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PAVING THE WAY FOR GRID MODERNIZATION

Blocking Device Placement for Mitigating the Effects of Geomagnetically Induced Currents

Hao Zhu

Dept. of Electrical & Computer Engineering

University of Illinois, Urbana-Champaign

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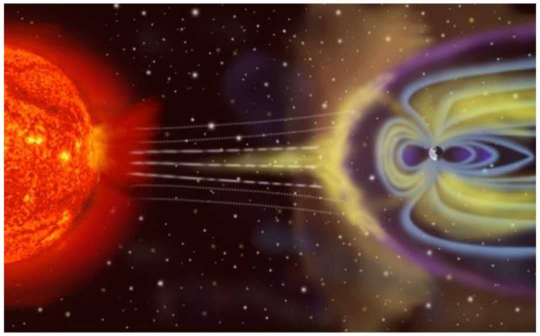
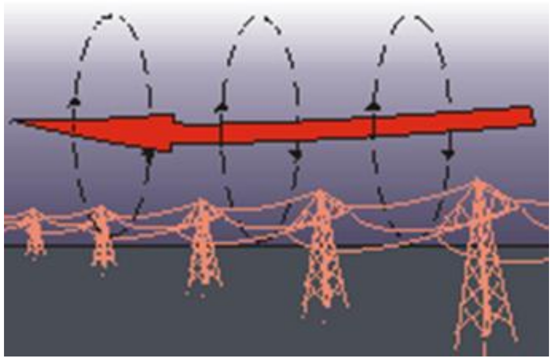
Geomagnetically Induced Currents (GICs)

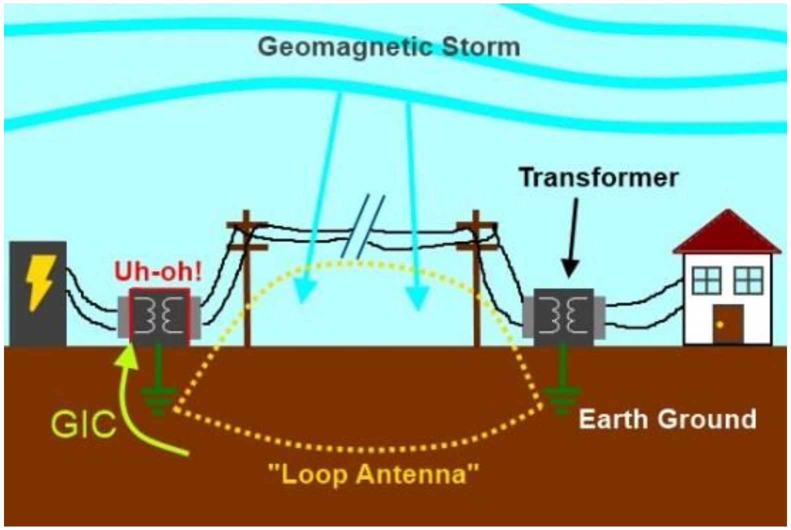
- Solar storms disturb the Earth's magnetic field



- Change of magnetic field induces electric field (E-field)

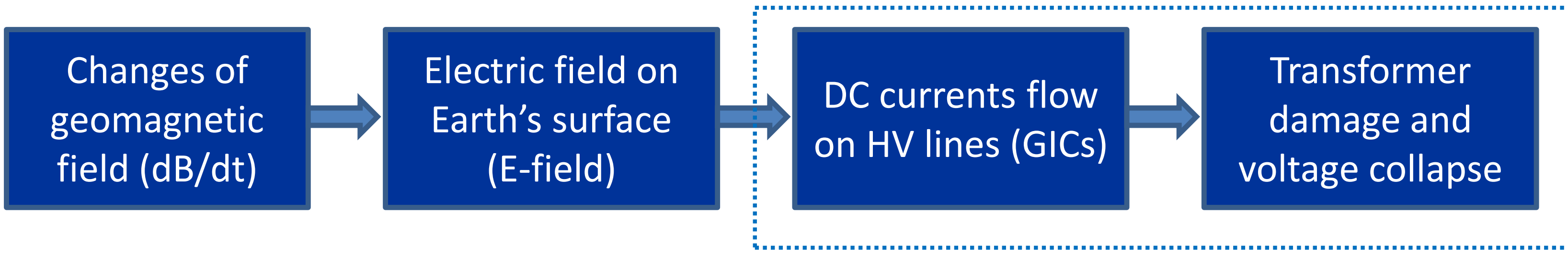


- Geomagnetic induced currents (GICs) flow through the power lines



- Quasi-dc GICs disrupt power grid with excessive *reactive power losses*

GIC Blocking Device Placement



- Blackouts due to voltage collapse and/or equipment failures (March 1989 in Quebec)

