Voltage Security Constraints in SPP Markets using Generalized DC Power Flow

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TGG

Introduction

- Why the interest in voltage security constraints?
  - Changing grid - 62% Wind Penetration
  - Online VSAT & TSAT
  - What can we do about voltage in the SPP market?
- Generalized DC Feasibility Study

Overview

GENERALIZED DC ALGORITHM, MARKET BENEFITS, SPP FEASIBILITY STUDY

How Today's Options (DC-OPF & AC-OPF) Handle Voltage

- Market Clearing Engine (MCE) uses a DC (MW only) power flow for reasons of performance and robustness
- Under gross assumptions, the DC powerflow sets the voltage magnitude at each bus to 1.0 per unit and removes resistance
  - You lose voltage information and MVAR flows by doing this
- Moving to an AC OPF would allow us to see voltage impacts, but would be less reliable and slower
- There are also impacts to settlements calculations

OPF Model	Speed	Accuracy	Robustness	Voltage?
DC	Linear & Fast	Less accurate under heavy load and high R/X ratios	Yes	No - Sets buses to 1.0 P.U.
AC	Nonlinear & Must iterate until convergence tolerance reached	Highly Accurate	No	Yes

Can We Introduce Voltage Constraints Into the Model without AC-OPF?

- We can generate voltage sensitivities (similar to generation shift factors) by linearizing a part of the nonlinear AC Power Flow model
  - Referred to as the Generalized DC Power Flow (GDC)*
- We can approximate bus voltages without iterative solution
  - As fast and robust/reliable as the DC power flow
  - Has the voltage information we desire

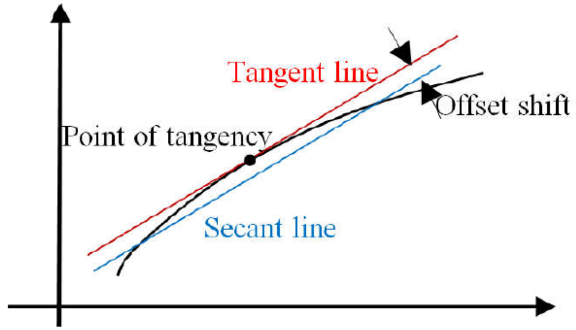


Figure 1. Tangent-line and Secant-line Approximations of a Nonlinear Function

*: M Hong, Z Ning, R Jamalzadeh, "Generalized DC power flow model and enhancing RTO Market clearing formulation with voltage security constraints," Power and Energy Society General Meeting (PESGM) 2016.

The Generalized DC Power Flow Model

$$\begin{bmatrix}\bar{P}(x)\\ \bar{Q}(x)\end{bmatrix}=\begin{bmatrix}\bar{P}(x)\\ \bar{Q}(x)\end{bmatrix}\Bigg|_{x_0}+\begin{bmatrix}\partial\bar{P}/\partial\bar{\delta} & \partial\bar{P}/\partial\bar{V}\\ \partial\bar{Q}/\partial\bar{\delta} & \partial\bar{Q}/\partial\bar{V}\end{bmatrix}\Bigg|_{x_0}\cdot\begin{bmatrix}\Delta\bar{\delta}\\ \Delta\bar{V}\end{bmatrix}+\bar{O}^2(\Delta\bar{\delta},\Delta\bar{V})$$

(x_0 is the point of tangency.)

$$\begin{bmatrix}\bar{P}_1(x)\\ \bar{P}_2(x)\\ \bar{Q}_1(x)\\ \bar{Q}_2(x)\end{bmatrix}=\begin{bmatrix}\bar{P}_1(x_0)\\ \bar{P}_2(x_0)\\ \bar{Q}_1(x_0)\\ \bar{Q}_2(x_0)\end{bmatrix}+\begin{bmatrix}\begin{bmatrix}J1_{11} & J1_{12}\\ J1_{21} & J1_{22}\end{bmatrix} & \begin{bmatrix}J2_{11} & J2_{12}\\ J2_{21} & J2_{22}\end{bmatrix}\\ \begin{bmatrix}J3_{11} & J3_{12}\\ J3_{21} & J3_{22}\end{bmatrix} & \begin{bmatrix}J4_{11} & J4_{12}\\ J4_{21} & J4_{22}\end{bmatrix}\end{bmatrix}\cdot\begin{bmatrix}\bar{\delta}_1-\bar{\delta}_{10}\\ \bar{\delta}_2-\bar{\delta}_{20}\\ \bar{V}_1-\bar{V}_{10}\\ \bar{V}_2-\bar{V}_{10}\end{bmatrix}$$
$$+\bar{O}^2(\Delta\bar{\delta},\Delta\bar{V})$$

