

Hierarchical Probabilistic Coordination and Optimization of DERs and Smart Appliances (5.3)



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Background and Motivation

Massive deployment of Distributed Energy Resources (DERs) (wind, solar, PHEVs, smart appliances, storage, etc.) with power electronic interfaces will change the characteristics of the distribution system:

- Bidirectional flow of power with ancillary services.
- Presence of non-dispatchable and variable generation.
- Non-conventional dynamics → inertial-less characteristics of inverters.

Market Approach: Incentive/price market and local controls

Our Approach: Create an active distribution system supervised with a distributed optimization tool. Specifically:

Develop an infrastructure for monitoring and control supervised by a hierarchical stochastic optimization tool that will enable:

- Maximize value of renewables.
- Improve economics by load levelization (peak load reduction) and loss minimization.
- Improve environmental impact by maximizing use of clean energy sources.
- Improve operational reliability by distributed ancillary services and controls.

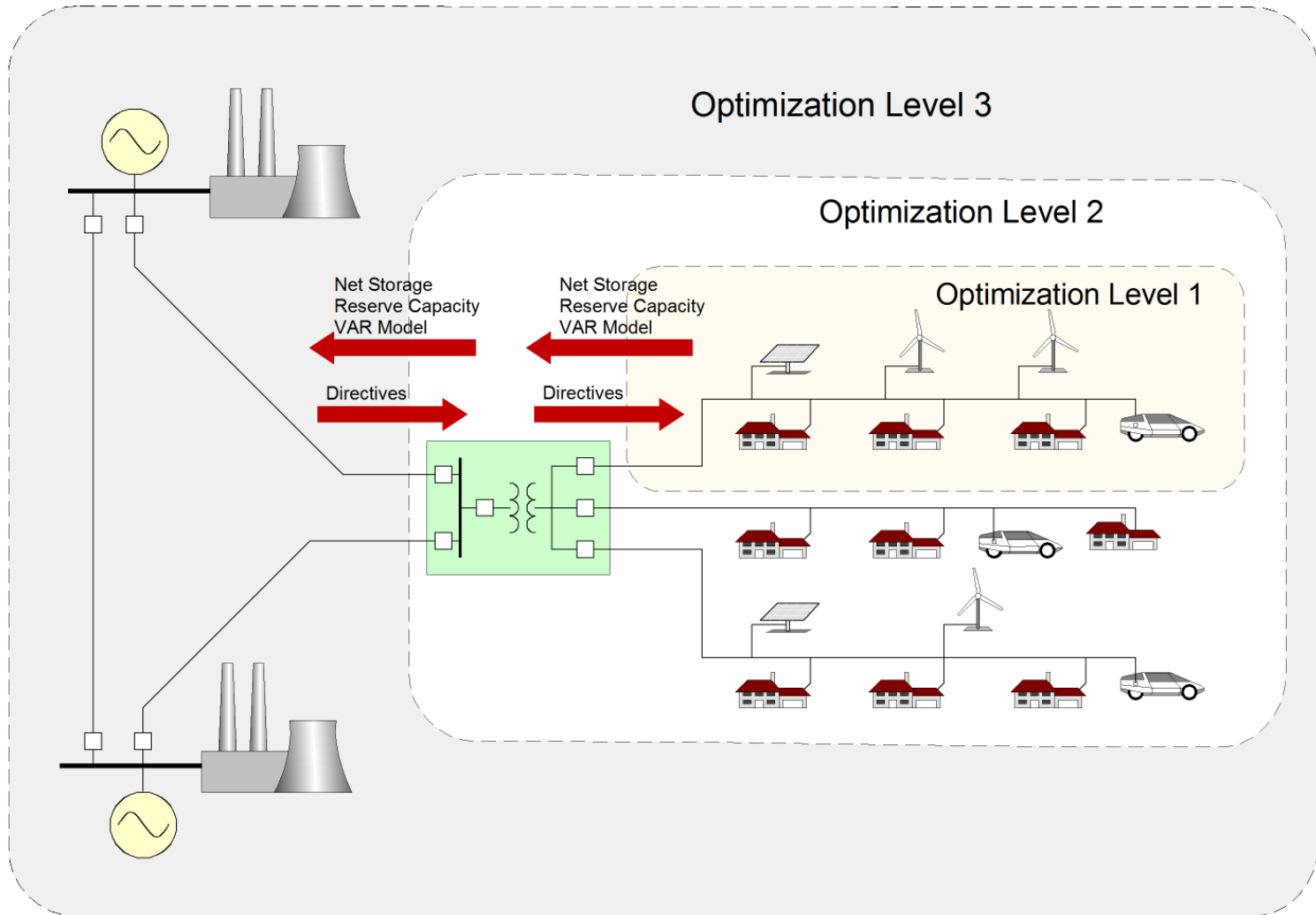
Hierarchical Optimization Scheme

Three-level hierarchical optimization architecture:

Optimization Level 1: feeder optimization (including aggregators, utility and customer owned resources, etc.)

Optimization Level 2: substation optimization (optimize all feeders connected to a substation)

Optimization Level 3: system optimization (optimize all substations)



Feeder Optimization Problem: Definition

Given:

A planning period (typically one day).

