Coordination Schemes for the Integration of Transmission and Distribution System Operations

Anthony Papavasiliou
Center for Operations Research and Econometrics
Université Catholique de Louvain

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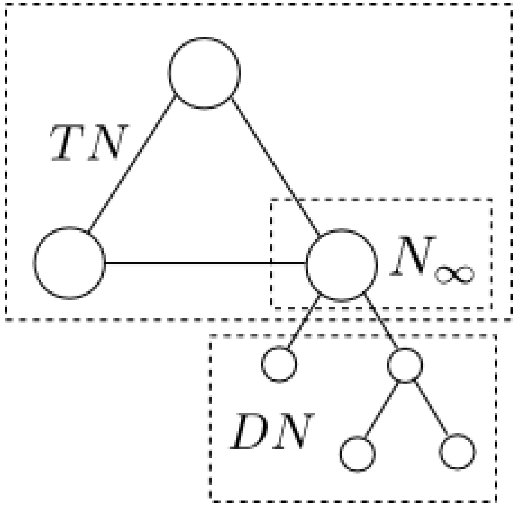
Context

- Rising importance of distribution system resources
    - Distributed supply (e.g. rooftop solar)
    - Majority of consumer flexibility: commercial and residential sector
- Computational challenges of distribution systems
    - Huge number of resources
    - Linear approximation of power flow is inadequate
- SmartNet project
    - EU research and innovation project
    - Budget: 12.7 million € over 3 years
    - *Our* focus in SmartNet: **activation** of reserves from distributed resources …
    - … as opposed to commitment of reserves (Caramanis, 2016)
- Modeling approach of SmartNet
    - Linear approximation of meshed transmission network
    - SOCP relaxation of (typically) radial distribution networks



SmartNet

M. Caramanis, E. Ntakou, W. Hogan, A. Chakrabortty, J. Schoene, “Co-Optimization of Power and Reserves in Dynamic T&D Power Markets with Non-Dispatchable Renewable Generation and Distributed Energy Resources”. Proceedings of the IEEE invited paper, April, 2016.

Modeling Activation of Reserve Capacity: The Transmission Network

Distributed resources contribute to reserve

$$\min \sum_{g\in G} C_g \cdot \Delta p_g + \boxed{\sum_{i\in DN} C_i^c \cdot \Delta p_i^c + \sum_{i\in DN} C_i^g \cdot \Delta p_i^g}$$

Reserve activation cost

Forward setpoint

Interface flow

$$\sum_{g\in G_n} (\bar{p}_g + \Delta p_g) + \sum_{l\in L:l=(m,n)} f_l = D_n + \sum_{l\in L:l=(n,m)} f_l + \boxed{pr_n} + \Delta D_n(\omega), n \in N_\infty$$

Power balance:
T&D interface

$$\sum_{g\in G_n} (\boxed{\bar{p}_g} + \Delta p_g) + \sum_{l\in L:l=(m,n)} f_l = D_n + \sum_{l\in L:l=(n,m)} f_l + \boxed{\Delta D_n(\omega)}, n \in TN - N_\infty$$

Power balance

Reserve capacity

$$0 \le \Delta p_g \le \boxed{R_g}, g \in G$$

Transmission system imbalance

Reserve activation limit

$$f_l = B_l \cdot (\theta_n - \theta_m), l = (m,n) \in L, \theta_0 = 0$$

DC power flow approximation

Modeling Activation of Reserve Capacity: The Distribution Network

- We use the SOCP relaxation proposed by (Farivar, 2013)

$$f_i^p - \sum_{j\in C_i}\left(f_j^p - l_jR_j\right) - \left(\bar{p}_i^g + \Delta p_i^g\right) + \left(\bar{p}_i^c + \boxed{\Delta D_i(\omega)} - \Delta p_i^c\right) + G_i v_i = 0, i \in DN$$

Real power balance

Distribution system imbalance

$$-\sum_{j\in C_i}\left(f_j^p - l_jR_j\right) - \boxed{pr_i} + G_i v_i = 0, i \in N_\infty$$

Real power balance: T&D interface

Interface flow

$$f_i^q - \sum_{j\in C_i}\left(f_j^q - l_jX_j\right) - q_i^g + q_i^c - B_i v_i = 0, i \in DN$$

Reactive power balance

$$-\sum_{j\in C_i}\left(f_j^q - l_jX_j\right) - qr_i - B_i v_i = 0, i \in N_\infty$$

Reactive power balance: T&D interface

Masour Farivar and Steven H. Low. Branch flow model: Relaxations and convexification - part I. IEEE Transactions on Power Systems, 28(3):2554–2564, 2013.

