An Iterative Control for Optimally Managing Export Limits of Distributed Generators

Grid of the Future 2022

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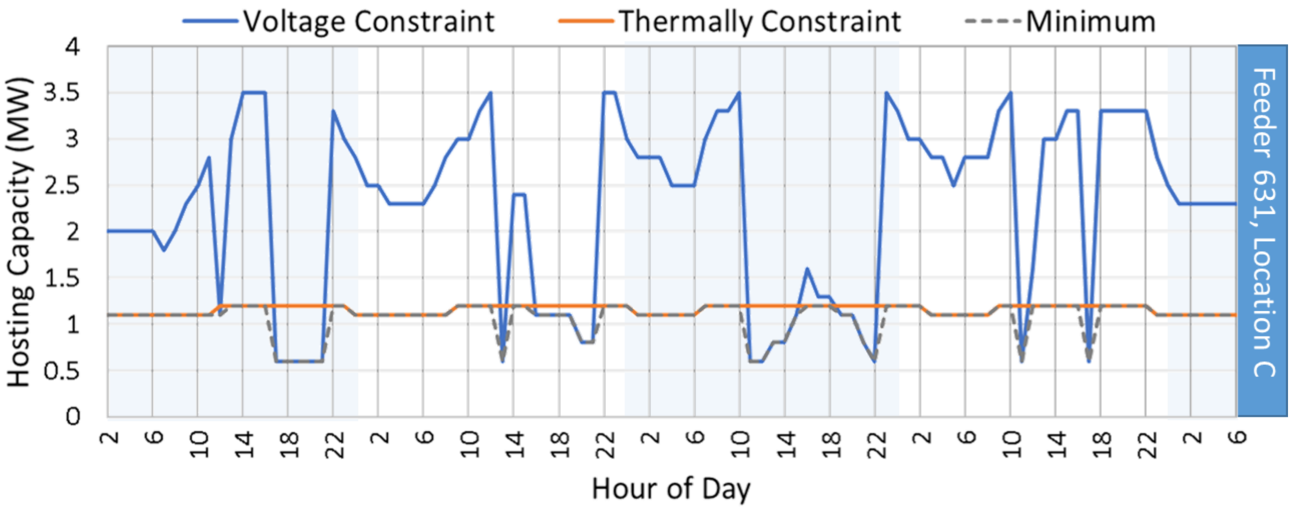
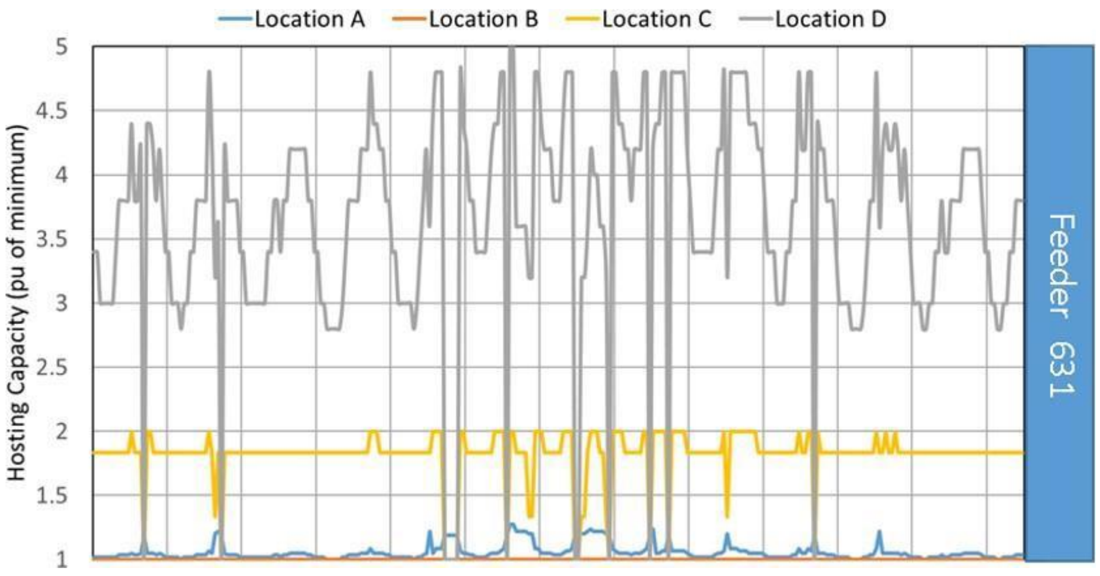
Temporal and Spatial Hosting Capacity

