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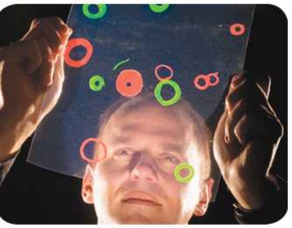

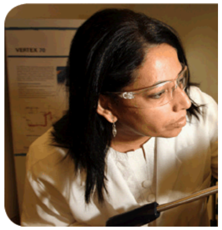

Global Solution Methods for Globally Optimal Energy Storage System (ESS) Integration

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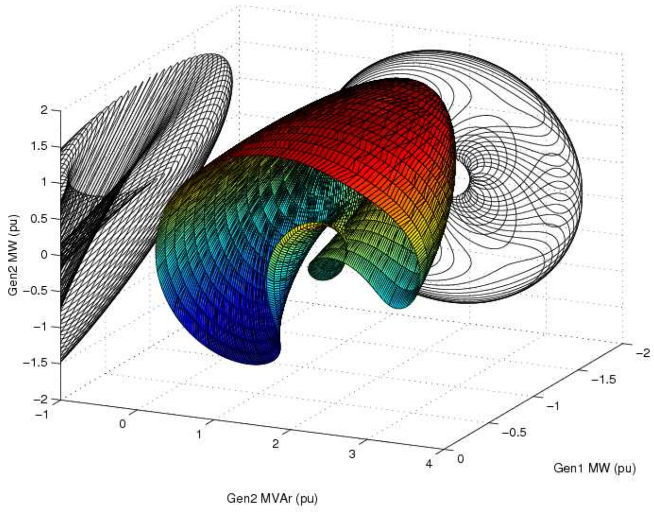
Overview

- Motivation and challenges
- Comparative literature review
- ACOPF-based storage integration
  - Formulation, semidefinite relaxation, and strong duality conditions
- Case studies to value energy storage system (ESS) + VAr support



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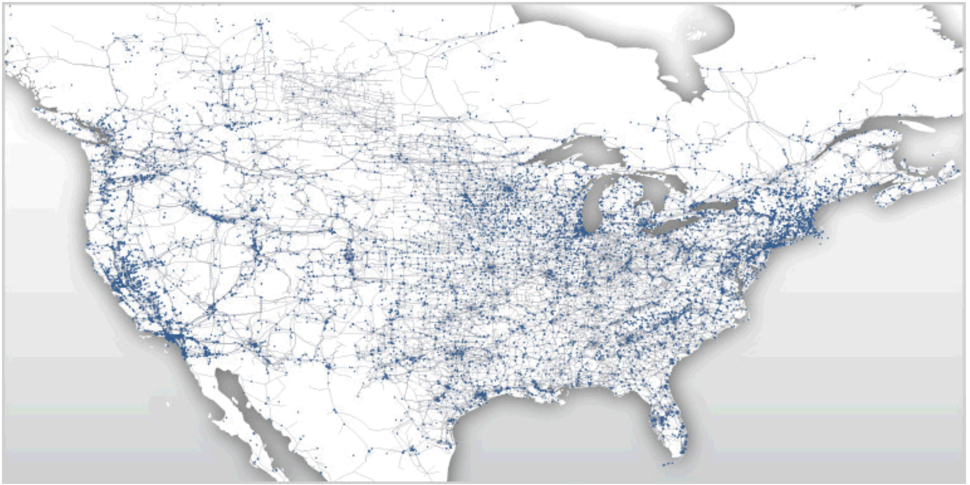
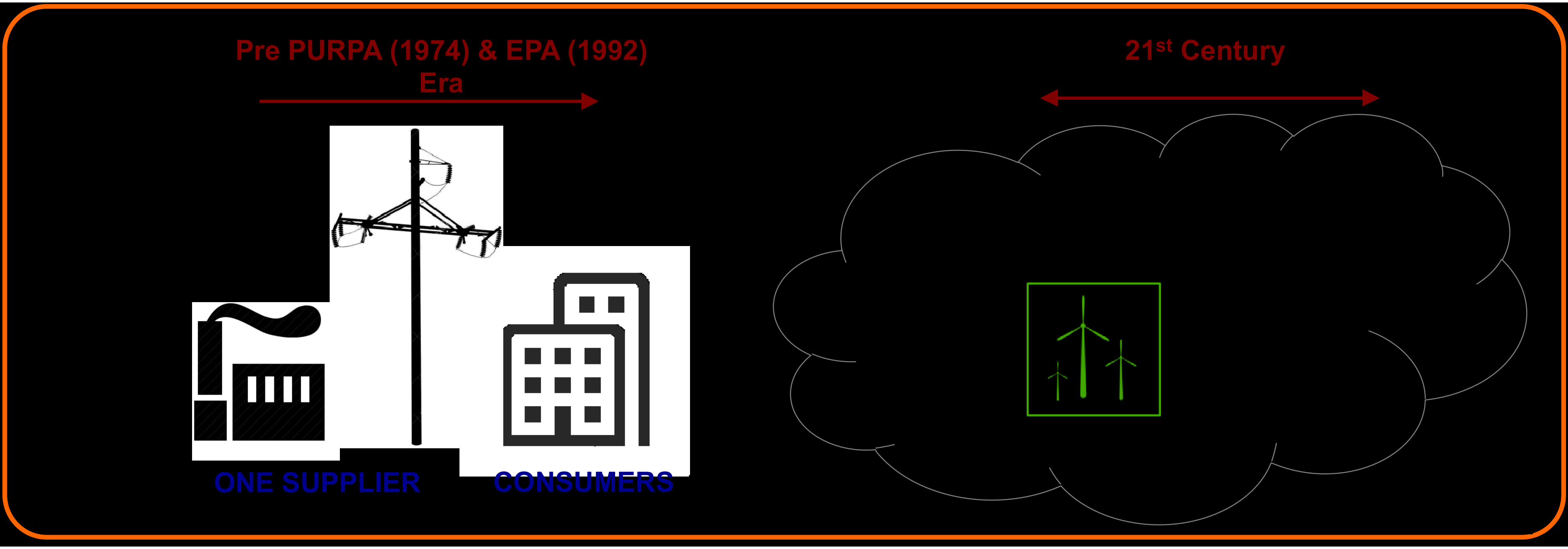