A feeder with a number of DERs and topology under direct control

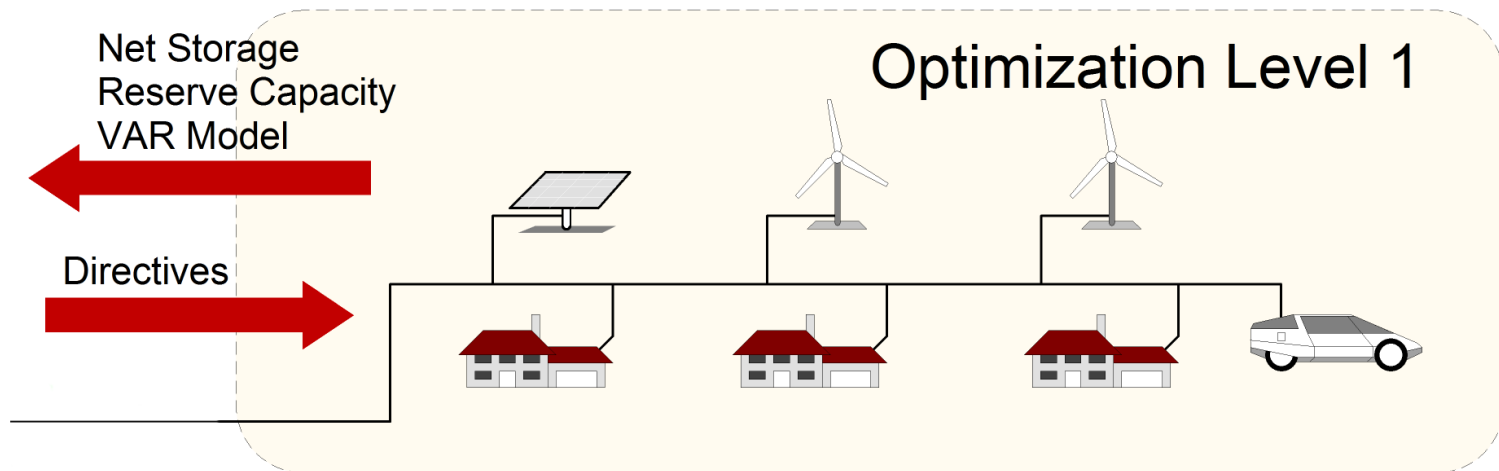
Directives from the higher level optimization

Total stored energy in all feeder resources during the planning period (plan).

Minimum reserve and spinning reserve margin in all feeder resources within the planning period (plan).

Determine:

The optimal (minimum cost) operating conditions of DERs, appliances, etc. subject to meeting the directives from the higher optimization level over the planning period – with no **inconvenience** to customers



Feeder Optimization Problem: Formulation

Reference Only

$\min = f(\mathbf{x}, \mathbf{u})$ Operating cost of the feeder

s.t

$E(t_h) = \sum_{si} E_{si}(t_h) \quad h = 0, \dots, n$: Total stored energy in all feeder resources during the planning period

$SR(t_h) \leq \sum_{\substack{si \\ P_{si}(t_h) \neq 0}} (S_{si,N} - P_{si}(t_h)) + \sum_{\substack{gi \\ P_{gi}(t_h) \neq 0}} (S_{gi,N} - P_{gi}(t_h)) \quad h = 0, \dots, n$: Spinning Reserve Capacity

$R(t_h) \leq \sum_{\substack{si \\ P_{si}(t_h) = 0}} (S_{si,N} - P_{si}(t_h)) + \sum_{\substack{gi \\ P_{gi}(t_h) = 0}} (S_{gi,N} - P_{gi}(t_h)) \quad h = 0, \dots, n$: Reserve Capacity

$$\left. \begin{aligned} E_{si,0} \leq E_{si}(t_h) = E_{si}(t_{h-1}) - P_{si}(t_h) \cdot \Delta t \leq E_{si,N} \\ 0 \leq \sqrt{P_{si}^2(t_h) + Q_{si}^2(t_h)} \leq S_{si,N} \end{aligned} \right\} \quad \begin{aligned} &h = 0, \dots, n \\ &\text{for all storage} \\ &\text{devices} \end{aligned}$$
 : Storage devices constraints

$$0 \leq \sqrt{P_{gi}^2(t_h) + Q_{gi}^2(t_h)} \leq S_{gi,N} \quad \begin{aligned} &h = 0, \dots, n \\ &\text{for all generating units} \end{aligned}$$
 : Generating units capacity constraints

$0 = g(x, u)$: Power flow constraints

$0 \leq h(x, u)$: Operational constraints of the feeder (eg. bus voltage magnitude, distribution lines and transformers capacity constraints)

Feeder Optimization Problem: Object-Oriented Methodology

Each Device is modeled with a set of Quadratized Equations in terms of State and Control variables in a standard syntax (QSnC model).

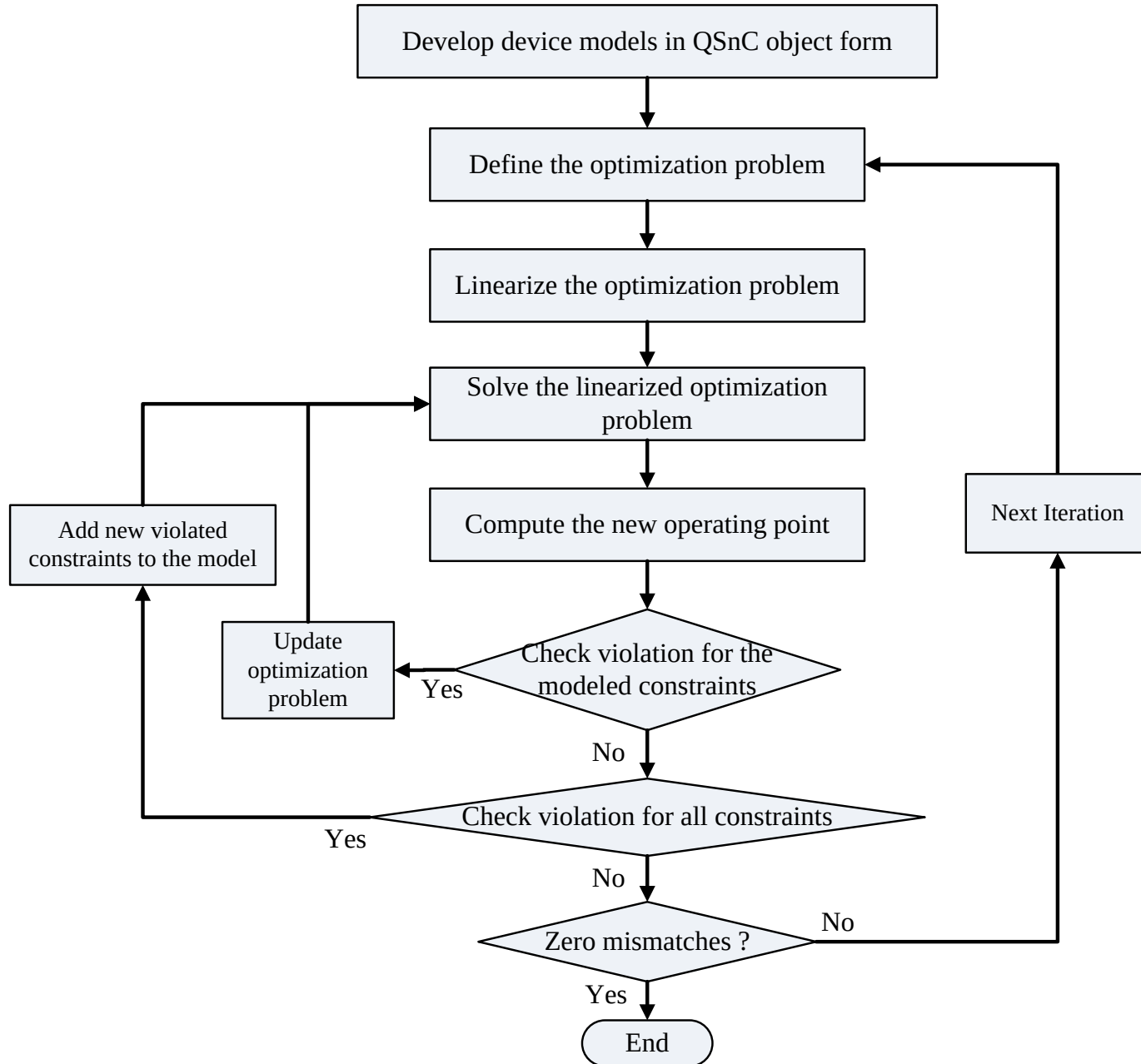
- Device QSnC model (Quadratized State 'n Control Form):

