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The Carrington GMD project

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UNCLASSIFIED

Outline

- Introduction
- Motivation of research – GMD and HEMP events
- Modeling GMD/HEMP-E3 events
- Halloween Solar Storm simulation and results
- Ongoing work

Introduction

The Carrington event:

- Richard Carrington (1826-1875), English amateur astronomer
- September 1859: largest geomagnetic storm on record
  - first observations of solar flares by Richard Carrington and Richard Hodgson
  - Carrington suspected solar-terrestrial connection -- influence upon the Earth
- storm caused strong auroral displays, failure of telegraph systems

Motivation of research

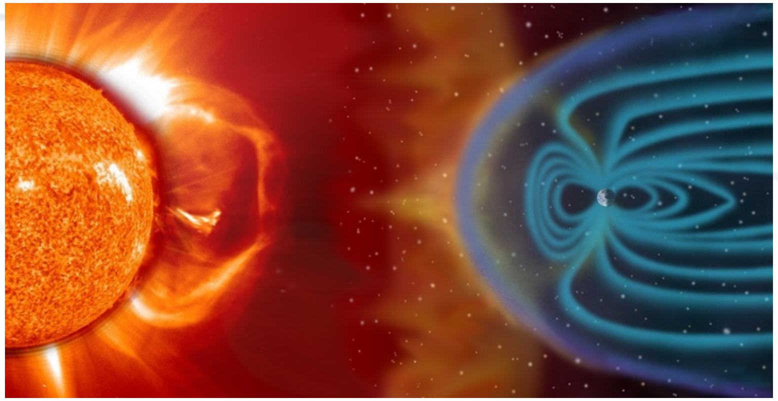
Importance of electricity:

- high dependency in all areas of our life
- short-term outages: nuisance, discomfort
- long-term outages: severe (chaotic) consequences

Nation's electrical grid

- key component of the critical infrastructure
- under constant threats

Geomagnetic Disturbances

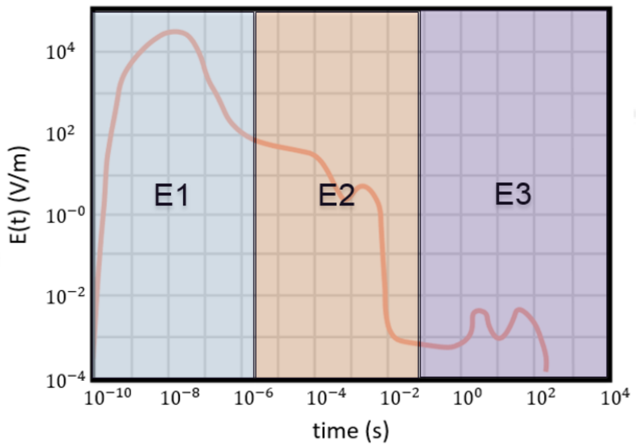


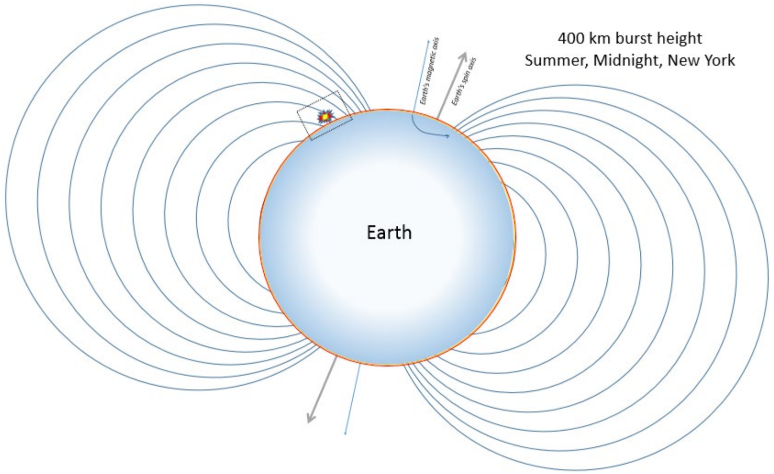
https://phys.org/news/2016-03-powerful-geomagnetic-storms-solar.html

- GMDs are caused by solar flares
  - charged and magnetized particles from the Sun, which may disrupt Earth’s magnetic field
  - coronal mass ejections (CMEs) lead to the largest GMDs
  - co-rotating interaction region (CIR): a high speed solar wind originating from a coronal hole
- results in auroral currents (electrojets)
  - magnetic field induces voltage in transmission lines

High-Altitude Electromagnetic Pulses

- brief, high-frequency electromagnetic waves
- HEMPs are caused by nuclear weapon detonations
  - E1 and E2: nearly instantaneous, damage to electronic components and low/medium-voltage infrastructure
  - E3: low-frequency GICs in transmission lines and power transformers ➡ similar to solar flares
- potential to cause significant damage





M. K. Rivera et al., "EMP/GMD phase 0 report, a review of EMP hazard environments and impacts," Los Alamos National Laboratory, LA-UR-16-28380, Nov. 2016.

