are often referred to as p-nodes (pricing nodes)

Locational Marginal Pricing

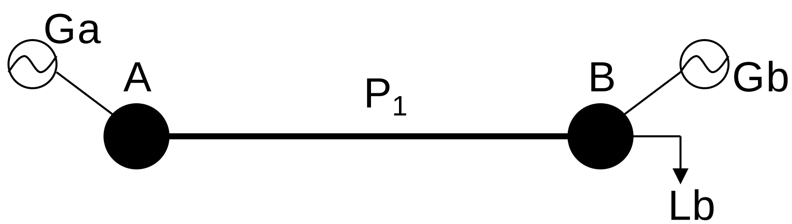
- Is an LMP based on:
- Uniform Pricing?
- Pay-as-Bid Pricing?
- Neither?
- Each generator (consumer) at a bus/node in the network is paid (pays) the LMP
  - Uniform Pricing
  - There is a deviation away from the practice that each gen at the same node gets the same price – CAISO’s RAS + Gen Loss Distribution Factor model, approved by FERC, implemented?

Locational Marginal Prices (LMPs)

- For these examples, we will use the following definition:

- Typical Definition:
  - Cost for the operator to deliver 1 additional MW (or a small increment) to a bus/node in the network

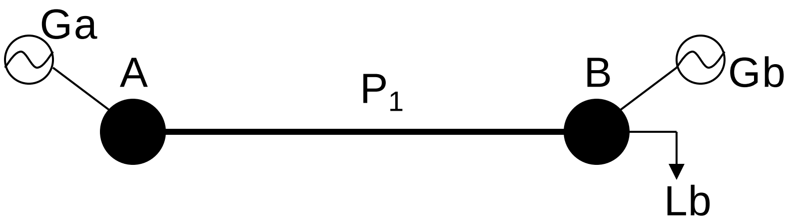
Example 1



- Ga: $50/MWh, Gb: $60/MWh
- Lb: 100MW
- P1: No capacity limit

- Result:
  - Ga = 100MW, Gb = 0MW
  - LMP_A = $50/MWh; LMP_B = $50/MWh
- No congestion & Lossless model
  - LMPs are the same throughout the network

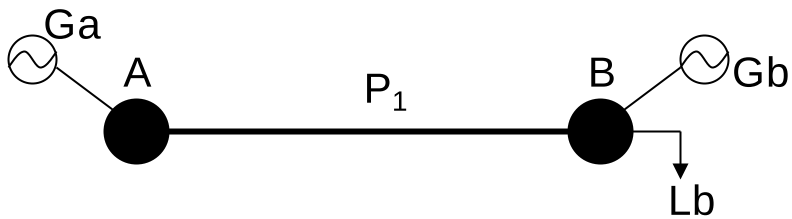
Example 2



- Ga: $50/MWh, Gb: $60/MWh
- Lb: 100MW
- P1 Limit: 100MW

- Result:
  - Ga = 100MW, Gb = 0MW
  - **LMP_A = $50/MWh; LMP_B = $60/MWh**
- Lossless model
- LMPs differ due to congestion

Example 3



- Ga: $50/MWh, Gb: $60/MWh
- Lb: 110MW
- P1 Limit: 100MW

- Result:
  - Ga = 100MW, Gb = 10MW
  - **LMP_A = $50/MWh; LMP_B = $60/MWh**
- Lossless model
- LMPs differ due to congestion

Break

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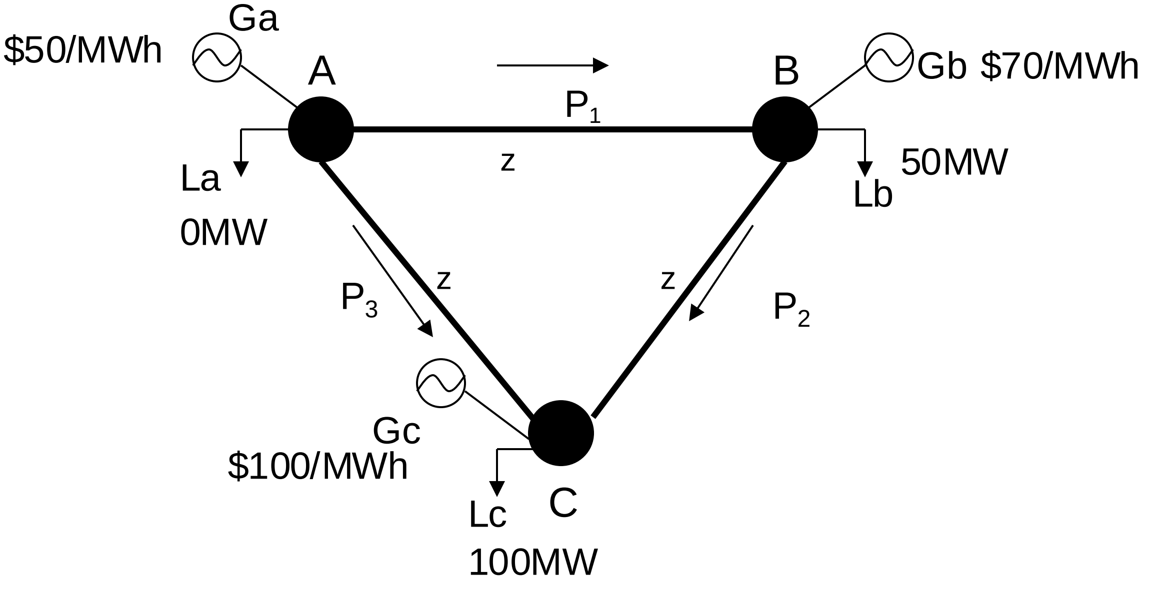
Example 4

- Can there be an LMP gap between two connected buses when the line connecting these buses has additional available capacity?
  - The line is not congested

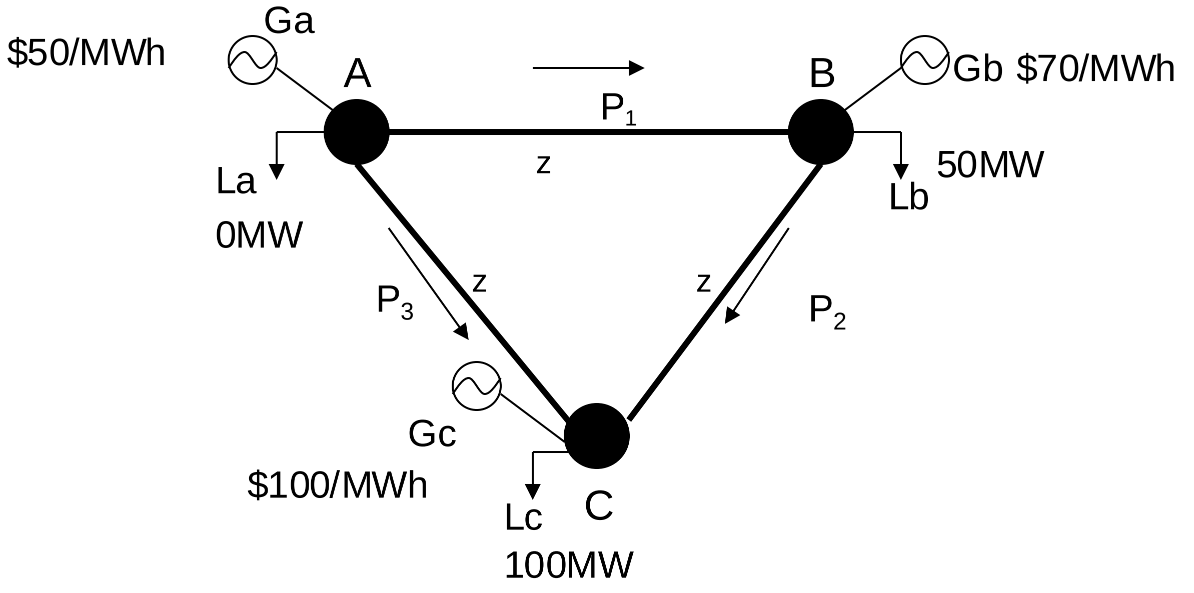
- Yes
- Due to Kirchhoff's laws, just because a line is not at its capacity does not mean that more energy can be sent across the line
- Congestion on other lines can cause a price separation for buses that are connected by a line that is not congested

Example 4



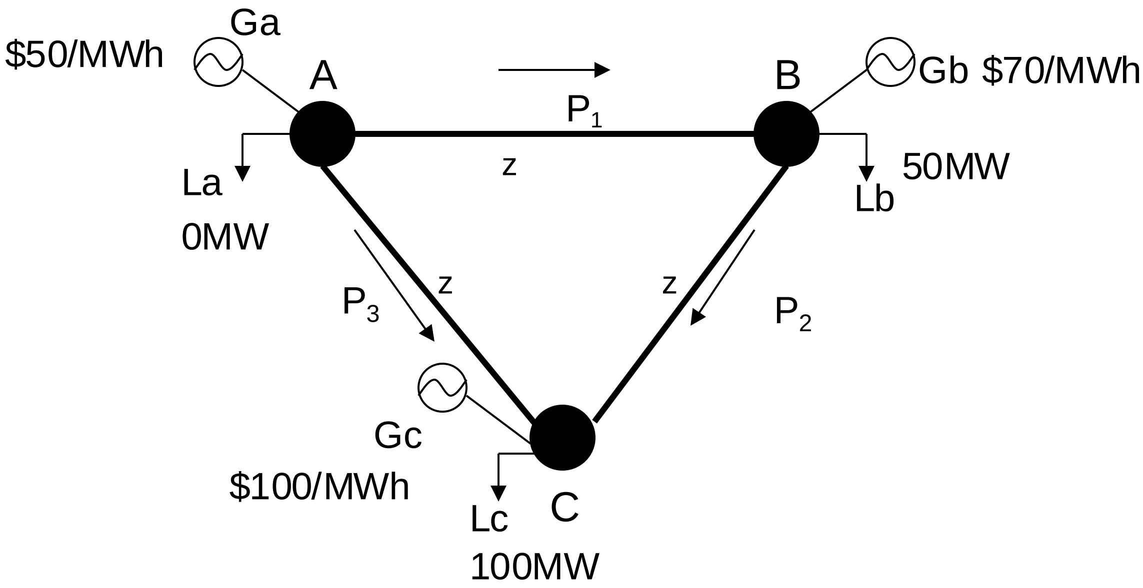
- P1 Limit: 25, P2 Limit: 25, P3 Limit: 25

Example 4



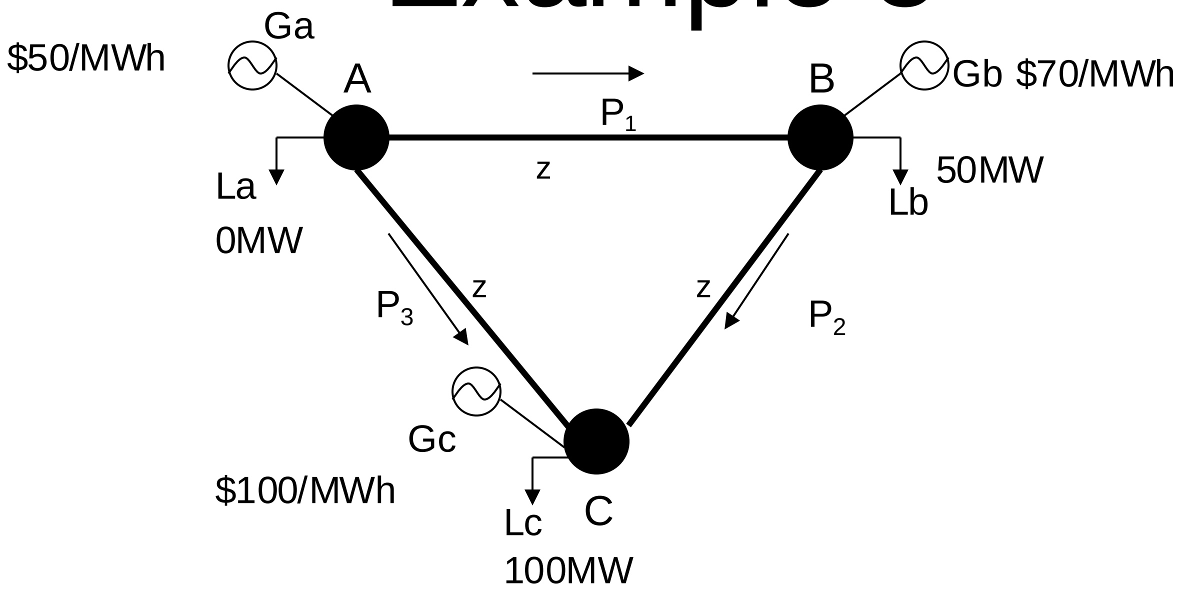
- Solution: Ga: 25, Gb: 75, Gc: 50
- LMP_A: $50/MWh, LMP_B: $70/MWh, LMP_C: $100/MWh
- **P1: 0MW**, P2: 25MW, P3: 25MW