$$\begin{bmatrix} \tilde{I}(t_k) \\ 0 \\ \tilde{I}(t_{k,m}) \\ 0 \end{bmatrix} = Y_{eq-x}(t_k) \begin{bmatrix} \tilde{X}_v(t_k) \\ \tilde{X}_u(t_k) \\ \tilde{X}_v(t_{k,m}) \\ \tilde{X}_u(t_{k,m}) \end{bmatrix} + \begin{bmatrix} \begin{bmatrix} \tilde{X}_v^T(t_k) & \tilde{X}_v^T(t_k) & \tilde{X}_u^T(t_{k,m}) & \tilde{X}_v^T(t_{k,m}) \end{bmatrix} \cdot F_{eq-x_{-1}}(t_k) \cdot \begin{bmatrix} \tilde{X}_v(t_k) \\ \tilde{X}_v(t_k) \\ \tilde{X}_u(t_{k,m}) \\ \tilde{X}_v(t_{k,m}) \end{bmatrix} \\ \vdots \\ \begin{bmatrix} \tilde{X}_v^T(t_k) & \tilde{X}_v^T(t_k) & \tilde{X}_u^T(t_{k,m}) & \tilde{X}_v^T(t_{k,m}) \end{bmatrix} \cdot F_{eq-x_{-n}}(t_k) \cdot \begin{bmatrix} \tilde{X}_v(t_k) \\ \tilde{X}_v(t_k) \\ \tilde{X}_u(t_{k,m}) \\ \tilde{X}_v(t_{k,m}) \end{bmatrix} \end{bmatrix} + Y_{eq-u}(t_k) \begin{bmatrix} \tilde{U}(t_k) \\ \tilde{U}(t_{k,m}) \end{bmatrix} + \begin{bmatrix} \begin{bmatrix} \tilde{U}^T(t_k) & \tilde{U}^T(t_{k,m}) \end{bmatrix} \cdot F_{eq-u_{-1}}(t_k) \cdot \begin{bmatrix} \tilde{U}(t_k) \\ \tilde{U}(t_{k,m}) \end{bmatrix} \\ \vdots \\ \begin{bmatrix} \tilde{U}^T(t_k) & \tilde{U}^T(t_{k,m}) \end{bmatrix} \cdot F_{eq-u_{-n}}(t_k) \cdot \begin{bmatrix} \tilde{U}(t_k) \\ \tilde{U}(t_{k,m}) \end{bmatrix} \end{bmatrix} + \begin{bmatrix} \begin{bmatrix} \tilde{X}_v^T(t_k) & \tilde{X}_v^T(t_k) & \tilde{X}_u^T(t_{k,m}) & \tilde{X}_v^T(t_{k,m}) \end{bmatrix} \cdot F_{eq-xu_{-1}}(t_k) \cdot \begin{bmatrix} \tilde{U}(t_k) \\ \tilde{U}(t_{k,m}) \end{bmatrix} \\ \vdots \\ \begin{bmatrix} \tilde{X}_v^T(t_k) & \tilde{X}_v^T(t_k) & \tilde{X}_u^T(t_{k,m}) & \tilde{X}_v^T(t_{k,m}) \end{bmatrix} \cdot F_{eq-xu_{-n}}(t_k) \cdot \begin{bmatrix} \tilde{U}(t_k) \\ \tilde{U}(t_{k,m}) \end{bmatrix} \end{bmatrix} - B_{eq}(t_k)$$

- In Matrix notation:

$$I(\mathbf{x}, \mathbf{u}) = Y_{eqx} \cdot \mathbf{x} + \left\{ \mathbf{x}^T \cdot F_{eqx,i} \cdot \mathbf{x} \right\} + Y_{equ} \cdot \mathbf{u} + \left\{ \mathbf{u}^T \cdot F_{equ,i} \cdot \mathbf{u} \right\} + \left\{ \mathbf{x}^T \cdot F_{eqxu,i} \cdot \mathbf{u} \right\} - B_{eq}$$

Feeder Optimization Problem: Flow Chart



Feeder Optimization Problem: Object Oriented Analytics

Example Computational Process: Linearization

- The linearization of the constraint is performed with the co-state method

$$\frac{dJ(\mathbf{x}^o, \mathbf{u}^o)}{d\mathbf{u}} = \frac{\partial J(\mathbf{x}^o, \mathbf{u}^o)}{\partial \mathbf{u}} - \hat{\mathbf{x}}^T \frac{\partial \mathbf{g}(\mathbf{x}^o, \mathbf{u}^o)}{\partial \mathbf{u}} \quad \hat{\mathbf{x}}^T = \frac{\partial J_k(\mathbf{x}^o, \mathbf{u}^o)}{\partial \mathbf{x}} \left(\frac{\partial \mathbf{g}(\mathbf{x}^o, \mathbf{u}^o)}{\partial \mathbf{x}} \right)^{-1}$$