Effect on Power Systems

- **Geomagnetically Induced Currents** – induced quasi-dc currents in conductive infrastructure – **are a major threat**
- GICs may lead to …
  - **voltage collapse** as a result of increased reactive power consumptions
  - increase of transformer temperatures, **overheating of power transformers**
  - **misoperation of protection devices** due to harmonics
  - potential **cascading collapse** of the entire grid
- Goal: **understanding and mitigating hazard** ➡ MODELING

Modeling GMD/HEMP-E3 events

Knowledge is required about …

- power system characteristics
  - geographical location of substations
  - resistance of system components, characteristics of power transformers
- geomagnetic source fields
  - amplitude, frequency content, spatial characteristics
- Earth conductivity structure
  - modeling method, substation grounding resistance, influence on geoelectric fields

Modeling GMD/HEMP-E3 events

Julia

- open-source
- high-performance
- just-in-time

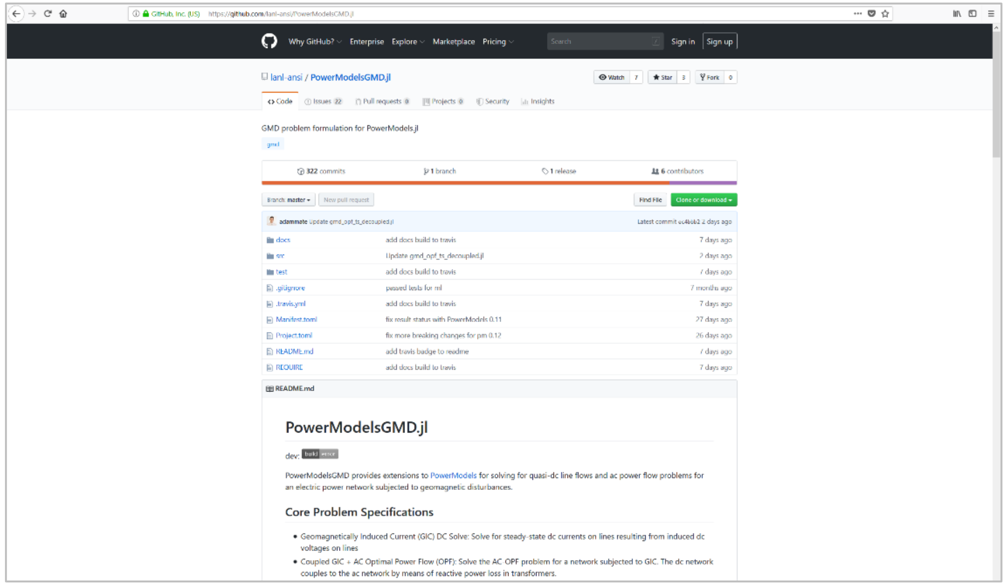
PowerModels.jl

- Julia/JuMP package
- steady-state power network optimization

PowerModelsGMD.jl

- based on PowerModels.jl
- analyzing the impact of GMD/HEMP-E3 events
- fast and reliable results