Source: Platts

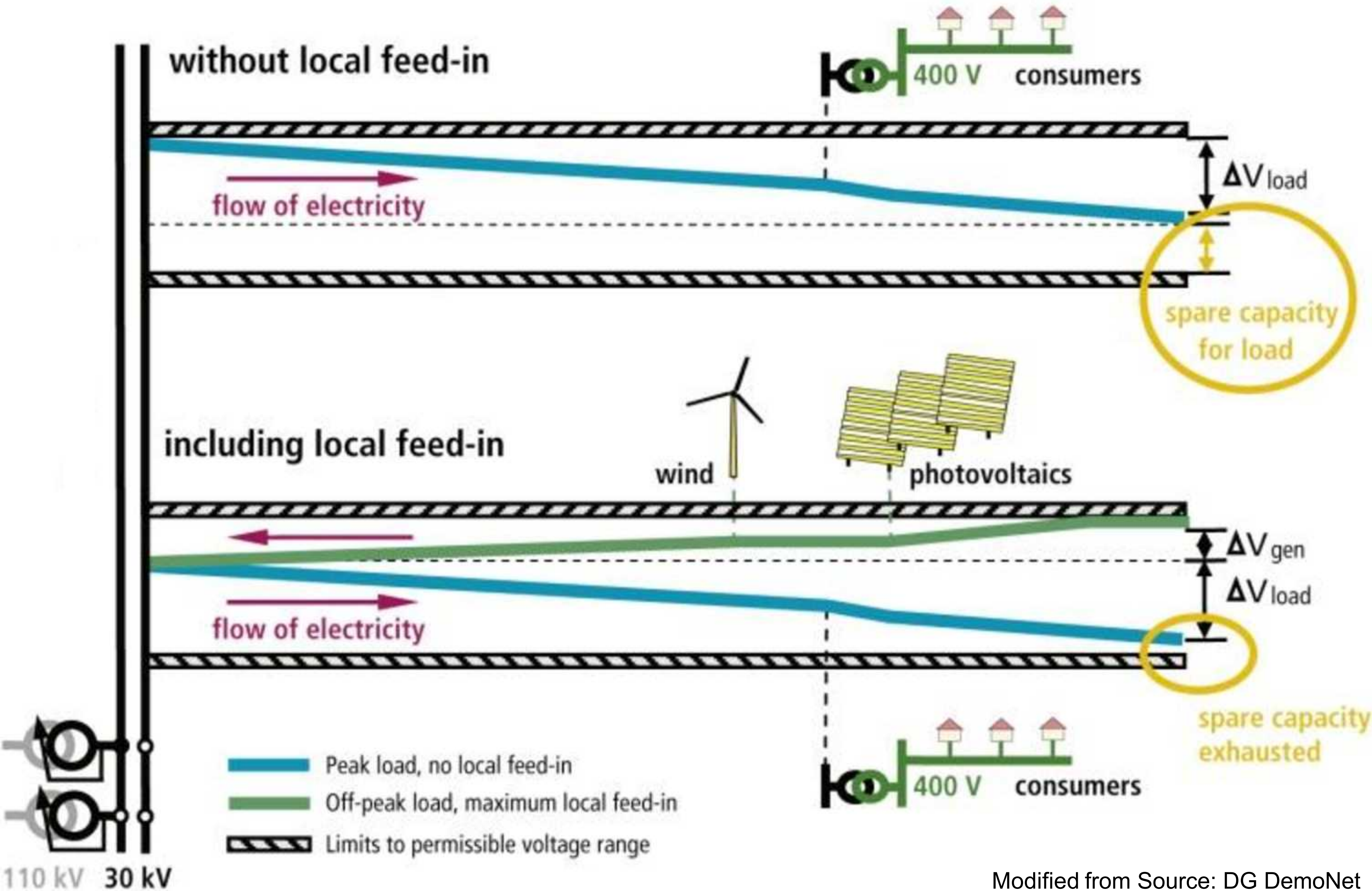
Changing Energy Landscape



Renewed interest in energy storage due to:

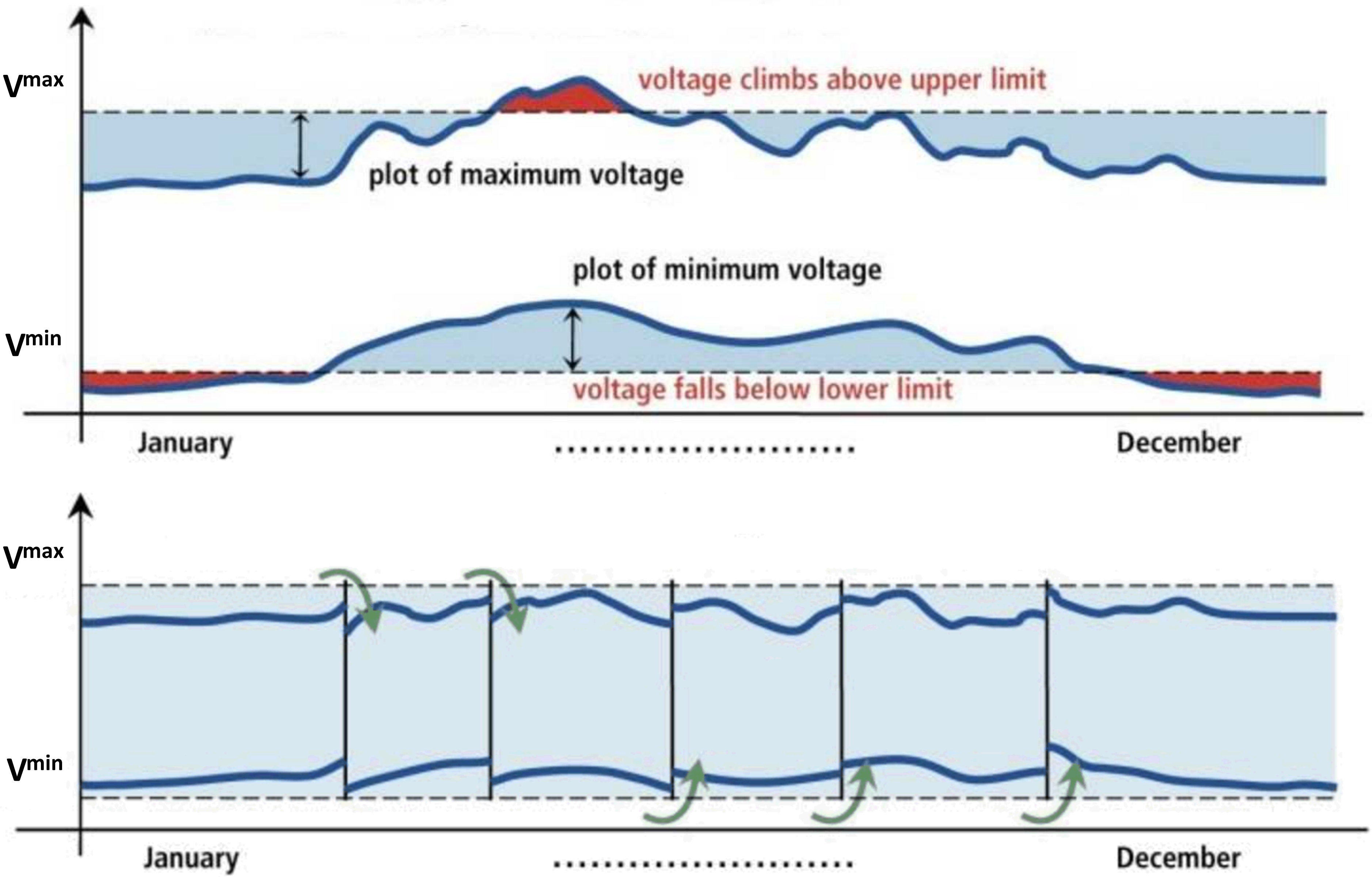
- Sustainable, renewable energy resources
- Outages due to severe weather
- Transmission and distribution upgrades
- Learning curve and economies of scale

Problems with DG Interconnection



Modified from Source: DG DemoNet

Problems with VER Interconnection



Modified from Source: DG DemoN

Markets for Reactive (VAr) Power

- CAISO (2015):

"The requirement to provide reactive power and voltage regulation capability should be the same for all asynchronous resources, with no disparate rules for these resources depending on whether they are wind or solar fueled generators, or battery storage."

- More ISOs making a pre-requisite for interconnect of asynchronous generation resources to have reactive power readily available to achieve voltage regulation
- Dynamic reactive power is not necessarily valued higher than static resources
- Cost of service payments (or none) on capability but not dispatch
- Needs are localized, but payments are not localized

Grid-Integrated Storage

- How do these interconnection pre-requisites effect storage integration?
- What drives optimal storage integration on the network?

- Storage at different locations and scales serve different functions
- Most studies are without network effects or assume perfect transfer efficiencies (no losses)
- No studies consider energy storage with dynamic VAr support

Storage Services

Energy/Power Services

- Arbitrage
- Load following
- Firm capacity
- Congestion relief
- Upgrade deferral

Ancillary Services

- Power quality services
- Transient stability services
- Regulation services
- Reactive power capability
- Voltage control
- Reserves
- Stability support
- Frequency support

Energy Storage System (ESS) Controls

- Our study: Optimal storage integration for ESS+VAr support

Single-Bus (Copperplate) Model
w/o Kirchhoff's Laws (KCL, KVL)