- Device QSnC model in matrix notation (object oriented model):

$$\mathbf{g}(\mathbf{x}, \mathbf{u}) = Y_{eqx} \cdot \mathbf{x} + \left\{ \mathbf{x}^T \cdot F_{eqx,i} \cdot \mathbf{x} \right\} + Y_{equ} \cdot \mathbf{u} + \left\{ \mathbf{u}^T \cdot F_{equ,i} \cdot \mathbf{u} \right\} + \left\{ \mathbf{x}^T \cdot F_{eqxu,i} \cdot \mathbf{u} \right\} - B_{eq}$$

- Constraint model in matrix notation (object oriented model):

$$J(\mathbf{x}, \mathbf{u}) = A_J \cdot \mathbf{x} + \mathbf{x}^T \cdot B_J \cdot \mathbf{x} + D_J \cdot \mathbf{u} + \mathbf{u}^T \cdot E_J \cdot \mathbf{u} + \mathbf{x}^T \cdot F_J \cdot \mathbf{u} + c$$

- Computation of each component based on the object oriented model:

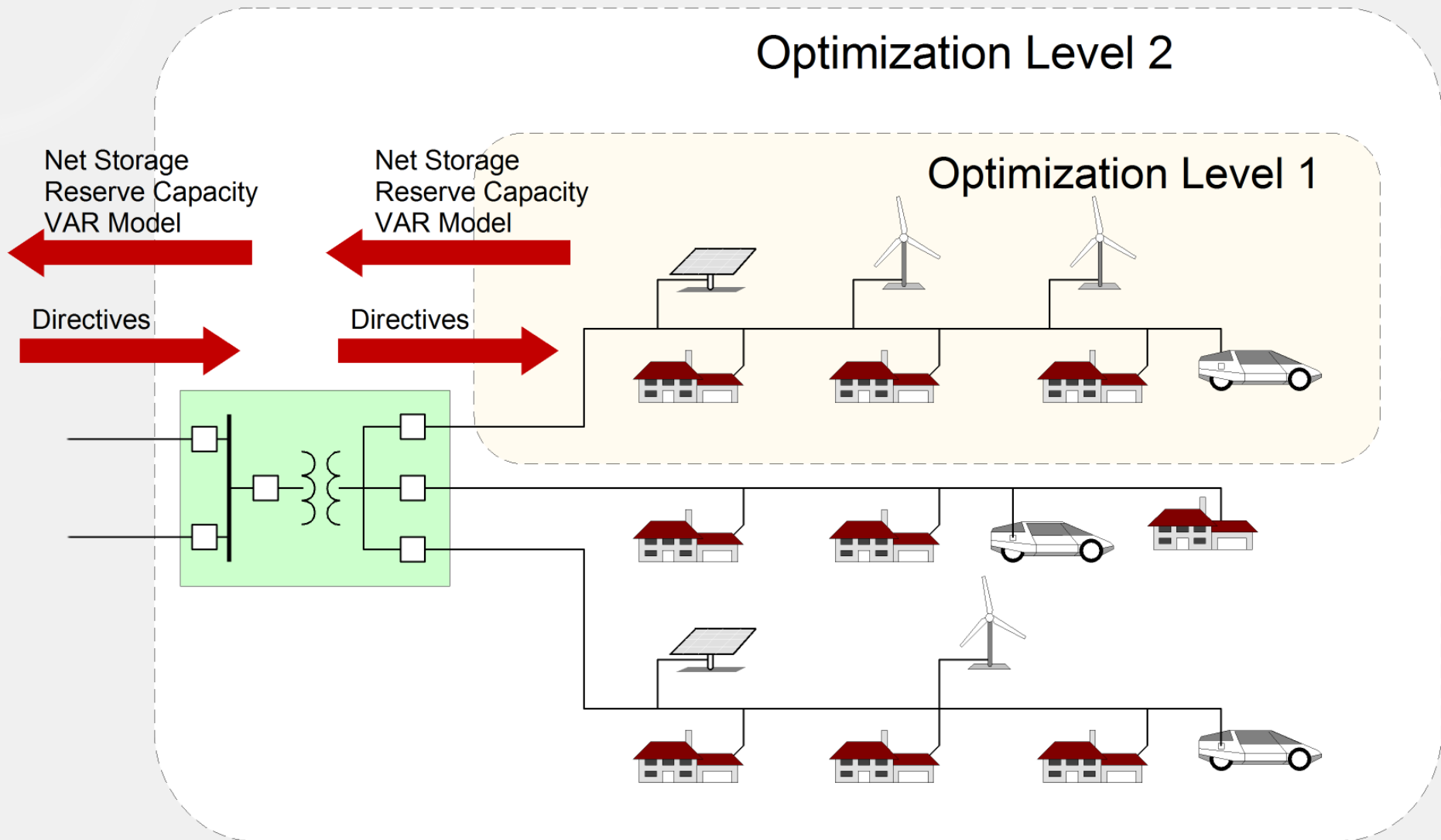
$$\frac{\partial \mathbf{g}(\mathbf{x}^o, \mathbf{u}^o)}{\partial \mathbf{u}} = Y_{equ} + \left\{ \mathbf{u}^{o,T} F_{equ,i} \right\} + \left\{ \left(F_{equ,i} \mathbf{u}^o \right)^T \right\} + \left\{ \mathbf{x}^{o,T} F_{eqxu,i} \right\}$$

$$\frac{\partial \mathbf{g}(\mathbf{x}^o, \mathbf{u}^o)}{\partial \mathbf{x}} = Y_{eqx} + \left\{ \mathbf{x}^{o,T} F_{eqx,i} \right\} + \left\{ \left(F_{eqx,i} \mathbf{x}^o \right)^T \right\} + \left\{ \left(F_{eqxu,i} \mathbf{u}^o \right)^T \right\}$$

$$\frac{\partial J(\mathbf{x}^o, \mathbf{u}^o)}{\partial \mathbf{u}} = D_J + \mathbf{u}^{o,T} \cdot E_J + \left(E_J \cdot \mathbf{u}^o \right)^T + \mathbf{x}^{o,T} \cdot F_J$$

$$\frac{\partial J(\mathbf{x}^o, \mathbf{u}^o)}{\partial \mathbf{x}} = A_J + \mathbf{x}^{o,T} \cdot B_J + \left(B_J \cdot \mathbf{x}^o \right)^T + \left(F_J \cdot \mathbf{u}^o \right)^T$$

Hierarchical Optimization Scheme: Substation



Substation Level Optimization: Stochastic DP

Given: A substation with several distribution feeders, Peak storage, peak capacity, etc. for each of the feeders, Performance criteria (e.g. operation cost), and A planning horizon (e.g. day, week, etc.)

