DOE/OE Transmission Reliability Program

Economical and Engineering Aspects of Proactive Demand Participation: Centralized versus Bilateral Control Structure

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Outline

- **Overall Project Objectives**
- **Looking Back**
  - Major accomplishment during the past year (project start-June 2017)
  - Deliverables and Remaining activities and schedule FY 2016 – 2017
  - List of accepted publications/presentations
- **Looking Forward**
  - Planned activities and schedule

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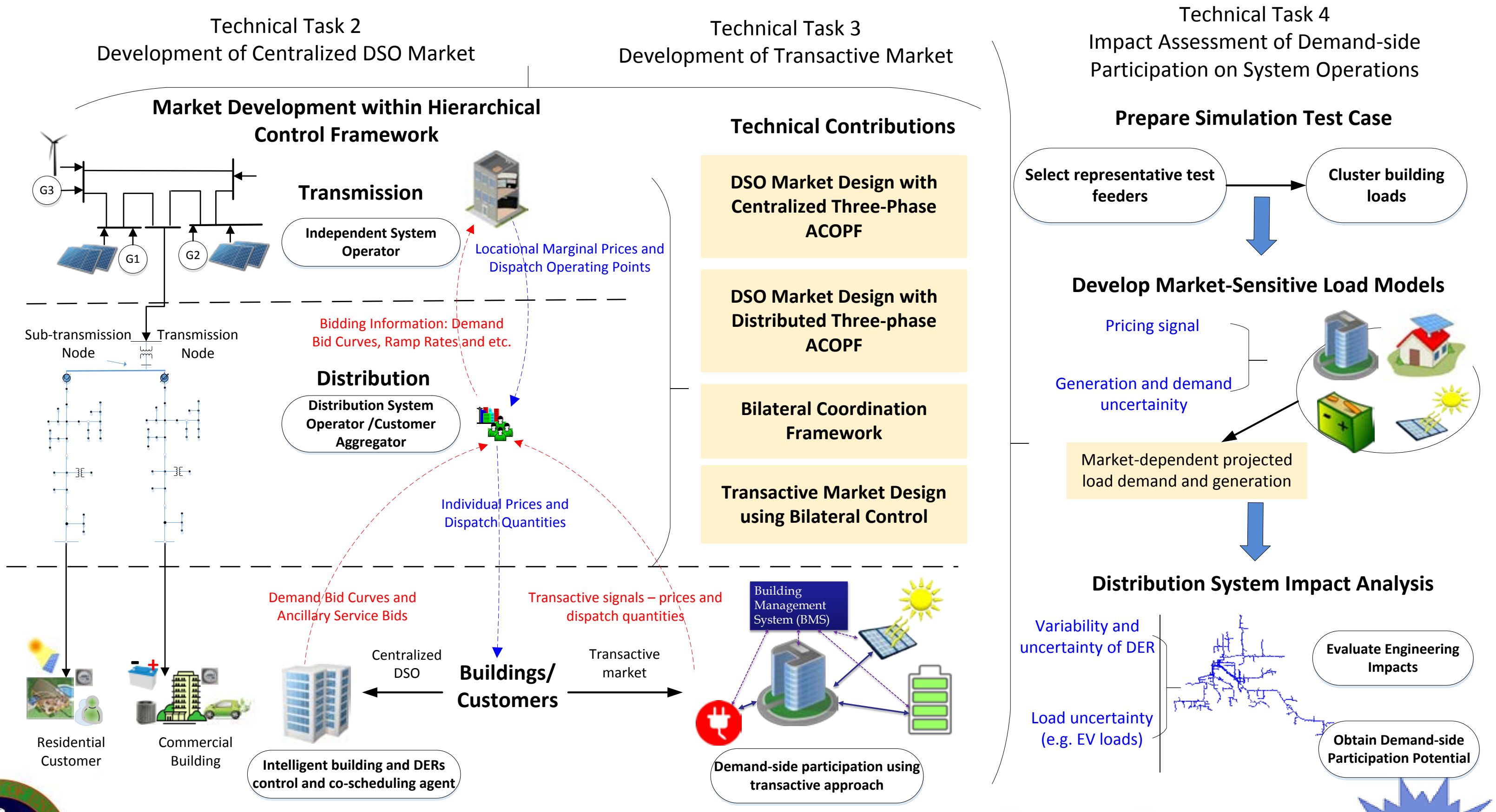
Project Objectives

Perform the critically needed research related to the *retail market development* , *impact assessment of demand-side participation* and its *integration into the wholesale market*.



Technical Task 2
Development of Centralized DSO Market

Technical Task 3
Development of Transactive Market

Technical Task 4
Impact Assessment of Demand-side Participation on System Operations

Market Development within Hierarchical Control Framework

Transmission

Independent System Operator

Distribution

Distribution System Operator /Customer Aggregator

Buildings/ Customers

Intelligent building and DERs control and co-scheduling agent

Demand-side participation using transactive approach

Technical Contributions

- DSO Market Design with Centralized Three-Phase ACOPF
- DSO Market Design with Distributed Three-phase ACOPF
- Bilateral Coordination Framework
- Transactive Market Design using Bilateral Control

Prepare Simulation Test Case

Select representative test feeders → Cluster building loads

Develop Market-Sensitive Load Models

Market-dependent projected load demand and generation

Distribution System Impact Analysis

Evaluate Engineering Impacts

Obtain Demand-side Participation Potential

Proposed Research Tasks

Transactive Energy Market

- **Task 2** Hierarchical DSO Market Design
- **Task 3** Distributed Transactive Market
- **Task 4** Impact Assessment
- **Task 5** Demonstration

Development of Hierarchical ***DSO Market*** Framework

- ➢ A highly scalable, and computationally efficient three-phase ACOPF algorithm.

Development of ***Transactive Market*** within Hierarchical Control Framework

- ➢ A decentralized market enabling energy bidding and price formation through bilateral negotiations of energy/electricity prices.

Impact Assessment of ***Demand-side Participation*** on Distribution System

- ➢ Market-sensitive impact assessment framework to evaluate the impacts of demand-side participation on the distribution system operations.

Demonstration of the Proposed ***Distributed Transactive Market***

- ➢ Implement the proposed transactive market using Smart City Testbed (SCT) at ESIC.

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Major Accomplishments: Task 2
First Quarter (Oct, 2016 – Dec, 2016)

Developed a proactive building demand participation scheme

- Developed an energy bid creation algorithm which convert the building control model and customers’ preferences into price sensitive demand bids.
- Developed a two-step procedure for buildings to optimize the frequency regulation service provision by leveraging HVAC system.
- Explored trade-off between frequency regulation performance and climate control performance of the building.

Proposed an integrated wholesale and retail market operations framework

- Developed the architecture for the DSO market
- Designed interface with between the ISO and DSO market

Major Accomplishments: Task 2
Second Quarter (Jan, 2017 – March, 2017)

Developed a highly scalable and computationally efficient three-phase ACOPF algorithm

- Synergistically combined the merits of the convex iteration approach and the chordal based conversion technique.
- A greedy grid partitioning scheme is designed to speed up the algorithm.

Performed comprehensive evaluation of the proposed three-phase ACOPF algorithm on IEEE test feeders

- The proposed algorithm is shown to be computationally efficient, scalable, and yields global optimal solutions while resolving the rank conundrum.

Three-phase ACOPF
- Motivation and Literature Review

Why do we need three-phase ACOPF in distribution systems?

- The distribution network is inherently unbalanced.
- Need to coordinate the operations of large-scale and heterogeneous DERs.

Why is the three-phase ACOPF problem difficult?

- The problem is highly nonlinear and nonconvex due to the nonlinear relationship between voltage and power injections.

Traditional Methods

- Newton-based methods, linear & quadratic programming, nonlinear and polynomial programming, interior point method, and heuristic optimization. (None of them guarantee global optimal solution)

Semidefinite Programing Relaxation based Methods

- Transforms the OPF problem into a SDP where the only nonconvex constraint is a matrix rank-one constraint. If the rank-one constraint is dropped, then convex optimization techniques can be used to solve the problem.
- Global optimality can only be guaranteed for single-phase tree networks. It can not be applied in three-phase distribution networks.