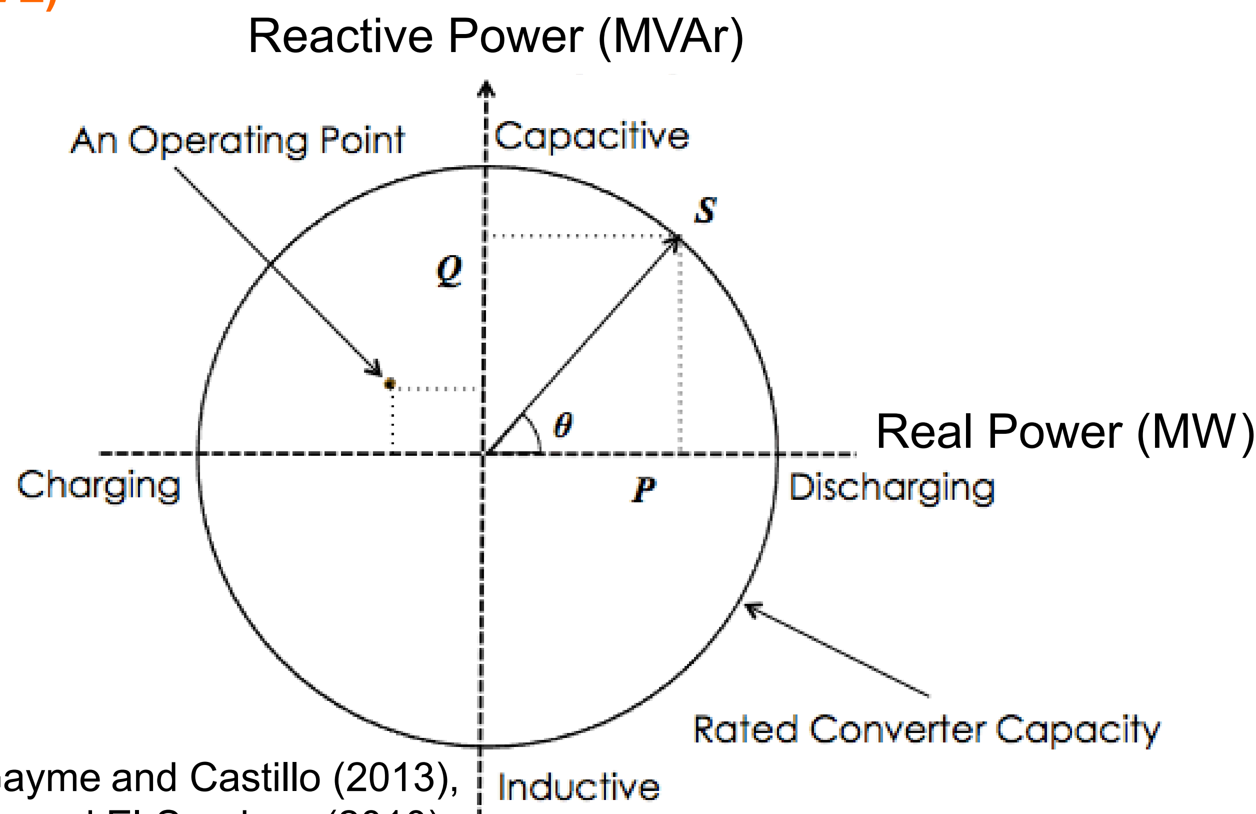
- Sioshansi et al. (2008), Denholm et al. (2010), Drury et al. (2011), Kraning et al. (2010), Su and Gamal (2013), etc.

DC-OPF Network Model
Approximated KCL, KVL

- Chandy et al. (2010), Dvijotham et al. (2011), Thrampoulidis (2013), Ghofrani et al. (2013), etc.

AC-OPF Network Model
Full KCL, KVL

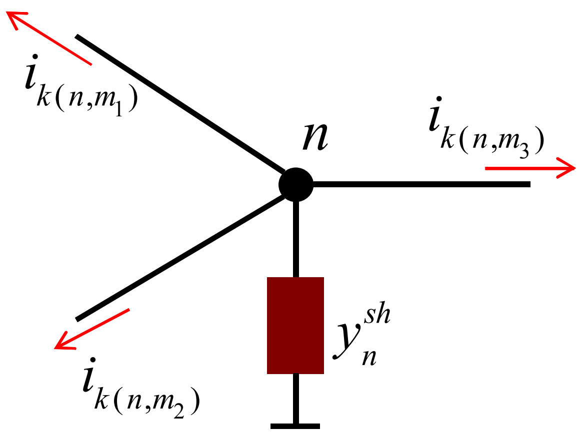
- **Castillo and Gayme (2017)**, Gayme and Castillo (2013), Gayme and Topcu (2012), Atwa and El-Saadany (2010), Bose et al. (2012), Lamadrid et al. (2012), Hu and Jewell (2011), Gabash and Li (2012), etc.

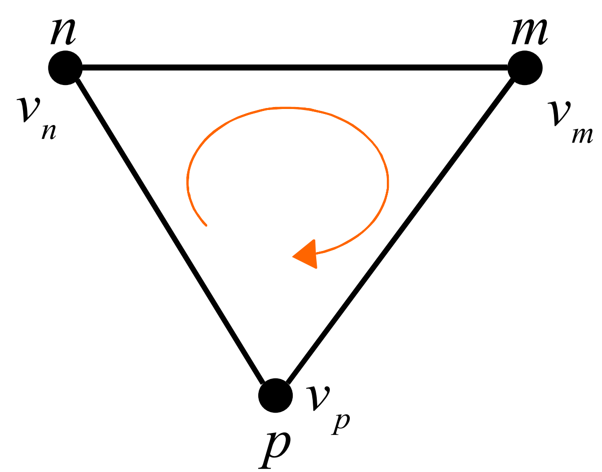


Steady-State Physics on AC Grids

- Nonconvex, NP-Hard QCQP
- Kirchhoff's Laws:

$$P + \mathbf{j}Q = VI^* = VV^*Y$$





Kirchhoff's Current Law (KCL)

$$i_n = \sum_{p \in \{1,2,3\}} i_{k(n,m_p)} + y_n^{sh} v_n$$

Kirchhoff's Voltage Law (KVL)

$$(v_n - v_m) + (v_m - v_p) + (v_p - v_n) = 0$$

Optimal power flow (OPF)

Cost Function $\min \sum_{l \in \mathcal{G}} f_l^g \left(P_l^g \right)$

$l \in \mathcal{G} :=$ set of generators
$n \in \mathcal{N} :=$ set of all nodes
$k \in \mathcal{K} :=$ set of all branches

$$P_l^{\min} \leq P_l^g \leq P_l^{\max}$$

$$Q_l^{\min} \leq Q_l^g \leq Q_l^{\max}$$

Real/Reactive Generation Limits

$$V_n^{\min} \leq \left| V_n \right| \leq V_n^{\max}$$

Voltage Limits

$$V_n I_n^* = P_n + \mathbf{j} Q_n = \sum_{l(n)} P_l^g - P_n^d + \mathbf{j} \left[\sum_{l(n)} Q_l^g - Q_n^d \right]$$

Power Balancing

$$\sqrt{P_k^2 + Q_k^2} \leq S_k^{\max}$$

Network Constraints

LMP and Q-LMP Basics

- Locational marginal pricing (LMP) goal is to provide economically accurate signals
- Dual variable (λ_n) to real power balancing at all buses in the network:

$$p_n = |v_n| \sum_{m \in N} |v_m| \left(G_{nm} \cos\theta_{nm} + B_{nm} \sin\theta_{nm} \right) \qquad \lambda_n \quad \text{(LMP ACOPF)}$$

$$p_n = \sum_{m \in N} B_{nm} \theta_{nm} \qquad \lambda_n \quad \text{(LMP DCOPF)}$$

$$p_n = \sum_{m \in N} \left(B_{nm} \theta_{nm} + G_{nm} \left(\theta_{nm} \right)^2 / 2 \right) \qquad \lambda_n \quad \text{(LMP lossy DCOPF)}$$

The cost of serving one incremental unit of load at bus n. LMP incorporates the marginal unit cost (bid), cost of congestion, and cost of thermal losses on the network.

$$q_n = |v_n| \sum_{m \in N} |v_m| \left(G_{nm} \sin\theta_{nm} - B_{nm} \cos\theta_{nm} \right) \qquad \varphi_n \quad \text{(Q-LMP ACOPF)}$$

Optimal Storage Integration (+S)

ACOPF+S Formulation

Objective

$$\min \sum_{t\in\mathcal{T}} \left\{ \sum_{i\in\mathcal{G}} f_{i,t}^{g}\left(p_{i,t}^{g}\right) + \sum_{i\in\mathcal{W}} C_i^{w,1} p_{i,t}^{w} + \sum_{n\in\mathcal{N}} C_n^{s,1} r_{n,t}^{d} \right\}$$

Power balance (KCL, KVL)

$$P_{n,t} = \sum_{i\in I(n)} \left(p_{i,t}^{g} + p_{i,t}^{w}\right) - \left[r_{n,t}^{c} - r_{n,t}^{d}\right] - P_{n,t}^{d}$$

$$Q_{n,t} = \sum_{i\in I(n)} q_{i,t}^{g} - z_{n,t} - Q_{n,t}^{d}$$

Generator output limits

$$\underline{P}_i \le p_{i,t}^{g} \le \overline{P}_i \qquad p_{i,t}^{w} \le C_{i,t}^{w}$$

$$-RR_l^{d} \le p_{i,t}^{g} - p_{i,t-1}^{g} \le RR_l^{u}$$

$$\underline{Q}_i \le q_{i,t}^{g} \le \overline{Q}_i$$

Transmission limits

$$-\overline{P}_k \le \left(p_{k(\cdot),t}\right)^2 + \left(q_{k(\cdot),t}\right)^2 \le \left(\overline{S}_k\right)^2 \le \overline{P}_k$$