Compute: Directive values for each feeder at each stage k that result in minimum optimal substation operation cost over planning horizon.

Solution method: Stochastic Dynamic Programming

$$R_{k+1}^*(E_{k+1}, R_{k+1}, SR_{k+1}) = \min_{E_k, R_k, SR_k} [R_k^*(E_k, R_k, SR_k) + E\{C^*(E_{k+1}, R_{k+1}, SR_{k+1}, G_A, L)\}]$$

Subject _to :

$$E_{\min} \leq E_k \leq E_{\max} \quad k = 0, 1, \dots$$

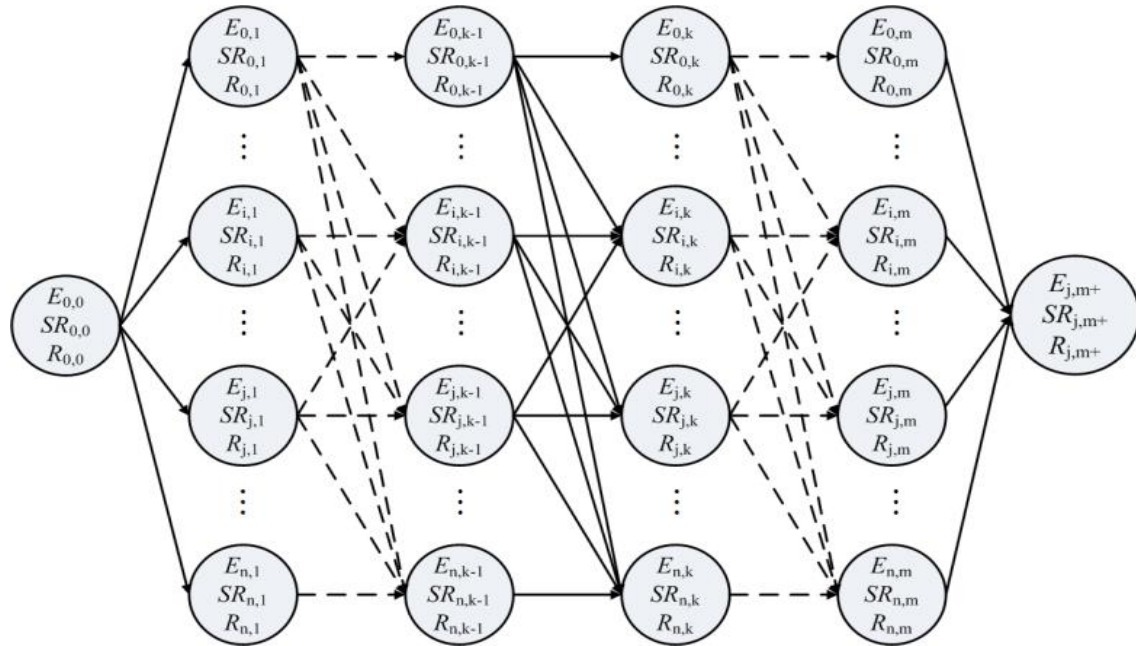
$$R_{\min} \leq R_k \leq R_{\max} \quad k = 0, 1, \dots$$

$$SR_{\min} \leq SR_k \leq SR_{\max} \quad k = 0, 1, \dots$$

$$Q_{\min} \leq Q_k \leq Q_{\max} \quad k = 0, 1, \dots$$

Transition cost:

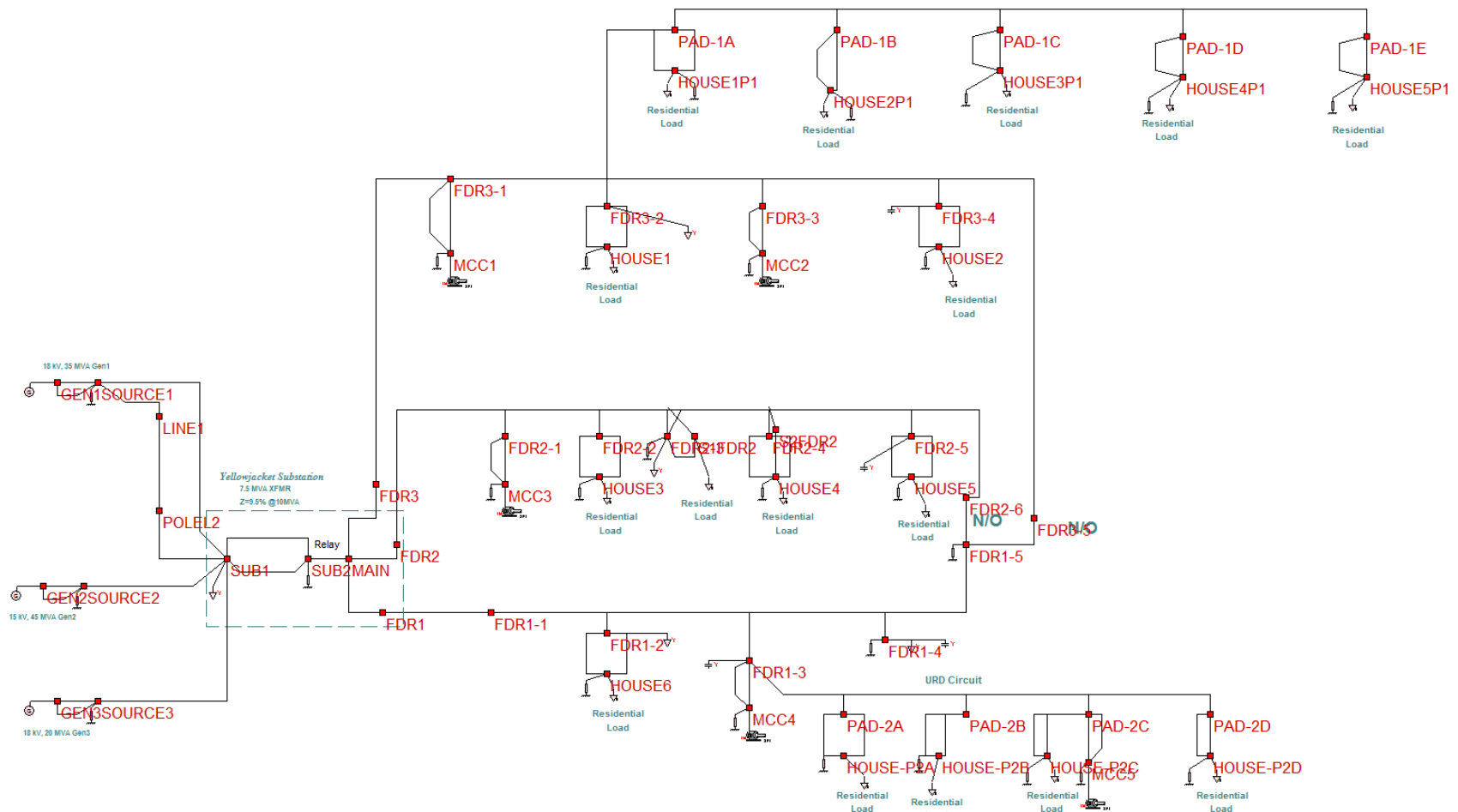
$$C(E_{j,k-1}, SR_{j,k-1}, R_{j,k-1}, E_{i,k}, SR_{i,k}, R_{i,k})$$