Modeling Activation of Reserve Capacity: The Distribution Network (II)

$$v_i = v_{A_i} + 2(R_i \cdot f_i^p + X_i \cdot f_i^q) - l_i(R_i^2 + X_i^2), i \in E$$

Voltage magnitude change

Conic relaxation

$$(f_i^p)^2 + (f_i^q)^2 \boxed{\leq} v_i l_i, i \in E$$

Second order conic relaxation

$$(f_i^p)^2 + (f_i^q)^2 \leq S_i^2, i \in E \qquad (f_i^p - R_i l_i)^2 + (f_i^q - R_i l_i)^2 \leq S_i^2, i \in E$$

Complex flow limit

$$0 \leq \Delta p_i^c \leq \boxed{R_i^c}, i \in DN \qquad 0 \leq \Delta p_i^g \leq \boxed{R_i^g}, i \in DN$$

Reserve activation limit

Reserve capacity

Voltage limits, reactive injection limits, current magnitude limits

Coordination Schemes

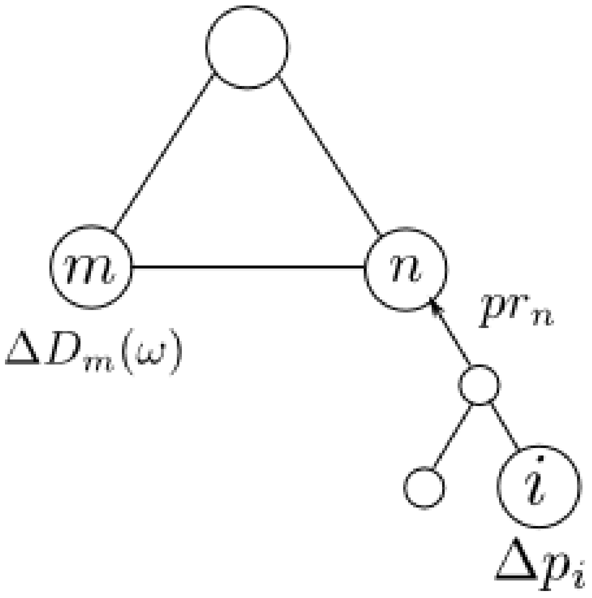
SmartNet Proposals for TSO-DSO Coordination

- Centralized Common TSO-DSO Market
- Decentralized Common TSO-DSO Market
- Centralized Ancillary Services Market
- Local Ancillary Services Market
- Shared Balancing Responsibility

Centralized Common TSO-DSO Market

- Full-blown optimization of entire network
- ‘Minimal DSO’ (Kristov, 2016)
- Sets golden standard in terms of operational efficiency
- Unlikely to be implementable in practice due to huge scale, communication constraints, institutional constraints