Voltage limits

$$\left(\underline{V}_n\right)^2 \le \left(v_n^{r}\right)^2 + \left(v_n^{j}\right)^2 \le \left(\overline{V}_n\right)^2$$

Total storage capacity constraint

$$\sum_{n\in\mathcal{N}} c_n \le h$$

Charge/discharge rate limits

$$0 \le r_{n,t}^{c} \le \overline{R}_n^{c}$$

$$0 \le r_{n,t}^{d} \le \overline{R}_n^{d}$$

$$\underline{Z}_n \le z_{n,t} \le \overline{Z}_n$$

Storage level

$$s_n(t+1) = b_n(t) + \eta_c r_n^{c}(t) - r_n^{d}(t)/\eta_d$$

$$0 \le s_{n,t} \le c_n, \quad s_n(0) = s_n(T)$$

Optimal Storage Integration (+S)

DCOPF+S and L-DCOPF+S (lossy) approximations

Objective

$$\min \sum_{t \in \mathcal{T}} \left\{ \sum_{i \in \mathcal{G}} f_{i,t}^{g}\left(p_{i,t}^{g}\right) + \sum_{i \in \mathcal{W}} C_i^{w,1} p_{i,t}^{w} + \sum_{n \in \mathcal{N}} C_n^{s,1} r_{n,t}^{d} \right\}$$

Power balance (KCL, KVL)

$$P_{n,t} = \sum_{i \in I(n)} \left(p_{i,t}^{g} + p_{i,t}^{w}\right) - \left[r_{n,t}^{c} - r_{n,t}^{d}\right] - P_{n,t}^{d}$$

[redacted]

Generator output limits

$$\underline{P}_i \le p_{i,t}^{g} \le \overline{P}_i \qquad p_{i,t}^{w} \le C_{i,t}^{w}$$

$$-RR_l^{d} \le p_{i,t}^{g} - p_{i,t-1}^{g} \le RR_l^{u}$$

[redacted]

Transmission limits

$-\overline{P}_k \le \left(p_{k(\cdot),t}\right)$ [redacted] $\le \overline{P}_k$

Voltage limits

[redacted]

Total storage capacity constraint

$$\sum_{n \in \mathcal{N}} c_n \le h$$

Charge/discharge rate limits

$$0 \le r_{n,t}^{c} \le \overline{R}_n^{c}$$

$$0 \le r_{n,t}^{d} \le \overline{R}_n^{d}$$

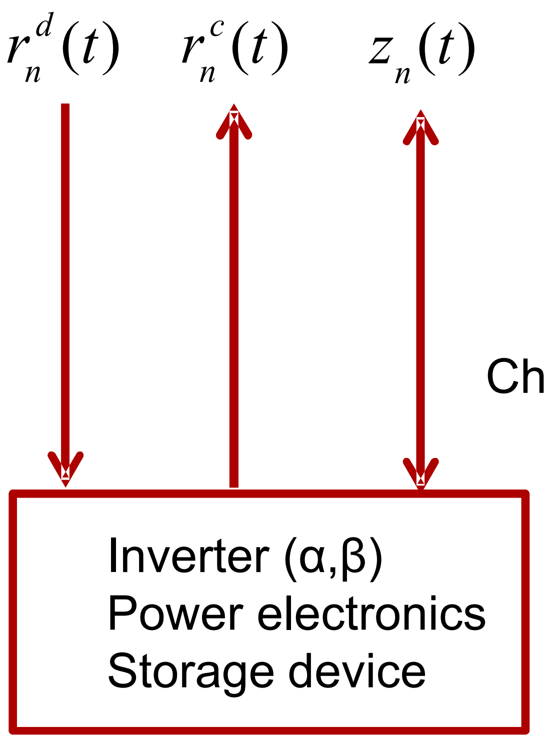
[redacted]

Storage level

$$s_n(t+1) = b_n(t) + \eta_c r_n^{c}(t) - r_n^{d}(t) / \eta_d$$

$$0 \le s_{n,t} \le c_n, \quad s_n(0) = s_n(T)$$

Steady-state storage model (+S)



Energy Capacity

Total storage capacity constraint

$$\sum_{n \in \mathcal{N}} C_n \le h$$

Real Power Charge/Discharge Ratings

Reactive Power Rating

Charge/discharge rate limits

$$0 \le r_n^c(t) \le R_n^{c,\max}$$

$$0 \le r_n^d(t) \le R_n^{d,\max}$$

$$-\alpha C_n \le z_n(t) \le \beta C_n$$

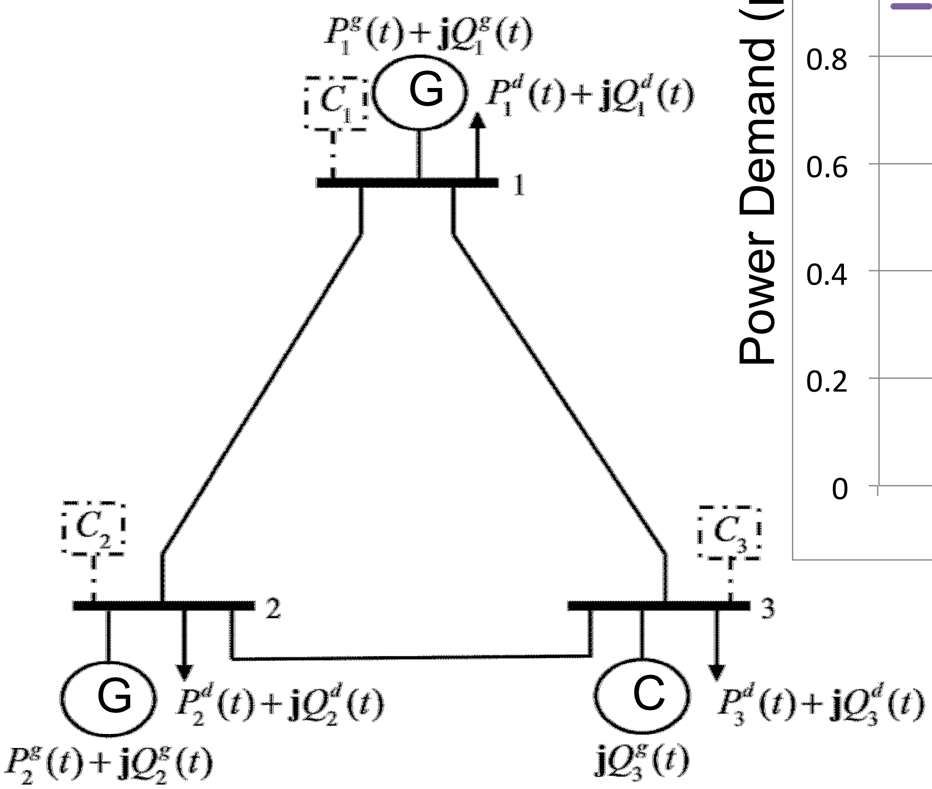
Storage Level with Round-trip Efficiencies