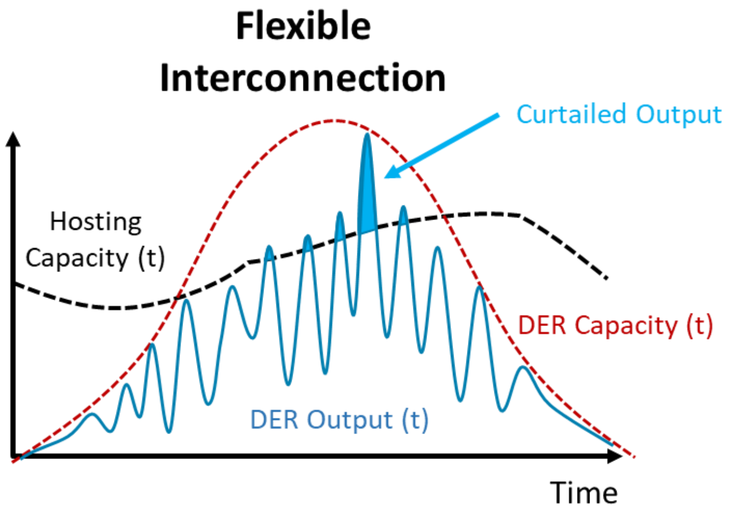
- Multiple system constraints determine the operational limit of a DG (distributed generator)
- Most constraints are time-variant, hence is the operational limit





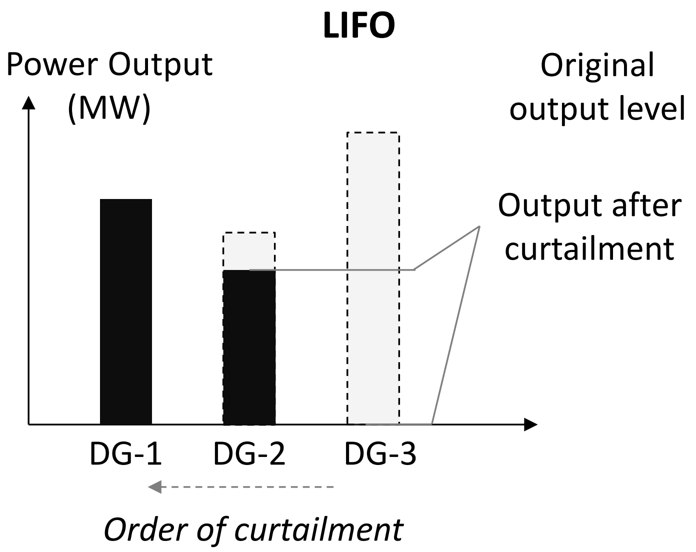
- System constraints at any given time are location-dependent
- The temporal variabilities are location-dependent and can differ significantly
- The operational limits between DGs are inter-dependent

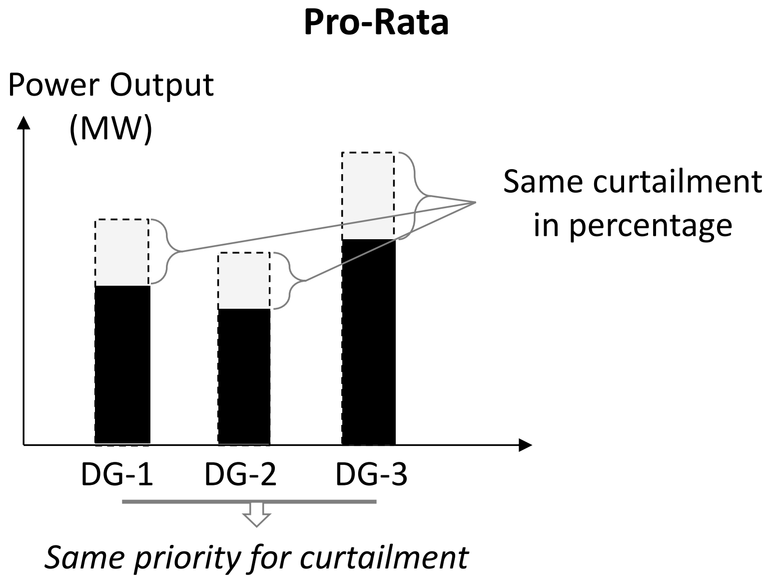
Flexible Interconnection & Principle of Access