developed by LANL-ANSI

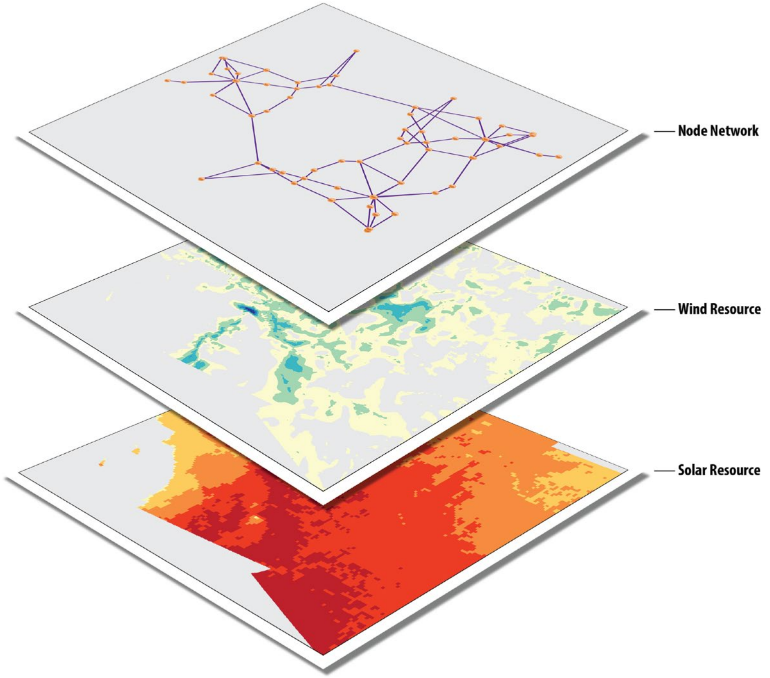


https://github.com/lanl-ansi/PowerModelsGMD.jl

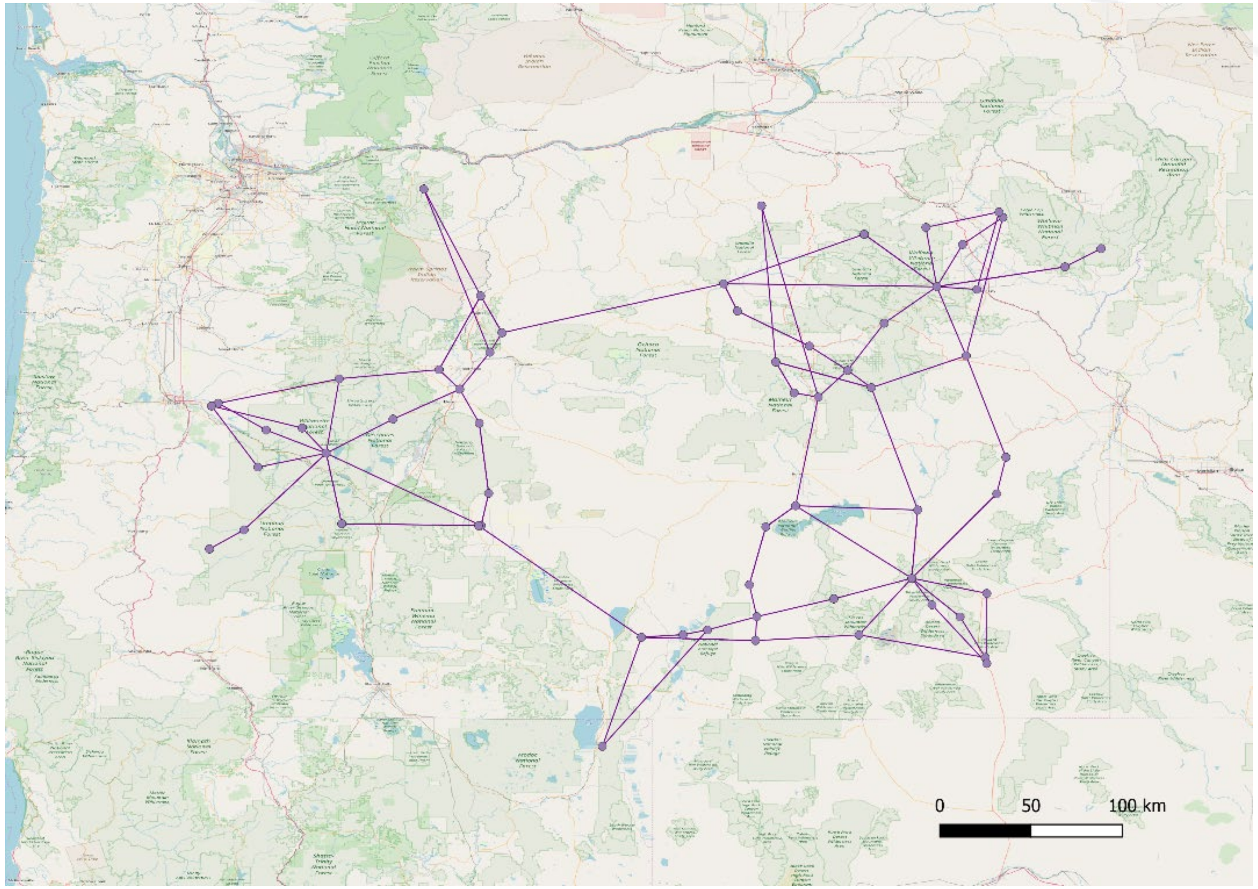
GMD event simulation

RTS-GMLC-GIC

Reliability Test System of the Grid Modernization Laboratory Consortium



https://github.com/GridMod/RTS-GMLC

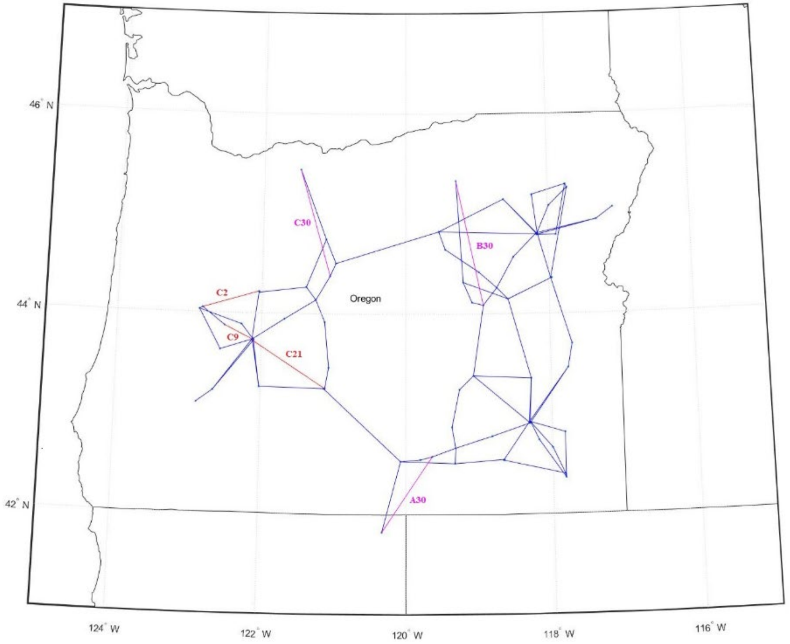


"PowerModelsGMD: An Open-Source framework for analyzing the impact of geomagnetic disturbances and high-altitude electromagnetic pulse E3 impact on bulk transmission systems based on PowerModels.jl," presented at the Military Operations Research Society 87th Symposium, Colorado Springs, CO, 19-Jun-2019.

GMD event simulation

Halloween Solar Storm