Formulation of Three-phase ACOPF Problem

Formulation 1

$$\min_X C(X)$$

subject to:

$$P^p_{G_k} - P^p_{D_k} = Tr\{\mathbf{Y}^p_k X\}, \quad k \in N \setminus G$$

$$Q^p_{G_k} - Q^p_{D_k} = Tr\{\overline{\mathbf{Y}}^p_k X\}, \quad k \in N \setminus G$$

$$\underline{P}^p_k - P^p_{D_k} \leq Tr\{\mathbf{Y}^p_k X\} \leq \overline{P}^p_k - P^p_{D_k}, \quad k \in G$$

$$\underline{Q}^p_k - Q^p_{D_k} \leq Tr\{\overline{\mathbf{Y}}^p_k X\} \leq \overline{Q}^p_k - Q^p_{D_k}, \quad k \in G$$

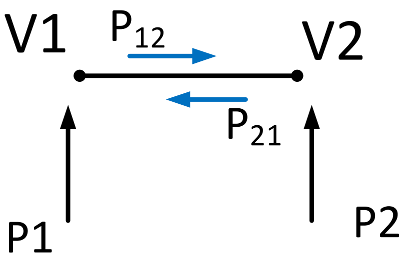
$$Tr\{\mathbf{Y}^p_{ik} X\}^2 + Tr\{\overline{\mathbf{Y}}^p_{ik} X\}^2 \leq (S^{p\ max}_{ik})^2, \quad i, k \in N$$

$$(\underline{V}^p_k)^2 \leq Tr\{M^p_k X\} \leq (\overline{V}^p_k)^2, \quad k \in N$$

$$X = VV^T \longleftrightarrow \begin{array}{c} X \succeq 0 \\ rank(X) = 1 \end{array}$$

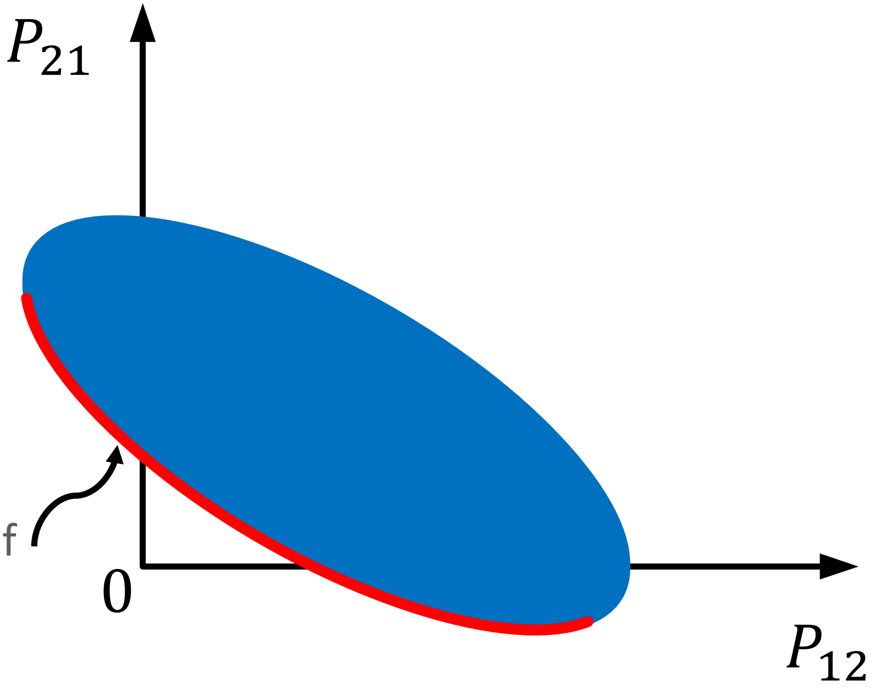
- Objective
  - Minimizes total power purchase cost or system losses
  - Maximize total social welfare.
  - Real and reactive power balance constraints for each node
  - Generation capacity constraints
  - Line flow constraints
  - Voltage constraints

Why does SDP Relaxation Method Work for Single-Phase Tree Network?



Ellipse corresponds to the feasible set

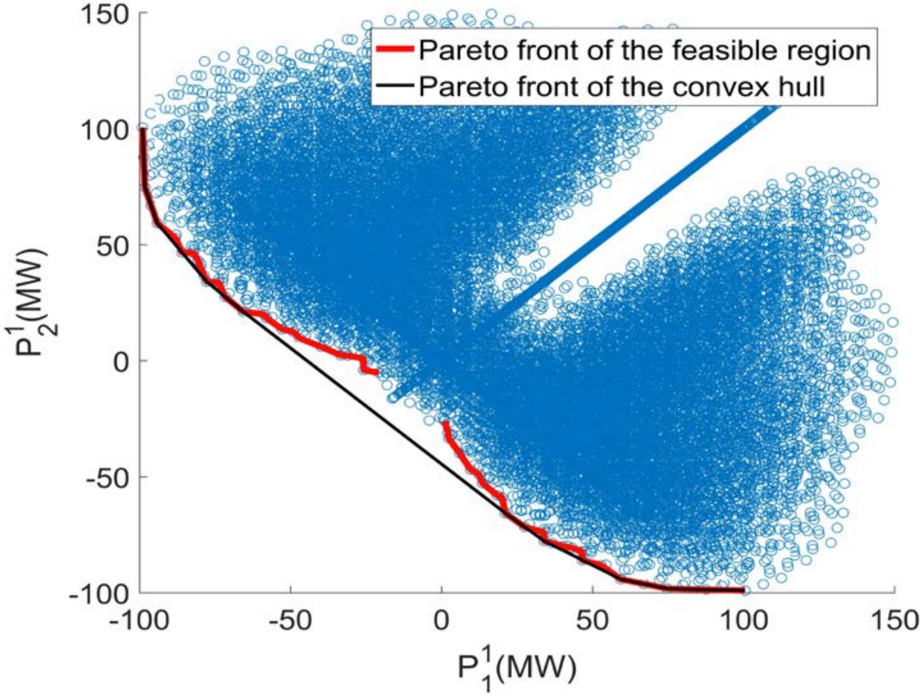
Convex hull of ellipse is the feasible set without rank-1 constraint



Pareto front of convex hull

Global optimality can be guaranteed if ellipse and its convex hull has the same Pareto front

Why doesn't SDP Relaxation Method Work for Three-phase ACOPF Problem?



Feasible power injection region of a two-node network with different supply offer prices on three-phases

The feasible region of the original problem and its convex hull does not have the same Pareto front.

Chordal Conversion based Convex Iteration Algorithm

Synergistically combine the merits of the convex iteration approach and the chordal based conversion algorithm

- The chordal based conversion algorithm exploit the chordal sparsity of radial distribution networks by converting the large SDP problem into another form with smaller-sized positive semidefinite variables.
- The convex iteration technique solves the rank-1 conundrum by expressing the rank-constrained optimization problem as iteration of convex problem sequence.

$$\min_{X} C(X) + wTr(XW^*)$$

subject to

$$X \in B$$

$$X \succeq 0$$

$$\min_{W \in S^{N_X}} Tr(X^*W)$$

subject to

$$0 \preceq W \preceq I$$

$$Tr(W) = N_X - 1$$

Feasibility & Optimality of Our Proposed Algorithm

SDP Relaxation Method versus the Convex Iteration Method

Test System	Method	Rank of Solution	Objective value ($/hour)
4-bus test feeder	SDP relaxation	3	3085.6
	Convex iteration	1	3121.9
13-bus test feeder	SDP relaxation	3	2319.5
	Convex iteration	1	2345.4
37-bus test feeder	SDP relaxation	1	1739.5
	Convex iteration	1	1739.5
123-bus test feeder	SDP relaxation	6	2413.6
	Convex iteration	1	2413.6
906-bus test feeder	SDP relaxation	6	38.219
	Convex iteration	1	38.149

- The SDP relaxation method does not yield a rank-one solution by directly removing the rank constraint. The rank-3/6 solution does not have any physical meaning.
- The proposed chordal conversion based convex iteration algorithm always produce a rank-1 solution, which is also the global optimum.

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Comparison with Traditional OPF Solvers

Test System	Bid Prices of three Phases ($/kWh)	Method		
		Powell	**Interior Point**	**Convex Iteration**
4-bus test feeder	1 / 0.5 / 0.2 0.9 / 0.45 / 0.18	3121.9 3091.9	3121.9 3091.9	3121.9 3086.9
13-bus test feeder	0.6 / 0.3 / 1 0.48 / 0.24 / 0.8	2345.4 2290.2	2345.4 2290.2	2345.4 2290.2
37-bus test feeder	0.6 / 0.3 / 1 0.54 / 0.27 / 0.9	1740.3 1675.9	1740.3 1675.9	1739.5 1675.4
123-bus test feeder	1 / 0.3 / 0.6 0.8 / 0.24 / 0.48	2414.6 2205.6	2414.5 2205.6	2413.6 2205.0
906-bus test feeder	0.6 / 0.7 / 0.5 0.54 / 0.63 / 0.45	38.356 37.915	38.348 37.915	38.149 37.745

- The traditional ACOPF solvers achieve global optimum solutions on 3 out of 10 cases.
- The proposed convex iteration algorithm always yield global optimum solutions with the same or a better result.

Scalability of Our Proposed Algorithm

Test System	Computation time (s)	Number of iterations	Number of nonzero elements
4-bus test feeder	0.373	4	2.95×10^4
13-bus test feeder	8.714	16	3.61×10^5
37-bus test feeder	3.261	1	2.06×10^6
123-bus test feeder	27.128	3	4.93×10^6
906-bus test feeder	217.099	11	1.19×10^7

- ☐ The computation times of the first four IEEE test feeders are all within 30 seconds using an entry level Dell workstation.
- ☐ The 123-bus test feeder represents a realistic distribution feeder with thousands of customers where all loads are aggregated to the primary side of the center-tapped transformers.