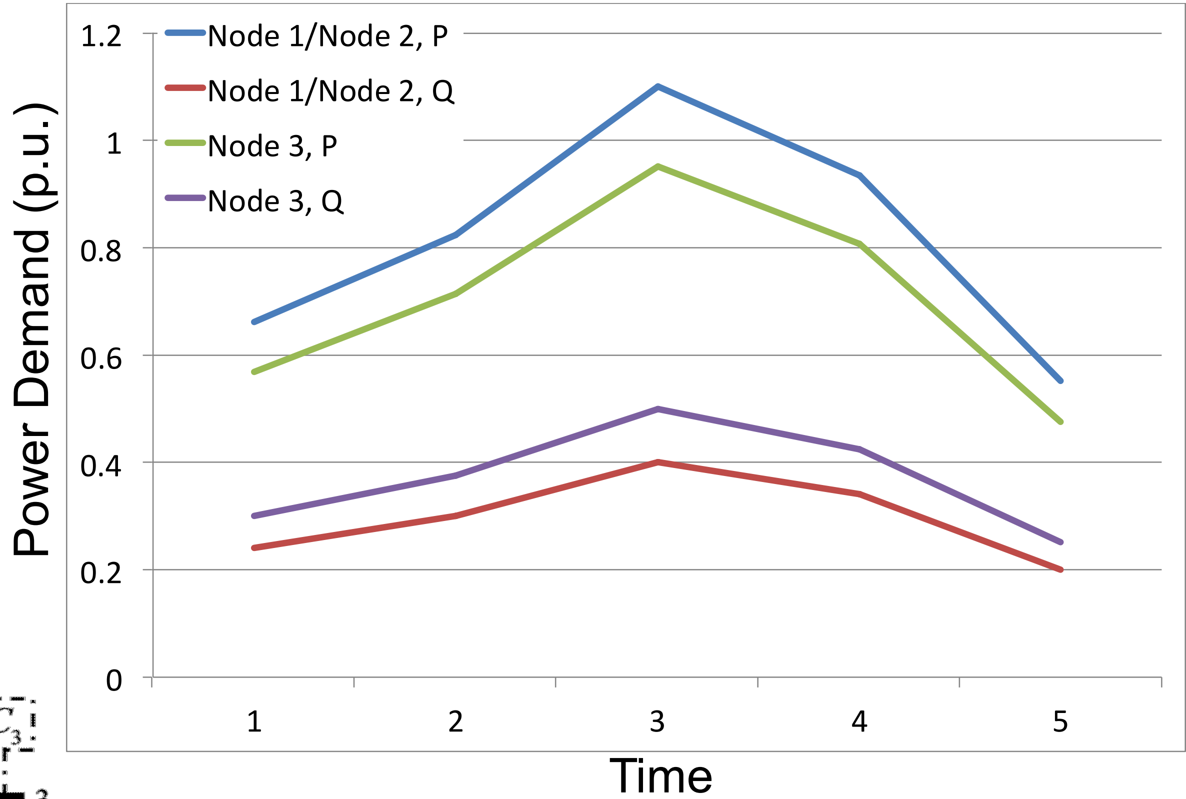
Storage level

$$s_n(t+1) = b_n(t) + \eta_c r_n^c(t) - r_n^d(t) / \eta_d$$

$$0 \le s_{n,t} \le c_n, \quad s_n(0) = s_n(T)$$

Non-global, local optima





- Quadratic Cost Functions
- Unlimited generation at Nodes 1, 2
- Unlimited synchronous condenser at Node 3

*** Note: 1st-order (KKT) conditions hold**

Solving OPF+S to global optimality

Basic idea to convexify $P + \mathbf{j}Q = VI^* = VV^*Y$

General Form of OPF (QCQP)

Let $x := V^r + \mathbf{j}V^j$

$$\min_{x \in \mathbb{C}^n} x^* C x$$

$$\text{subject to: } x^* Y_i x \leq b_i,\ i \in \mathcal{I}$$

$$C \succ 0,\ Y_i \text{ Hermitian}$$

Nonconvex

NP-Hard

Semidefinite Relaxation

Let $W := xx^T,\ x := \begin{bmatrix} V^r & V^j \end{bmatrix}^T$

$$\min_{W \succeq 0} tr\left(CW\right)$$

$$\text{subject to: } tr\left(Y_i W\right) \leq b_i$$

$$W \succeq 0$$

Convex

Polynomial time solution

[Lavaei & Low 2012; Bai et al., 2008]

$$\text{Relaxation is exact if } \operatorname{rank}(W^*) = 1$$

Solution Techniques

- **DCOPF**: Apply a LP solver
- **L-DCOPF**: Nonconvex QCQP (NLP solver)

$$\tilde{p}^{\ell}_{k,t} = \frac{1}{2} g_k \left(\theta_{nm,t}\right)^2$$

  - Propose semidefinite relaxation (SDR) → semidefinite program (SDP) and second-order relaxation (SOCR) → second-order program (SOCP)

- **ACOPF+S**: Nonconvex QCQP (NLP solver)
  - Solved as a SDP as proposed by Lavaei & Low [2012], and extended to optimal storage integration by Gayme & Topcu [2013]

$$\mathrm{tr}\left\{\Phi_n W_t\right\} = r^d_{n,t} - r^c_{n,t} + \sum_{i \in \mathcal{I}(n)} \left(p^g_{i,t} + p^w_{i,t}\right) - P^d_{n,t}$$

$$\mathrm{tr}\left\{\Psi_n W_t\right\} = z_{n,t} + \sum_{i \in \mathcal{I}(n)} \left(q^g_{i,t} + q^w_{i,t}\right) - Q^d_{n,t}$$

$$W_t \succeq 0$$

Convex Problems and Strong Duality

- OPF+ SConvex Reformulations

If Slater's condition is satisfied [Gayme & Topcu, 2013], then strong duality holds.

KKT Point (Optima) to Convex Reformulation

↕

Global Optimum to Original, Nonconvex Problem

Unimodal Operations

	Unimodal Operations			
Time-Period (h)	t = 1	t = 2	t = 3	Total Profit ($)
Storage Level (MWh)	1	1.5	0	
Charge (MW withdrawal)	$-1.\overline{11}$	$-0.\overline{55}$	0	
Discharge (MW injection)	0	0	1.35	
Positive LMP Scenario				
LMP ($/MWh)	$\lambda > 0$	$\lambda > 0$	$2\lambda > 0$	
Profit ($)	$-1.\overline{11}\lambda$	$-0.\overline{55}\lambda$	2.70λ	$= 1.04\lambda$
Negative LMP Scenario				
LMP ($/MWh)	$\lambda > 0$	$\lambda < 0$	$2\lambda > 0$	
Profit ($)	$-1.\overline{11}\lambda$	$0.\overline{55}\lambda$	2.70λ	$= 2.14\lambda$

	Multimodal Operations			
Time-Period (h)	t = 1	t = 2	t = 3	Total Profit ($)
Storage Level (MWh)	1	1.5	0	
Charge (MW withdrawal)	$-1.\overline{11}$	$-1.\overline{66}$	0	
Discharge (MW injection)	0	0.9	1.35	
Positive LMP Scenario				
LMP ($/MWh)	$\lambda > 0$	$\lambda > 0$	$2\lambda > 0$	
Profit ($)	$-1.\overline{11}\lambda$	$-0.7\overline{6}\lambda$	2.70λ	$= 0.83\lambda$
Negative LMP Scenario				
LMP ($/MWh)	$\lambda > 0$	$\lambda < 0$	$2\lambda > 0$	
Profit ($)	$-1.\overline{11}\lambda$	$0.7\overline{6}\lambda$	2.70λ	$= 2.35\lambda$

Unimodal Operations

Theorem‡

Consider a storage unit at bus n with capacity $c_n > 0$ and a positive cost coefficient at the KKT point of the SDR-OPF+S. If the Lagrangian multiplier $\lambda_{n,t}$ associated with the real power balance at bus n is nonnegative, i.e., $\lambda_{n,t} \geq 0$, then $r^c_{n,t} \times r^d_{n,t} = 0$ for all $t \in \mathcal{T}$.

Corollary‡

The condition $\lambda_{n,t} \geq 0$ for all $n \in \mathcal{N}, t \in \mathcal{T}$ if and only if $r^c_{n,t} + P_{n,t} + P^d_{n,t} \leq r^d_{n,t} + \sum_{i \in I(n)} \left(p^g_{i,t} + p^w_{i,t} \right)$.