$$\begin{bmatrix}\bar{\delta}_1\\ \bar{\delta}_2\\ \bar{V}_2\end{bmatrix}=\underbrace{\begin{bmatrix}J1_{11} & J1_{12} & J2_{12}\\ J1_{21} & J1_{22} & J2_{22}\\ J3_{21} & J3_{22} & J4_{22}\end{bmatrix}^{-1}}_{\text{Sensitivities}}\cdot\begin{bmatrix}\bar{P}_1(x)\\ \bar{P}_2(x)\\ \bar{Q}_2(x)\end{bmatrix}+\underbrace{\left\{\begin{bmatrix}\bar{\delta}_{10}\\ \bar{\delta}_{20}\\ \bar{V}_{20}\end{bmatrix}-\begin{bmatrix}J1_{11} & J1_{12} & J2_{12}\\ J1_{21} & J1_{22} & J2_{22}\\ J3_{21} & J3_{22} & J4_{22}\end{bmatrix}^{-1}\left(\begin{bmatrix}\bar{P}_1(x_0)\\ \bar{P}_2(x_0)\\ \bar{Q}_2(x_0)\end{bmatrix}+\begin{bmatrix}J2_{11}\\ J2_{21}\\ J4_{21}\end{bmatrix}(\bar{V}_1-\bar{V}_{10})\right)\right\}}_{\text{Constant Offset}}$$

Sensitivity Computation from the GDC Model

Elements of the inversed matrix:

$$\begin{bmatrix} J1_{11} & J1_{12} & J2_{12} \\ J1_{21} & J1_{22} & J2_{22} \\ J3_{21} & J3_{22} & J4_{22} \end{bmatrix}^{-1}$$

represent:

- sensitivities of the voltage angle to active power injection. These sensitivities can be used to further derive the branch flow to active power injection sensitivity *PFS*.
- sensitivities of the voltage angle to reactive power injection. These sensitivities can be used to further derive the branch flow to reactive power injection sensitivity *QFS*.
- sensitivities of the voltage magnitude to active power injection *PVS*.
- sensitivities of the voltage magnitude to reactive power injection *QVS*.

What does GDC Add to MCE?