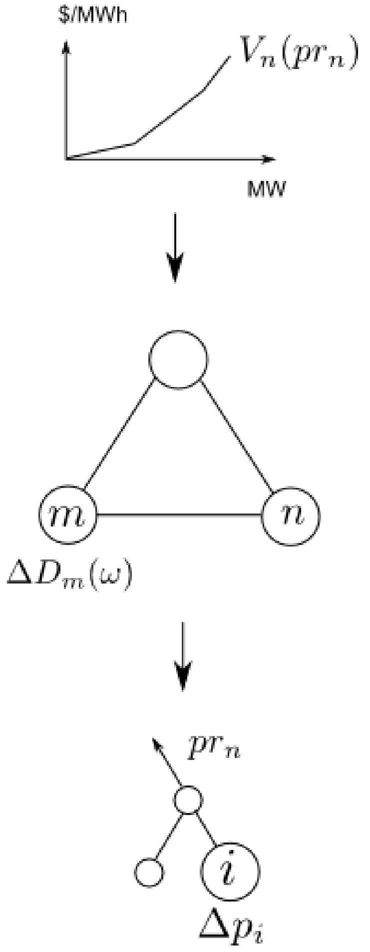
TSO



L. Kristov, P. De Martini, J. D. Taft, “A Tale of Two Visions: Designing a Decentralized Transactive Electric System”. *IEEE Power and Energy Magazine*, vol. 14, no. 3 pp. 63-69, 2016.

Decentralized Common TSO-DSO Market

- DSO submits residual supply function $V_n(pr_n)$ to TSO, assuming e.g. zero imbalance and a *given* real power injection at T-D interface
- TSO balances transmission network only, using TSO resources and DSO residual supply functions
- DSO balances distribution network, *given* flow pr_n at the interface



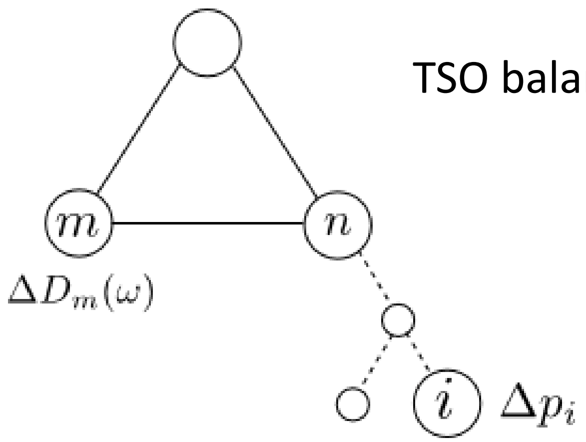
Bid by DSO to TSO

TSO balancing

DSO balancing

Centralized Ancillary Services Market

- TSO activates transmission and distribution resources, but while ignoring distribution network constraints
- Distribution resources need to be pre-qualified, so that if they are activated they do not violate distribution network constraints

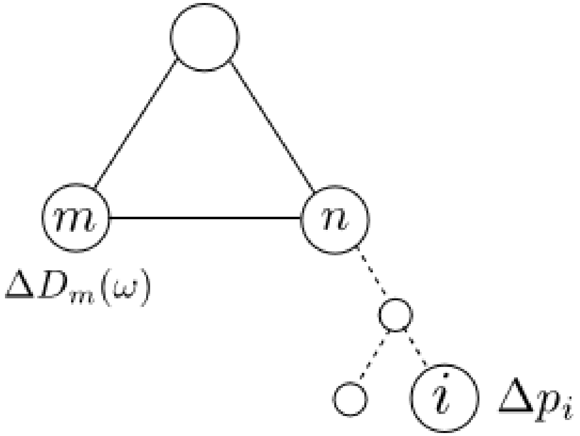


TSO balancing

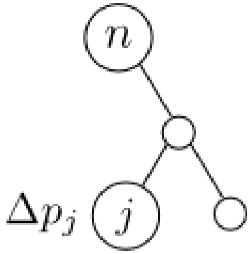
Local Ancillary Services Market

- DSO clears distribution system imbalances using its distributed resources
- TSO clears transmission system imbalances using transmission system resources, and distributed resources *that are not used* by the DSO
- TSO does not take distribution constraints into account when activating distribution system resources

TSO balancing



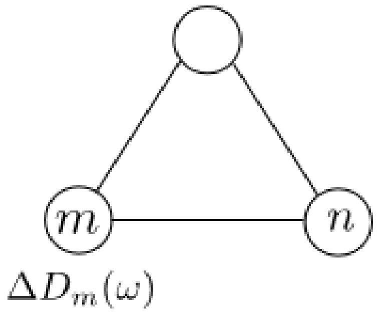
DSO balancing

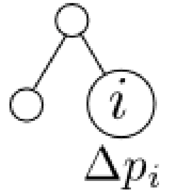


Shared Balancing Responsibility

- TSO clears transmission imbalances $\Delta D_n(\omega)$ with transmission resources *only*
- DSO clears distribution imbalances $\Delta D_n(\omega)$ with distribution resources *only*