Better utilization of distribution system through optimal curtailment

- Multiple DGs connected at different locations
- Different contribution to different constraints
- User-defined objective functions
    - Minimum curtailed energy
    - Minimum operational cost
    - Fair curtailment

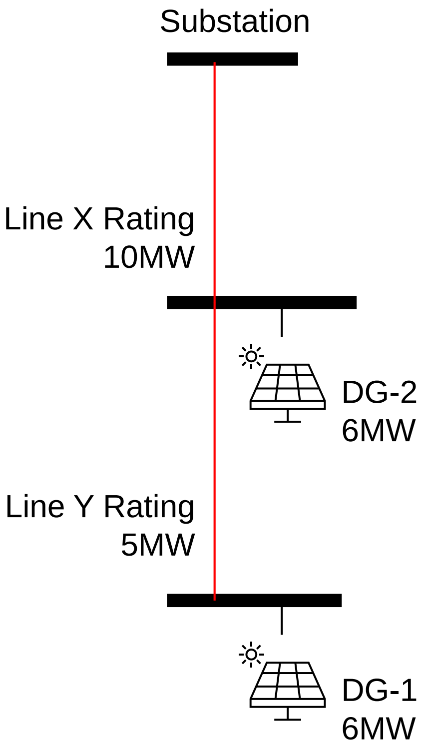




A Simple Example

LIFO Priority Order : DG-1 > DG-2

(i.e., DG-2 will be curtailed before DG-1)



Case 1: Evaluating Line X first

Constraint Evaluation	Curtailment (MW)		Generation (MW)	
	ΔDG-1	ΔDG-2	DG-1	DG-2
Line X	0	2	6	4
Line Y	1	0	5	4

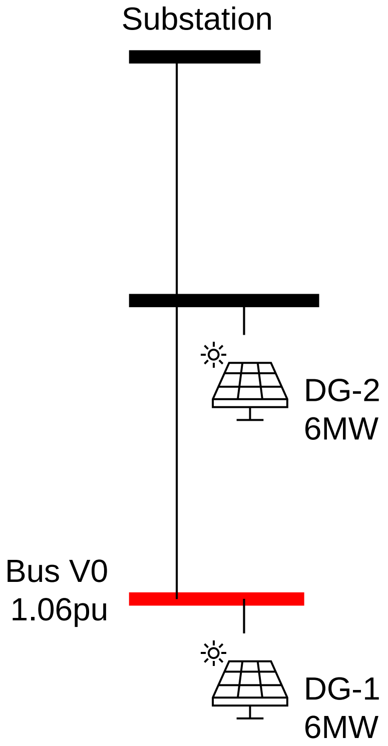
Case 2: Evaluating Line Y first

Constraint Evaluation	Curtailment (MW)		Generation (MW)	
	ΔDG-1	ΔDG-2	DG-1	DG-2
Line Y	1	0	5	6
Line X	0	1	5	5

Multiple Constraints should be Evaluated Simultaneously

A Simple Example (Continued)

$\partial V / \partial P$ (puV/MW)	
DG-1	DG-2
0.01	0.001



LIFO Priority Order	Curtailment (MW)		Generation (MW)	
	ΔDG-1	ΔDG-2	DG-1	DG-2
DG-1 > DG-2	0.4	6	5.6	0
DG-2 > DG-1	1	0	5	6

Questions raised from the example:

- How strictly should priority order be followed?
- What if $\partial V / \partial P$ is negative?
- How to include contribution factors into curtailment optimization?
- How to handle more complicated priority rules (e.g., (DG-1 = DG-2) > (DG-3 = DG-4))?