Storage Operator Subproblem

$$\max_{\lambda,\varphi,\rho,\sigma} g_s(\cdot) = \min_{r^c, r^d, s, z, B} \Lambda_S(\cdot)$$

Maximize Lagrange Dual

for Lagrange Function Λ_s

s.t.

$$b_n(t+1) = b_n(t) + \eta_c r_n^c(t) - r_n^d(t) / \eta_d$$

$$0 \le b_n(t) \le C_n$$

$$0 \le r_n^c(t) \le R_n^{c,\max}$$

$$0 \le r_n^d(t) \le R_n^{d,\max}$$

$$-\alpha C_n \le z_n(t) \le \beta C_n$$

Storage steady-state model

where

$$\Lambda_S(\cdot) = f_n^s(\cdot)$$

Primal Objective Function

$$+\sum_{t=1}^{T} \sum_{n \in N} \left\{ \lambda_n(t) \left[r_n^c(t) - r_n^d(t) \right] \right.$$

Dual Term on Active Power

$$\left. -\varphi_n(t) \left[z_n(t) \right] \right.$$

Dual Term on Reactive Power

Storage Operator Subproblem

$$g^s(\boldsymbol{\lambda}, \boldsymbol{\varphi}) := \min_{\mathbf{r^c}, \mathbf{r^d}, \mathbf{z}, \mathbf{s}, \mathbf{c}} \quad \Lambda^s(\cdot)$$

subject to

$$s_{n,t} = s_{n,t-1} + \eta_n^c r_{n,t}^c - \left(\eta_n^d\right)^{-1} r_{n,t}^d, \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$0 \leq r_{n,t}^c \leq R_n^c, \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$0 \leq r_{n,t}^d \leq R_n^d, \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$0 \leq s_{n,t} \leq c_n, \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

$$\underline{Z}_n \leq z_{n,t} \leq \overline{Z}_n, \qquad \forall n \in \mathcal{N}, \forall t \in \mathcal{T}$$

where $\Lambda^s(\cdot)$ is defined as

$$C_n^{s,1} r_{n,t}^d + \sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}} \left\{ \lambda_{n,t} \left[r_{n,t}^c - r_{n,t}^d \right] - \varphi_{n,t} z_{n,t} \right\}$$

ESS profits at KKT optimal point *

$$\pi_n^{s,*} = Revenues - Costs$$

$$\sum_n \lambda$$

Real Power Revenues (LMP based)

enues

$$\lambda_n(t)^* r_n^d(t)^*$$

Reactive Power Revenues (Q-LMP based)

$$\sum_{t\in T} \varphi_n(t)^* z_n(t)^* \left| \begin{matrix} \varphi_n(t)^* \geq 0, z_n(t)^* \geq 0 \\ \varphi_n(t)^* \leq 0, z_n(t)^* \leq 0 \end{matrix} \right\rangle$$

Real Power Costs (LMP based)

ts

$$^{,*}(\cdot) - \sum_{t\in T} \lambda_n(t)^* r_n^c(t)^*$$

Reactive Power Costs (Q-LMP based)

$$\sum_{t\in T} \varphi_n(t)^* z_n(t)^* \left| \begin{matrix} \varphi_n(t)^* \leq 0, z_n(t)^* \geq 0 \\ \varphi_n(t)^* \geq 0, z_n(t)^* \leq 0 \end{matrix} \right\rangle$$

Profit Maximizing Storage Allocation

Theorem‡

For an arbitrary operating cycle $\mathcal{T} := \{1, \ldots, T\}$, the energy storage capacity c_n receives the most incremental value at the bus n where

$$\max_{n \in \mathcal{N}} \left(\max_{\boldsymbol{\lambda}, \boldsymbol{\varphi}} \; \pi_n^{s,*} \right)$$

$$\textit{for} \quad \pi_n^{s,*} = \pi_n^{s^P,*} + \pi_n^{s^Q,*},$$

$$\pi_n^{s^P,*} = -f_n^{s,*}(\cdot) + \sum_{t \in \mathcal{T}} \lambda_{n,t}^{*} \left[r_{n,t}^{d,*} - r_{n,t}^{c,*} \right],$$

$$\textit{and} \quad \pi_n^{s^Q,*} = \sum_{t \in \mathcal{T}} \varphi_{n,t}^{*} \left[z_{n,t}^{*} \right].$$

Profit Maximizing Storage Allocation

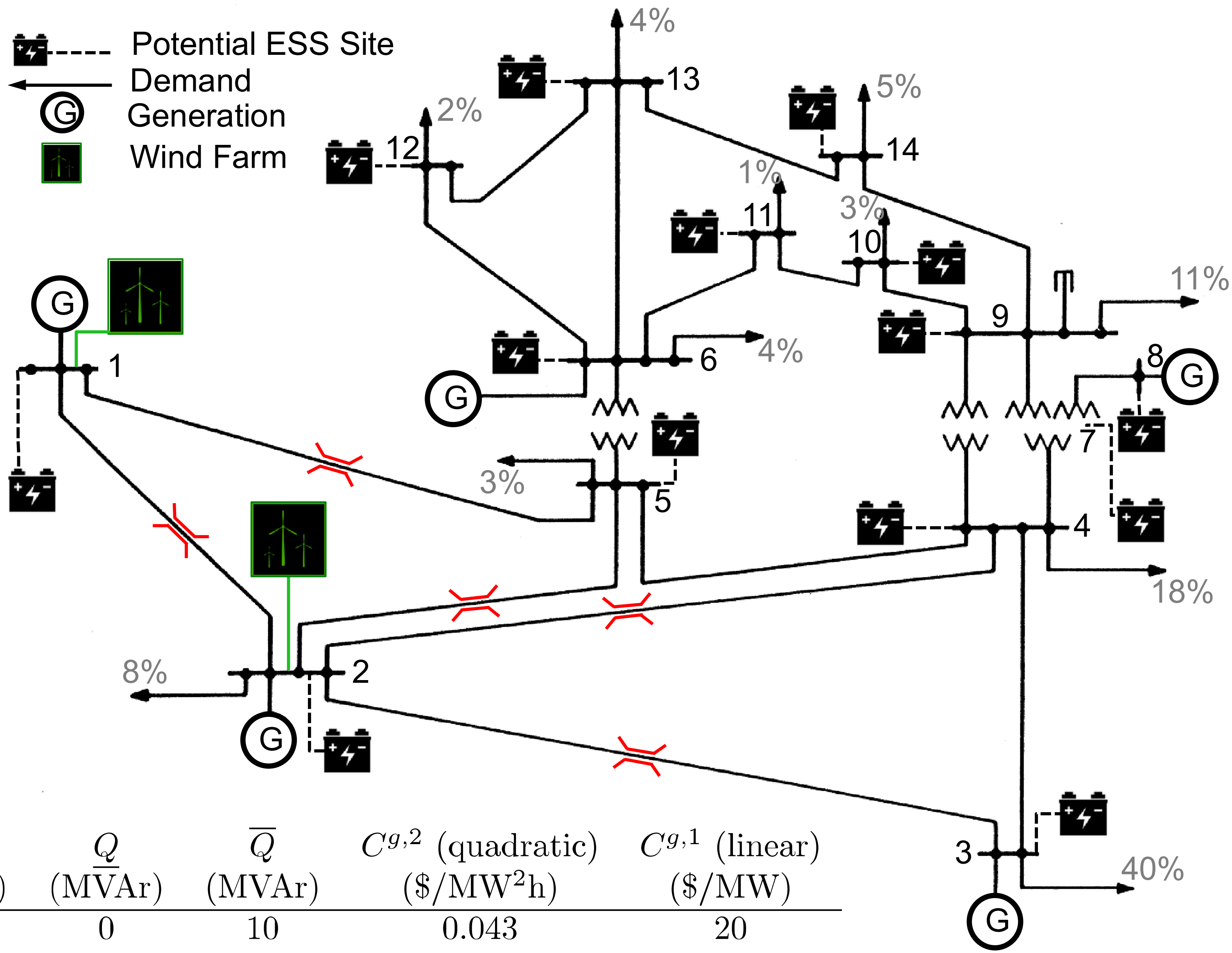
Corollary‡

Given the KKT point of the SDR-OPF+S, the marginal profit to the storage at bus n must be nonnegative, i.e., $\pi_n^s \geq 0$, whenever $C_n > 0$. Therefore,