TSO balancing



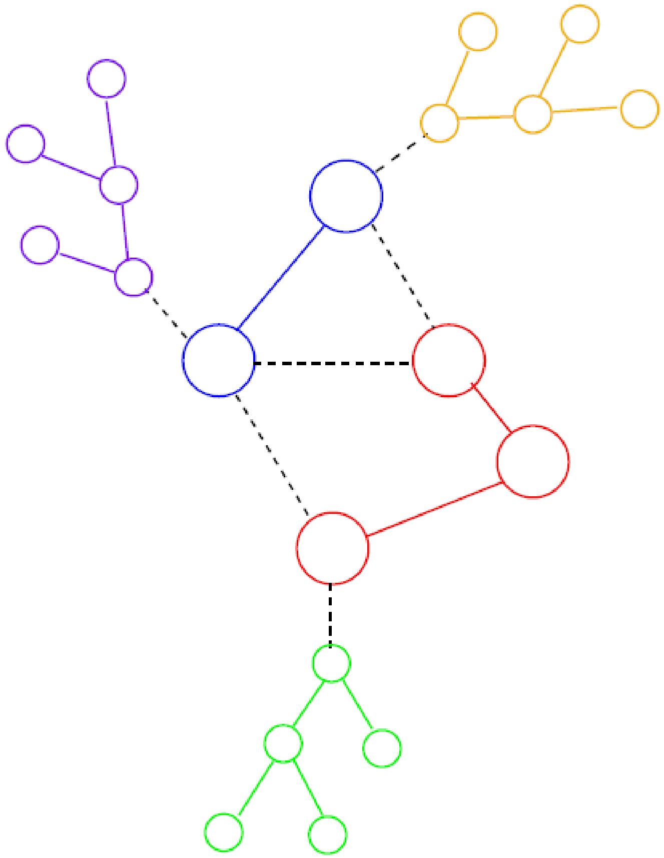


DSO balancing

Solving Coordinated TSO-DSO Dispatch

Spatial Decomposition

- Partition network into subnetworks, where every node must be assigned to a unique subnetwork
- Define interface edges (IE) as edges that are connect nodes of different subnetworks
- Define interface nodes (IN) as nodes that are adjacent to interface edges
- Each network has internal variables x and shared variables y



Problem Formulation

- Centralized common TSO-DSO model can be written out as

$$max \sum_{s \in SN} f_s(y_s, x_s)$$

$$y_{F(i),i} = y_{T(i),i}, i \in IE$$

$$x_{SN(n),n} = y_{s,n}, n \in IN, s \in AS(n)$$

- SN: set of sub-networks
- f_s: objective function of each subnetwork
- $F(i)$: sub-network that interface edge is outgoing from
- $T(i)$: sub-network that interface edge is pointing into
- $AS(n)$: set of adjacent sub-networks of n

Decomposition Strategy

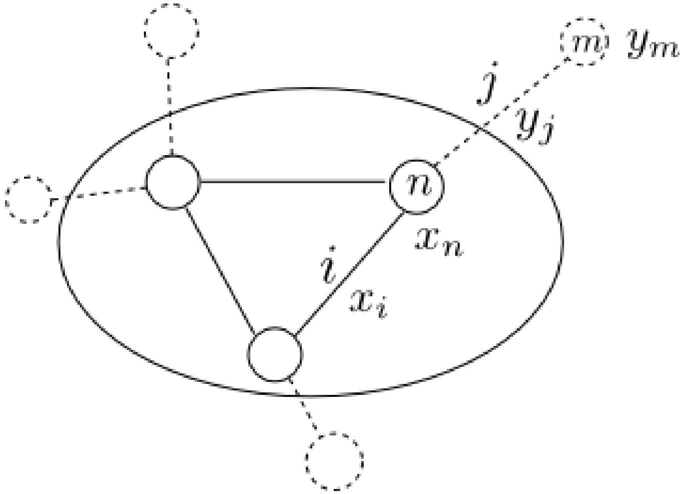
- Dual decomposition did not work, too unstable
- Instead, we solve the problem using ADMM
- Related solution strategies: (Kim, 1997), (Kraning, 2013)