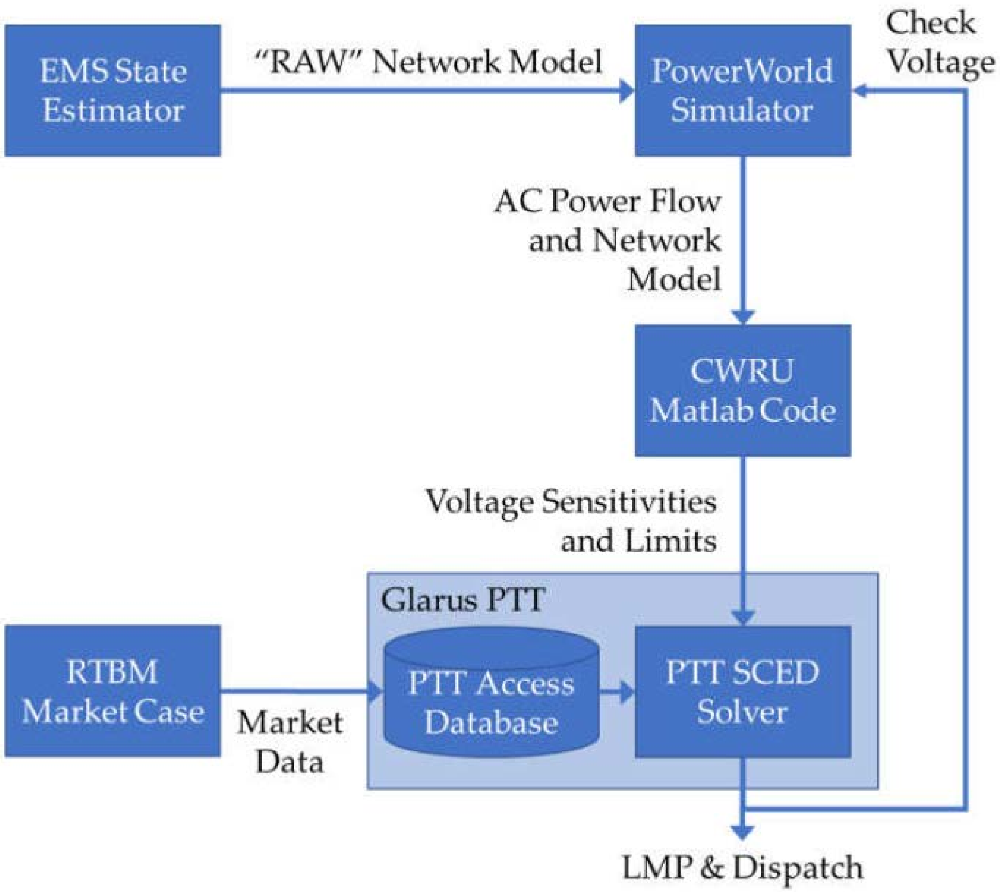
- Ability to monitor and relieve bus voltage constraints with either real and/or reactive power
- Optional modeling of reactive power
  - Reactive power information in MCE
    - This is embedded in the DC model and you can’t see it
  - Reactive power or generation voltage set-point dispatch
  - Reactive power prices to represent market incentive for voltage support

SPP Model GDC Feasibility Study

- "Voltage Management in Southwest Power Pool Electricity Markets using Generalized DC Power Flow"
- Compares a base SCED case that contained a voltage issue which had to be fixed outside of the market, with an enhanced SCED case with GDC-based voltage constraints and compares both reliability and economic metrics
- Validates the GDC-based SCED model formulation in correcting voltage-security violations

Scenario	Voltage Issue	Fixed Outside Market	Fixed in Market
Base SCED	1	1	0
Voltage enhanced SCED	1	0	1

Study Analysis Process



Some Acronyms:
CWRU: Case Western Reserve University.
Glarus PTT: The Glarus Group in-house ProtoType Tool for market clearing.
RTBM: SPP Real-Time Balance Market

Formulation

DC-OPF VS. GDC-OPF

Main MCE Formulation Changes

SCED Formulation	GDC Change: Active Power Only	GDC Change: Reactive Dispatch
Objective Function	No	Reactive Power Cost
Global Power Balance Constraint	No	No
Resource Active/Reactive Power Limit Constraint	No	Yes
Branch Flow Security Constraints	No	Yes
Bus Voltage Security Constraints	Yes	Yes
Active Power LMP	Yes – include voltage constraint impact	Yes
Reative Power LMP	No	Yes

Objective Function - Minimize Production Cost

DC Model	GenDC Model
$\sum_{r,t} P(r,t) \cdot C_P(r,t)$	$\sum_{r,t} P(r,t) \cdot C_P(r,t) + f\left(Q(r,t), C_Q(r,t)\right)$

- **P(r,t)** is the active power injection (or withdrawal when < 0) of location "r" at time "t"
- **C_P(r,t)** is the offered cost of active power of location "r" at time "t"
- **Q(r,t)** is the reactive power injection (or withdrawal when < 0) of location "r" at time "t"
- **C_Q(r,t)** is the offered cost of reactive power of location "r" at time "t"
- "**r**" is the set of resource locations
- "**t**" is the set of time intervals in the study

Global Power Balance Constraint

DC Model	GenDC Model
$\sum_i P(i,t) - NetLoss(t)$	$[\lambda_t]$
$NetLoss(t) = \sum_i P(i,t) \cdot LossSens(i,t) + LossOffset(t)$	