Example 5



- P1 Limit: 25, **P2 Limit: 50, P3 Limit: 60**

Example 5



- Solution: Ga: 80, Gb: 70, Gc: 0
- LMP_A: $50/MWh, LMP_B: $70/MWh, **LMP_C: $90/MWh**
- **P1: 20MW, P2: 40MW, P3: 60MW**

Example 5

- Why is the LMP at C $90/MWh and not $100/MWh?
- If the load changes to 101 at node C, new optimal dispatch: Ga = 79MW, Gb = 72MW
- New line flows: P1: 19, P2: 41, P3: 60
- Re-dispatch of the system is to decrease Ga by 1MW (reduces objective by $50) and to increase Gb by 2MW (increases objective by $140)
  - Net change: $90/MWh
  - Thus, the LMP = $90/MWh at node C

$$\Delta G_A + \Delta G_B = \Delta L_c = 1$$

$$\Delta P_3 = 0 = \frac{2}{3}\Delta G_A + \frac{1}{3}\Delta G_B$$

$$\Delta G_A = -1, \Delta G_B = 2$$

$$\frac{\Delta Cost}{\Delta L_c} = \frac{(50\Delta G_A + 70\Delta G_B)}{\Delta L_c} = LMP_C$$

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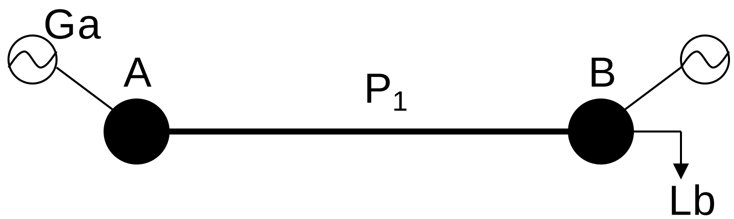
LMPs based on Dual Variables

Dual Variables

- Dual variables:
  – Shadow prices
  – Reflect the change to the objective of the primal if you make a minor change to the right hand side of the constraint
  – This change to the right hand side can be positive or negative
- LMP: Dual variable of the node balance constraint in the OPF formulation

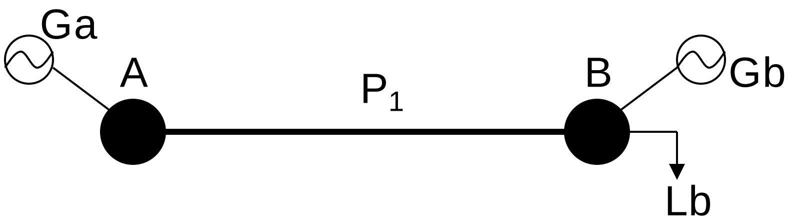
Re-examine Example 1



- Ga: $50/MWh, Gb: $60/MWh
- Lb: 100MW
- P1 Limit: No capacity limit

- Result is the same as before, LMP is $50/MWh at each node

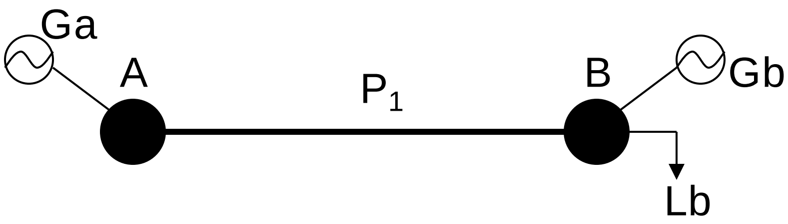
Re-examine Example 2



- Ga: $50/MWh, Gb: $60/MWh
- Lb: 100MW
- P1 Limit: 100MW

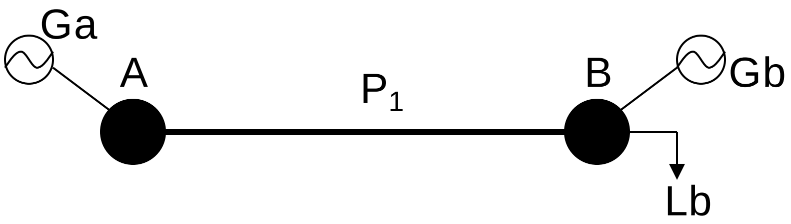
- Result:
  - Ga = 100MW, Gb = 0MW
  - **LMP_A = $50/MWh; LMP_B = [50, 60] $/MWh**
- Viewing the LMP as a dual variable – now we have a range of optimal LMPs
- If Load B reduces its consumption, the cost to satisfy the load in the network decreases by $50/MWh
  - Gen A reduces its output by 1MW
- To consume more will cost $60/MWh
  - Gen B must supply 1 MW

Re-examine Example 2



- Proof of LMP result to be done on the board

Re-examine Example 3



- Ga: $50/MWh, Gb: $60/MWh
- Lb: 110MW
- P1: 100MW

- Result:
  - Ga = 100MW, Gb = 10MW
  - **LMP_A = $50/MWh; LMP_B = $60/MWh**

- Same result as before

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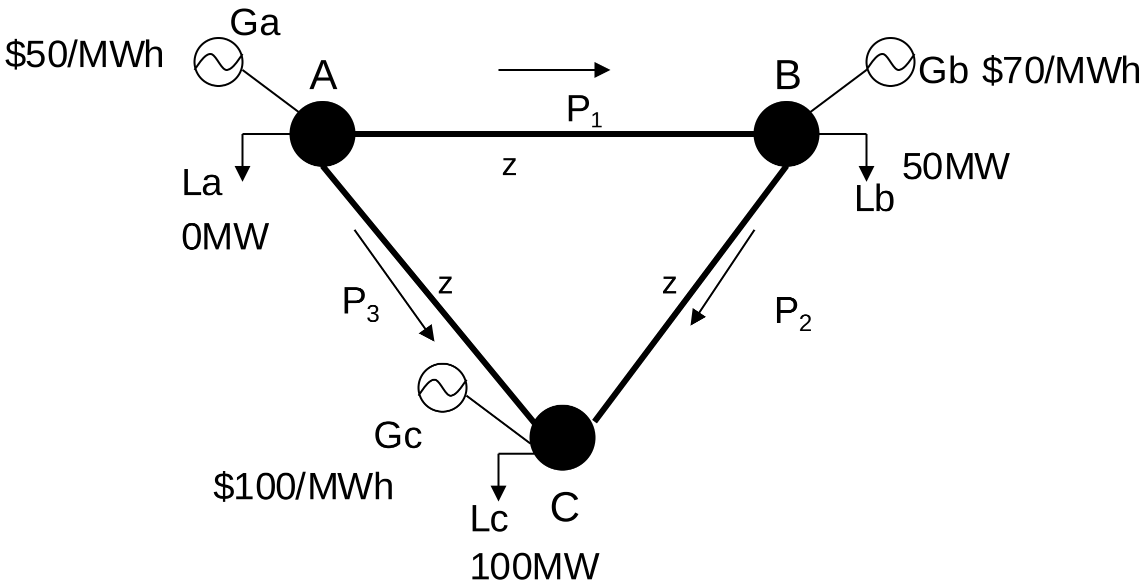
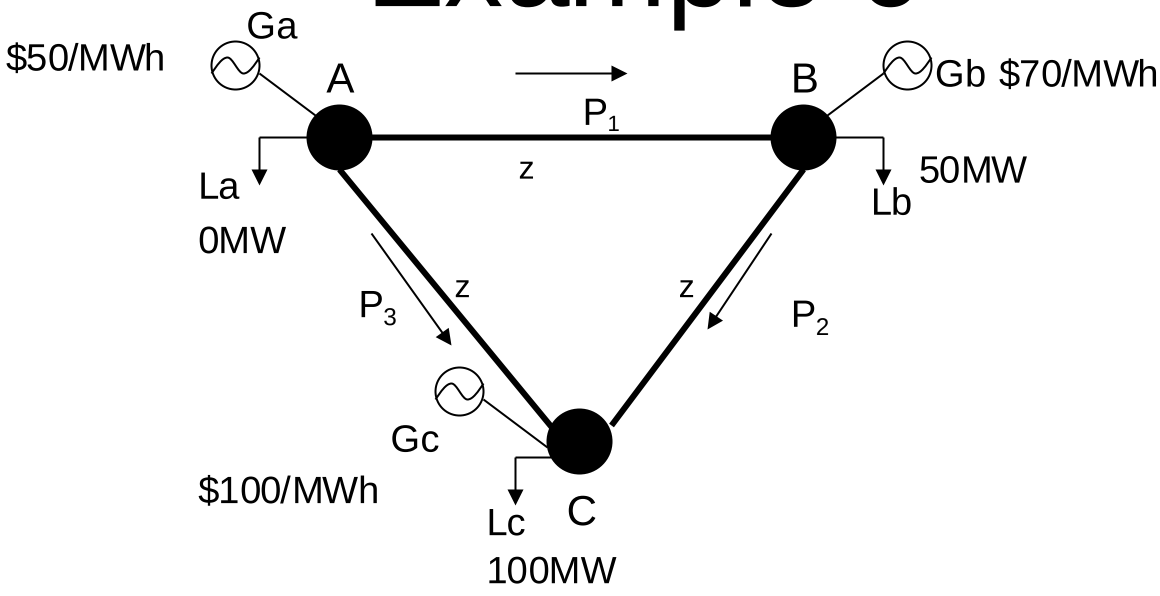
Example 6



- P1 Limit: 25, **P2 Limit: 50, P3 Limit: 50**

Example 6



- Solution: Ga: 50, Gb: 100, Gc: 0
- *AMPL reports:* LMP_A: $50/MWh, LMP_B: $70/MWh, **LMP_C: $90/MWh**
- **Do you agree? Any other possible solution?**
- **P1: 0MW, P2: 50MW, P3: 50MW**

Example 6

- If the load at node C were to increase, the only way to serve this increase is with Generator C
- Thus, the LMP should be $100/MWh
- Why does AMPL report $90/MWh?
- If the load at node C decreases to 99MW, then the reduction in the total cost would be $90/MWh
  - Re-dispatch: Ga = 51MW (cost increases by $50), Gb = 98MW (cost decreases by $140)
  - Net change in cost: -$90/MWh

Example 6

- Two lines congested in example 6.
- … shorthand way to calculate LMP at C (reduction in load):
- Option 1: both lines stay congested… generate system of equations
  - Confirm your assumption (do both lines stay congested)
  - Not possible
- Option 2: line P3 stays congested and P2 becomes uncongested…. Set up system of eqs
  - Does P3 stay congested and P2 reduce?
- Option 3: line P2 stays congested and P3 becomes uncongested… set up system of eqs
  - Does P2 stay congested and P3 reduce?