Major Accomplishments: Task 3
First Quarter (Oct, 2016 – Dec, 2016)

Proposed a theoretical framework for the decentralized distribution systems market

- ☐ Architecture for the decentralized market
- ☐ Description of actors, roles, products, and mechanisms to enable the negotiation of electricity supply and demand

Explored market settling practices

- ☐ Explored algorithms to determine supply/demand transactions through auctions, matching market mechanism, and optimal social welfare allocation concepts.

Demonstration of the transactive scheme auction over a set of VOLTTRON nodes

- ☐ Implemented a one-sided second price sealed bid auction (one-sided VCG auction) scheme for the spot market to enable transactive control and bilateral coordination.

Major Accomplishments: Task 3
Second Quarter (Jan, 2017 – March, 2017)

Proposed a distributed optimization algorithm to clear the distribution system spot market

- Linear optimization model for optimal social welfare allocation by means of distributed computation approach.
- MATLAB® algorithm for clearing the spot market using Dantzig-Wolfe decomposition.
- Bilateral negotiation prices are considered in the problem.

Nash Equilibrium based strategy for the Bilateral Transactive Coordination Framework

- Explored the NE strategies for electricity bidding and using linear optimization models to clear the market.

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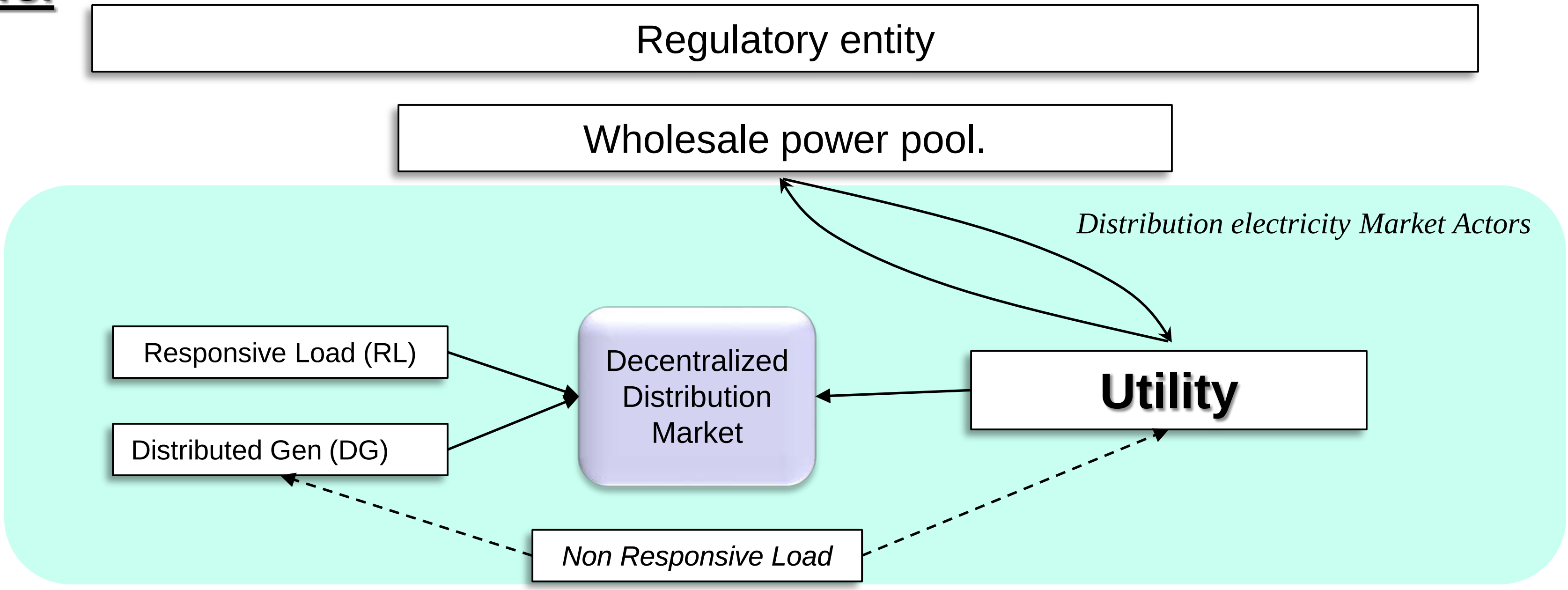
Distribution Market Architecture

Actors:



Regulatory entity

Wholesale power pool.

Distribution electricity Market Actors

Responsive Load (RL)

Distributed Gen (DG)

Decentralized Distribution Market

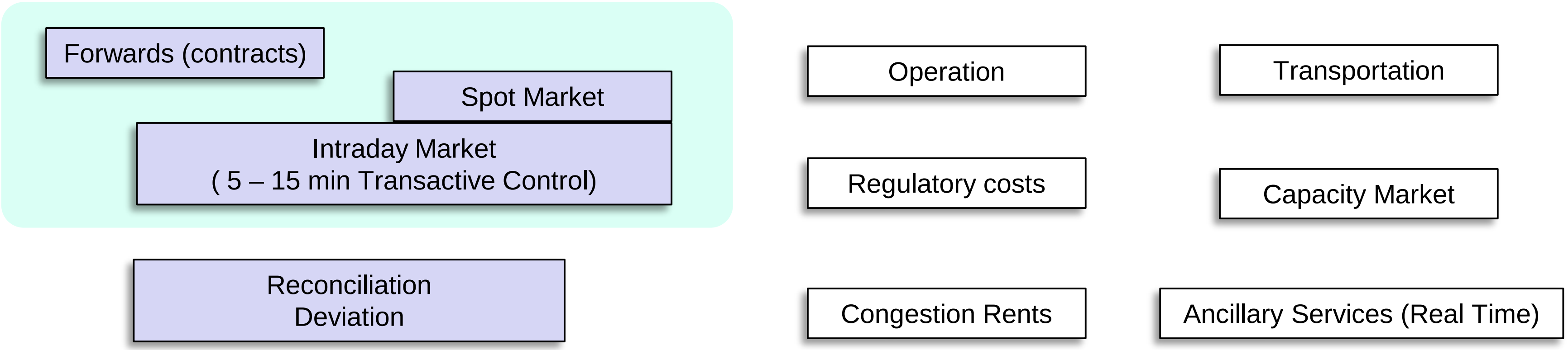
Utility

Non Responsive Load

- ❑ Actors of the market including distributed generators (DG) and responsive loads (RL) participate actively in the price formation.
- ❑ Non-responsive (NRL) loads participate passively. Electricity consumption patron is considered.
- ❑ Utility company plays a crucial role in ensuring demand-supply balance and price formation.

Distribution Market Architecture

Products



Forwards (contracts)

Spot Market

Intraday Market
(5 – 15 min Transactive Control)

Reconciliation
Deviation

Operation

Transportation

Regulatory costs

Capacity Market

Congestion Rents

Ancillary Services (Real Time)

Considered in the WSU Distribution Market proposal

- In a **contract** (bilateral) energy to be delivered in the future is traded. Generators and loads manage their financial risks by assuring a fixed cash flow for the future transactions.

- In the **spot market** the actors can negotiate the electricity to supply their energy deficit or selling electricity surplus on short-term basis (day ahead, and intraday transactions 5~15 minutes). This ensures balancing forwards (contracts) using real time production/demand.

- Differences between the actual outputs (generation or reduction of demand) and agreed amounts (contracts and spot market) are reconciliated by the means of a penalization price.

Distribution Market Architecture

Distributed Gen (DG) | Responsive Load (RL) | Utility (U) | *Non Responsive Load (NRL)*

Months, years

Forwards (Long term Contracts)

- Designed for trading energy for future delivery.
- Producers limit their investment risk by means of these products.
- ***Take or Pay***, ***Pay as demand***, and ***Energy Contracts.*** For the Distribution Market, only bilateral contracts.
- They can be between DG-RL, DG-U or U-RL, any of them acting as buyer or seller.
- U-NRL, DG-NRL, where the NRL is always a buyer.

One day
5-15 mins

Spot Market (Short term Negotiation)

- Designed for trading product of immediate delivery in order to balance forwards contracts vs. real time production/demand.
- Different mechanism can be deployed in the spot market:
  - Day Ahead mechanism *(not proposed for this Distribution Market)*
  - Intraday Market (5 to 15 min markets): **Transactive Control Mechanisms**

How to match bids and ask?