Balho H. Kim and Ross Baldick. Coarse-grained distributed optimal power flow. IEEE Transactions on Power Systems, 12(2):932-939, May 1997.

Matt Kraning, Eric Chu, Javad Lavaei, and Stephen Boyd. Dynamic network energy management via proximal message passing. Foundations and Trends in Optimization, 1.(2):73-126, 2013.

Illustration of Internal/Copy Variables

- In order to create a subnetwork subproblem, we need to isolate the subnetwork constraints from the rest of the network
- Examining the linear approximation and SOCP relaxation, we notice that it is enough to create copies for the periphery of the subnetwork



ADMM Iterations

- Step 1: In increasing order of $s \in SN$, solve subproblem of subnetwork s (next slide)
- Step 2: For all $i \in IE$, let

$$\lambda_i^{(k+1)} = \lambda_i^{(k)} - \rho(y_{F(i),i}^{(k+1)} - y_{T(i),i}^{(k+1)})$$
$$\lambda_{s,n}^{(k+1)} = \lambda_{s,n}^{(k)} - \rho(x_{SN(n),n}^{(k+1)} - y_{s,n}^{(k+1)})$$

- Step 3: If the convergence criterion has been met, stop. Otherwise, return to step 1

Subproblem of Subnetwork s

$$\left(x_s^{(k+1)}, y_s^{(k+1)}\right) \in argmax_{x,y} f_s(x, y)$$

$$+ \sum_{i \in IE: s=F(i)} \lambda_i^{(k)} y_i - \sum_{i \in IE: s=T(i)} \lambda_i^{(k)} y_i$$

Linear penalty of copy variables

$$+ \sum_{n \in IN: s=SN(n)} \left(\sum_{s' \in AS(n)} \lambda_{s',n}^{(k)} \right) x_n$$

Linear penalty of internal variables

$$- \sum_{n \in IN: s \in AS(n)} \lambda_{s,n}^{(k)} y_n$$

Linear penalty of internal variables

$$- \frac{\rho}{2} \sum_{i \in IE: s=F(i), T(i)<F(i)} (y_i - y_{T(i),i}^{(k+1)})^2$$

Regularization term for edge copy variables

$$- \frac{\rho}{2} \sum_{i \in IE: s=T(i), F(i)<T(i)} (y_{F(i),i}^{(k+1)} - y_i)^2$$