A Mathematic Definition of Priority is Needed

Proposed Solution using Quadratic Programming

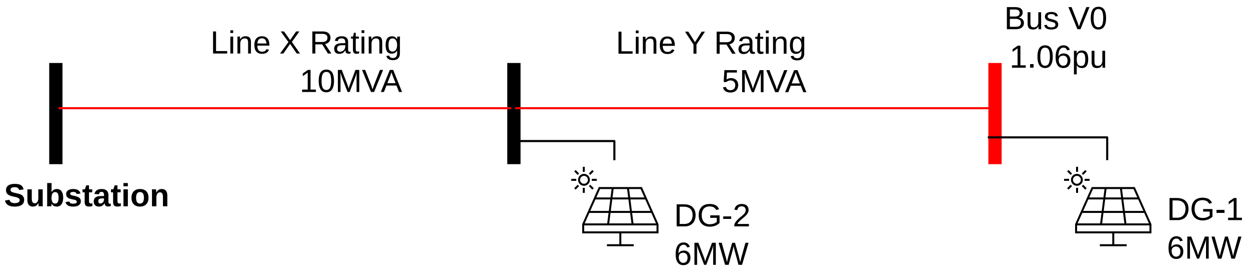
$$minimize\ f(\boldsymbol{x}) = \frac{1}{2}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}^T \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$subject\ to:$$

x_1: curtailment of DG-1
x_2: curtailment of DG-2

q_1: priority factor of DG-1
q_2: priority factor of DG-2

$$\begin{bmatrix} -1 & 0 \\ 0 & -1 \\ 1 & 0 \\ 0 & 1 \\ -1 & -1 \\ -1 & 0 \\ -0.01 & -0.001 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \leq \begin{bmatrix} 0 \\ 0 \\ 6 \\ 6 \\ 10-12 \\ 5-6 \\ 1.05-1.06 \end{bmatrix} \begin{array}{l} \left.\begin{array}{l} \\ \\ \end{array}\right\} \text{Lower limit of curtailment} \\ \left.\begin{array}{l} \\ \\ \end{array}\right\} \text{Upper limit of curtailment} \\ \left.\begin{array}{l} \\ \\ \end{array}\right\} \text{Line rating constraint} \\ \leftarrow \text{Bus voltage constraint} \end{array}$$



Contributing Factor

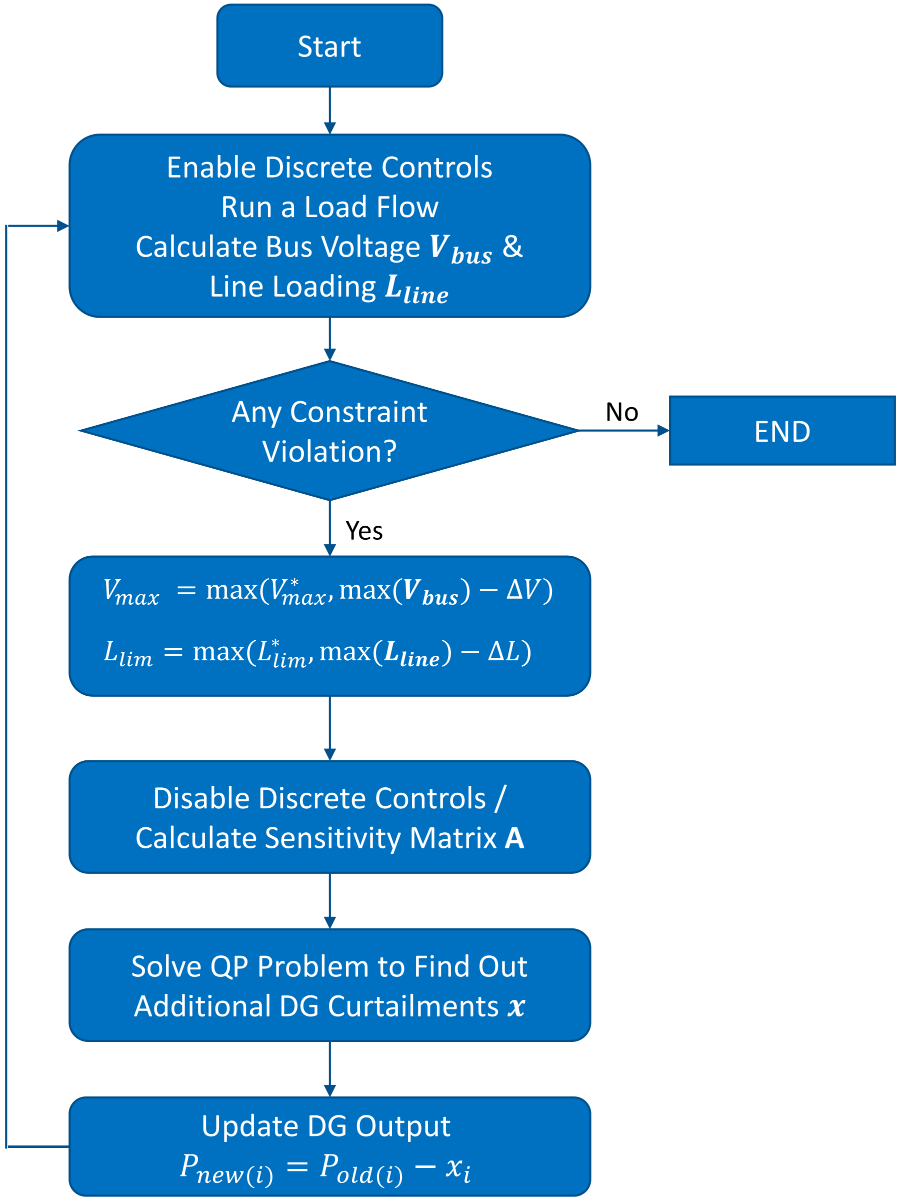
$\partial V/\partial P$ (puV/MW)	
DG-1	DG-2
0.01	0.001