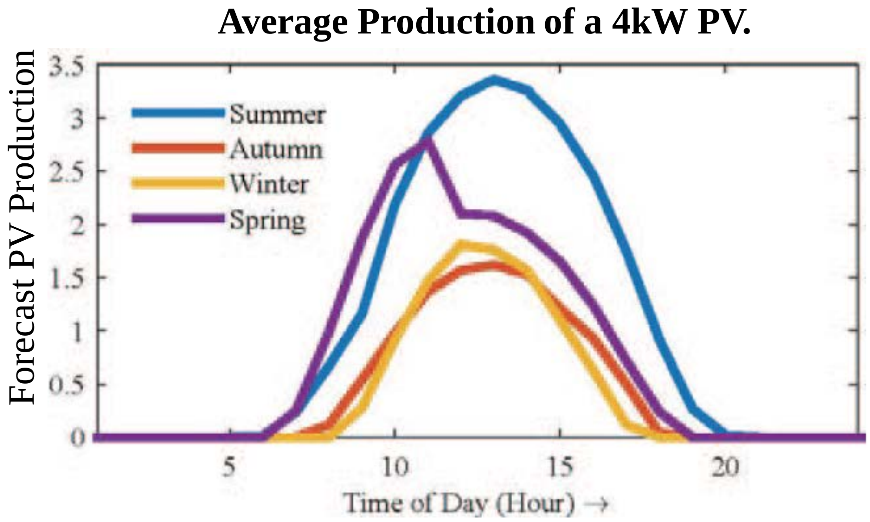
- Matching Market.
- Nash Equilibrium combination.
- Auctions mechanism (*First price Sealed bid, Vickrey-Gloves-Clark Auction, Generalize second price sealed bid auction), among others.*

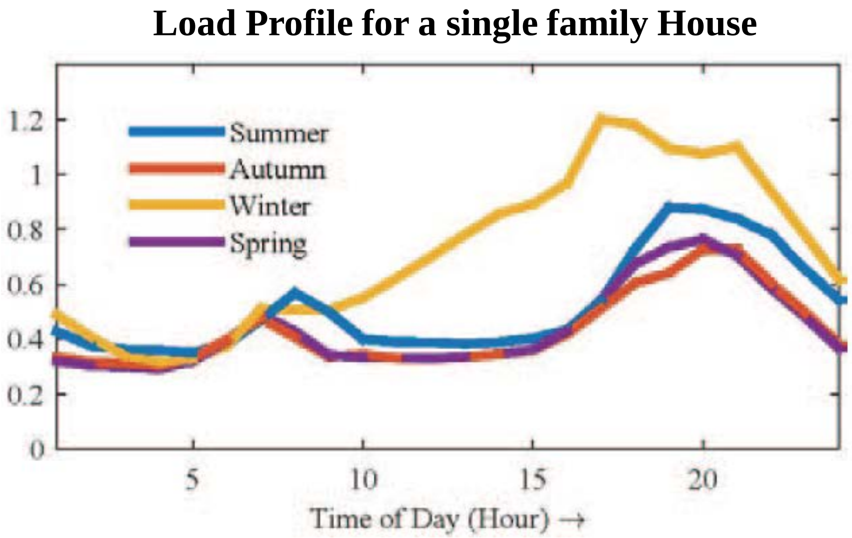
Expost

Reconciliation Deviation

- Determining the differences of the real operation vs the market quantities and settle them.
- Liquidate the penalties for deviation from the agreed upon values.

Forward Market Operation - Example


Average Production of a 4kW PV.

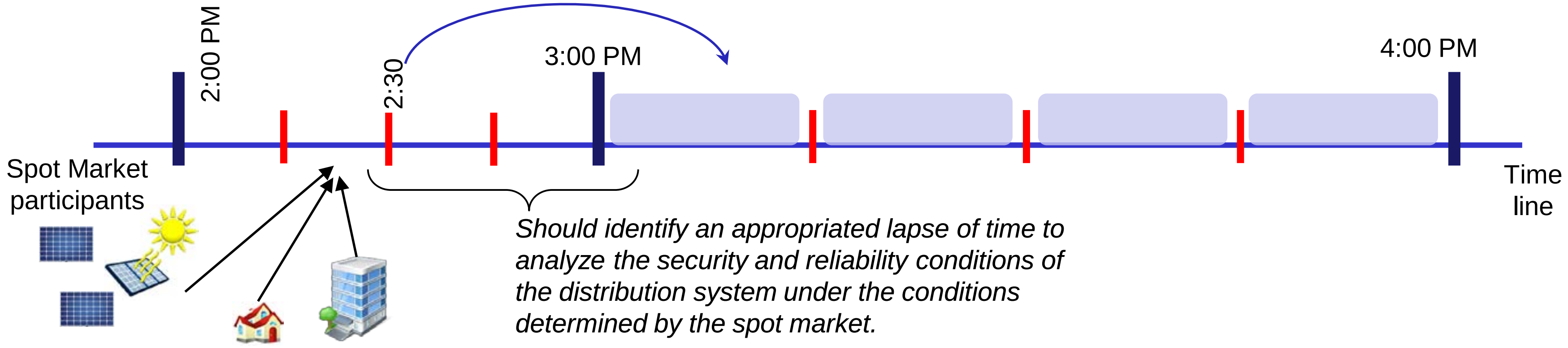

Load Profile for a single family House

- In this example, the PV can subscribe an agreement (Forward contract) to provide electricity to two different houses during winter.
- Two parameters are defined: Quantities and Price.

Example of two contracts for winter season, subscribed between a 4kW PV and a house.

		H01	...	H10	...	H15	H16	H17	...	H24
House 1	kWh	0		0.3	...	0.6	0.6	0.2	...	0
	ctv/kWh	0		5	...	5	5	5	...	0
House 2	kWh	0		0.3	...	0.6	0.6	0.2	...	0
	ctv/kWh	0		4	...	6	6	6	...	0

Spot Market Operation - Example

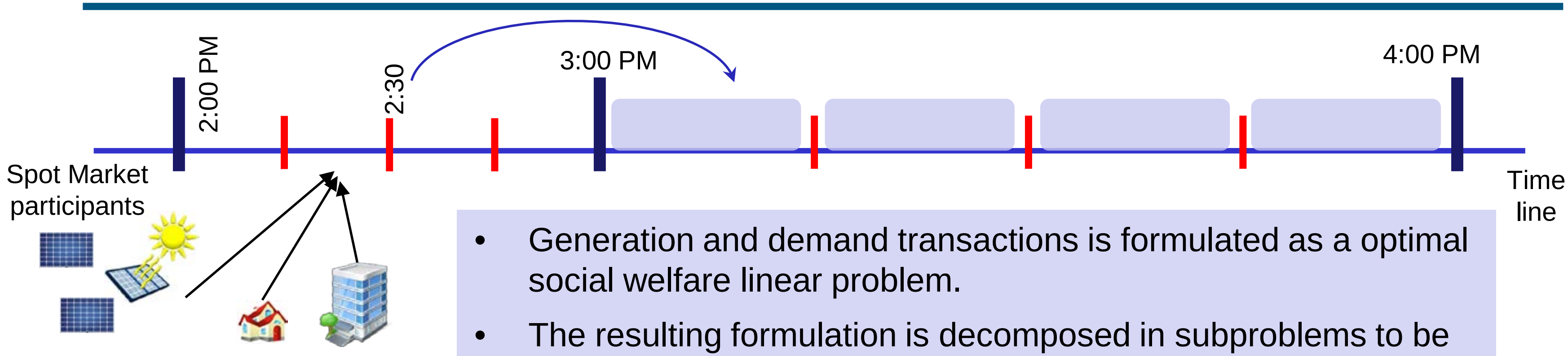


Should identify an appropriated lapse of time to analyze the security and reliability conditions of the distribution system under the conditions determined by the spot market.

Suppose that before 2:30 p.m.:

- A few PV panels have predicted that based on current weather conditions they will not have enough energy production to meet their commitments between 3:00 – 3:15 p.m. ***(ASK).***
- A few loads has projected that their electricity consumption between 3:00 – 3:15 p.m. will be higher than the sum of their contracted values. ***(ASK).***
- A few PVs have identified that they will have electricity surplus between 3:00 – 3:15 p.m. as compared to their contracted value. ***(BID).***
- A few responsive loads have identified their willingness to reduce their consumption between 3:00 – 3:15 p.m. in exchange of a remuneration. ***(BID)*.**

Spot Market Clearing – Problem Formulation



- Generation and demand transactions is formulated as a optimal social welfare linear problem.
- The resulting formulation is decomposed in subproblems to be individually solved by each participating actor.