Regularization term for edge copy variables

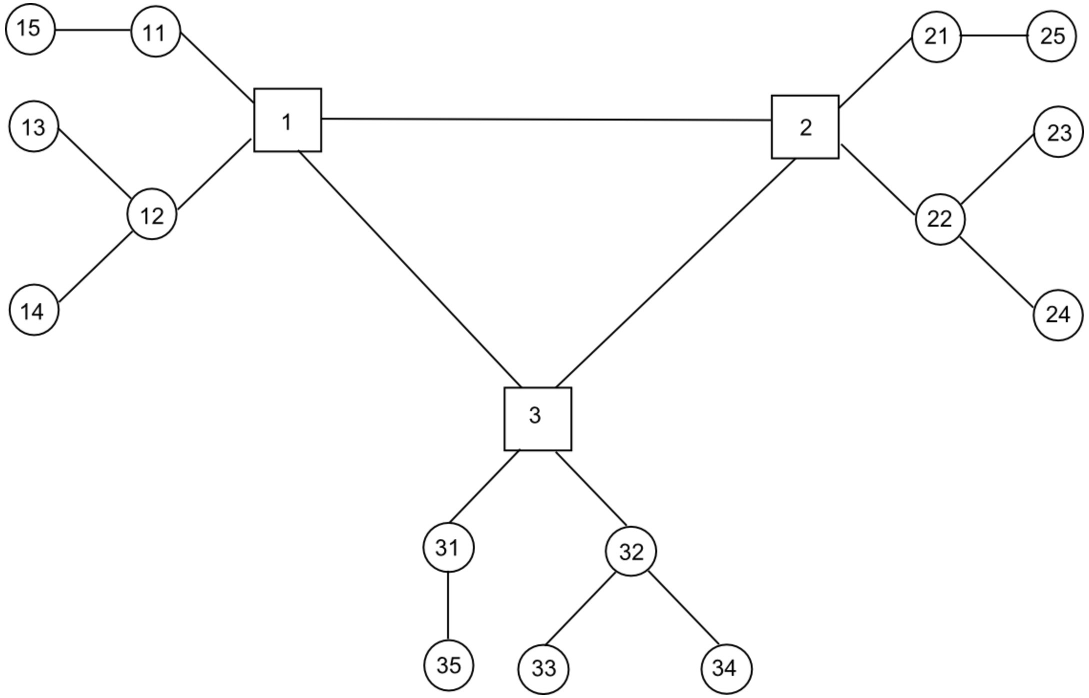
Subproblem of Subnetwork s

$-\frac{\rho}{2}\sum_{i\in IE:s=F(i),F(i)<T(i)}(y_i-y_{T(i),i}^{(k)})^2$	Regularization term for edge copy variables
$-\frac{\rho}{2}\sum_{i\in IE:s=T(i),T(i)<F(i)}(y_{F(i),i}^{(k)}-y_i)^2$	Regularization term for edge copy variables
$-\frac{\rho}{2}\sum_{n\in IN:s=SN(n),s'\in AS(n),s'<s}(x_n-y_{s',n}^{(k+1)})^2$	Regularization term for node internal variables
$-\frac{\rho}{2}\sum_{n\in IN:s=SN(n),s'\in AS(n),s'>s}(x_n-y_{s',n}^{(k)})^2$	Regularization term for node internal variables
$-\frac{\rho}{2}\sum_{n\in IN:s\in AS(n),SN(n)<s}(x_{SN(n),n}^{(k+1)}-y_n)^2$	Regularization term for node copy variables
$-\frac{\rho}{2}\sum_{n\in IN:s\in AS(n),SN(n)>s}(x_{SN(n),n}^{(k)}-y_n)^2$	Regularization term for node copy variables

Numerical Illustration

Test System

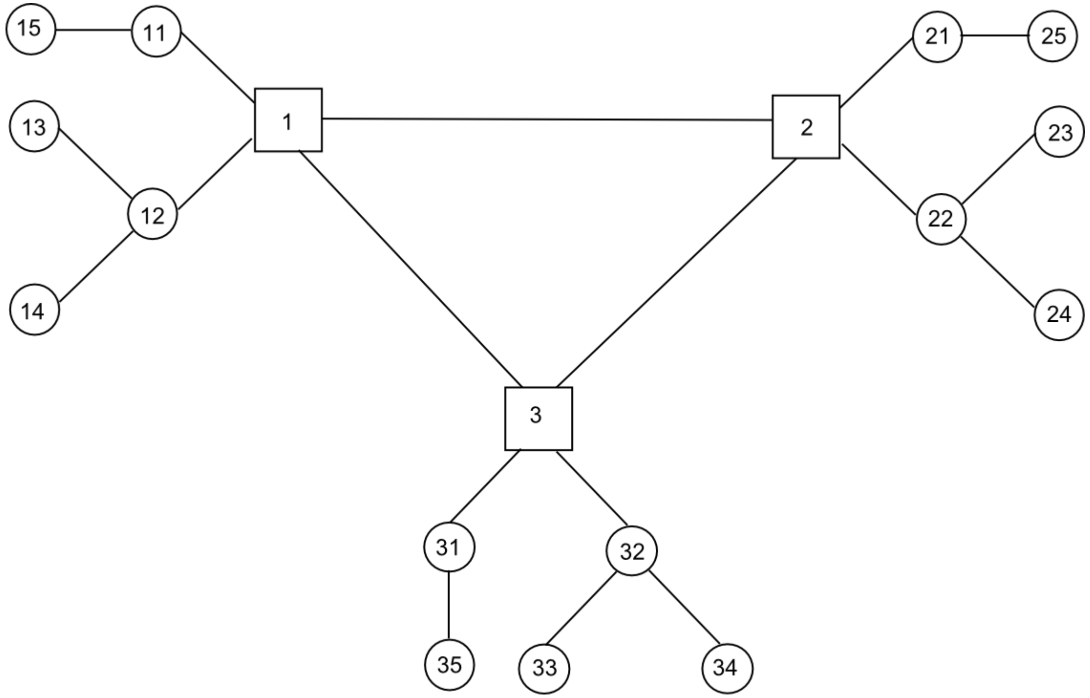
- Transmission network:
  - Generator at 1: 390 MW @ 10 €/MWh
  - Generator at 2: 150 MW @ 20 €/MWh
  - Inelastic demand at 1: 350 MW
- Idential distribution networks
  - Every distribution node: net supply of 5 MW
  - Every distribution node: flexible consumer with 50 MW @ 0-19.1 €/MWh