Line	$\partial L/\partial P$ (MW/MW)	
	DG-1	DG-2
X	1.0	1.0
Y	1.0	0.0

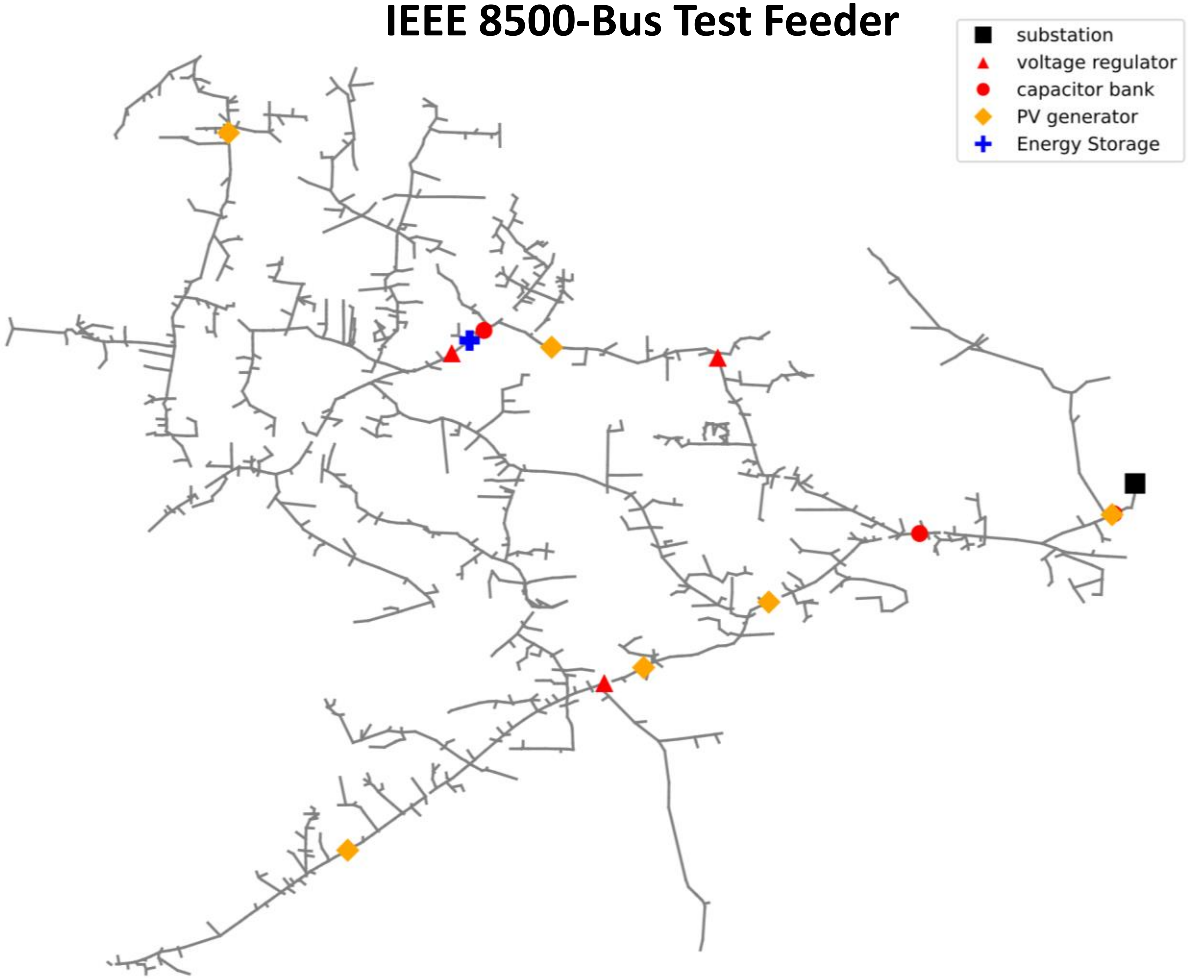
Curtailment Result

Priority Order	Curtailment (MW)		Generation (MW)	
	ΔDG-1	ΔDG-2	DG-1	DG-2
DG-1 > DG-2 (q_1=10q_2)	1.00	1.00	5.00	5.00
DG-1 < DG-2 (q_2=10q_1)	1.82	0.18	4.18	5.82
DG-1 < DG-2 (q_2=100q_1)	1.98	0.02	4.02	5.98
DG-1 = DG-2 (Pro-Rata)	1.00	1.00	5.00	5.00