Optimal Social Welfare Problem

Operation Cost

$$Minimize\ \ f(x_1, x_2, \dots, x_n) = c_1x_1 + c_2x_2 + \cdots + c_nx_n$$

$$\begin{array}{lllllll} A_1x_1 + & A_2x_2 + & \dots & +A_nx_n & \le & b_0 \\ B_1x_1 & & & & \le & b_1 \\ & B_2x_2 & & & \le & b_2 \\ & & \ddots & & & \vdots \\ & & & B_nx_n & \le & b_n \end{array}$$

Demand – supply balance

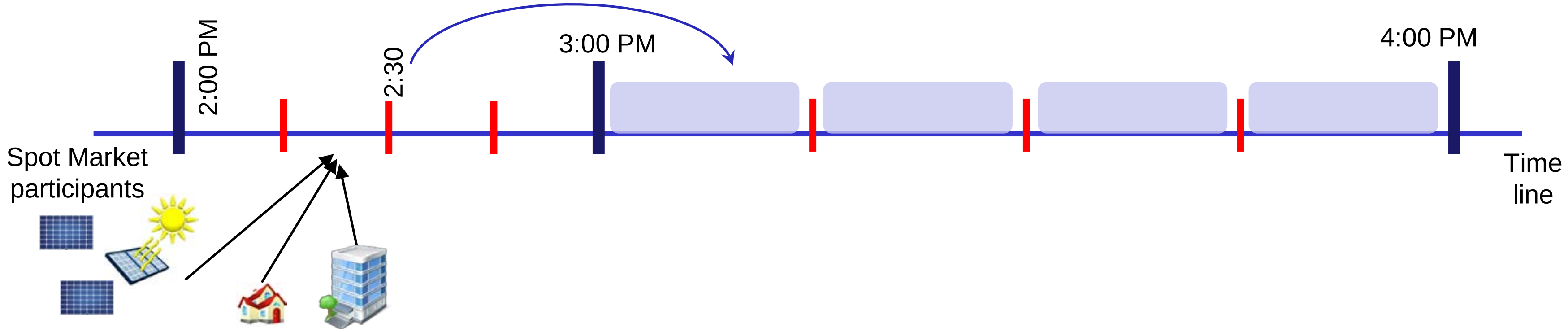
Actor's constraints

Decentralized Problem

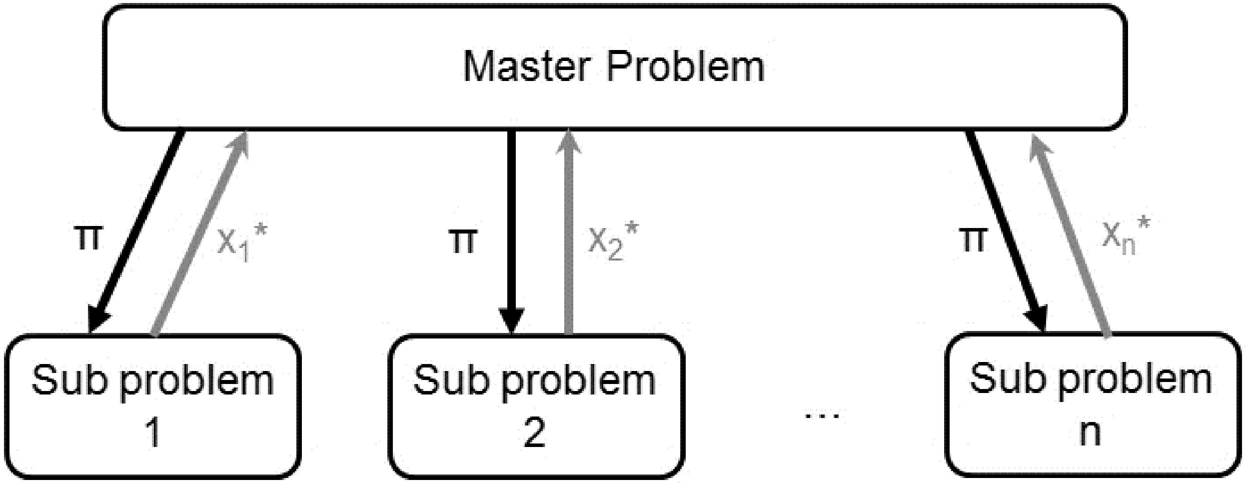
$$Min\ \ L(x_1, x_2, \dots, x_n, \pi) = c_1x_1 + c_2x_2 + \cdots + c_nx_n - \pi(b_0 - A_1x_1 - A_2x_2 - \cdots - A_nx_n)$$

$$\begin{array}{lllllll} B_1x_1 & & & & \le & b_1 \\ & B_2x_2 & & & \le & b_2 \\ & & \ddots & & & \vdots \\ & & & B_nx_n & \le & b_n \end{array}$$

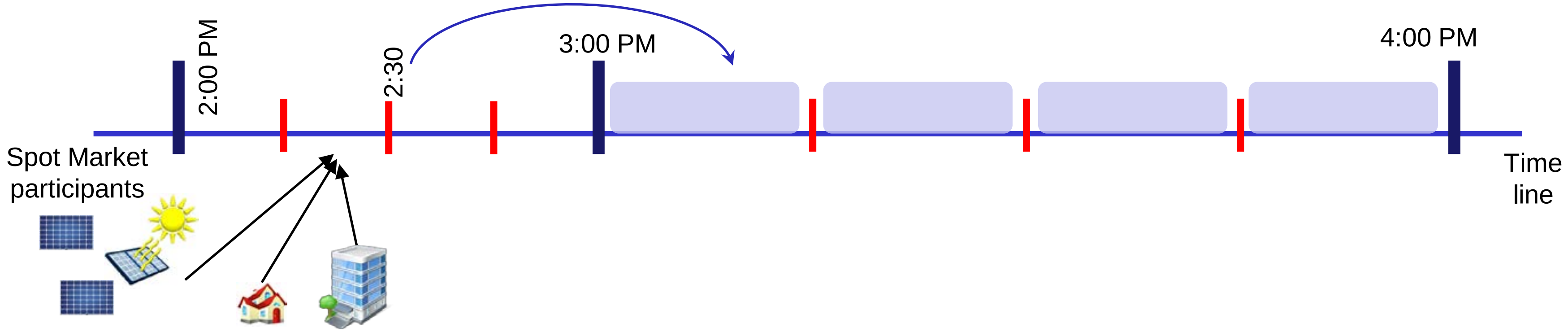
Spot Market Clearing – Problem Formulation



Dantzig-Wolfe decomposition



Spot Market Clearing – Problem Formulation



Master Problem

$$Minimize \sum_j (c_1x_1^* + c_2x_2^* + \cdots + c_nx_n^*)\,\lambda_j$$

$$\text{St:} \quad \sum_j (A_1x_1^* + A_2x_2^* + \cdots + A_nx_n^*)\,\lambda_j \le b_0 \quad ; \quad \sum_j \lambda_j = 1$$

Satellite problems

$$x_1^* = Min(c_1 - \pi A_1)x_1 \qquad x_2^* = Min(c_2 - \pi A_2)x_2 \qquad x_n^* = Min(c_n - \pi A_n)x_n$$

$$B_1x_1 \le b_1 \qquad B_2x_2 \le b_2 \qquad B_nx_n \le b_n$$

The final solution is represented as a convex combination of the extreme optimal points of each satellite problem.

$$X^* = \sum_j \lambda_j x_j = 1$$

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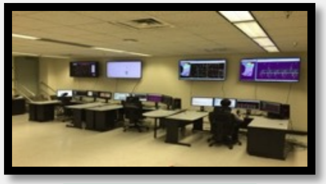
WSU Transactive Energy Demo

Sloan Building

Smart City Testbed



VOLTTRON (Sloan)

VOLTTRON (Commons)