- Mitigation strategies: installation of GIC blocking devices
  - Capacitive circuits to block dc GIC flows, but may redistribute to other parts of system [Bolduc et al'05] [Arajarvi et al'11]

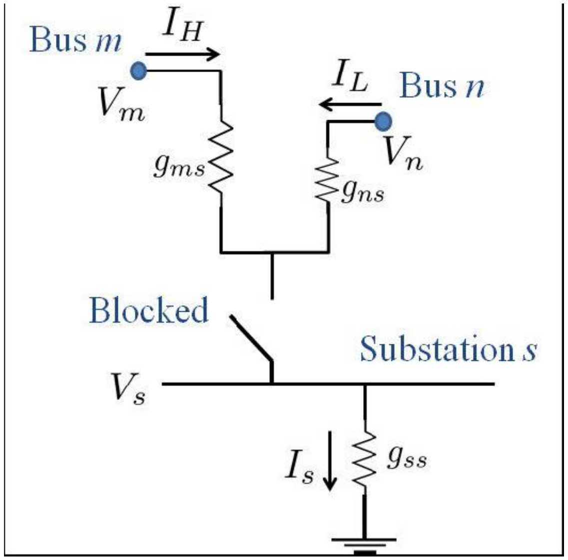
  → placement is important!

GIC Modeling

- Linear dc network analysis computes effective GIC: $\mathbf{I}^{GIC} = \mathbf{\Phi V} = (\mathbf{\Phi G}^{-1}\mathbf{H})\mathbf{E}$
- At each transformer $Q_t = K_t \left| I_t^{GIC} \right| \ \forall\, t.$
- Collectively, $\mathbf{Q} = |\mathbf{CE}| = |\mathbf{K\Phi G}^{-1}\mathbf{HE}|$

  where the coefficient matrix $\mathbf{C} := \mathbf{K\Phi G}^{-1}\mathbf{H}$
- GIC blocking devices (GBDs) disconnect buses from substation, and thus change the network topology (effectively update matrices $\mathbf{\Phi}$ and $\mathbf{G}$)
- Given all blocked transformers with GBDs in $\mathcal{B}$

$$\mathbf{C}(\mathcal{B}) = \mathbf{K}\Big(\mathbf{\Phi} - \sum_{t\in\mathcal{B}} \mathbf{\Phi}_t\Big)\Big(\mathbf{G} - \sum_{t\in\mathcal{B}} \mathbf{G}_t\Big)^{-1}\mathbf{H}$$



Example: GBD modeling at a conventional transformer located in Substation *s*, with HV Bus *m* and LV Bus *n*

$$\mathbf{G} \leftarrow \underbrace{\mathbf{G} - g_{ms}\mathbf{e}_{ms}\mathbf{e}_{ms}^T - g_{ns}\mathbf{e}_{ns}\mathbf{e}_{ns}^T}_{\mathbf{G}_t}$$

GBD Placement Problem

- Two QLoss metrics robust to worst-case E-field scenario:

  i) the maximum QLoss among all transformers

$$\mathcal{Q}^{\max}(\mathcal{B}) := \max_t \max_{\|\mathbf{E}\|_2=1} \left|\mathbf{C}_t(\mathcal{B})\mathbf{E}\right| = \max_t \|\mathbf{C}_t(\mathcal{B})\|_2$$

  ii) the sum-squared (ss) QLoss over all transformers

$$\mathcal{Q}^{\mathrm{ss}}(\mathcal{B}) := \sum_t \max_{\|\mathbf{E}\|_2=1} \left|\mathbf{C}_t(\mathcal{B})\mathbf{E}\right|_2^2 = \|\mathbf{C}(\mathcal{B})\|_F^2$$