Common Misinterpretation of LMPs

- Our standard way of discussing LMPs leads us to the understanding that LMPs only reflect a positive incremental change, increase in consumption
  - **This is not the full definition of an LMP**
- **LMPs can, in fact, reflect a positive increment or a negative increment (decrement)**

- Note: Many people **(including myself)** will often describe LMPs as reflecting an incremental increase in consumption but many people understand that this incremental change can be positive or negative

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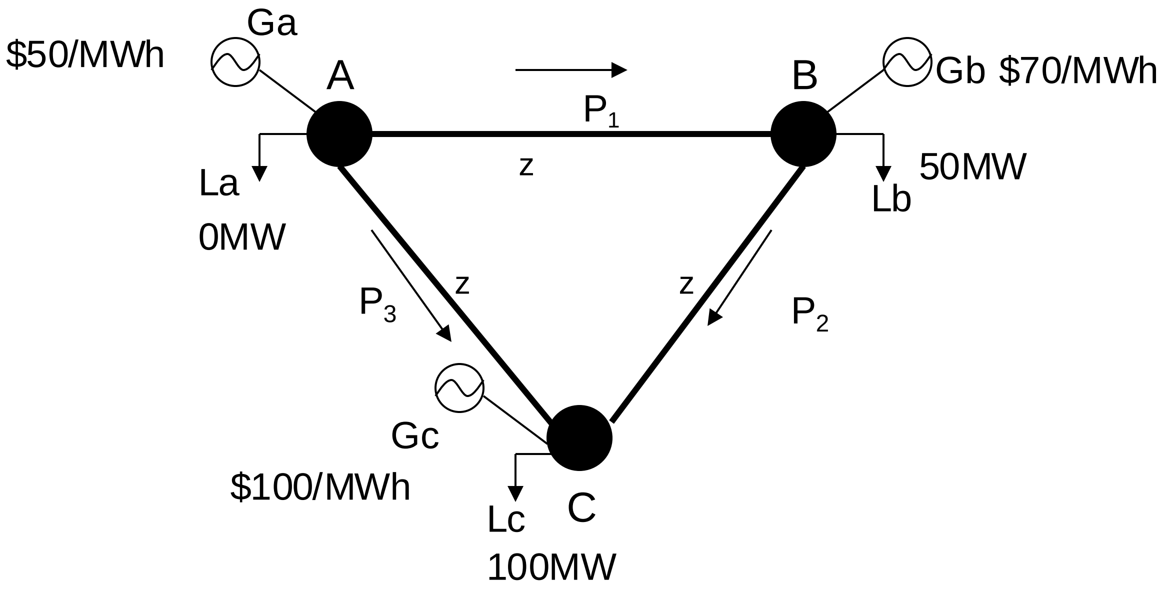
Counter-intuitive Flows

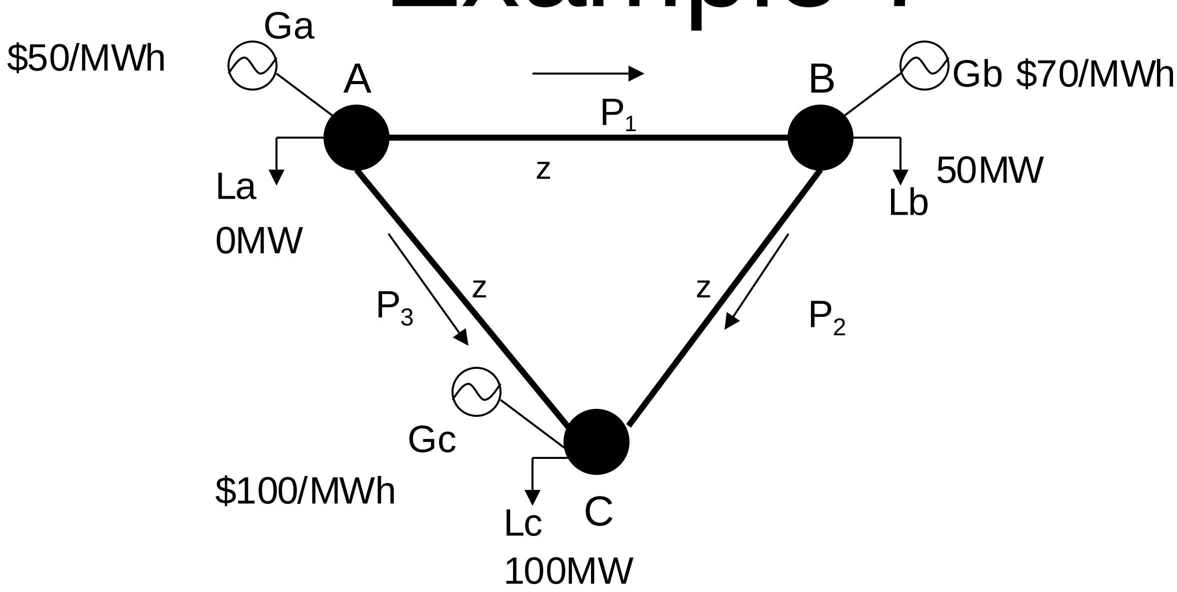
- We expect flow of energy to be from a cheaper bus/node to a more expensive bus/node
  - **Would Alaska ship Oranges to California?**
- Is it possible for the flow of energy to flow from an expensive bus to a cheap bus?
- Yes
- This is a counter-intuitive result that is possible due to Kirchhoff's laws

Example 7



- P1 Limit: 25, **P2 Limit: 50, P3 Limit: 100**

Example 7



- Solution: Ga: 87.5, Gb: 62.5, Gc: 0
- *AMPL reports:* LMP_A: $50/MWh, LMP_B: $70/MWh, **LMP_C: $60/MWh**
- **Flows: P1: 25MW, P2: 37.5MW, P3: 62.5MW**

Example 7

- The flow of electric energy is from bus B to bus C
  - Node B LMP: $70/MWh
  - Node C LMP: $60/MWh
  - Flow is from the **expensive** bus to the **cheap** bus
- Change in the consumption (positive or negative) at node B will change the objective by $70/MWh
- Change in consumption (positive or negative) at Node C will change the objective by $60/MWh
  - More consumption at Node C:
  - Gen A: Increases by 0.5MW (increases cost by $25)
  - Gen B: Increases by 0.5MW (increases cost by $35)
  - This maintains the flow on line 1 at: 25MW

$$\Delta G_A + \Delta G_B = \Delta L_c = 1$$

$$\Delta P_1 = 0 = \frac{1}{3}\Delta G_A - \frac{1}{3}\Delta G_B$$

$$\Delta G_A = 0.5, \Delta G_B = 0.5$$

$$\frac{\Delta Cost}{\Delta L_c} = \frac{(50\Delta G_A + 70\Delta G_B)}{\Delta L_c} = LMP_C$$

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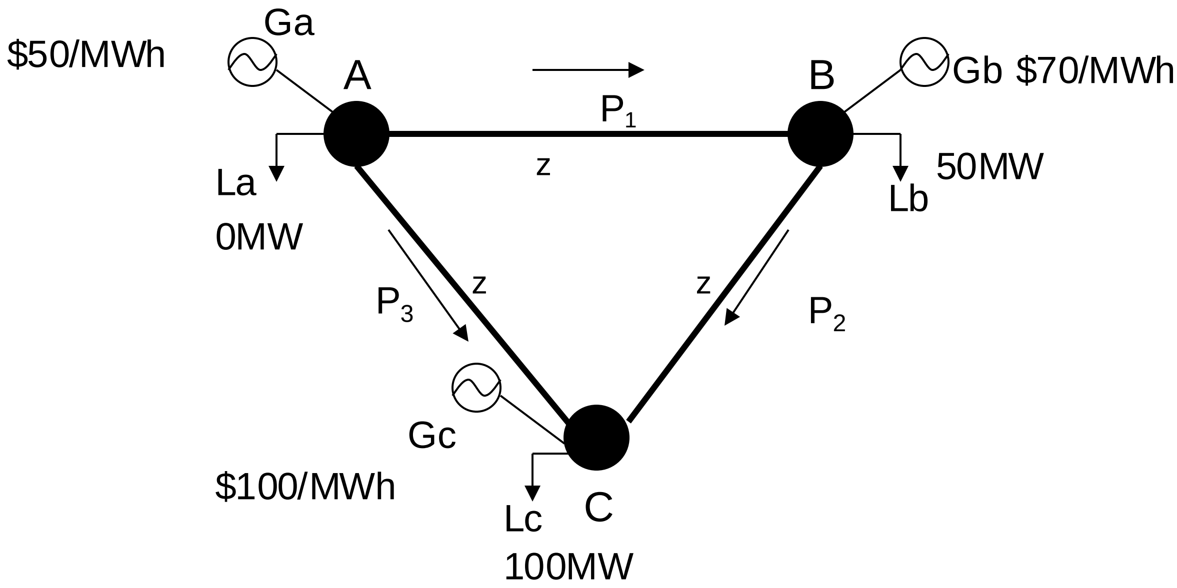
Locational Marginal Prices

Can Efficiency Improvements Increase Prices?

Improvements in Efficiency and Prices

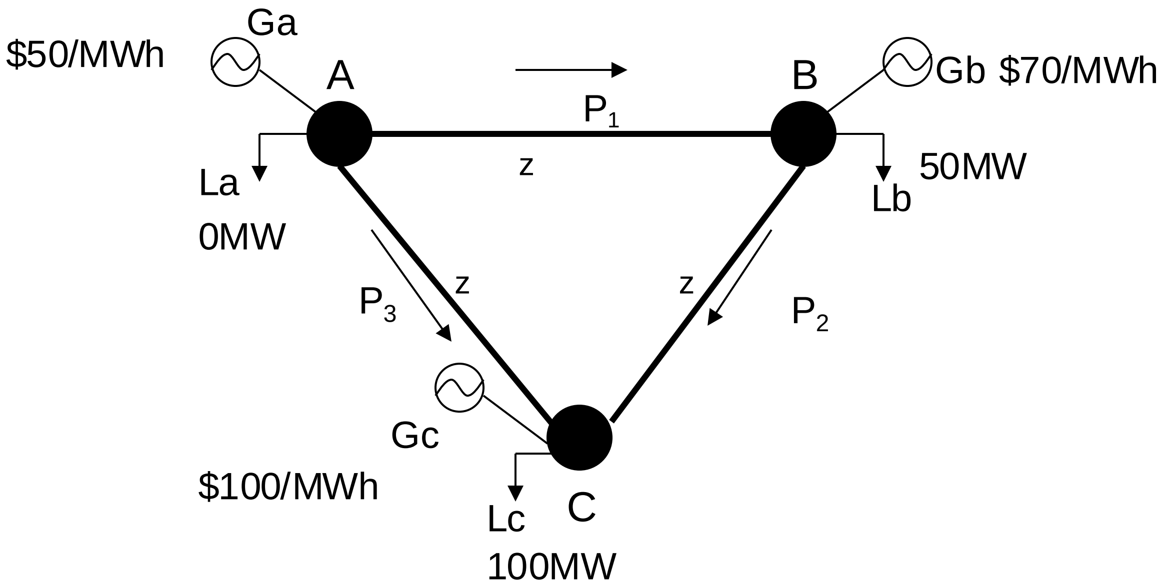
- One may expect that if we increase the capacity of a line this should result in lower prices
- By increasing the capacity of a line (not adding a new line but merely increasing the capacity of a line), we are guaranteed to get at least as good of a solution as we originally had, if not better
- Total cost should decrease (improve the efficiency of the system)
- This does not mean that the LMPs will reduce