The transition costs are computed from the feeder optimization level

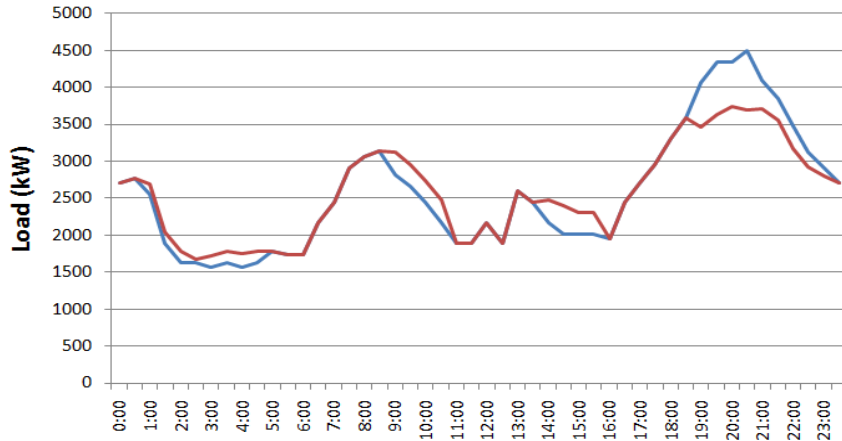
Hierarchical Optimization: Example Test System

12.47 kV, 9 MVA substation, 3 distribution feeders

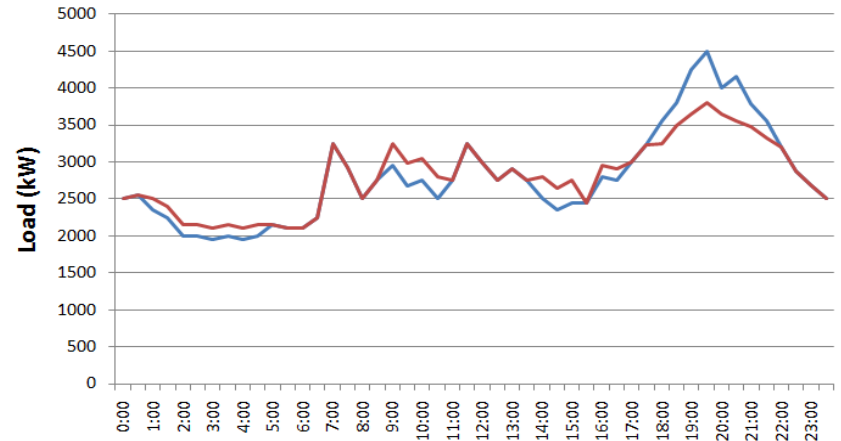


- The loading of the feeder is about 50% of its capacity, i.e. 4.5 MVA
- 3.3% penetration of DERs (total of 300kW).
- 60% of the houses are assumed to have storage devices that comprise an additional 3.3% of the feeder rating (300 kW total capacity) with a storage capability of 600 kWh.

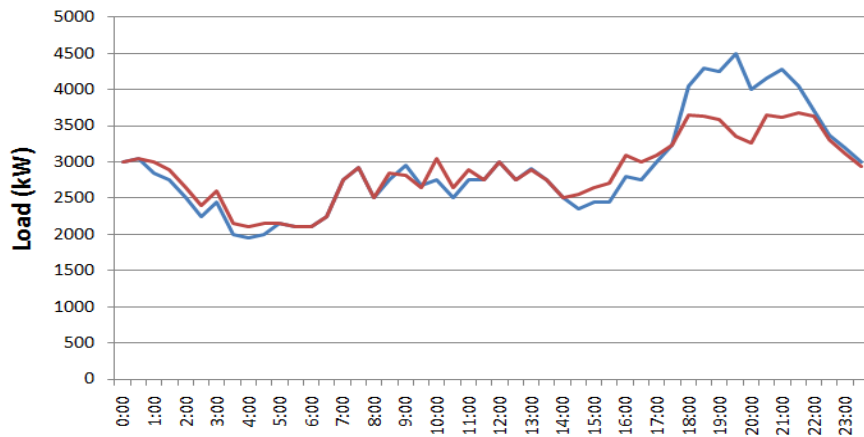
Hierarchical Optimization Results (One Day)