WSU Campus

Research Park

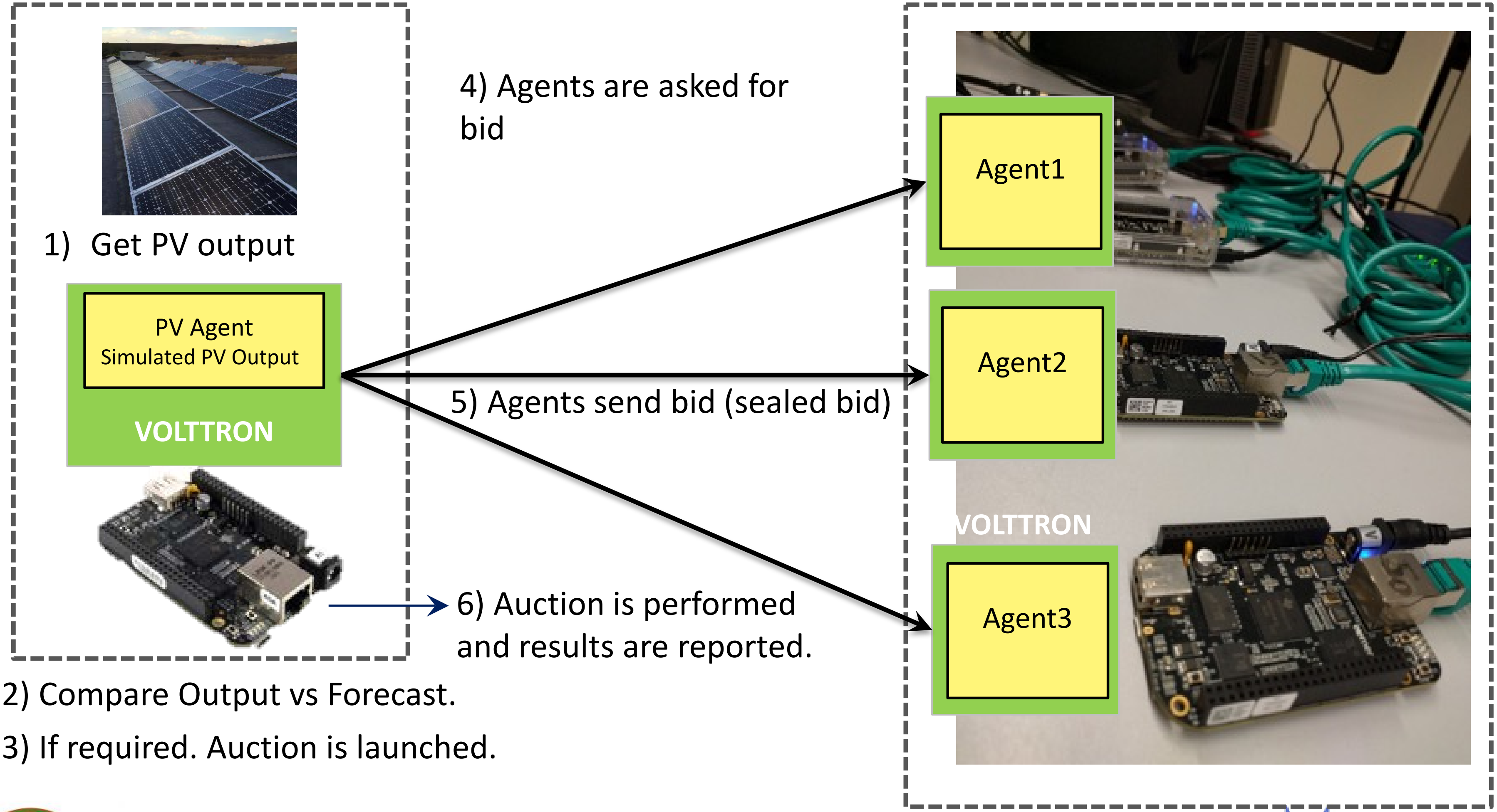
Commons Building

McCluskey (WSU Building Automation)

HMI

Historian

PV-Agent and VOLTTRON (Testbed)



1) Get PV output

2) Compare Output vs Forecast.

3) If required. Auction is launched.

4) Agents are asked for bid

5) Agents send bid (sealed bid)

6) Auction is performed and results are reported.

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Remaining Activities – FY16

- In the proposed distributed market, the operational point achieves the ***optimal social welfare***. Both, producers and customers maximize their surplus.
- The utility, however, still plays a major role in energy dispatch and price formation. This is because demand-supply balance is modeled within the market clearing algorithm.
- The next task is develop a ***fully decentralized market***, where utility only intervenes when there is a potential system reliability problem due to demand supply imbalance or the violations of feeder voltage constraints.

Fully Decentralized Market

- We propose to model the spot market as fully decentralize market using bargaining theory.
- The utility runs power flow solution independently from the market to check the system impacts of the ongoing decentralized market transactions.
- Utility only intervenes in the free market when the proposed decentralized transactions result in a violation of operational constraints.

Remaining Activities – FY16

Remaining activities for FY2016-2017:

Decentralized market model:

- Designing a completely free and bilateral transaction framework. Each participant maximizes its own surplus, based in a non-cooperative, fully decentralized model.
- Nash bargaining problem, efficiency, and economic core theory will be used to match bilateral negotiations.

Satisfaction of Grid Security Constraints:

- Algorithm to modify the market negotiated quantities under potential violations of the security on the network.

Fully decentralized market vs optimal social welfare negotiations:

- Comparison between the market based on bargaining strategy and the solutions for optimal social welfare problem.

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List of Publications / Presentations

[1] Wei Wang and Nanpeng Yu, "LMP decomposition with three-phase DCOPF for distribution system," *2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Melbourne, VIC, pp. 1-8, 2016.

[2] Yang Liu, Nanpeng Yu, Jie Shi, Bing Dong, Wei Ren, and Xiaohong Guan, “Evaluation of frequency regulation provision by commercial building HVAC systems“ *to appear in IEEE International Conference on Automation Science and Engineering*, pp. 1-6, Xi'an, China, 2017.

[3] Wei Wang and Nanpeng Yu, "Chordal Conversion based Convex Iteration Algorithm for Three-phase Optimal Power Flow," submitted to *IEEE Transactions on Power Systems*, 2017.

[4] Juan Carlos Bedoya, Chen-Ching Liu, Anamika Dubey "Distributed optimal social welfare formulation for a bilateral transactive distribution system market " *IEEE Transactions*, in preparation.

[5] Juan Carlos Bedoya, Chen-Ching Liu, Anamika Dubey " A conceptual framework for decentralized distribution system spot market design" *IEEE PES GM 2018*, in preparation.

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Impact Assessment of Demand-side Participation (Task 4)

Prepare Simulation Test Case and Input Data

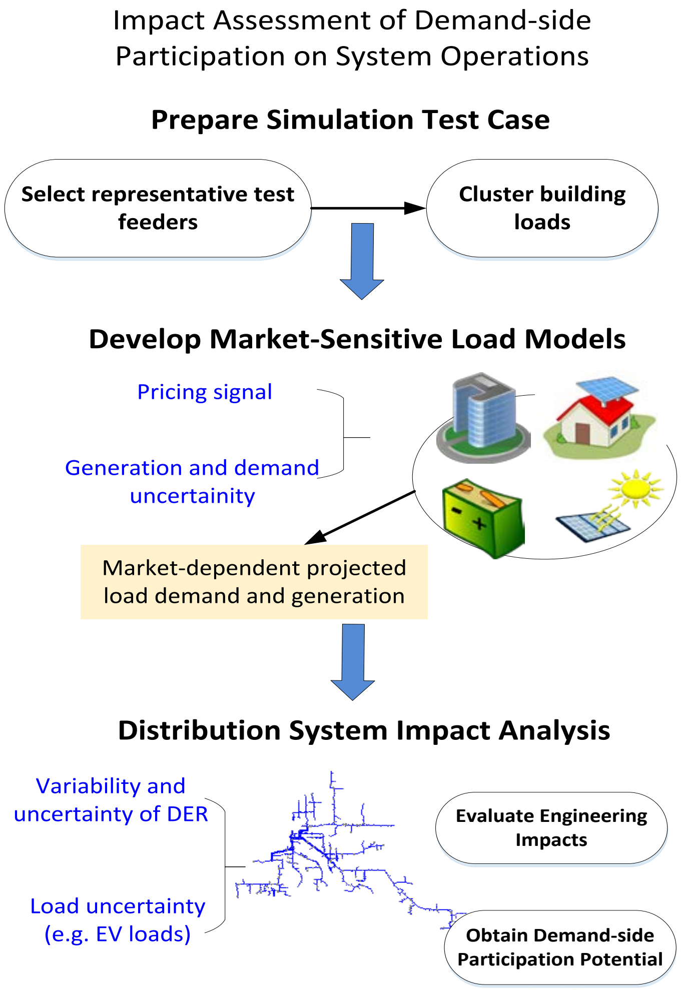
- ☐ Test case based on SCE distribution feeders.

Develop Market-sensitive Models for Customers

- ☐ Characterize the probabilistic supply/demand for the customer while including uncertainty and elasticity due to market participation.

Distribution System Impact Analysis and Demand-side Participation Potential

- ☐ Investigate the impacts of demand-side participation on distribution system operation for both centralized and decentralized frameworks.



Impact Assessment of Demand-side Participation on System Operations

Prepare Simulation Test Case

Select representative test feeders → **Cluster building loads**

Develop Market-Sensitive Load Models

Pricing signal

Generation and demand uncertainity

Market-dependent projected load demand and generation

Distribution System Impact Analysis

Variability and uncertainty of DER

Load uncertainty (e.g. EV loads)

Evaluate Engineering Impacts

Obtain Demand-side Participation Potential

Demonstration of Distributed Transactive Market (Task 5)

Demonstration of Transactive Market on Smart City Testbed

- Demonstrate transactive market concepts using Smart City Testbed (SCT).
- The proposed market framework will be implemented on SCT by modelling campus building and PV array as transactive nodes on VOLTTRON.
- The transaction-based control algorithm will be implemented to demonstrate the energy trading between VOLTTRON nodes.

Summary of the Project Outcomes

- A *scalable* and *computational efficient* three-phase ACOPF algorithm
- *Transactive market framework* to enable energy transactions among distribution customers in a decentralized manner.
- *Integration* of the developed transactive market to the *wholesale market* using DMS.
- A *value based transactive market* that simultaneously optimizes grid economy and operation.
- Evaluate and compare *impacts of demand-side participation* of distribution system operation.
- Small-scale campus *demonstration* of transactive control approach.

Questions?