- **NetLoss(t)** is the modeled transmission losses at time "t"
- **LossSens(i,t)** is the sensitivity of incremental losses to active power injection at location "i" at time "t"
- **LossOffset(t)** is the estimated correction to align linearized incremental losses with total system losses at time "t"
- **P(i,t)** is the active power injection (or withdrawal when < 0) at location "i"
- "**i**" is the set of network locations including resources loads, and the sites of other power injections and withdrawals

Generation Resource Active and Reactive Power Limit Constraints

DC Model	GenDC Model
$P_{min}(r,t) \leq P(r,t) \leq P_{max}(r,t)$	
No reactive power model	$Q_{min}(r,t) \leq Q(r,t) \leq Q_{max}(r,t)$

P_{min}(r,t), P_{max}(r,t) are the minimum and maximum active power output at location “r” at time “t”, respectively
Q_{min}(r,t), Q_{max}(r,t) are the minimum and maximum reactive power output at location “r” at time “t”, respectively

Branch Flow Security Constraints (Base or Contingent Topology)

DC Model	GenDC Model
$\sum_i PSF(i,t,k) \cdot P(i,t) + F_{DC}^{0}(k,t) \leq F_{max}(k,t)$	$\sum_i PSF(i,t,k) \cdot P(i,t) + \sum_i QSF(i,t,k) \cdot Q(i,t) + F_{GenDC}^{0}(k,t) \leq F_{max}(k,t) \quad [\mu_{k,t}]$

- **PSF(i,t,k)** is the sensitivity of active power injection at location "i" at time "t" to flow on constraint "k"
- $\mathbf{F^0_{DC}(k,t)}$, $\mathbf{F^0_{GenDC}(k,t)}$ are the model offset constants for transmission flow constraint "k" at time "t" for the DC and GenDC formulations, respectively. $\mathbf{F_{max}(k,t)}$ is maximum flow on constraint "k" at time "t"
- **QSF(i,t,k)** is the sensitivity of reactive power injection at location "i" at time "t" to flow on constraint "k"
- $\boldsymbol{\mu_{k,t}}$ is the shadow price of the branch flow constraint.

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Bus Voltage Security Constraints (Base or Contingent Topology)

DC Model	GenDC Model
Not modeled, voltage assumed to be 1.0 p.u.	$V_{min}(n,t) \leq \sum_i PVS(i,t,n) \cdot P(i,t) + \sum_i QVS(i,t,n) \cdot Q(i,t) + V^0_{GenDC}(n,t) \leq V_{max}(n,t)$ $\quad [\eta^{min}_{n,t}, \eta^{max}_{n,t}]$

- **Vmin(n,t), Vmax (n,t)** are the minimum and maximum voltages at location "n" at time "t", respectively.
- **PVS (i,t,n)** is the sensitivity of active power injection at location "i" at time "t" to voltage at location "n".
- **QVS (i,t,n)** is the sensitivity of reactive power injection at location "i" at time "t" to voltage at location "n".
- $\mathbf{V^0_{GenDC}(n,t)}$ are the model offset constants for voltage at location "n" at time "t" for GenDC formulation
- $\boldsymbol{\eta^{min}_{n,t}}, \boldsymbol{\eta^{max}_{n,t}}$ are the shadow prices of the bus voltage security constraints

Active Power LMP

DC Model	GenDC Model
$LMP_p(i,t) = \lambda_{i,t} \cdot [1 - LossSens(i,t)] + \sum_k \mu_{k,t} \cdot PSF(i,t,k)$	$LMP_p(i,t) = \lambda_{i,t} \cdot [1 - LossSens(i,t)] + \sum_k \mu_{k,t} \cdot PSF(i,t,k) + \sum_n (\eta_{n,t}^{max} - \eta_{n,t}^{min}) \cdot PVS(i,t,n)$

- When voltage security constraints are not binding, the active power LMP would be very similar between DC-based SCED and GDC-based SCED.
- When voltage security constraints are binding, the LMP in GDC-based SCED includes voltage related components.