Example 8



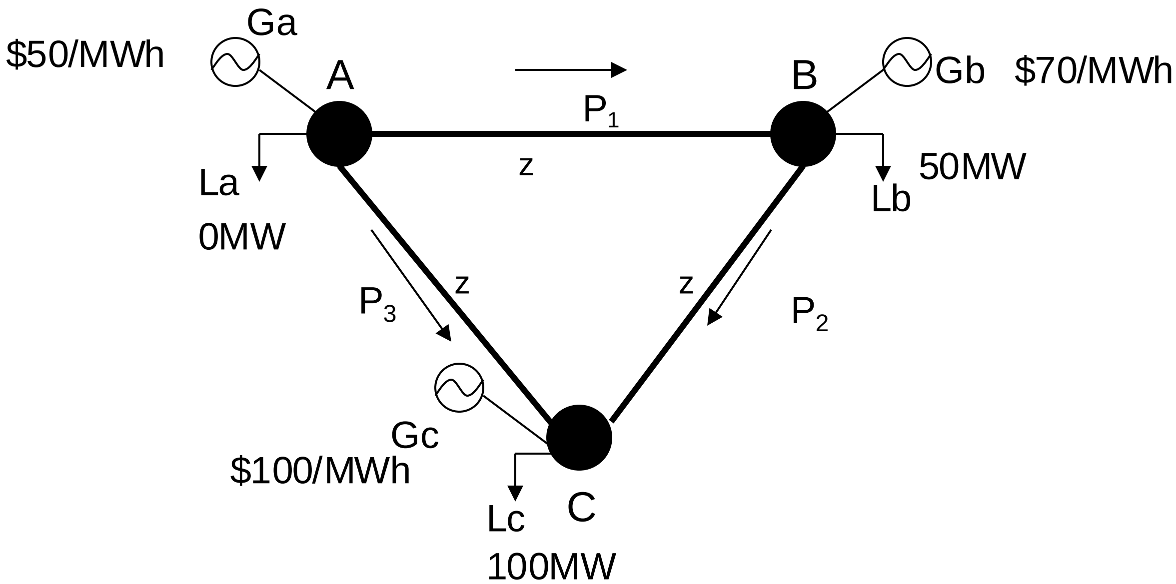
- P1 Limit: 25MW, P2 Limit: 25MW, P3 Limit: 25MW
- **Ga Capacity: 40MW**

Example 8



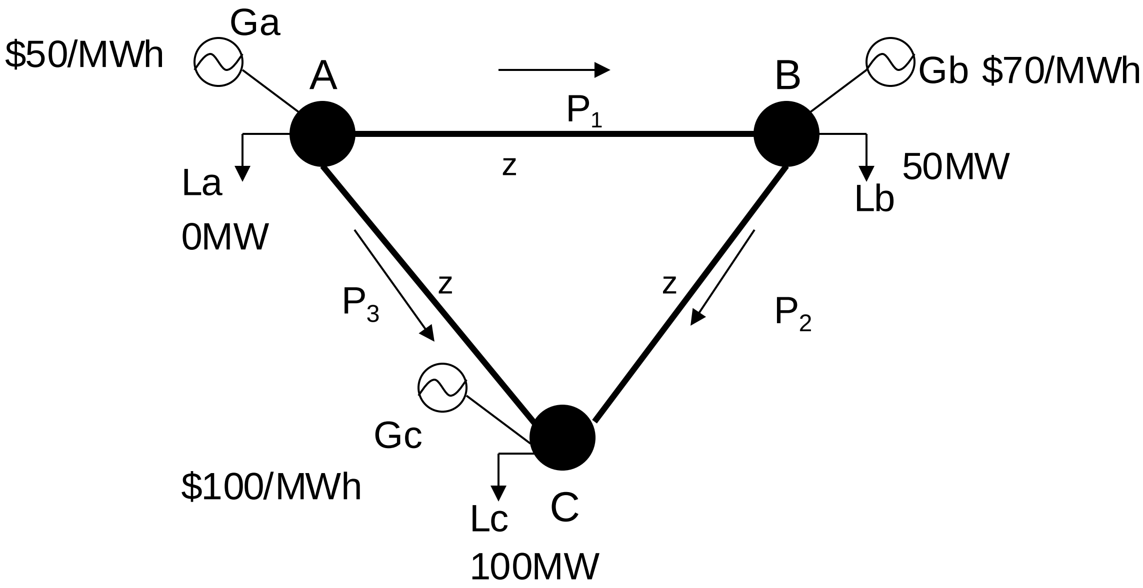
- Solution: Ga: 25MW, Gb: 75MW, Gc: 50MW
- **LMP_A: $50/MWh**, LMP_B: $70/MWh, LMP_C: $100/MWh
- Flows: P1 = 0, P2 = 25MW, P3 = 25MW

Example 9



- P1 Limit: 25MW, **P2 Limit: 40MW, P3 Limit: 50MW**
  - Same as Example 8 but P2 is 40MW and P3 is 50MW
- **Ga Capacity: 40MW**

Example 9



- Solution: Ga: 40MW, Gb: 90MW, Gc: 20MW
- **LMP_A: $85/MWh**, LMP_B: $70/MWh, LMP_C: $100/MWh
- Flows: P1 = 0MW, P2 = 40MW, P3 = 40MW

Comparison of Examples 8 and 9

- Example 8:
  - Line Ratings: 25, **25, 25** for P1, **P2, P3**
  - LMPs: **50**, 70, 100 for **A**, B, C
  - Objective: $11,500
- Example 9:
  - Line Ratings: 25, **50, 40** for P1, **P2, P3**
  - LMPs: **85**, 70, 100 for **A**, B, C
  - Objective: $10,300
- Increasing the capacities of P2 and P3 brought Ga to its upper limit
- With Ga at its upper limit, the LMP at node A is a result of a redispatch by Gb and Gc
  - Higher LMP as a result
- **All LMPs are as high if not HIGHER than before!**
- **There was not a single LMP that decreased!**
- **Keep in mind that Generator A has a Capacity limit of 40MW**

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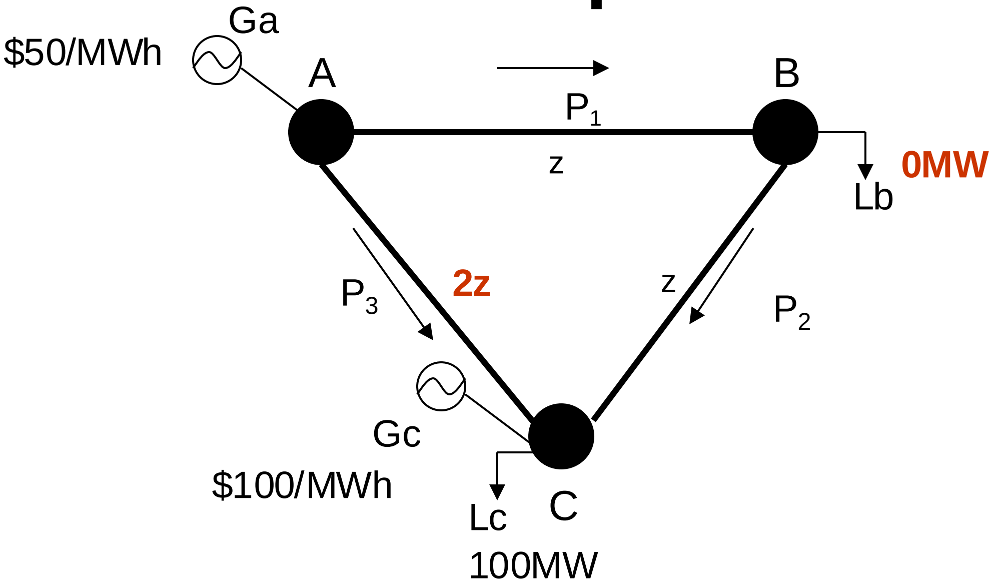
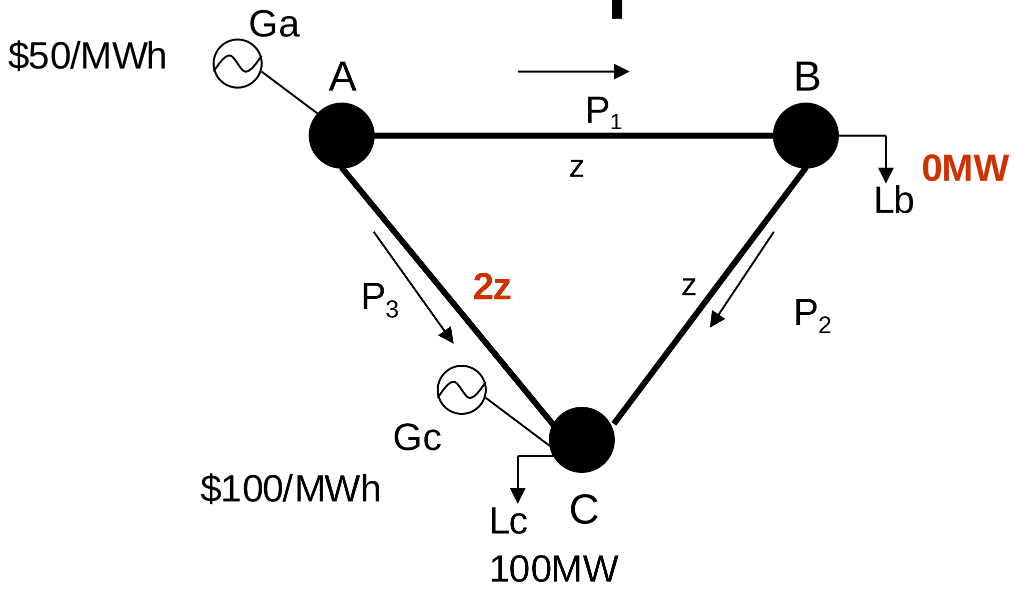
Can an LMP be lower than the lowest generator's bid (or marginal cost)?

Example 10



- Modifications: Generator B removed
- Load at B: 0MW
- Line 3: Impedance = 2z
- Line Limits:
  - P1: 25MW, **P2: 20MW,** P3: 50MW

Example 10



- Solution: Ga = 40MW, Gc = 60MW
  - Objective: $8,000
- P1 = 20MW, P2 = 20MW, P3 = 20MW
- LMP_A = $50/MWh
- **LMP_B = $25/MWh**
- LMP_C = $100/MWh

Example 10

- The LMP at Node B is $25/MWh
- The cheapest generator has a marginal cost of $50/MWh
- How is it possible that the LMP is less than the cheapest generator?
- The only congested line is P2 = 20MW
- To serve another 1MW to Node B, this would require Gen A to increase by 1.5MW (costs $75) and Gen C to decrease by 0.5MW (saves $50)
- So the net cost to the system is $25/MWh!

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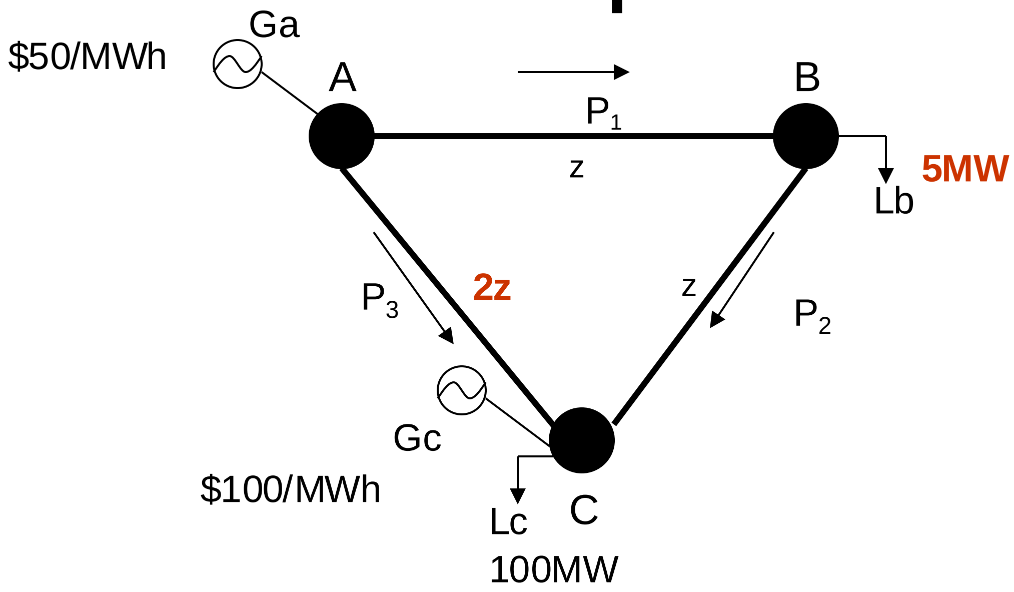
Can an LMP be lower than the lowest generator’s bid (or marginal cost)?