Full data: http://perso.uclouvain.be/anthony.papavasiliou/public html/Spider.dat

Test System (II)

- Reserve commitment using (Caramanis, 2016):
  - Generator at 2: 149.1 MW @ 20 €/MWh
  - Consumer at 15: 49.1 MW @ 19.1 €/MWh
  - Consumer 25: 6.3 MW @ 15 €/MWh
  - Consumer 34: 49.1 MW @ 19 €/MWh
- Imbalance at node 3: $\Delta D_3(\omega) = +100$ MW



Full data: http://perso.uclouvain.be/anthony.papavasiliou/public html/Spider.dat

Results

	Generator cost [$]	Consumer benefit [$]	Constraint violation [MW]	Transmission price [€/MWh]
Centralized Common Market	3900.0	212.4	0.0	19.3
Decentralized Common Market	3900.0	202.2	0.0	19.7
Centralied Ancillary Services Market	3900.0	283.7	4.0	19.1
Local Ancillary Services Market	4693.3	1026.0	3.9	20.0
Shared Balancing Responsibility	5900.0	2009.0	0.0	20.0

Results Summary

- Centralized common TSO-DSO market
  - Perfectly efficient benchmark
- Decentralized common TSO-DSO market
  - Relative to benchmark, shifts sourcing of reserve slightly from pockets 1 and 2 to pocket 3 due to approximation of residual supply functions
  - Dispatch is feasible
- Centralized AS market
  - Real-time price in transmission network is 19.1 €/MWh, slightly lower than benchmark due to unaccounted losses
  - This scheme produces no DLMP
  - Dispatch is 4.0 MW short of being feasible (due to unaccounted losses)

Results Summary (II)

- Local AS market
  - Transmission price: 20 €/MWh (notably higher than benchmark), due to depletion of distribution-level reserves that TSO can access
  - In general, same resource can be activated in opposite directions
- Shared balancing responsibility
  - Transmission price: 20 €/MWh (notably higher than benchmark), because TSO has no access to distribution system reserves
  - Dispatch is feasible

Conclusions and Next Steps

- Observations
  - Centralized common market sets first-best standard, however it presents communications and optimization challenges
  - Decentralized common market: favorable balance between efficiency and scalability of computation and optimization
  - Local AS dominated by centralized AS in terms of efficiency
  - Shared balancing responsibility: although feasible, least efficient solution
- Have prototyped ADMM method for centralized TSO-DSO market. Next goals:
  - Test on large-scale systems (Spain, Italy, Denmark)
  - Introduction of binary variables
- Game-theoretic modeling could be meaningful

Thank you

For more information

- anthony.papavasiliou@uclouvain.be
- http://perso.uclouvain.be/anthony.papavasiliou/public_html/home.html