Iterative Implementation Applied to Realistic Feeder Circuits

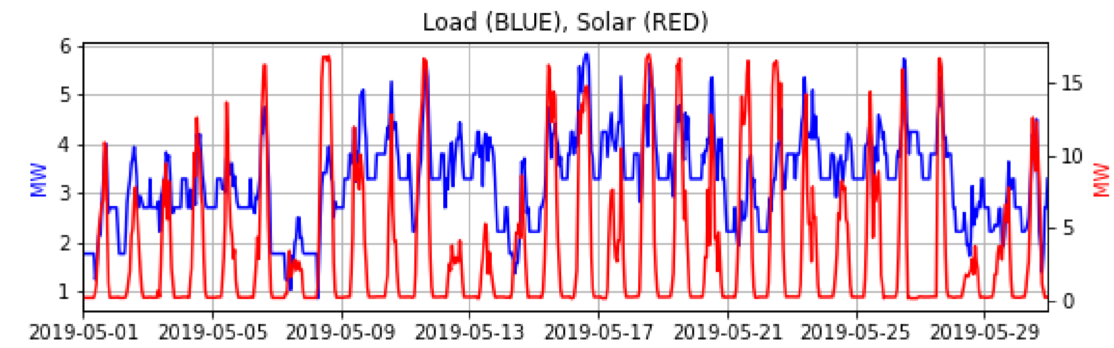


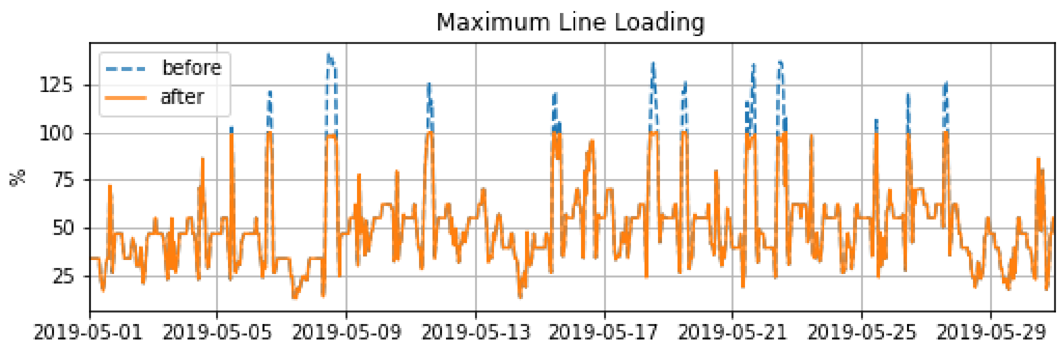
IEEE 8500-Bus Test Feeder

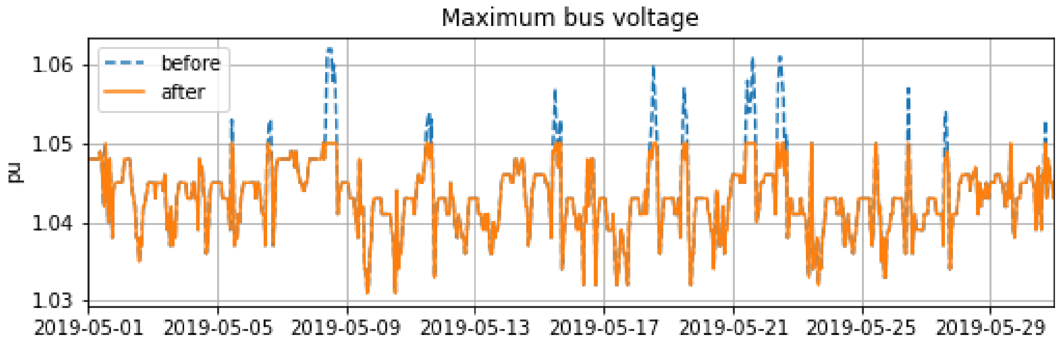


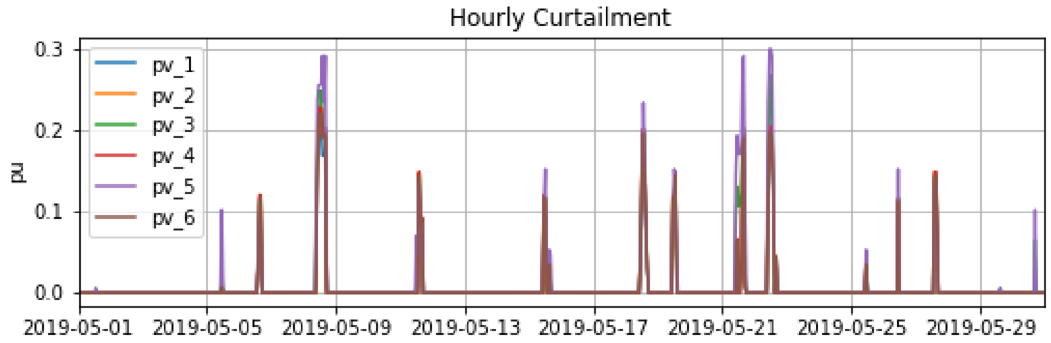
- Six PV generators added to randomly selected buses
- Hourly optimization performed for 8760 hours of a full year

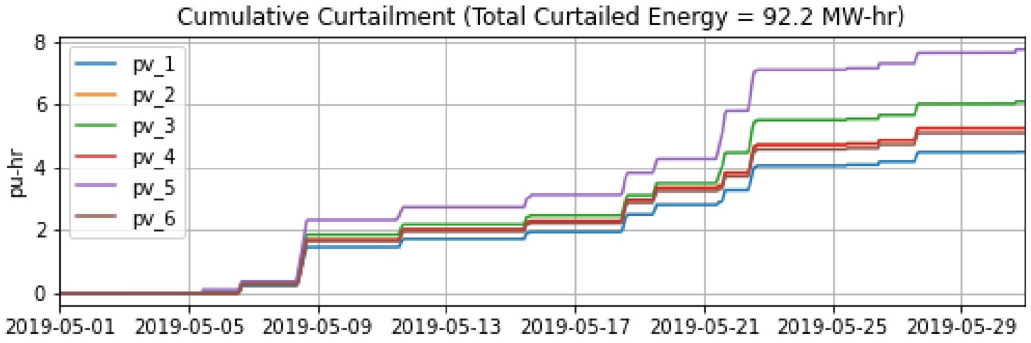
Simulation Result











Name	Bus	Distance from Substation (km)	Rated kW	Constant PF (- inductive)	Generation (MW·Hr)	Curtailment (MW·Hr)	Energy Yield (%)
PV-1	E192201	0.56	4000	1.0	5866	268	95.6%
PV-2	E183493	4.36	4000	-0.95	5825	309	95.0%
PV-3	M1089141	5.99	3000	-0.95	4324	277	94.0%
PV-4	N1134475	7.76	3000	-0.95	4369	232	95.0%
PV-5	M1047292	9.81	1500	-0.95	2121	179	92.2%
PV-6	L3254213	14.4	1500	-0.95	2188	112	95.1%