$$g^{s,*}(\boldsymbol{\lambda}, \boldsymbol{\varphi}) \geq 0.$$

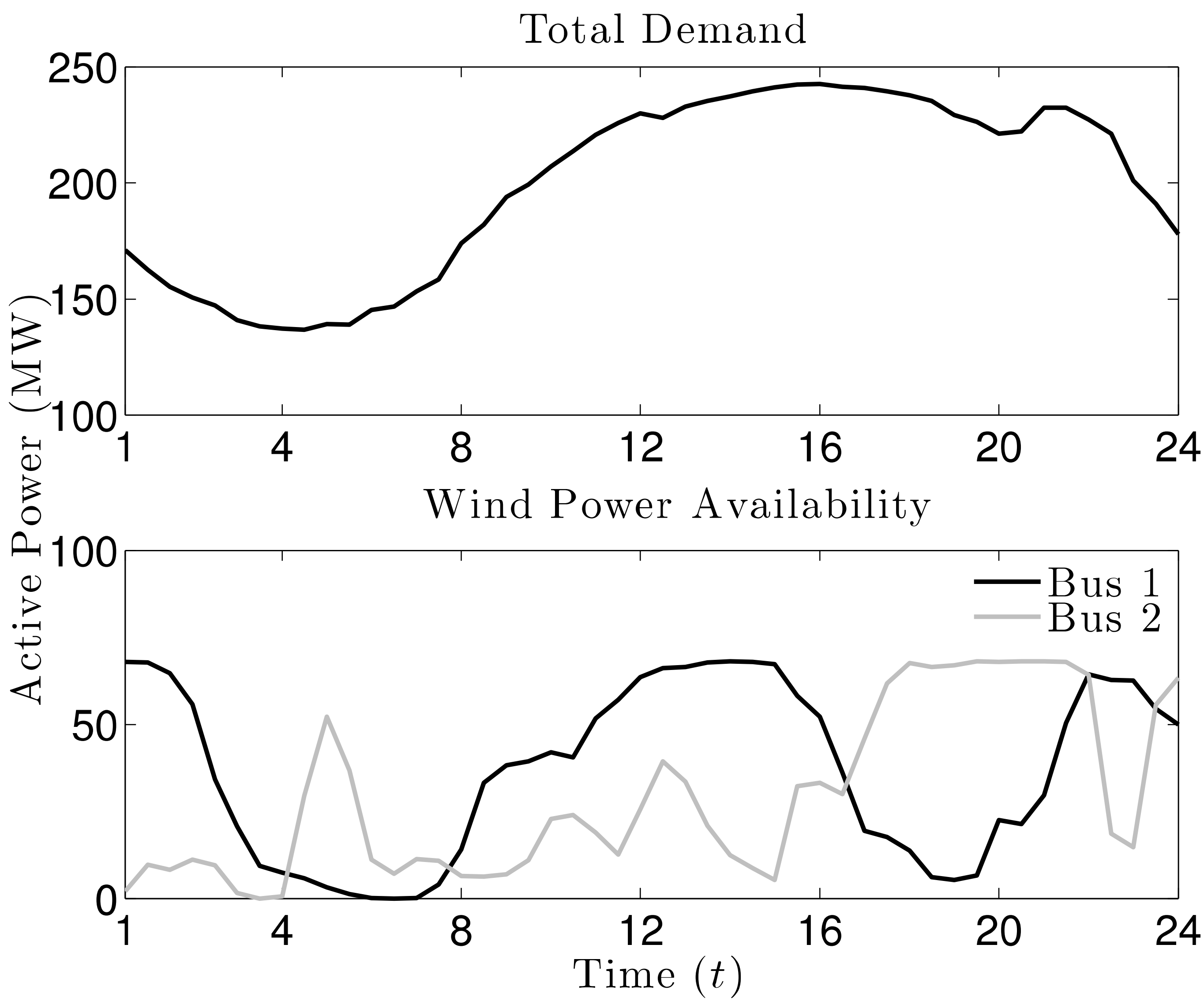
This condition holds true for the optimal solution to the SDR-OPF+S dual, which in turn minimizes costs in the SDR-OPF+S problem for a purely competitive market.

IEEE-14 Bus Network



Bus	$\underline{P}$ (MW)	$\overline{P}$ (MW)	$\underline{Q}$ (MVAr)	$\overline{Q}$ (MVAr)	$C^{g,2}$ (quadratic) ($/MW^{2}h)	$C^{g,1}$ (linear) ($/MW)
1	0	332.4	0	10	0.043	20
2	0	140	-40	50	0.25	20
3	0	100	0	40	0.01	40
6	0	100	-6	24	0.01	40
8	0	100	-6	24	0.01	40

Demand and 15% Wind Integration



ESS v. ESS+VAr summary results

Bus	ESS Storage Capacity (MWΔt)	ESS Profits ($)	ESS+VAr Support Storage Capacity (MWΔt)	ESS+VAr Support Profits ($)
1	1.7	20.79	0	0
2	11.4	145.85	6.0	110.87
3	0	0	0	0
4	75.8	553.84	54.1	609.24
5	0	0	36.6	445.84
6-11	0	0	0	0
12	1.0	6.74	0	0
13	3.4	24.09	0	0
14	6.7	46.91	3.3	36.31
Total	100	798.37	100	1,202.39

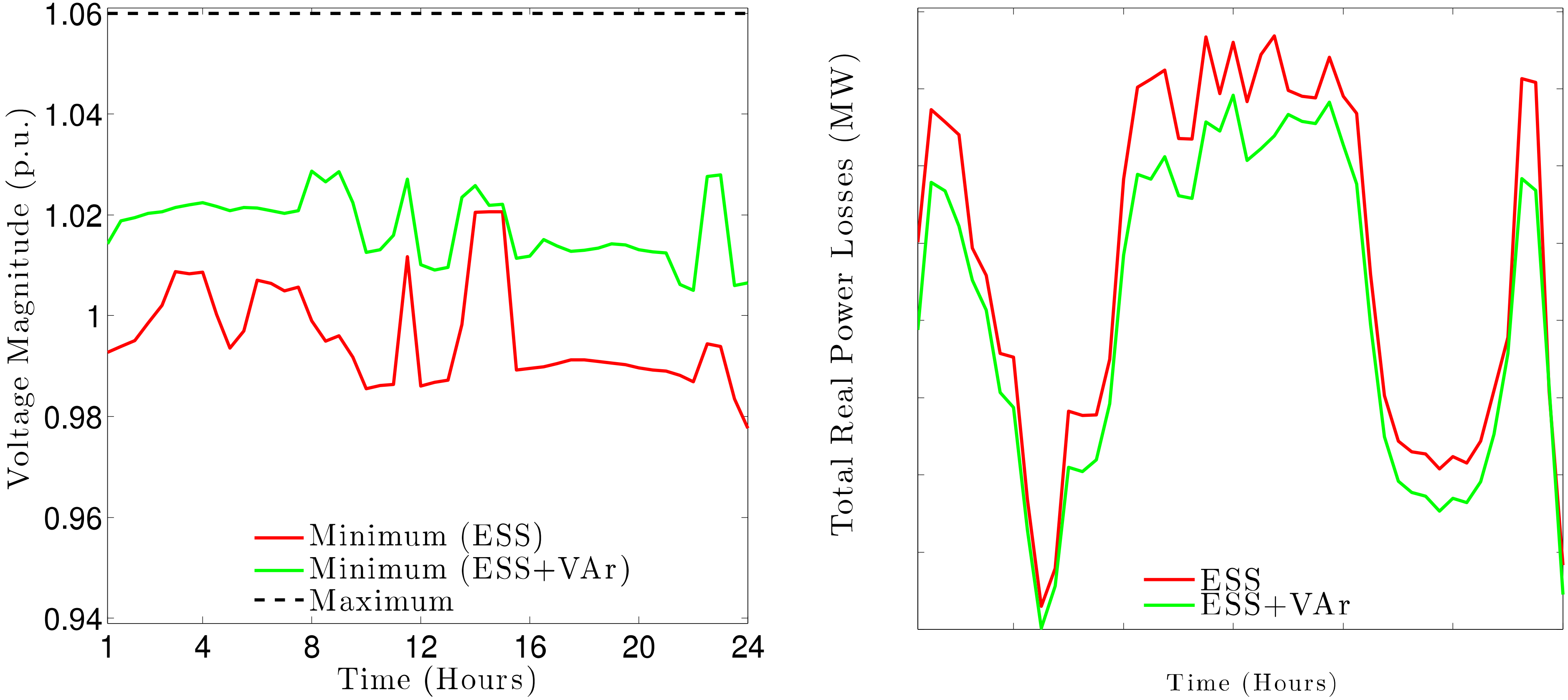
- ESS+VAr support results in different storage integration
- Higher profits for the storage operator when also providing VAr services

ACOPF+S for VAr Support

	ESS	ESS + VAr Support
Total System Cost ($)	205,164.00	204,697.28
I^2R Losses (MW)	151.7	145.1
Total Marginal Profit to ESS ($)	798.37	1,202.39