Backup Material

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Energy Systems Innovation Center

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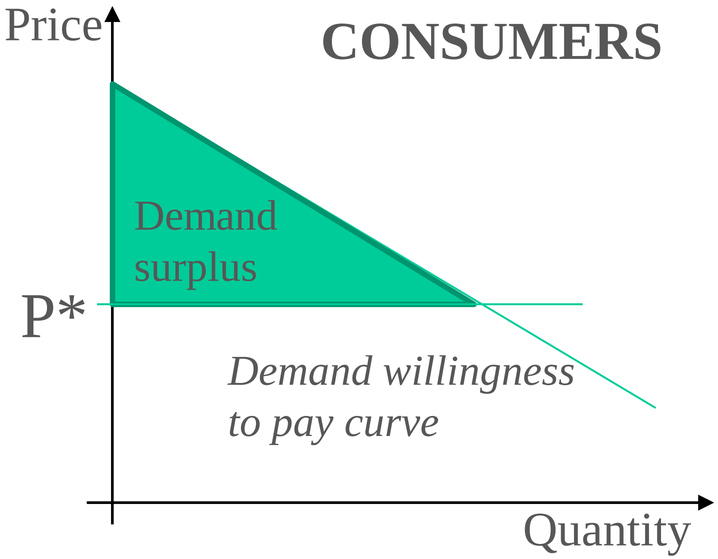
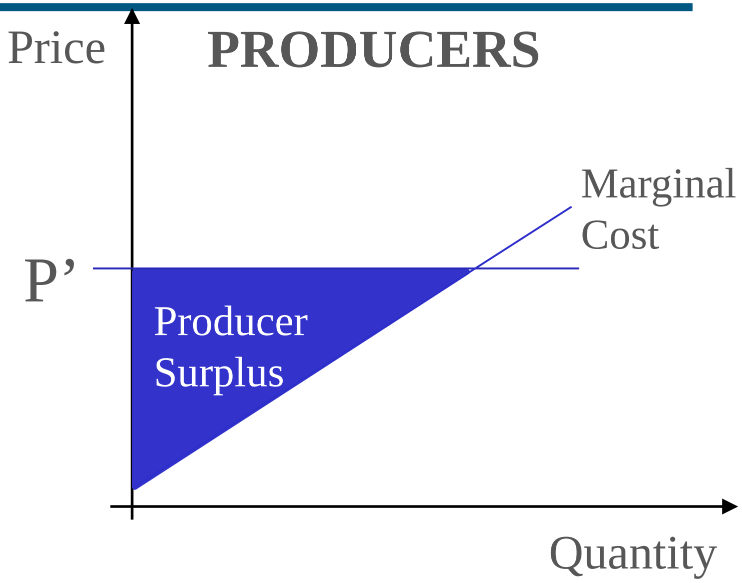
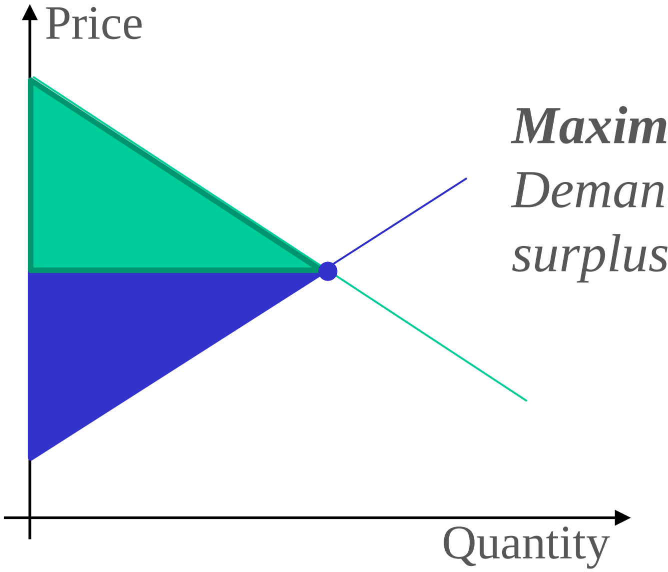
Spot Market Operation – Optimal Social Welfare

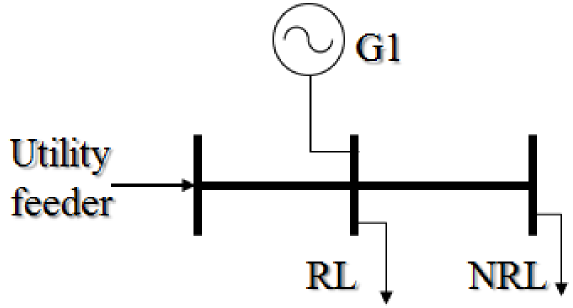


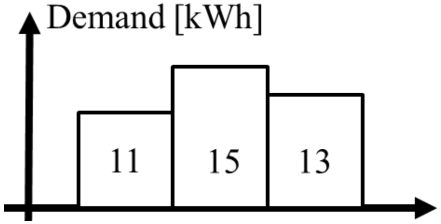




Maximum social welfare*:*
Demand and producer surplus is maximized

Spot Market Clearing – Example





Utility Prices [cts/kWh]
16 18 16

$$\text{Minimize} \sum_{t=1}^{T}\sum_{g=1}^{n} p_{g,t}G_{g,t} + \sum_{t=1}^{T}\sum_{RL=1}^{m} p_{RL,t}R_{RL,t} + \sum_{t=1}^{T} p_{u,t}G_{u,t}$$

$$\text{St:} \sum_{g=1}^{n} G_{g,t} + \sum_{RL=1}^{m} R_{RL,t} + G_{u,t} = D_t \qquad t = 1 \ldots T$$

$$G_{g,t} \le G_{g,t}^{max} \qquad t = 1 \ldots T$$

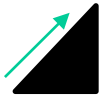
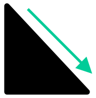
$$R_{RL,t} \le R_{RL,t}^{max} \qquad t = 1 \ldots T$$

$$G_{g,t} - G_{g,t-1} \le RUp_g \qquad t = 1 \ldots T$$

$$G_{g,t-1} - G_{g,t} \le RDw_g \qquad t = 1 \ldots T$$

Utility: [16 18 16] cents/kWh

RL	[5 11 6] cents/kWh	[5 5 10] kWh
G1	8 cents/kWh	[21 18 21] kWh

5 kW  3 kW  3 kW. (Initial condition)

Spot Market Clearing – Example

$$Minimize\ (8-16)G_{1,1}+(8-18)G_{1,2}+(8-16)G_{1,3}+(5-16)R_{RL,1}$$
$$+(11-18)R_{RL,2}+(6-16)R_{RL,3}+\sum_{t=1}^{3}D_t p_{u,t}$$

St:

$$\begin{bmatrix} 1 & & & 1 & & \\ & 1 & & & 1 & \\ & & 1 & & & 1 \\ -1 & 1 & & & & \\ & -1 & 1 & & & \\ 1 & -1 & & & & \\ & 1 & -1 & & & \\ 1 & & & & & \\ & 1 & & & & \\ & & 1 & & & \\ & & & 1 & & \\ & & & & 1 & \\ & & & & & 1 \end{bmatrix} \begin{bmatrix} G_{1,1} \\ G_{1,2} \\ G_{1,3} \\ R_{RL,1} \\ R_{RL,2} \\ R_{RL,3} \end{bmatrix} \leq \begin{bmatrix} D_1 \\ D_2 \\ D_2 \\ RUp_1 \\ RUp_1 \\ RDw_1 \\ RDw_1 \\ mi\,n(\,IC_1+RUp_1, G_{1,1}^{max}) \\ G_{1,2}^{max} \\ G_{1,3}^{max} \\ R_{RL,1}^{max} \\ R_{RL,2}^{max} \\ R_{RL,3}^{max} \end{bmatrix}$$

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Spot Market Clearing – Example

Master Problem

$$Min\sum_{j}\left(-8G_{1,1}^{*}-10G_{1,2}^{*}-8G_{1,3}^{*}-11R_{Rl,1}^{*}-7R_{Rl,2}^{*}-10R_{Rl,3}^{*}\right)\lambda_j$$

St:

$$\begin{bmatrix}1 & & & 1 & & \\ & 1 & & & 1 & \\ & & 1 & & & 1\end{bmatrix}\begin{bmatrix}G_{1,1}\\ G_{1,2}\\ G_{1,3}\\ R_{RL,1}\\ R_{RL,2}\\ R_{RL,3}\end{bmatrix}\leq\begin{bmatrix}D_1\\ D_2\\ D_2\end{bmatrix}$$

$$\sum_{j}\lambda_j=1$$

Spot Market Clearing – Example

Satellite problems

$$\begin{bmatrix} G^*_{1,1} \\ G^*_{1,2} \\ G^*_{1,3} \end{bmatrix} = Max \left[\begin{bmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \end{bmatrix}^T \begin{bmatrix} 1 & & \\ & 1 & \\ & & 1 \end{bmatrix} - \begin{bmatrix} -8 \\ -10 \\ -8 \end{bmatrix}^T \right] \begin{bmatrix} G_{1,1} \\ G_{1,2} \\ G_{1,3} \end{bmatrix}$$

$$x_1^* = Min(c_1 - \pi A_1)x_1$$

St:

$$\begin{bmatrix} -1 & 1 & \\ & -1 & 1 \\ 1 & -1 & \\ & 1 & -1 \\ 1 & & \\ & 1 & \\ & & 1 \end{bmatrix} \begin{bmatrix} G_{1,1} \\ G_{1,2} \\ G_{1,3} \end{bmatrix} \leq \begin{bmatrix} 5 \\ 5 \\ 3 \\ 3 \\ 8 \\ 18 \\ 21 \end{bmatrix}$$

Recall A_1 is the identity matrix

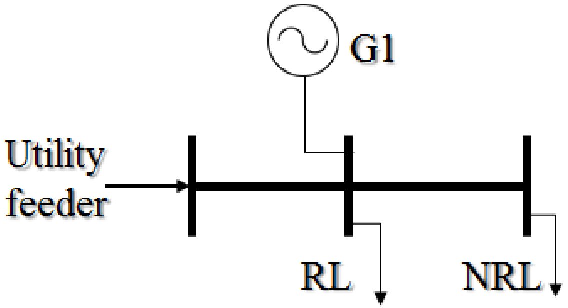
$$x_1^* = Max(\pi - c_1)x_1$$

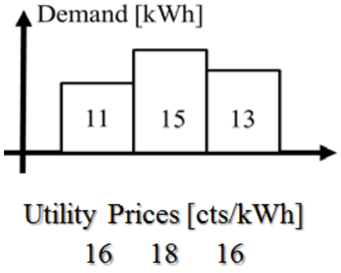
This means: Generator G_1 tries to maximize its income according to the “dual variables” (*market price*).