- largest ever recorded GMD event
- 10/29/2003 12:00am – 10/30/2003 11:50pm



3-D geophysical modeling technique by OSU:

- determine earth conductivity structure model
- maximum induced voltage: on line C21 - 53.63V (at 10/30 7:56pm)
- longest line not necessarily going to see the largest GICs

AC-OPF results

General Information:

- machine: Intel(R) Core(TM) i7-8809G CPU @ 3.10GHz, 15.9 Gb memory
- simulation period: most intense 30 minutes (10/30 7:45 pm – 8:14 pm) in one-minute time intervals

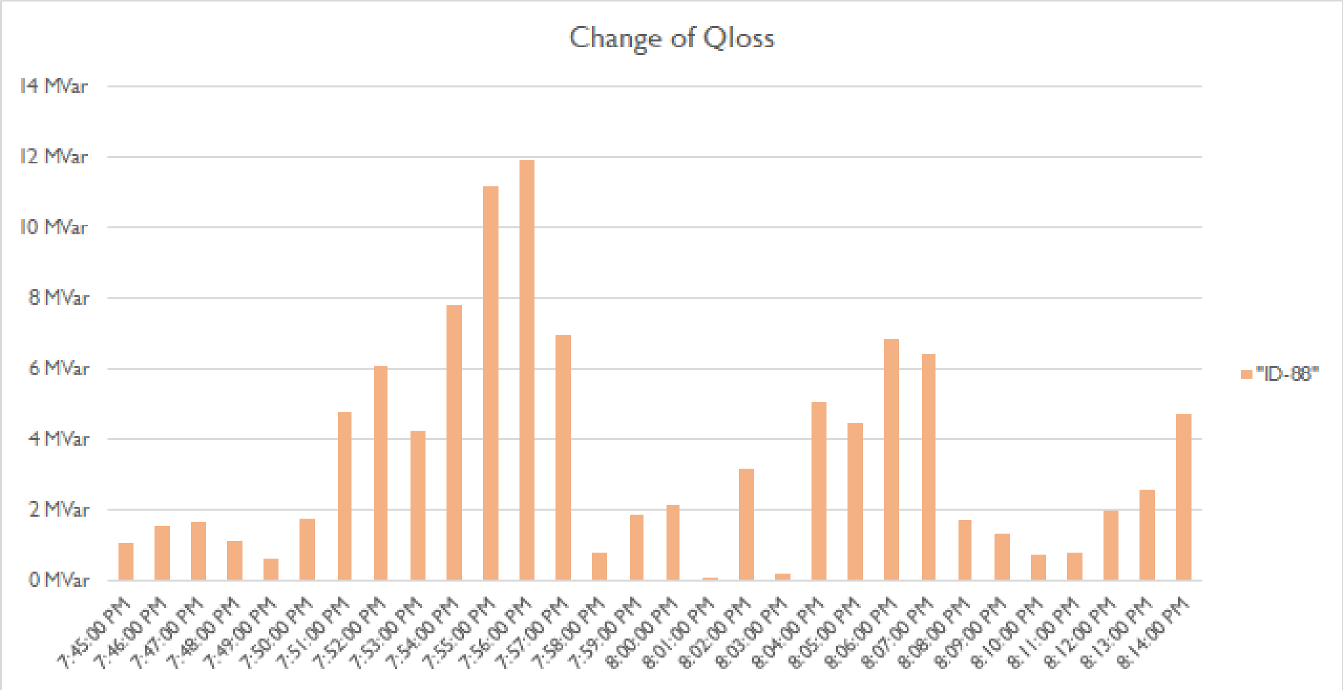
Number of converged periods	30 out of 30
Total comp. time	11.4805 sec
Avg. comp. time	0.3826 sec / period
Avg. cost of operation	$ 87360.49