Reactive Power LMP

DC Model	GenDC Model
No reactive power model	$LMP_Q(i,t) = \sum_k \mu_{k,t} \cdot QSF(i,t,k) + \sum_n (\eta_{n,t}^{max} - \eta_{n,t}^{min}) \cdot QVS(i,t,n)$

- The reactive power LMP is composed of the reactive power's impact on branch flow and bus voltage constraints (transmission deliverability constraints)
- Reactive power LMP has no reactive power balance term as the GDC model is assuming that system can handle incremental changes
  - As a result, the Reactive power LMP has no MEC or MLC terms (transmission power balance components)

Flexible Incremental Changes

Active-Power-Only to Start With

- The change from dispatching only real power to dispatching both real and reactive power can be a significant operational change with many challenges.
- The GDC model can be implemented to exclude reactive power dispatch and maintain the current dispatch of only real power where assumptions would be made about the impacts of reactive injection changes (Such as the reactive injection changes have zero incremental impact on transmission constraints. These sensitivities are in fact very small.)

Move to Active & Reactive Power Dispatch

- After confidence has been gained using the Active-Power-Only method of GDC, reactive power dispatch can be added
- Reactive power dispatch adds more capabilities to MCE in addressing branch-flow & bus-voltage constraints
- Reactive LMP also incentivizes voltage support

Case Study

MANUAL ACTION VS. GDC

Case Study Question

Although declaring a TLR (Transmission Load Relief) offers an effective method of returning reliable operation to the grid with available tools, could an enhancement of the SCED through the GDC power flow model provide more effective and/or more economic alternatives?

Description of Case Study Scenarios

Case	Purpose	Voltage Constraint Enforced	TLR Model Enforced	Reactive Dispatch
As-Is	Baseline with no correction to the voltage	No	No	No
Operator Flow Control (TLR)	Operator correction applied in real time	No	Yes	No
Voltage Constraint (Active Power Only)	Voltage constraint control by active power	Yes	No	No
Voltage Constraint (Active and Reactive)	Voltage constraint control by active and reactive power	Yes	No	Yes

GDC Accuracy: SPP Voltage at Bus of Concern

After the GDC-based SCED dispatch, the GDC computed voltages are compared to the AC Power Flow results. The differences may be attributed to the simplifying measures in GDC sensitivity calculation. Future efforts can be made to remove some of the assumptions.

Case	GenDC (p.u.)	AC Power Flow (p.u.)	Difference (p.u.)
As-Is	0.9647	0.9721	0.0074
Operator Flow Control (TLR)	0.9926	0.9814	0.0112
Voltage Constraint (Active Power Only)	0.9800	0.9756	0.0044
Voltage Constraint (Active and Reactive)	0.9800	0.9750	0.0050

Economic Effectiveness of Voltage Control

Case	Production Cost ($)	Cost Above As-is ($)	Cost Percent Above As-Is (%)	SPP Bus of Concern's Voltage (P.U.)
As-Is	5150	0	--	0.9647
Operator Flow Control (TLR)	6878	1728	33.6%	0.9926
Voltage Constraint (Active Power Only)	5589	439	8.5%	0.98
Voltage Constraint (Active and Reactive)	5153	3	0.1%	0.98

Comparisons of Active Power LMP

- The TLR case shows reduced LMPs in general as expected
- The Active Power Only case generally shows higher LMPs due to voltage constraint.
- The Active and Reactive Power shows LMPs that are almost the same as the As-Is case.