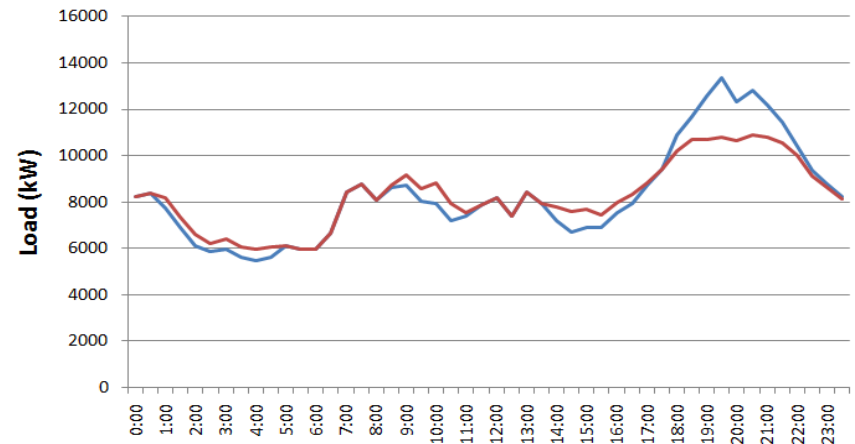
Feeder 1



Feeder 2



Feeder 3

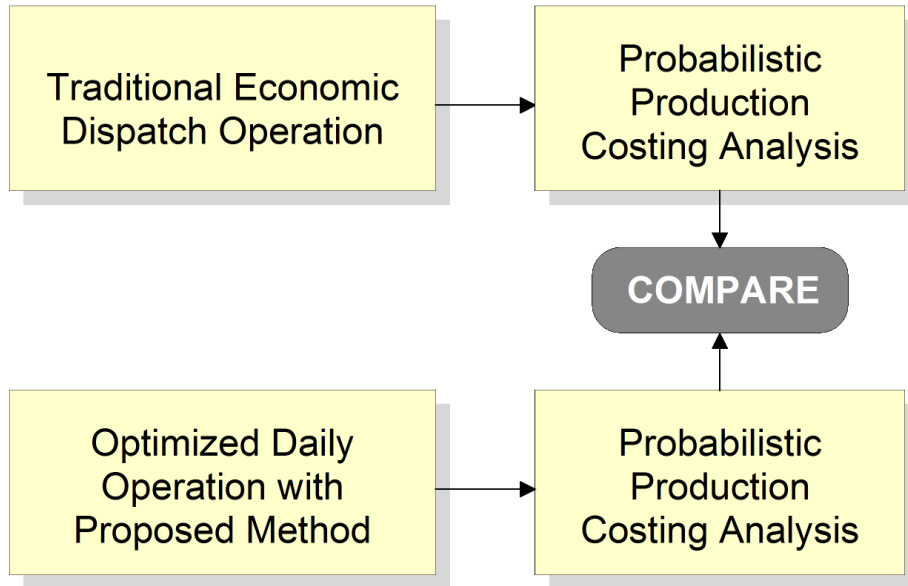


Substation (Total)

Byproduct: Achieved 20% peak load reduction

Business Case

Probabilistic Production Cost (PPC) Analysis



Comparison Methodology:

- (a) Probabilistic simulations to evaluate and compare operating costs, fuel utilization (pollution) and reliability with and without the proposed optimization.
- (b) Quantify benefits resulting from the proposed optimization scheme

Given a probabilistic “composite load” model (composite load demand curves - forecast) for the time period under consideration and the available generating units of the system:



The expected generated energy for each unit taking into account the effects of scheduling functions (economic dispatch, pollution dispatch, etc.) within the time period considered, the random forced outages of the units and maintenance schedules

The expected operating cost and fuel utilization
Reliability indices such as LOL, EUE, etc.

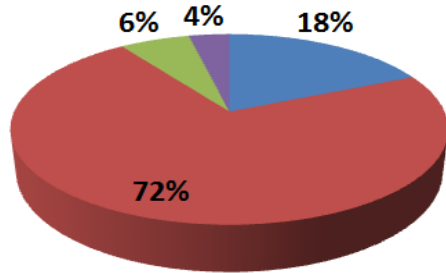
PPC Analysis—Results

(Thermal Units: Economic Dispatch based on Fuel Cost)

A typical utility system was used as a test-bed with 22 GW capacity and 40 generator units (coal, nuclear, oil, natural gas).

Assumed 6.6% penetration of DERs and storage devices.

■ Nuclear ■ Coal ■ Natural Gas ■ Oil



	Non-Optimized Scenario	Optimized Scenario
Loss of load probability	0.04173	0.00227
Generated energy (MWh)	297,841.709	297,018.599
Unserviced energy (MWh)	1,103.695	32.896
Total production cost (k\$)	8,234.674	7,945.566
Average production cost (cents/KWH)	2.7648	2.6751
Total CO2 emissions (kg)	125,671,208.46	124,906,337.604
Total NOx emissions (kg)	381,722.746	379,289.922

Increased Reliability

Annual Production Cost Savings:

$$(\text{k\$ } 8234.67 - \text{k\$ } 7945.57) \times 365 \text{ days} = \$ 105.520 \text{ M}$$

Decreased Pollutant emissions

Cost / Benefit Analysis

Expected Investment Cost

Investment	Cost (Million \$)	Comments
DERs & Storage	1,470	Investment Cost
AMI	200	Instrumentation Cost
DMS Software & Hardware	5	Distribution Management System Cost
Total	1,675	Total Investment Cost

Annualized Equivalent Cost (AE) – Assume: Interest rate of 8%, 20 year Economic Lifetime, Zero Salvage Value at the End of Life

$$1,675 = \sum_{n=0}^{19} \frac{AE}{1.08^n} \quad \longrightarrow \quad AE = \mathbf{\$157.96 \text{ Million}}$$

The cost of the infrastructure is higher (by 33.2%) than the expected benefit. However if the benefits from improved reliability, and reduced pollutants is taken into account, the attractiveness of the proposed approach will increase.

SIDE BENEFIT 1: Generating Unit Cycling: Definition, Effects and Evaluation Indexes

Definition of Cycling: Operation of a generating unit at short duration varying output levels

Effects of cycling:

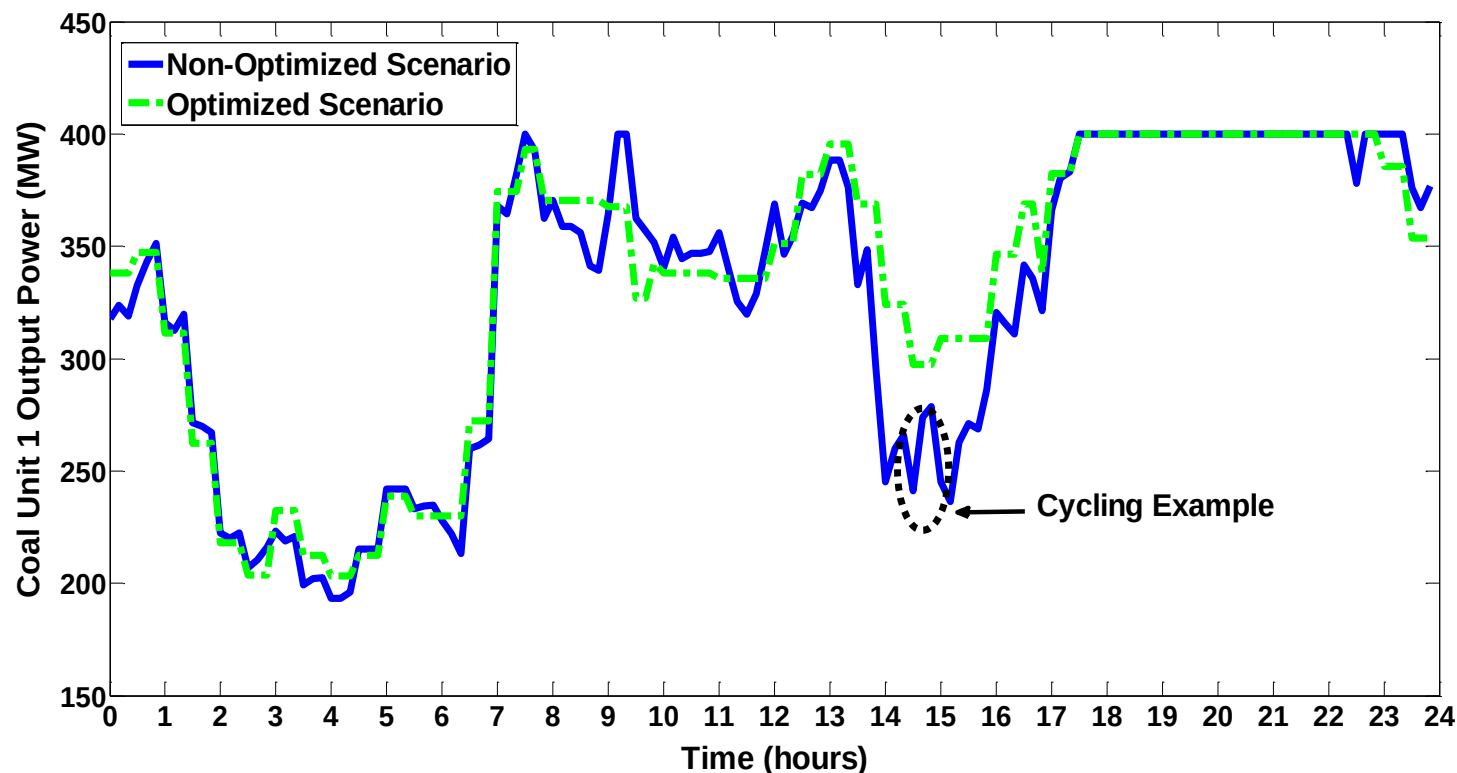
- Increased operation and maintenance costs
- Reduced unit and system reliability

Cycling Evaluation Indexes:

- Number of Cycles: the number of cycles which have a duration less than 1 hour, that a unit experiences within one day
- Average MW variation per cycle: The sum of the MW variation of all the cycles during a day over the number of the cycles within one day.

$$\text{Average MW Variation} = \frac{\sum_{\text{cycles}} \text{MW Variation per cycle}}{\text{Number of cycles}}$$

Coal Unit Cycling Example



Economic Dispatch result for a coal unit.

Non-optimized and optimized scenarios.

Coal Unit	Number of Cycles	Average MW Variation per cycle
Non-Optimized Scenario	22	56.23
Optimized Scenario	0	0

Conventional generator cycling reduction as a byproduct of the hierarchical optimization scheme

SIDE BENEFIT 2: Capacity Credit of Non-Dispatchable Generation

Wind Farm Capacity Credit is the capacity of a dispatchable unit with a specific forced outage rate (FOR) that will provide exactly the same reliability improvement as the wind farm capacity.

The Reliability of System is Evaluated with:

- Loss of Load Probability (**LOLP**)
- Expected Amount of Un-serviced Energy (**EAUE**)

Computational Approach: The PPC tool is used to evaluate the capacity credit of wind farms using the LOLP and EAUE.

FOR	Capacity Credit (MW) Wind Capacity 2000 MW (10%)	Capacity Credit (MW) Wind Capacity 4000 MW (20%)
0.19	500	915
0.15	435	830
0.12	411	796
0.08	397	767
0.06	385	752

Accomplishments and Potential Uses

Accomplishments

- Infrastructure for real time monitoring and extraction of the real time model of the system (utility and customer owned equipment).
- Object-oriented and autonomously executed hierarchical stochastic optimization algorithm that provides the control signals for the distributed resources (model based control).
- Business case analysis that quantifies implementation costs and benefits / comprehensive studies.

Potential Uses

- Load Levelization (peak load reduction) with no customer inconvenience (coordinated approach to demand response).
- Loss minimization by balancing the feeder (coordinated scheduling of non-essential customer loads and resources).
- Increased Operational Reliability by utilizing (a) the ability of inverters to provide ancillary services, (b) the ability of distributed resources (smart appliances, thermal loads, EVs, etc.) to provide reserve capacity, and (c) the ability of the proposed system to provide coordinated demand response.
- Reduction of conventional generating unit cycling

Project Publications to Date

A. P. Meliopoulos, G. Cokkinides, R. Huang, E. Farantatos, S. Choi, Y. Lee, and X. Yu, “Smart Grid Technologies for Autonomous Operation and Control”, *IEEE Trans. on Smart Grid*, vol. 2, issue 1, 2011.

A. P. Meliopoulos, G. Cokkinides, R. Huang, and E. Farantatos, “Integrated Smart Grid Hierarchical Control”, in *Proceedings of the 45th Annual Hawaii International Conference on System Sciences (HICSS)*, Maui, Hawaii, Jan. 4-7, 2012.

R. Huang, E. Farantatos, G. Cokkinides and A. P. Meliopoulos, “Impact of Non-Dispatchable Renewables on Generator Cycling and Control via a Hierarchical Control Scheme”, in *Proceedings of the 2012 IEEE PES Transmission & Distribution Conference & Exposition*, Orlando, FL, May 7-10, 2012.

A. P. Meliopoulos, Evangelos Polymeneas, Zhenyu Tan, Renke Huang and Dongbo Zhao, “Advanced Distribution Management System”, *IEEE Transactions on Smart Grid*, Accepted February 2013.