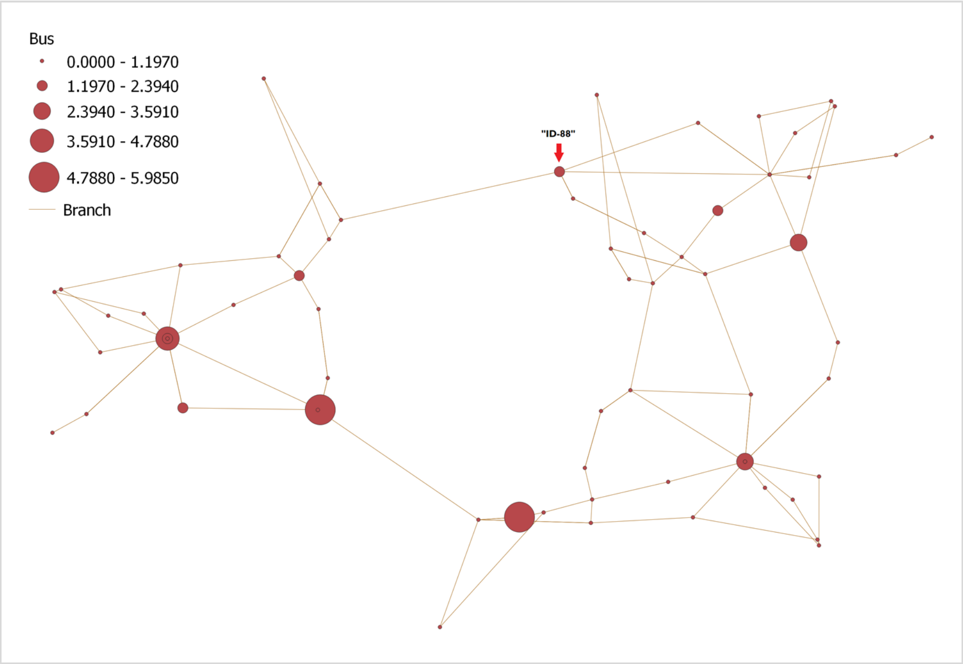
AC-OPF results

Avg. Q_{loss}	77.66 MVar
Lowest Q_{loss}	63.05 MVar (TP-1)
Highest Q_{loss}	116.06 MVar (TP-12)

Caused Q losses:

- greatest loss on “branch ID-88”