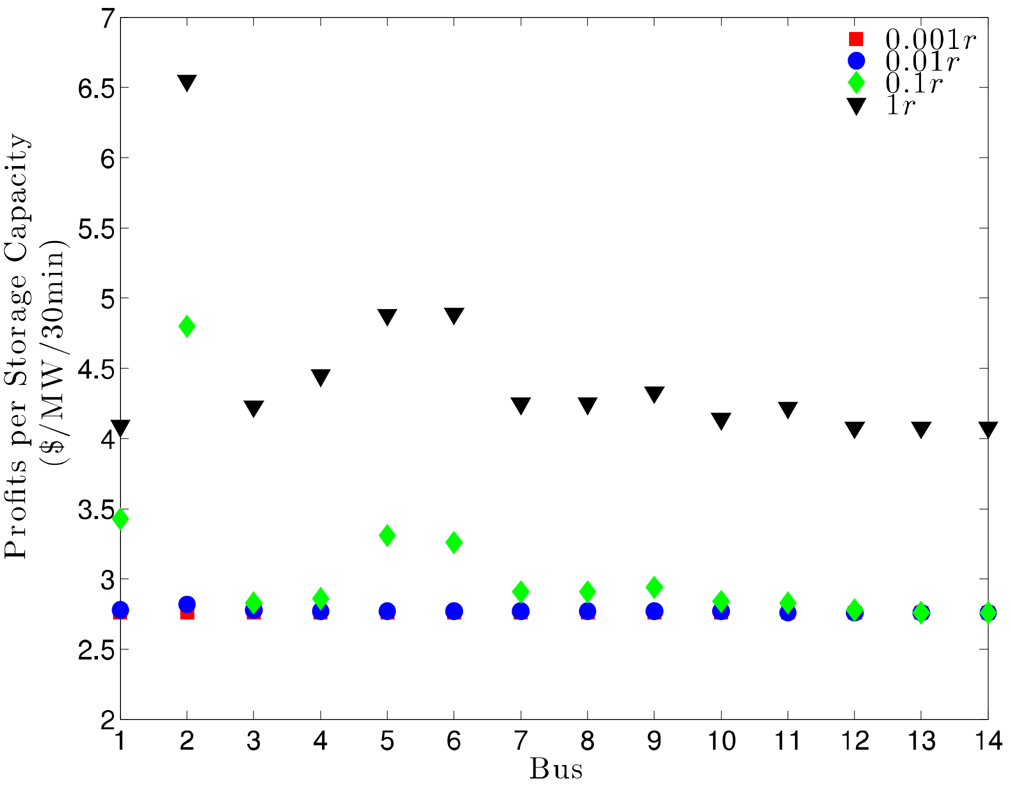
Energy Services	ESS	ESS + VAr Support
Revenues ($)	5,304.55	4,798.65
Costs ($)	4,506.17	4,056.19
Profits ($)	798.37	742.46
Reactive Power Compensation		
Revenues ($)	0	459.93
Costs ($)	0	0
Profits ($)	0	459.93
Total Marginal Profits ($)	798.37	1,202.39

VAr Support and Operational Efficiency



Effects of Network Modeling

	Approximations				Full	
	DCOPF+S		ℓ-DCOPF+S		OPF+S	
Bus	C_n	$\pi_n^{s,*}$	C_n	$\pi_n^{s,*}$	C_n	$\pi_n^{s,*}$
1	7.1	19.73	0.03	0.11	0	0
2	7.1	19.73	1.9	12.42	1	6.45
3	7.1	19.73	37	156.62	37.1	150.96
4	7.1	19.73	10.7	47.82	12.1	52.92
5	7.1	19.73	0.1	0.67	0	0
6	7.1	19.73	0.2	0.78	0	0
7	7.1	19.73	1.5	6.52	0.2	1.10
8	7.1	19.73	1.5	6.44	0.2	1.01
9	7.1	19.73	1.1	4.56	1.1	5.31
10	7.1	19.73	3.6	15.05	4.6	18.24
11	7.1	19.73	0.4	1.58	0.1	0.35
12	7.1	19.73	3.4	13.82	4.0	15.55
13	7.1	19.73	13.0	53.03	13.6	53.25
14	7.1	19.73	25.5	103.99	26.2	102.96
Total	100	276.22	100	423.40	100	408.10



Reactive power compensation mechanisms

Bus	Reactive Power Capability (MVAr)	max $|z|$ Reactive Dispatch (MVAr)
1	0	0
2	3.0	0.08
3	0	0
4	27.05	27.05
5	18.3	18.3
6-13	0	0
14	1.65	1.63
Total	50	47.06

Bus	Q-LMP ($/Day)	NYISO Capability Rate ($/Day)	ISO-NE Capability Rate ($/Day)
1	0	0	0
2	0.04	32.21	18.00
3	0	0	0
4	213.61	290.43	162.30
5	233.06	196.49	109.80
6-13	0	0	0
14	13.22	17.72	9.90
Total	459.93	536.85	300.00

Concluding Remarks

- Reactive power is a localized benefit
- Current market design may dis-incentivize investment in inverter sizing and power controllers for additional provision of VAr support
- System is economically and operationally more efficient with asynchronous units that are paid to provide these services
- Current market mechanisms do not deal with locational scarcity of reactive power (out-of-market operator intervention = reliability commitments + uplift)

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Thank **You!**

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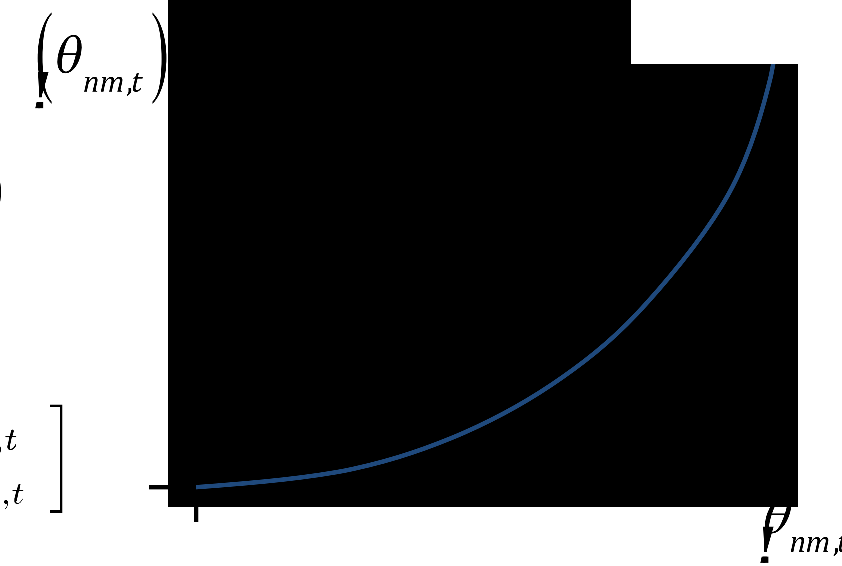
References (denoted by ‡)

- A. Castillo and D. F. Gayme, “Evaluating the effects of real power losses in optimal power flow based storage integration,” IEEE Transactions on Control of Network Systems, 2017, **DOI:** 10.1109/TCNS.2017.2687819.
- A. Castillo and D. F. Gayme, “Profit Maximizing Storage Integration in AC Power Networks.” To appear in a Springer IMA Volume, 2017.

BACKUP SLIDES

Proposed SOCR and SDR Reformulations

$$\tilde{p}^{\ell}_{k,t} = \frac{1}{2} g_k \left(\theta_{nm,t}\right)^2$$



$$\tilde{p}^{\ell}_{k,t} = \mathrm{tr}\left(M^{\ell}_k \tilde{\Theta}_{nm,t}\right)$$

$$M^{\ell}_k := \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{2} g_k \end{bmatrix}$$

Reformulation

$$\tilde{\Theta}_{nm,t} := \begin{bmatrix} 1 & \theta_{nm,t} \\ \theta_{nm,t} & \Theta_{nm,t} \end{bmatrix}$$

Convex Relaxations

SDR

$$\tilde{\Theta}_{nm,t} := \begin{bmatrix} 1 & \theta_{nm,t} \\ \theta_{nm,t} & \Theta_{nm,t} \end{bmatrix} \succeq 0$$

SOCR

$$\left(1 - \Theta_{nm,t}\right)^2 + 4\theta^2_{nm,t} \le \left(1 + \Theta_{nm,t}\right)^2$$

$$\longmapsto \left\| \begin{pmatrix} 1 - \Theta_{nm,t} \\ 2\theta_{nm,t} \end{pmatrix} \right\|_2 \le 1 + \Theta_{nm,t}$$

Exact Reformulations‡

$$\Theta_{nm,t} = \left(\theta_{nm,t}\right)^2$$

L-DCOPF+S Sensitivity