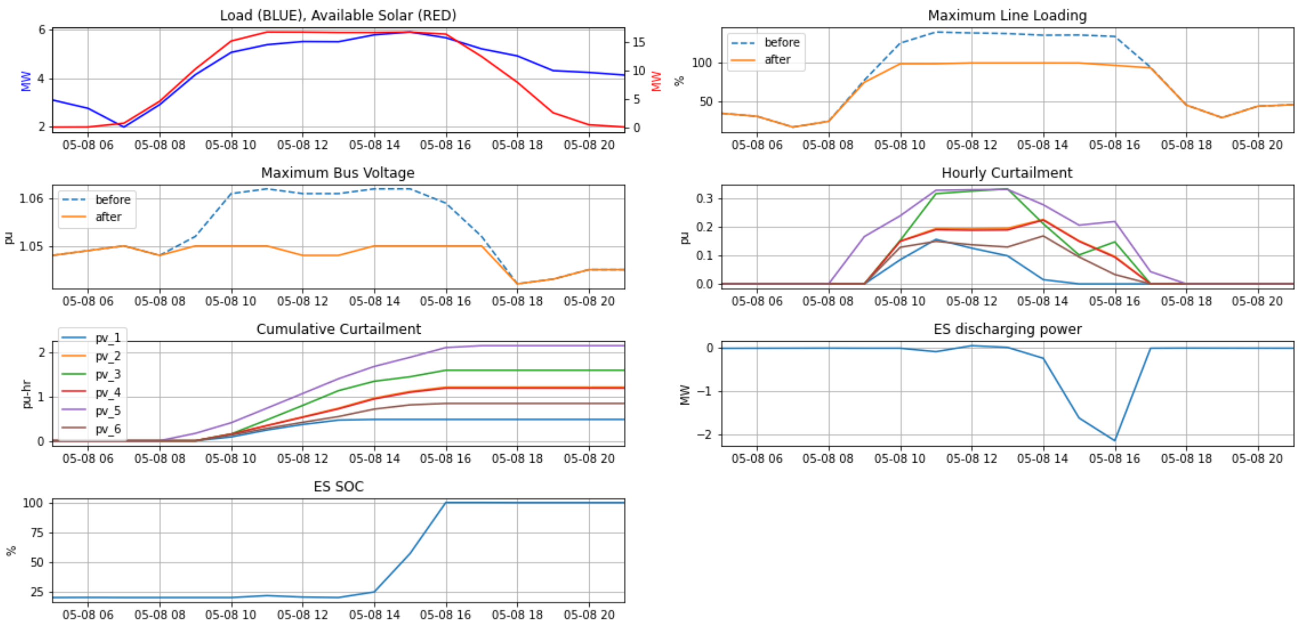
Expansion to Include Energy Storage Systems

- Optimization of a time window instead of a single time stamp
- Additional inequalities for each time segment

$$-\begin{bmatrix} & \vdots & \\ \cdots & -1. & \cdots \\ \cdots & 1.0 & \cdots \\ & \vdots & \end{bmatrix}\begin{bmatrix}\vdots\\ x_{ES(th)}\\ \vdots\end{bmatrix} \le \begin{bmatrix}\vdots\\ P_{chg\_max(th)}\\ P_{dis\_max(th)}\\ \vdots\end{bmatrix}$$

$$-\begin{bmatrix} \vdots \\ 1, \dots 1, \dots 0, \dots 0 \\ -1, \dots -1, \dots 0, \dots 0 \\ \vdots \end{bmatrix}\begin{bmatrix} x_{ES(t1)} \\ \vdots \\ x_{ES(th)} \\ \vdots \\ x_{ES(tk)} \\ \vdots \\ x_{ES(tZ)} \end{bmatrix} \le \begin{bmatrix} \vdots \\ \frac{E_{Rate}}{\Delta t}\left(SOC_{ES}(t0) - SOC_{ES\_MIN}\right) \\ -\frac{E_{Rate}}{\Delta t}\left(SOC_{ES}(t0) - SOC_{ES\_MAX}\right) \\ \vdots \end{bmatrix}$$

With a 2.5MW-2hr battery



Name	Generation (MW·Hr)	Curtailment (MW·Hr)	Energy Yield (%)	Reduced Curtailment (MW*hr)
PV-1	6088	47	99.2%	221
PV-2	5933	201	96.7%	108
PV-3	4411	189	95.9%	88
PV-4	4455	145	96.8%	86
PV-5	2113	187	91.9%	-8
PV-6	2252	48	97.9%	64
All	25253	818	96.9%	560

Take-Aways

- Flexible interconnection may help utilities accommodate higher penetration of DGs until traditional system infrastructure reinforcement is built
- Optimal curtailment of multiple DGs must consider various objectives and constraints simultaneously
- The proposed iterative QP-based algorithm is found flexible and efficient to the problem
- National Grid has successfully conducted a curtailment estimation study using a tool (built by EPRI with Python and CYME) that utilizes the iterative QP-based algorithm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