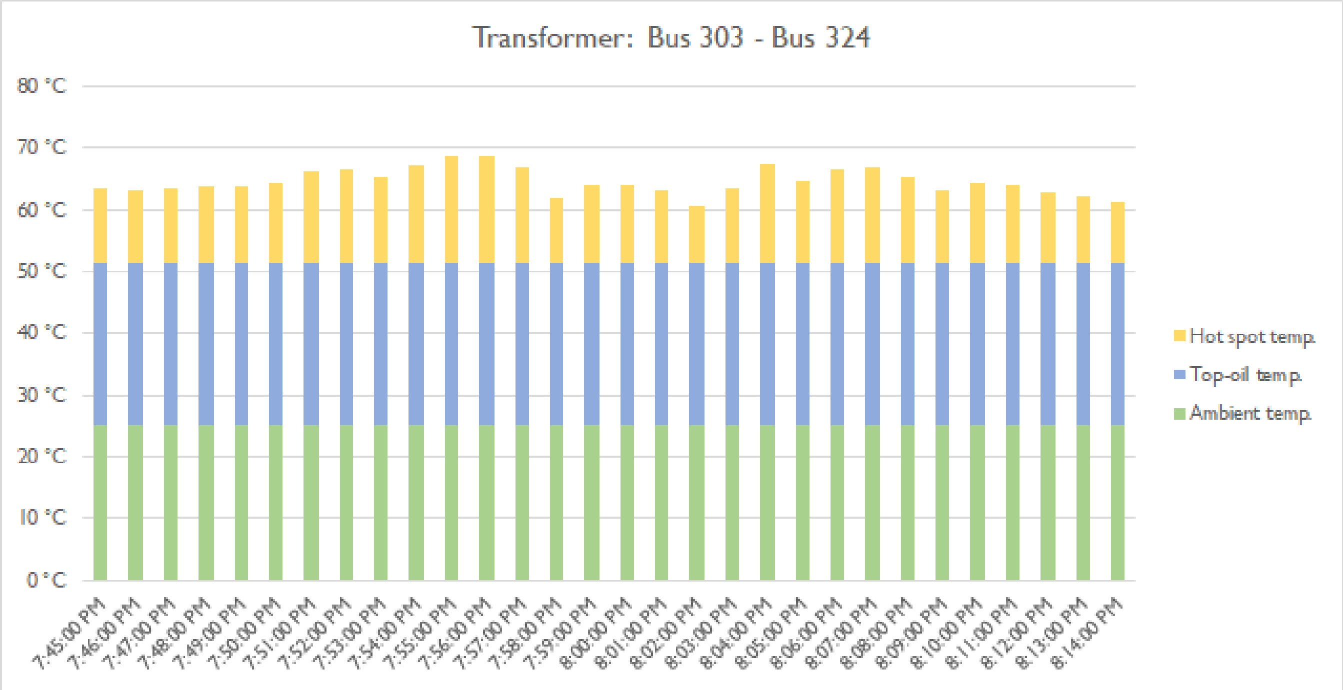


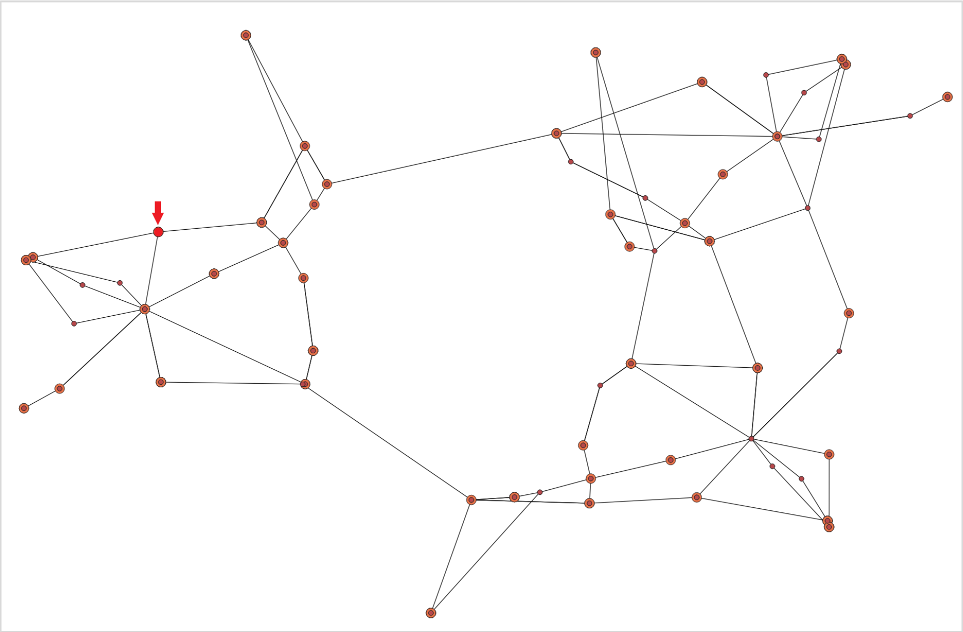
10/30 7:58 PM

AC-OPF results

Transformer temperatures:

- Actual = Ambient + Top-oil + Hot spot

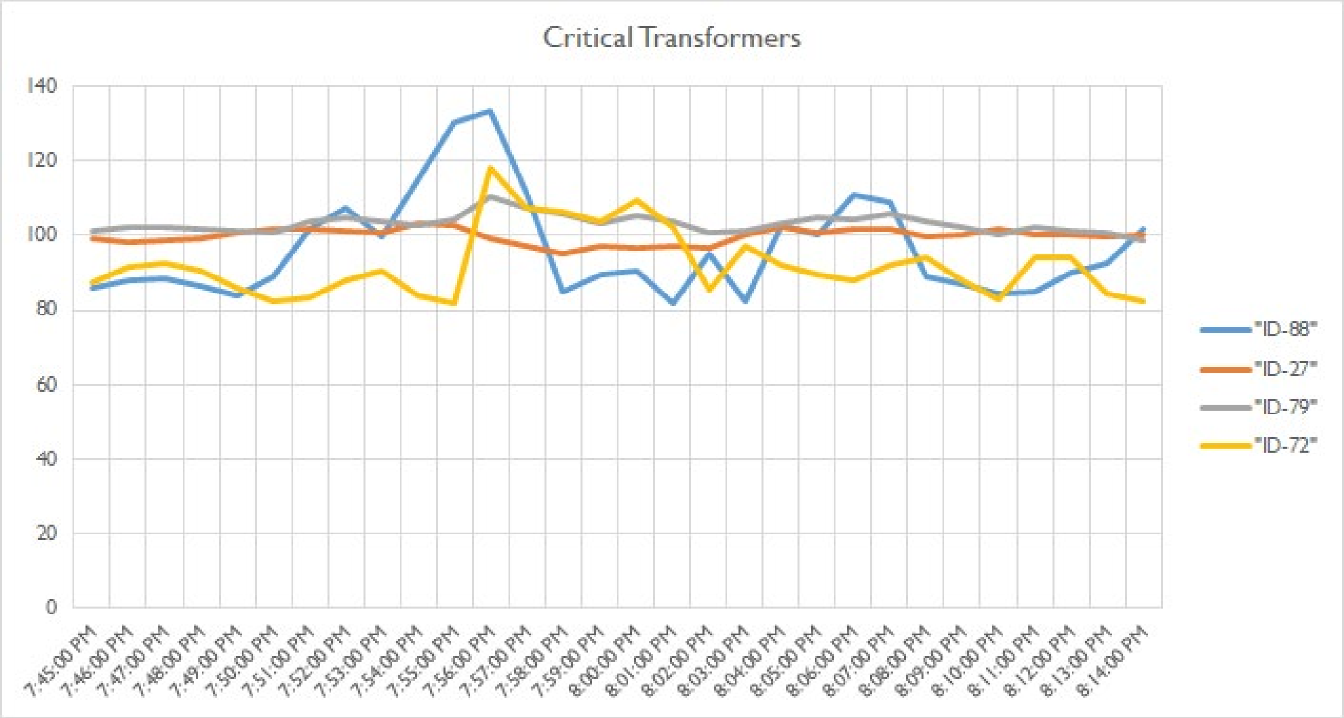


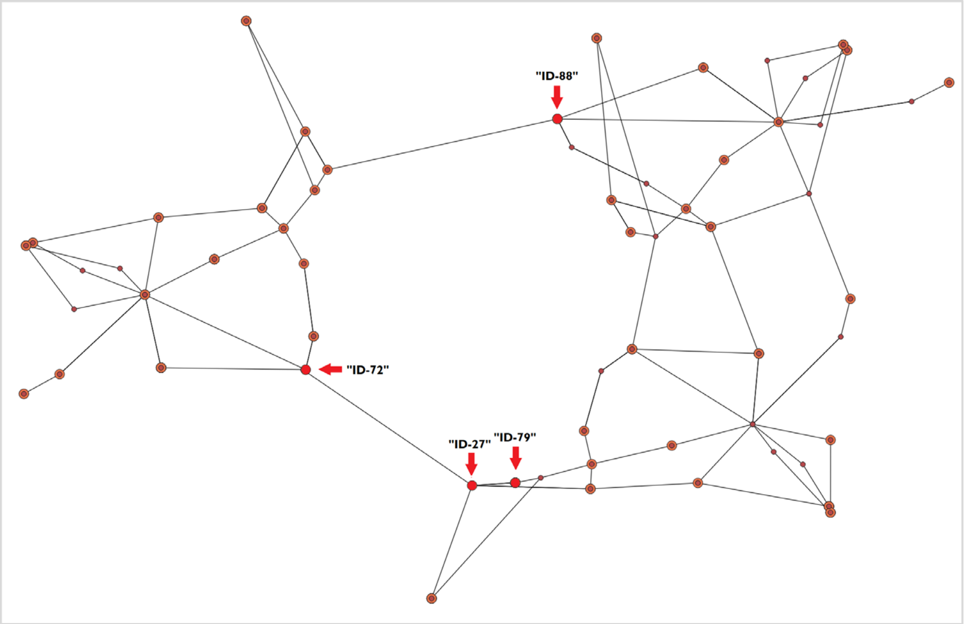


AC-OPF results

Transformer temperatures:

- most critical transformers





Ongoing work

Development of PowerModelsGMD.jl

- Current capabilities:
  - quasi-dc power flow and ac optimal power flow (decoupled and coupled)
  - ac minimum load-shed (MLS)
  - ac optimal transmission switching with load-shed (OTS-MLS)
- Working on:
  - multi-time-period extension of OTS-MLS, since observed GMDs show time-varying behavior => mitigating transformer overheating

Ongoing work

AC power flow equations

$$\sum_{e_{ij}\in E_i^+} p_{ij}^t - \sum_{e_{ji}\in E_i^-} p_{ij}^t = \sum_{g\in G_i} p_g^t - p_i^t - (V_i^t)^2 g_i \quad \forall i\in N^a, t\in T^a$$

$$\sum_{e_{ij}\in E_i^+} (q_{ij}^t + \lambda_e^t) - \sum_{e_{ji}\in E_i^-} q_{ij}^t = \sum_{g\in G_i} q_g^t - q_i^t + (V_i^t)^2 b_i \quad \forall i\in N^a, t\in T^a$$

$$p_{ij}^t = z_e(g_e(V_i^t)^2 - V_i^tV_j^t g_e \cos(\theta_i^t - \theta_j^t) - V_i^tV_j^t b_e \sin(\theta_i^t - \theta_j^t)) \, \forall e_{ij} \in E^a, t\in T^a$$

$$q_{ij}^t = z_e(-(b_e + \frac{c_e}{2})(V_i^t)^2 + V_i^tV_j^t b_e \cos(\theta_i^t - \theta_j^t) - V_i^tV_j^t g_e \sin(\theta_i^t - \theta_j^t)) \, \forall e_{ij} \in E^a, t\in T^a$$

$$p_{ji}^t = z_e(g_e(V_j^t)^2 - V_i^tV_j^t g_e \cos(\theta_j^t - \theta_i^t) - V_i^tV_j^t b_e \sin(\theta_j^t - \theta_i^t)) \, \forall e_{ij} \in E^a, t\in T^a$$

$$q_{ji}^t = z_e(-(b_e + \frac{c_e}{2})(V_j^t)^2 + V_i^tV_j^t b_e \cos(\theta_j^t - \theta_i^t) - V_i^tV_j^t g_e \sin(\theta_j^t - \theta_i^t)) \, \forall e_{ij} \in E^a, t\in T^a$$