If the market price $\boldsymbol{\pi}$ is greater that G_1 bid price “c_1”, the generator optimal decision is to sell energy ($G^*_{1,1}$, $G^*_{1,2}$, and $G^*_{1,3}$ greater than zero).

If the market price $\boldsymbol{\pi}$ is lower that G_1 bid price “c_1”, the generator optimal decision is not to sell energy.

Spot Market Clearing – Example

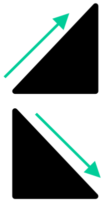




Utility: [16 18 16] cents/kWh

RL

G1	RL
8 cents/kWh	[5 11 6] cents/kWh
[21 18 21] kWh	[5 5 10] kWh



5 kW

3 kW

3 kW. Init condition

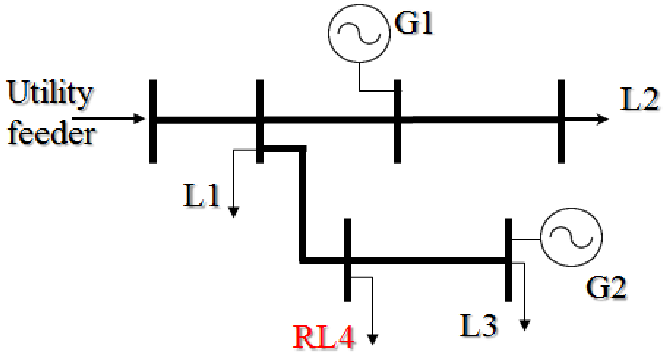
The following solution results in the maximum social welfare

	Period 1	Period 2	Period 3	Units
G_1	6	11	8	kWh
RL	5	4	5	kWh
Utility Feeder	0	0	0	kWh
Total Cost (OSW)	2.99			USD

Spot Market Clearing – with Bilateral Prices

Bilateral bidding prices –

- Different costs for selling/buying electricity for different combinations of generators and loads
- Modeling seller/buyer preferences



	t=1	t=2	t=3	t=4	t=5
ctvs/kWh	**NR Load 1**				
Generator 1	9.000	9.000	11.000	11.000	9.000
Generator 2	3.500	3.500	5.500	5.500	3.500
Resp Load 1	6.500	6.500	8.500	8.500	6.500

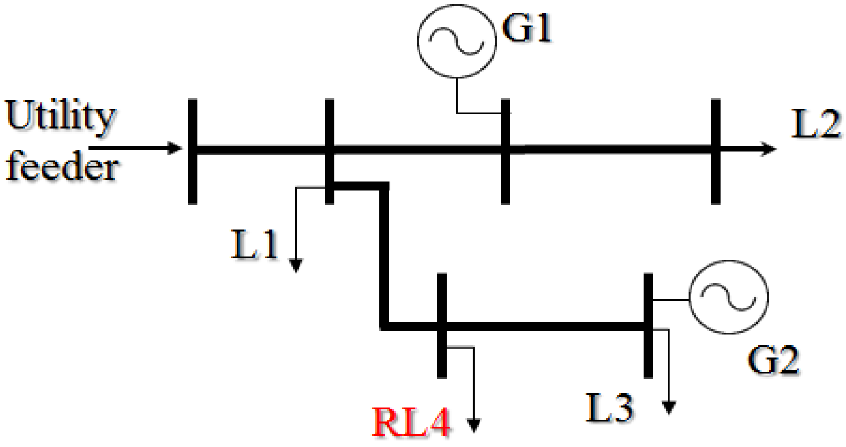
	t=1	t=2	t=3	t=4	t=5
ctvs/kWh	**NR Load 2**				
Generator 1	3.200	3.200	5.200	5.200	3.200
Generator 2	10.500	10.500	12.500	12.500	10.500
Resp Load 1	6.500	6.500	8.500	8.500	6.500

	t=1	t=2	t=3	t=4	t=5
ctvs/kWh	**NR Load 3**				
Generator 1	6.800	6.800	8.800	8.800	6.800
Generator 2	15.600	15.600	17.600	17.600	15.600
Resp Load 1	6.500	6.500	8.500	8.500	6.500

	t=1	t=2	t=3	t=4	t=5
ctvs/kWh	**Responsive Load 4**				
Generator 1	3.100	3.100	5.100	5.100	3.100
Generator 2	4.500	4.500	6.500	6.500	4.500
Resp Load 1	20.000	20.000	20.200	20.200	20.000

	t=1	t=2	t=3	t=4	t=5
Pr Utility	20.00	21.00	22.00	23.00	24.00

Spot Market Clearing – with Bilateral Prices

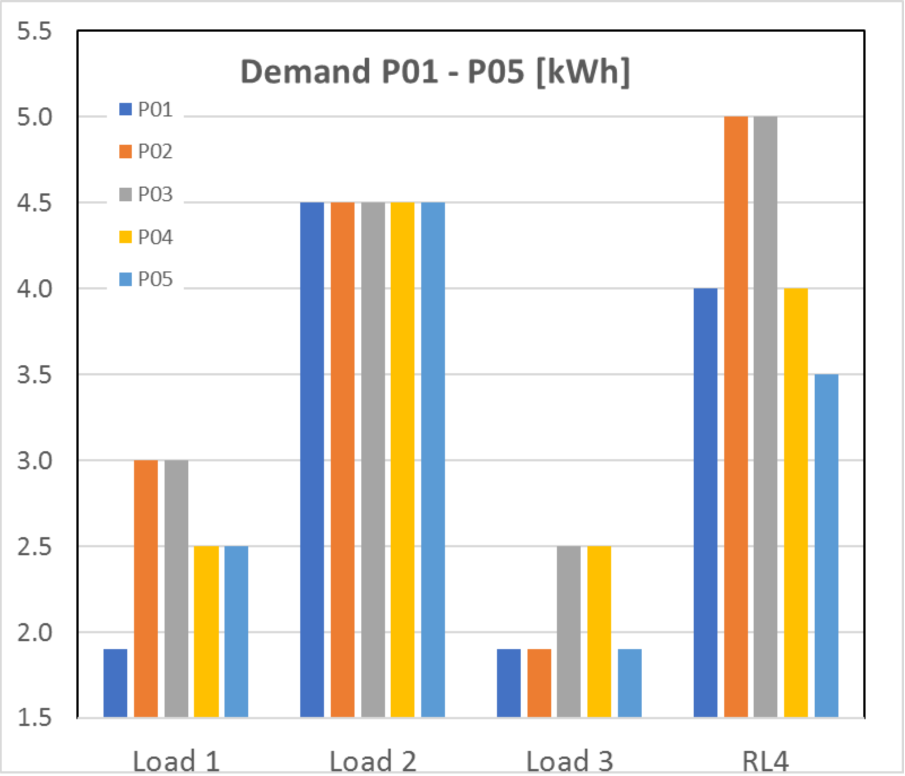


Capacity

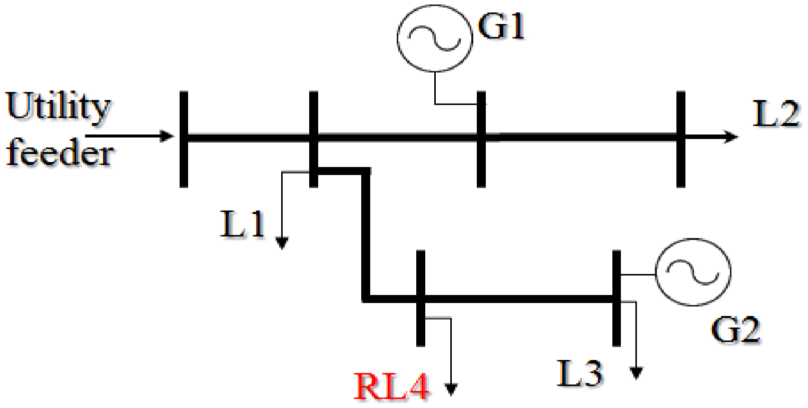
kWh	*t=1*	*t=2*	*t=3*	*t=4*	*t=5*
Generator 1	10	10	10	10	10
Generator 2	8	8	8	8	8
Resp Load 1	3	3	3	3	3

Capacity and Ramp Constraints

Demand supply requirement



Spot Market Clearing – with Bilateral Prices



Generation and Load match that produces the maximum social welfare