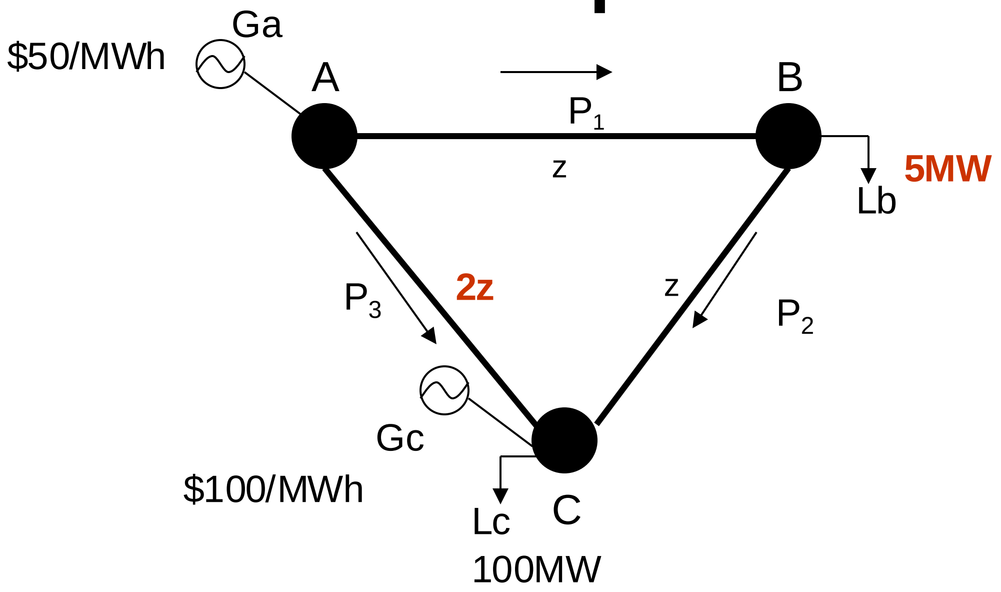
Can an LMP be higher than the highest generator’s bid (or marginal cost)?

Example 11



- Modifications made to Example 10:
  - Change load at B to 5MW
  - Will we still see an LMP less than the cheapest unit?
- Line Limits:
  - P1: 25MW, **P2: 20MW,** P3: 50MW

Example 11



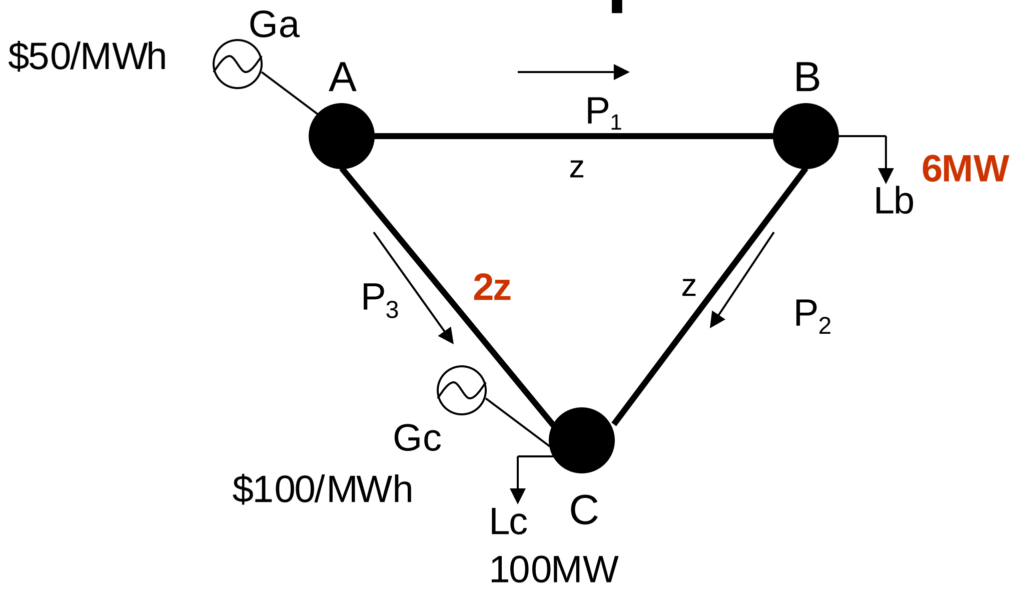
- Solution: Ga = 47.5MW, Gc = 57.5MW
  - Objective: $8,125
- P1 = 25MW, P2 = 20MW, P3 = 22.5MW
- LMP_A = $50/MWh
- **LMP_B = $25/MWh**
- LMP_C = $100/MWh

Example 11

- For example 11, the load is increased to 5MW at bus B
- The LMP at Node B is still $25/MWh

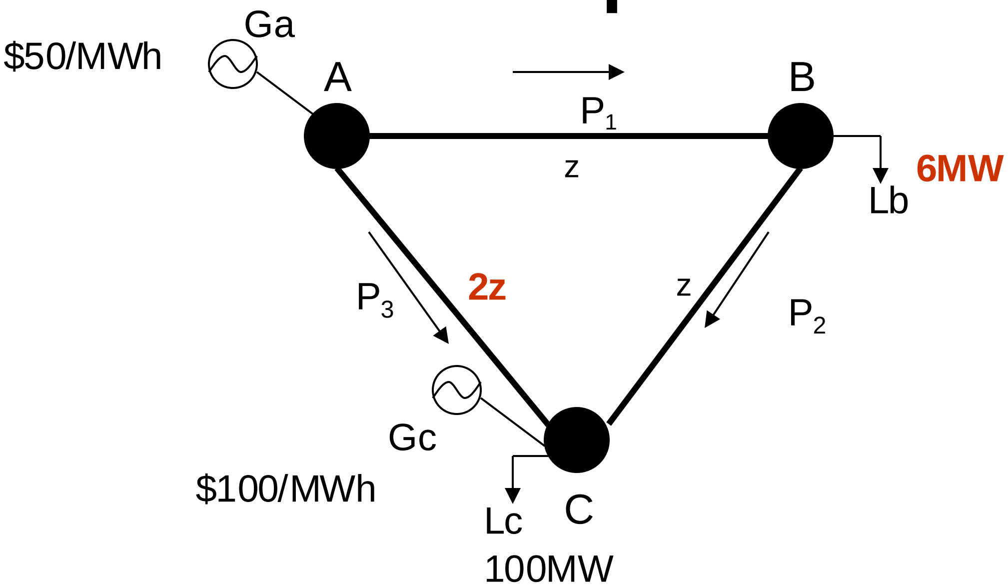
- The optimal cost for Example 10 is $8,000
- The optimal cost for Example 11 is $8,125
- So we see that the LMP does reflect the change in the objective: $8,125 - $8,000 = 125 = 5MW*$25/MWh

Example 12



- Modifications made to Example 10:
  - Change load at B to 6MW
  - Will we still see an LMP less than the cheapest unit?
- Line Limits:
  - P1: 25MW, **P2: 20MW,** P3: 50MW

Example 12



- Solution: Ga = 47MW, Gc = 59MW
  - Objective: $8,250
- P1 = 25MW, P2 = 19MW, P3 = 22MW
- LMP_A = $50/MWh
- **LMP_B = $125/MWh**
- LMP_C = $100/MWh

Example 12

- For example 12, the load is increased to 6MW at bus B
- The LMP at Node B jumps now to $125/MWh

- What happened:
  - P1 now becomes constrained while P2 is not constrained
  - Therefore, the required redispatch to deliver another MW to Node B is now:
    - Reduce Ga by 0.5MW
    - Increase Gc by 1.5MW
  - This change is a result of P1 being at its capacity as opposed to P2

- The optimal cost for Example 10 is $8,000
- The optimal cost for Example 11 is $8,125
- The optimal cost for Example 12 is $8,250

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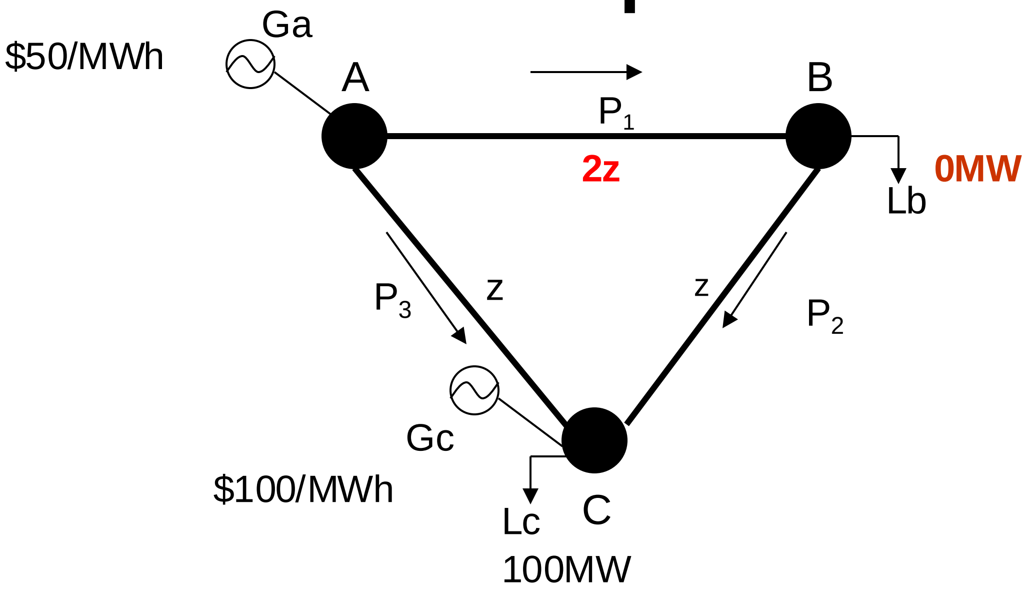
Can an LMP be negative when all bids are positive?

Example 13



- Load at B: 0MW
- Line 1: Impedance = 2z
- Line Limits:
  - P1: 25MW, **P2: 20MW, P3: 150MW**

Slack bus: C

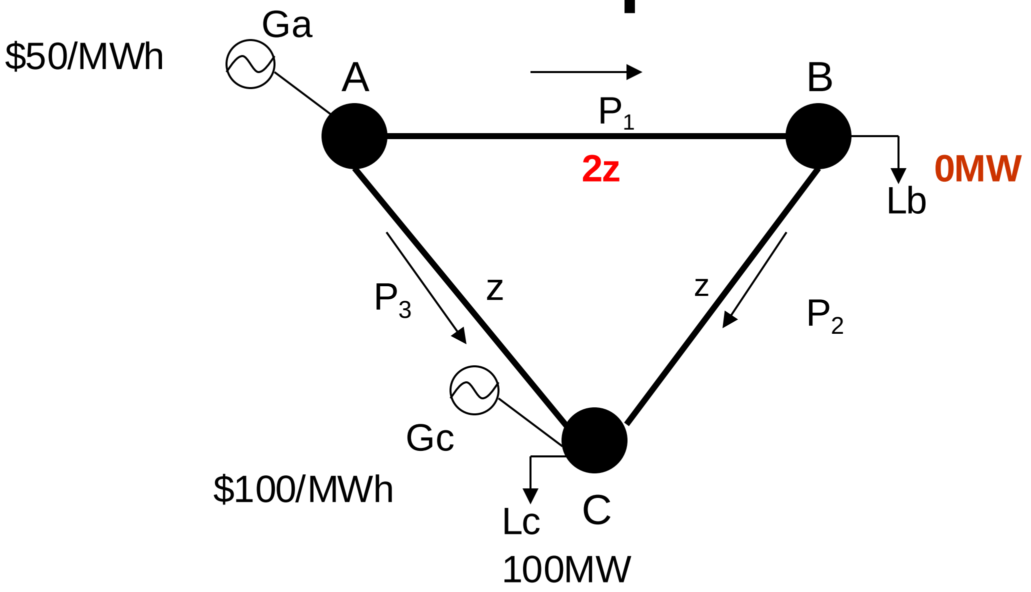
$$P_1 = \frac{1}{4}G_A, \; P_2 = \frac{1}{4}G_A \; , \; P_3 = \frac{3}{4}G_A$$

$$P_1 Limit: 25MW, P2\ Limit: 20MW, P3\ Limit: 150MW$$

$$G_A = 80MW$$

Max production from Ga is dictated by P2.