Operational limit constraints

$$(p_{ij}^t)^2 + (q_{ij}^t)^2 \le z_e s_e^2, \quad (p_{ji}^t)^2 + (q_{ji}^t)^2 \le z_e s_e^2 \quad \forall e_{ij} \in E^a, t\in T^a$$

$$\underline{v}_i \le v_i^t \le \overline{v}_i \quad \forall i\in N^a, t\in T^a$$

$$|\theta_i^t - \theta_j^t| \le z_e \overline{\theta} + (1 - z_e)\theta^M \quad \forall e_{ij}\in E^a, t\in T^a$$

$$z_g \underline{p}_g \le p_g^t \le z_g \overline{p}_g \quad \forall g\in G, t\in T^a$$

$$z_g \underline{q}_g \le q_g^t \le z_g \overline{q}_g \quad \forall g\in G, t\in T^a$$

$$z_g^t = z_g^{t-1} + y_g^t - \zeta_g^t \quad \forall\, g\in G, t\in T^a \setminus \{0\}$$

$$y_g^t + \zeta_g^t \le 1 \quad \forall\, g\in G, t\in T^a$$

$$\sum_{\rho\in\beta_g} y_g^\rho \le z_g^t \quad \forall\, g\in G, t\in T^a$$

$$\sum_{\rho\in\xi_g} z_g^\rho \le 1 - z_g^t \quad \forall\, g\in G, t\in T^a$$

$$\overline{\gamma}_g \ge p_g^t - p_g^{t-1} - \overline{p}_g y_g^t \quad \forall\, g\in G, t\in T\setminus\{0\}$$

$$\underline{\gamma}_g \ge p_g^{t-1} - p_g^t - \overline{p}_g z_g^t \quad \forall\, g\in G, t\in T\setminus\{0\}$$

$$0 \le p_i^t \le \overline{p}_t^i \quad 0 \le q_i^t \le \overline{q}_t^i \quad \forall i\in N, t\in T^a$$

GIC effects on transformers

$$\sum_{e\in E_i^+} I_e^t - \sum_{e\in E_i^-} I_e^t = a_i V_i^d \quad \forall i\in N^d$$

$$I_e^t = z_{\vec{e}}\, a_e(V_i^t - V_j^t + J_{\vec{e}}) \quad \forall e_{ij}\in\mathcal{E}^d, t\in T^d$$

$$\widetilde{I}_e^t \ge \begin{cases} I_{eH}^t & \text{if } e\in E^\Delta \\ \frac{\alpha_e I_{eH}^t + I_{eL}^t}{\alpha_e} & \text{if } e\in E^y \\ \frac{\alpha_e I_{eS}^t + I_{eC}^t}{\alpha_e + 1} & \text{if } e\in E^\infty \\ 0 & \text{otherwise} \end{cases} \quad \widetilde{I}_e^t \ge - \begin{cases} I_{eH}^t & \text{if } e\in E^\Delta \\ \frac{\alpha_e I_{eH}^t + I_{eL}^t}{\alpha_e} & \text{if } e\in E^y \\ \frac{\alpha_e I_{eS}^t + I_{eC}^t}{\alpha_e + 1} & \text{if } e\in E^\infty \\ 0 & \text{otherwise} \end{cases} \quad \forall e\in E^a, t\in T^a$$

$$0 \le \widetilde{I}_e^d \le \overline{I}_e^d \quad \forall e\in\mathcal{E}^\tau$$

Eqs. (5), (6)

$$\delta_e^t + \eta_e^t \le \mathcal{T}_e \quad \forall e\in E^\Delta \cup E^y \cup E^\infty, t\in T^a$$

$$\lambda_e^t = k_e V_i^t \widetilde{I}_e^t \quad \forall e_{ij}\in E^a, t\in T^a$$

$$z_e, z_g, y_g, \zeta_g \in \{0,1\} \quad \forall e\in\mathcal{E}^a, g\in G$$

Supporting Constraints

$$z_g \le \sum_{e\in E_i^+\cup E_i^-} z_e \quad \forall i\in N_l^a, g\in G_i$$

$$z_g \psi_g^t \ge \kappa_g^2 (p_g^t)^2 \quad \forall g\in G, t\in T^a$$

$$\widetilde{I}_e^t \le z_e \overline{I}_e^d \quad \forall e\in E^a, t\in T^a$$

THANK YOU!