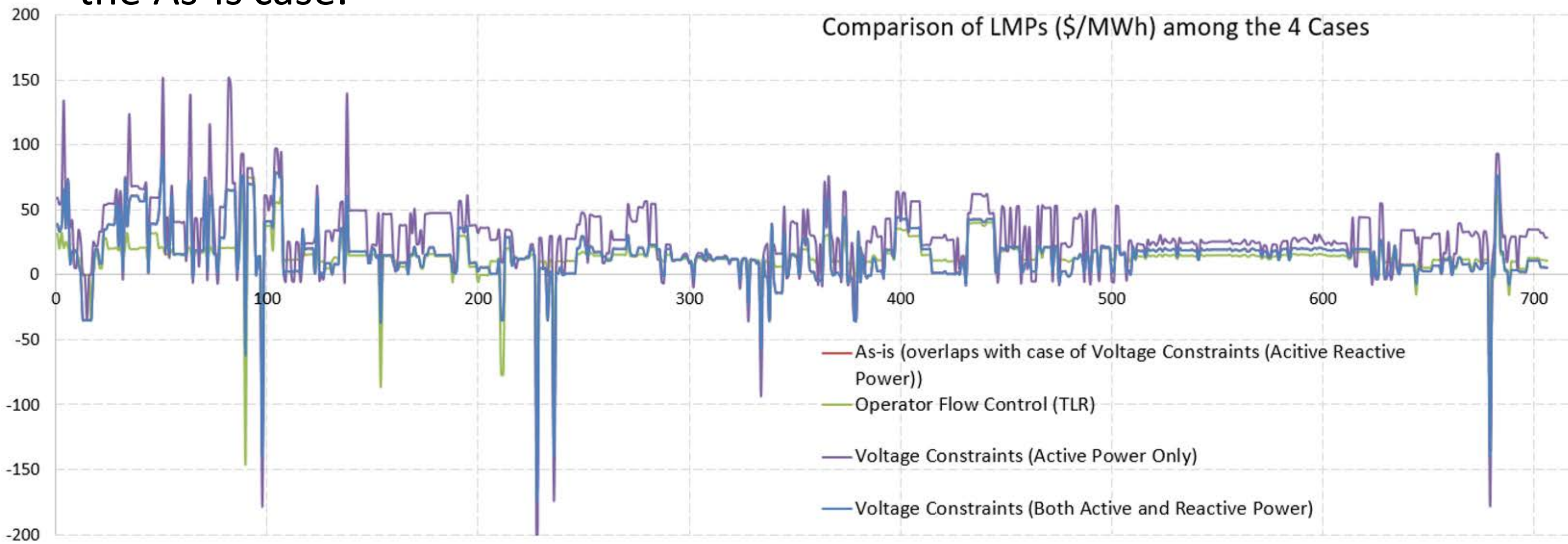

Figure 3. Case Active Power LMPs Across 706 SPP Generator Locations

Wrap Up

IMPLEMENTATION, RT VS DA, AND CONCLUSION

Implementation Effort for Real/Active Power only GDC

Component	Description	Anticipated Effort
All not listed below	Incorporate voltage constraints as a subset of today's transmission operating constraints	Small
MKTNET	Calculate the constraint parameters (sensitivities and limits) around a point of tangency describing active and reactive power profiles such as the state estimator in real time and an AC study power flow in forward markets	Real time: Small Forward: Big
MKTNET – SFT	Reactive profiles are needed to enable more accurate reactive convergence check in SFT power flow to provide meaningful reactive solution and identification of voltage constraints. Potential future VSAT integration also possible.	Small
Administration	Accommodate of voltage constraint needs such as independent VRL values	Small

MKTNET: EMS application for computing generation shift factors;
SFT: EMS application for contingency analysis; computes sensitivities.

Implementation Effort for Real & Reactive Power GDC

Component	Description	Anticipated Effort
Resource Dispatch Systems	Infrastructure does not support communication of real-time reactive power dispatch instructions	Big
Reliability	Validate reliability of new reactive power dispatch approach	Big
MktNet/MCE	Calculation and incorporation of reactive power sensitivities for flow and voltage transmission constraints from an AC power flow solution	Medium
MCE	Pricing of reactive power	Small
Market Participant Interface and Pricing Models	Design and support reactive power offer prices and/or opportunity cost modeling	Big
Settlement	Measurement and settlement of reactive power	Medium

Real-Time vs. Day-Ahead Market Implementation

- The current case study was performed with the real time SCED where the current operating state as available from EMS state estimation was used as the ***Point of Tangency***.
- To apply the GDC method to DA SCED, a current operating state is not available. The Point of Tangency can be chosen based on the operation planning study case that reveals voltage security problem.
- The GDC power flow model can be implemented in SCUC to support resource commitment for voltage security.

Conclusion

- SPP Feasibility Study suggests that GDC can work in Market Clearing and is economically advantageous.
- Provides a path to implementing voltage security constraints while avoiding the impacts of ACOPF.
- Challenges do exist for implementation for this new method.
- SPP is investigating building an offline prototype for analysis purposes.