Example 13



- Solution: Ga: 80MW, Gc: 20MW
- P1: 20MW, P2: 20MW (binding), P3: 60MW
- LMP A: $50/MWh (set by Ga)
- LMP C: $100/MWh (set by Gc)
- LMP B: -$50/MWh
  (set by Ga and Gc – see next slide)

Ref bus still C with new load of 1MW at B, solve for redispatch

$$\Delta G_A + \Delta G_C = \Delta L_B = 1$$

$$\Delta P_2 = 0 = \frac{1}{4}\Delta G_A + \frac{3}{4}(-\Delta L_B)$$

$$\Delta G_A = 3, \Delta G_C = -2$$

$$\frac{\Delta Cost}{\Delta L_B} = \frac{(50\Delta G_A + 100\Delta G_C)}{\Delta L_B} = LMP_B$$

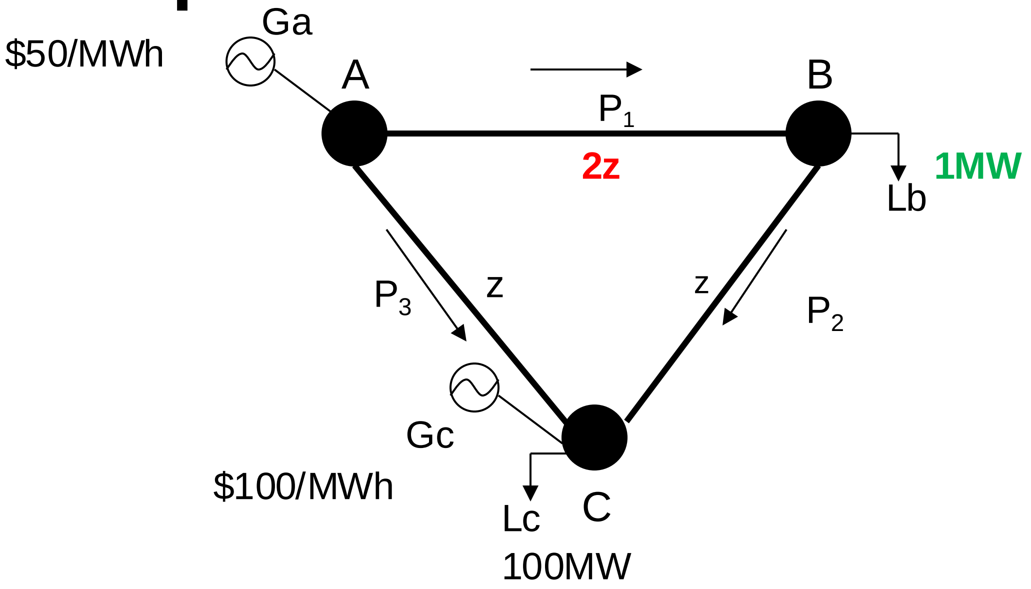
Ref bus still C with new load of 1MW at B, solve for redispatch

$$\Delta P_3 = \frac{3}{4}\Delta G_A + \frac{1}{4}(-\Delta L_B) = 2$$

$$\Delta P_1 = \frac{1}{4}\Delta G_A - \frac{1}{4}(-\Delta L_B) = 1$$

$$\Delta G_A = 3, \Delta G_C = -2$$

Example 13 with B increased



- Solution: Ga: 83MW, Gc: 18MW
- P1: 21MW, P2: 20MW (binding), P3: 63MW

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EEE 598
Electric Energy Markets

School of ECEE, ASU

Professor Kory W. Hedman

Locational Marginal Prices

Can an LMP decrease as you increase load?

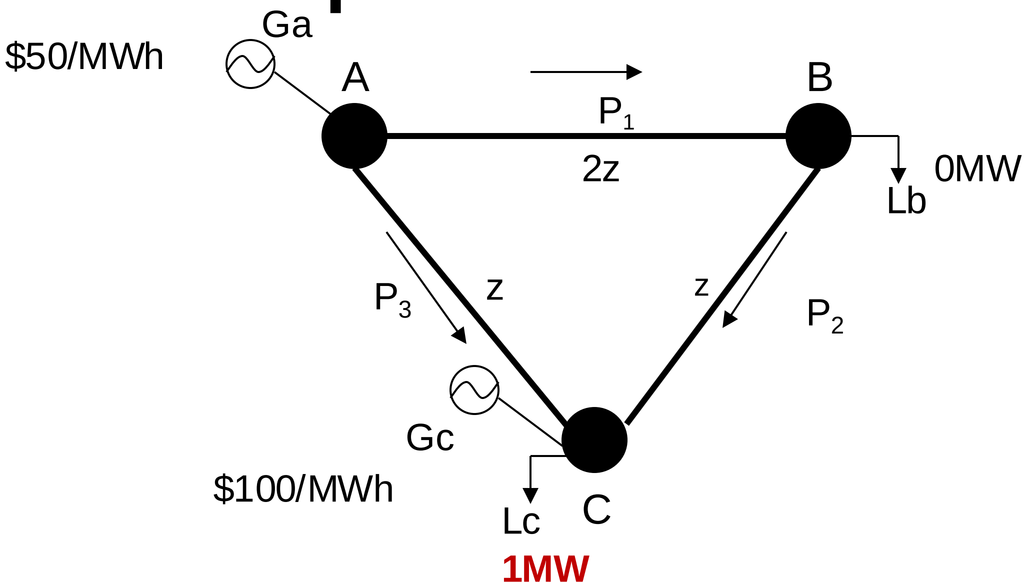
Is this possible even without involving unit commitment (nonconvexities)?

Is this possible with generators with zero Pmin, infinite gen Pmax, constant marginal costs, no losses?
---- very simple linear examples?

Can an LMP decrease when load increases somewhere?

- Example 13 gives you a clue to this answer…
- Example 13 shows you that prices can be negative….
- If an LMP could not decrease with an increase in load somewhere in the system, then that would mean that example 13 was not possible…
- And I will demonstrate that Example 13 itself shows that the answer to this question must be yes…
- Simple proof by contradiction: An LMP can decrease even if load has increased…

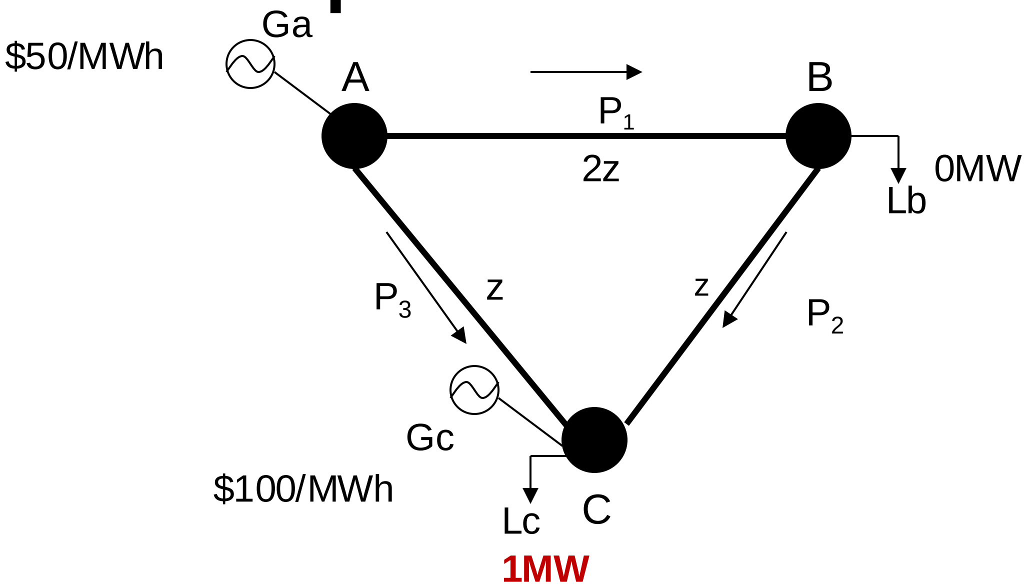
Example 14: mod of 13



- Load at C: 1MW
  (Example 13 originally had 100MW at C)
- Line Limits:

  P1: 25MW, **P2: 20MW**, P3: 150MW

Example 14: mod of 13



- Solution: Ga: 1MW, Gc: 0MW
- Example 13 has: P1: 20MW, P2: 20MW (binding), P3: 60MW
- Example 14 has no line congested!
- LMP A: $50/MWh (set by Ga)
- LMP C: $50/MWh (set by Ga)
- LMP B: $50/MWh (set by Ga)

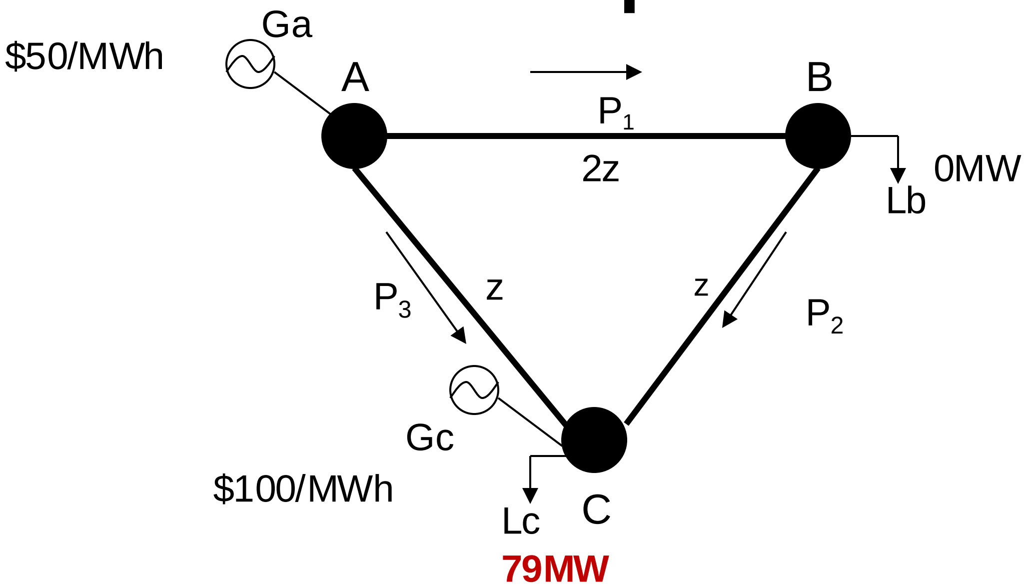
Can an LMP decrease when load increases somewhere?

- Example 13 gives you a clue to this answer…
- Example 13 shows you that prices can be negative….
- Example 14 starts with such a small load in the system such that there is uniform pricing set by the cheapest generator, Ga
- Example 14: All prices are $50/MWh
- Example 14: All loads are at or below Example 13
- Example 13: Has a negative LMP at B: -$50/MWh
- All systems can start with low loads, no congestion, and uniform LMPs set by the cheapest generator…
- If increasing the load meant that LMPs must never decrease, that would mean that the congestion component could never decrease more than the energy component increases…
- Example 13 has a negative price and that is caused by a very large negative congestion component that overtakes the energy component…
- Example 13 would be false if this statement is false.

Can an LMP decrease when load increases somewhere?

- YES!
- Simple comparison between Examples 13 and 14
- …. Example 14 is trivial… sometimes the easiest examples provide great insight!

Example 15



- Load at C: 79MW
  (Example 13 originally had 100MW at C)
- Line Limits:

  P1: 25MW, **P2: 20MW**, P3: 150MW

Slack bus: C

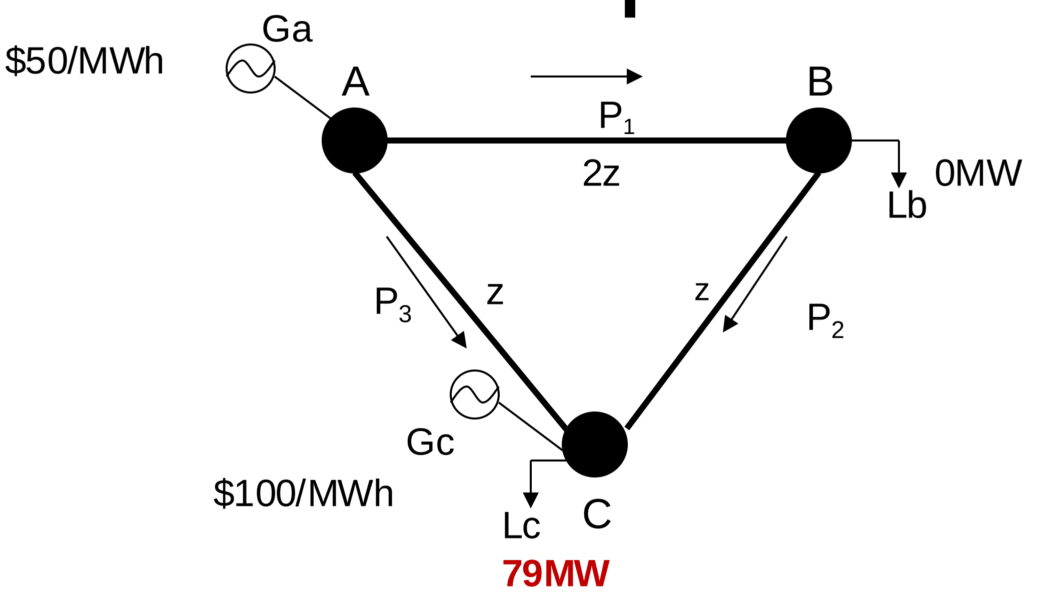
$$P_1 = \frac{1}{4}G_A, \; P_2 = \frac{1}{4}G_A \;, \; P_3 = \frac{3}{4}G_A$$

$$P_1 Limit: 25MW, P2\ Limit: 20MW, P3\ Limit: 150MW$$

$$G_A = 80MW$$

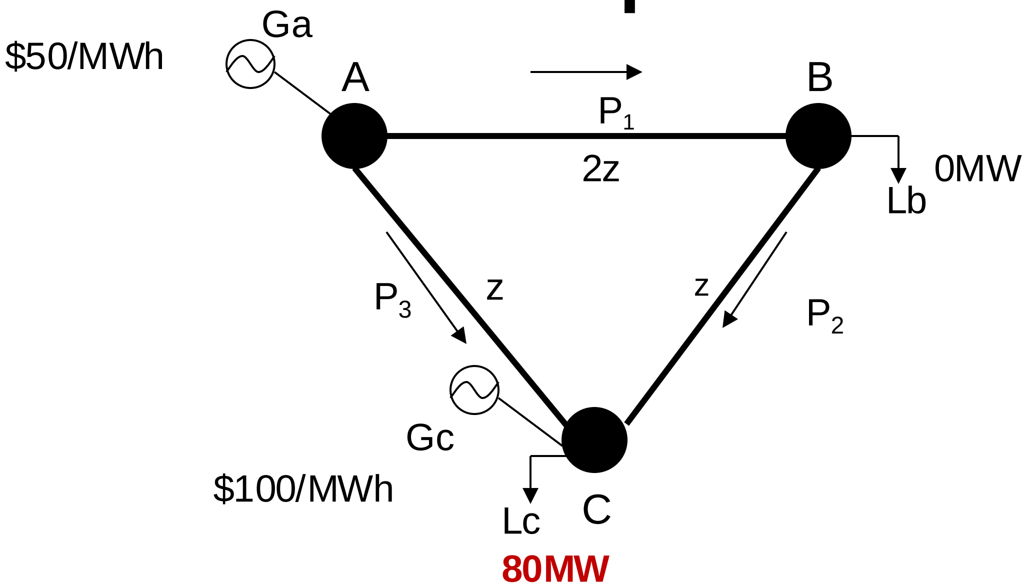
Max production from Ga is dictated by P2.

Example 15



- Solution: Ga: 79MW, Gc: 0MW
- P1: 19.75MW, P2: 19.75MW, P3: 59.25MW
- LMP A: $50/MWh (set by Ga)
- LMP C: $50/MWh (set by Ga)
- LMP B: $50/MWh (set by Ga)

Example 16



- Load at C: 80MW
  (Example 13 originally had 100MW at C)
- Line Limits:

  P1: 25MW, **P2: 20MW**, P3: 150MW

Slack bus: C

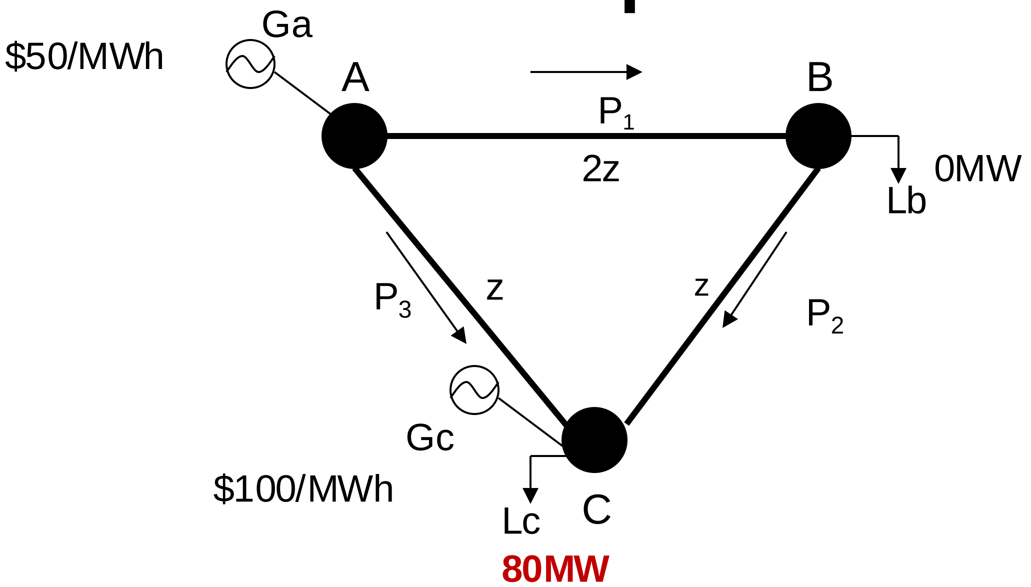
$$P_1 = \frac{1}{4}G_A, \; P_2 = \frac{1}{4}G_A \; , \; P_3 = \frac{3}{4}G_A$$

$$P_1 Limit: 25MW, P2\ Limit: 20MW, P3\ Limit: 150MW$$

$$G_A = 80MW$$

Max production from Ga is dictated by P2.

Example 16



- Solution: Ga: 80MW, Gc: 0MW
- P1: 20MW, P2: 20MW (binding), P3: 60MW
- LMP A: $50/MWh (set by Ga)
- LMP C: [$50/MWh, $100/MWh] non unique solutions set by Ga (decrease Lc) and Gc (increase Lc)
- LMP B: -$50/MWh (set by Ga and Gc, see next slide)

Ref bus still C with new load of 1MW at B, solve for redispatch:

LMP at B is back to being neg

$$\Delta G_A + \Delta G_C = \Delta L_B = 1$$

$$\Delta P_2 = 0 = \frac{1}{4}\Delta G_A + \frac{3}{4}(-\Delta L_B)$$

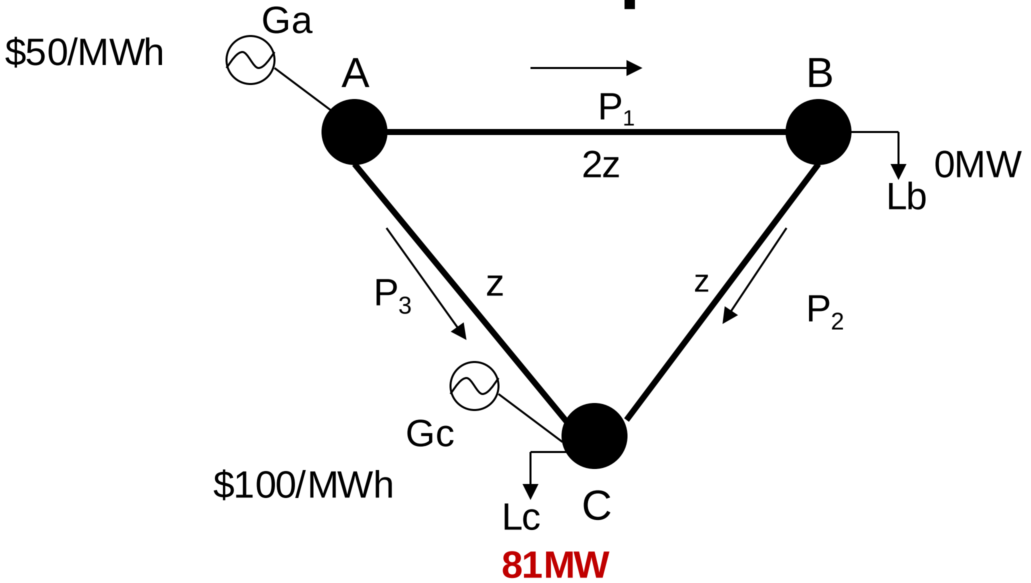
$$\Delta G_A = 3, \Delta G_C = -2$$

$$\frac{\Delta Cost}{\Delta L_B} = \frac{(50\Delta G_A + 100\Delta G_C)}{\Delta L_B} = LMP_B$$

LMP at C Examined

- If you decrease the load at C, you get the solution of Example 15. Overall cost decreases by $50/MWh for a decrease of 1MW load so the LMP is +$50/MWh
- If you increase the load at c, you get example 17 next, showing the result…
- Ga = 80MW, Gc = 1MW for Lc = 81. The LMP reflects an increase in load at C from 80 to 81 causing a change in Gc with a marginal cost of $100/MWh

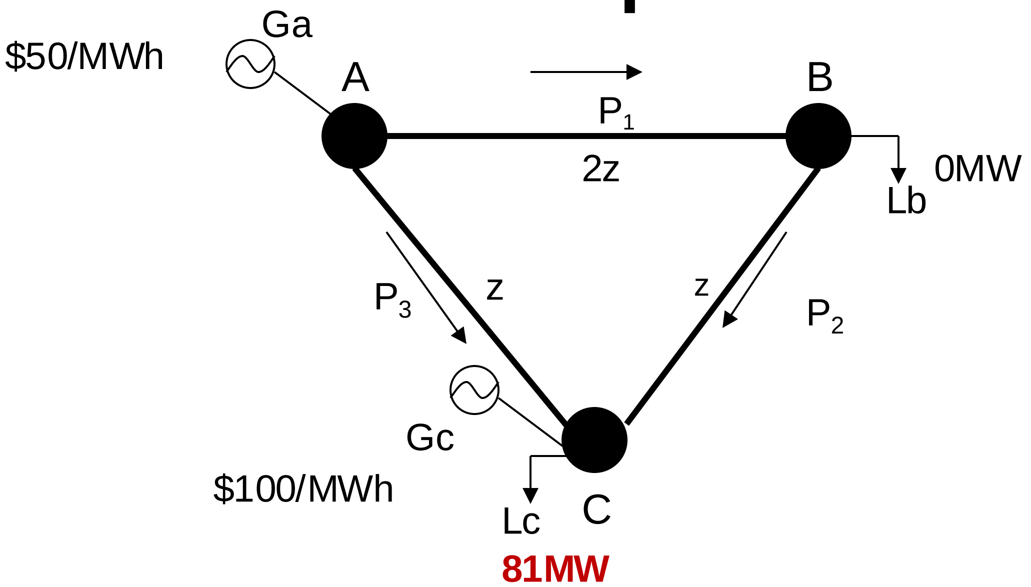
Example 17



- Load at C: 81MW
  (Example 13 originally had 100MW at C)
- Line Limits:

  P1: 25MW, **P2: 20MW**, P3: 150MW

Example 17



- Solution: Ga: 80MW, Gc: 1MW
- P1: 20MW, P2: 20MW (binding), P3: 60MW
- LMP A: $50/MWh (set by Ga)
- LMP C: $100/MWh (set by Gc alone now)
- LMP B: -$50/MWh (set by Ga and Gc)

Break

Slides taken from:

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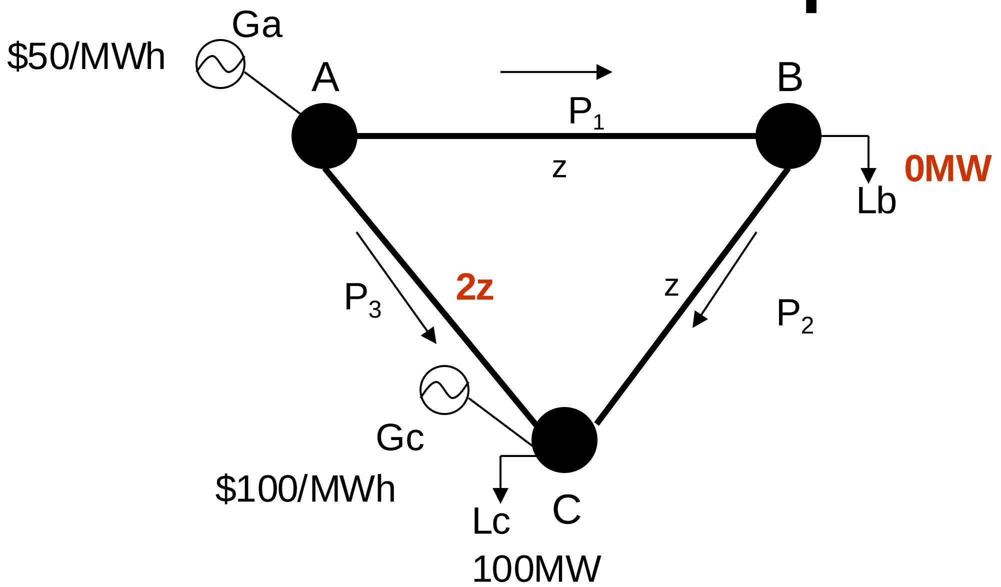
Locational Marginal Prices

A Question in the next HW

- States, consumers, load serving entities worry about high prices (LMPs)
  - Desire a limit on the LMP
- Thus, many ISOs implemented bid caps
  - Many people thought that if a generator cannot bid above X $/MWh, then the LMP will never exceed X $/MWh
- Is this true?
- If we limit all generator bids to be <= X $/MWh, does this limit the LMP?

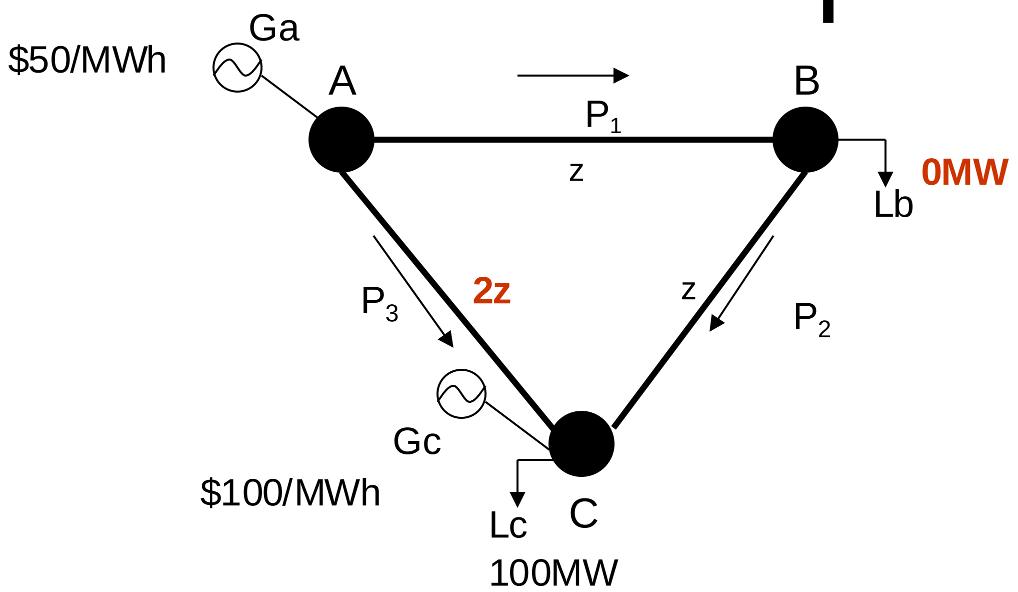
Back to Example 10



Suppose there is a minimum price to bid: $50/MWh

- Modifications: Generator B removed
- Load at B: 0MW
- Line 3: Impedance = 2z
- Line Limits:
  - P1: 25MW, **P2: 20MW,** P3: 50MW

Back to Example 10

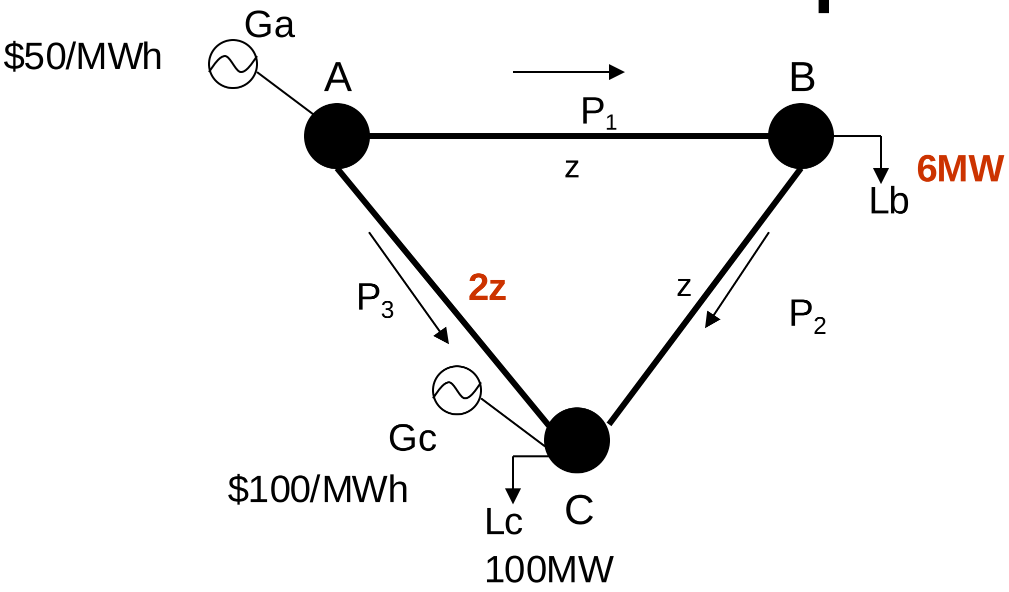


Suppose there is a minimum price to bid: $50/MWh

LMP B is below lowest bid

- Solution: Ga = 40MW, Gc = 60MW
  - Objective: $8,000
- P1 = 20MW, P2 = 20MW, P3 = 20MW
- LMP_A = $50/MWh
- **LMP_B = $25/MWh**
- LMP_C = $100/MWh

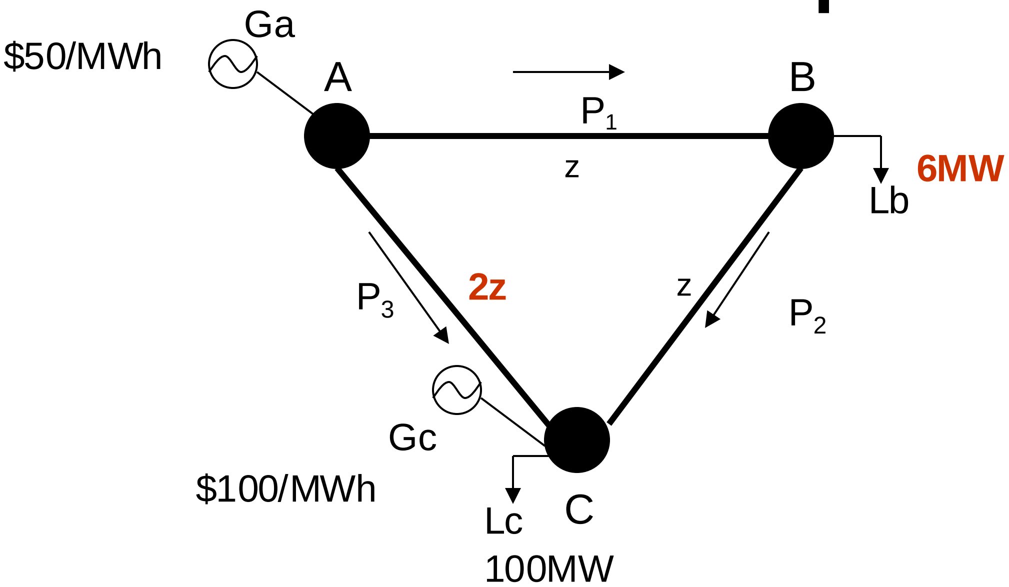
Back to Example 12



Suppose there is a max price to bid: $100/MWh

- Modifications made to Example 10:
  - Change load at B to 6MW
  - Will we still see an LMP less than the cheapest unit?
- Line Limits:
  - P1: 25MW, **P2: 20MW,** P3: 50MW

Back to Example 12



Suppose there is a max price to bid: $100/MWh

LMP B is above highest bid

- Solution: Ga = 47MW, Gc = 59MW
  - Objective: $8,250
- P1 = 25MW, P2 = 19MW, P3 = 22MW
- LMP_A = $50/MWh
- **LMP_B = $125/MWh**
- LMP_C = $100/MWh

A Question in the next HW

- States, consumers, load serving entities worry about high prices (LMPs)
  - Desire a limit on the LMP
- Thus, many ISOs implemented bid caps
  - Many people thought that if a generator cannot bid above X $/MWh, then the LMP will never exceed X $/MWh
- Is this true?
- If we limit all generator bids to be <= X $/MWh, does this limit the LMP?

- Can you think of anything else that can happen?
- Key lessons learned:
- The grid is the most complex engineered system ever built…
- Do not be surprised if you are surprised by a counter-intuitive result
- Use as simple as possible examples to understand what is going on

Break

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Locational Marginal Prices

LMP Components

LMP: Energy, Congestion, Losses

- ISOs report three components to LMPs

- LMPs are dual variables
  - Do LMPs capture the impact of congestion?
  - Do LMPs capture the impact of Losses?
  - Do we have to calculate three different components of an LMP?
    - If so, where do the components come from?
  - Or does the dual variable of the node balance constraint capture the cost of energy, congestion, and losses?

LMP: Energy, Congestion, Losses

- Do LMPs capture the impact of congestion?
- If line limits exist and the optimal solution is influenced by line limits, then LMPs will capture the impact of congestion
- Dual variables will inherently reflect the influence of their respective constraints

LMP: Energy, Congestion, Losses

- Do LMPs capture the impact of Losses?
- If you do not model losses, then no
- If you model losses as a fixed load, then *(sort of)* no
  - The losses would affect the solution (and LMPs), absolutely yes, but LMPs have a non-zero loss component when the LMPs directly sees the sensitivity of losses on the solution… computers only know what you tell it… so if losses are modeled as a fixed load, the solution and LMPs will communicate an answer compliant with losses behaving as a fixed load
  - Losses change with network conditions… so to get LMPs that properly reflect losses, you want a problem description that shows the math dependency between losses and power flow… the better you approximate/model losses, the better your solution and pricing will be
- If your losses are a function of your power flow state, then yes
  - If losses are internally determined by the power flow mathematics, then LMPs would reflect that dependency

LMP: Energy, Congestion, Losses

- Do we have to calculate three different components of an LMP?
  - If so, where do the components come from?

- Depends on how accurate your formulation is
- LMPs depend on the mathematics of your model
- Models vary therefore what drives the LMPs will vary based on the math
- **A good model will not require calculating components separately**

LMP: Energy, Congestion, Losses

- Or does the dual variable of the node balance constraint capture the cost of energy, congestion, and losses?
- Again, a good model does not have to calculate components separately
- Dual variables capture the sensitivity of a constraint on the objective… each linear program has a primal-dual pair
- When you accurately capture congestion and losses, dual vars would automatically capture their influence
- The 3 components and the derivation of each part separately is more common (in my opinion) as a way to educate people regarding LMPs (break into pieces) rather than a necessity of understanding or determining LMPs