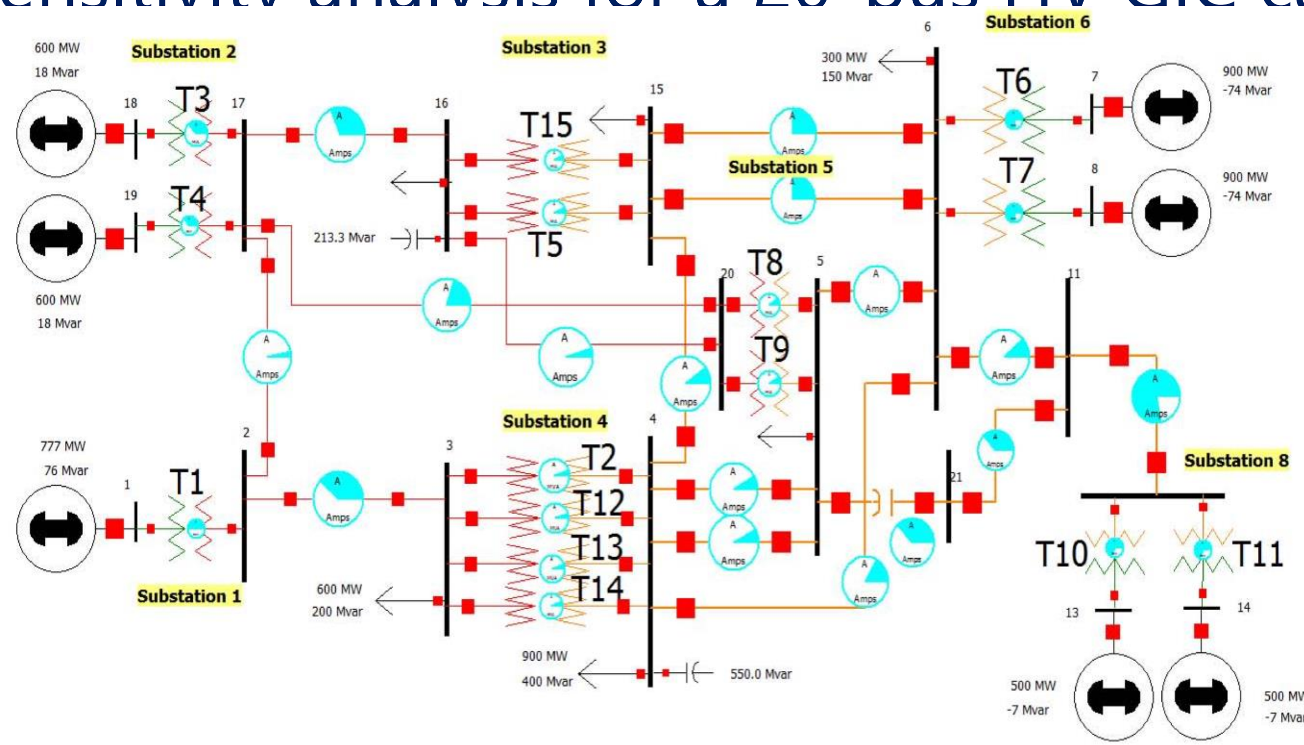
- Given the number of GBDs N_B, the placement problem formulated as

$$\begin{aligned} \min \quad & \mathcal{Q}(\mathcal{B}) \\ \text{s. t.} \quad & |\mathcal{B}| \leq N_B \end{aligned} \qquad \textbf{(GBD)}$$

with either QLoss metric as the minimization objective

Linear Sensitivity Analysis

- Local GIC blocking effects have been observed
  - Blocked GICs redistributed to other transformers at the same substation
- Linear sensitivity analysis for a 20-bus HV GIC case [Horton



Sensitivity Factor Results

TABLE I
TBDF COEFFICIENTS AT TRANSFORMER τ FOR BLOCKING TRANSFORMER t

t \ τ	T1	T2	T3	T6	T8	T10	T14	T15
T1	∼	-0.0015	**0.2159**	0.0478	0.1095	0.0043	-0.0216	0.0574
T5	0.0027	0.0009	0.0028	0.0081	0.0052	0.0007	0.0011	**0.6567**
T12	0.0014	**0.2445**	0.0002	0.0004	0.0009	0.0000	**0.2253**	0.0004
T13 (HV)	-0.0017	**0.2683**	0.0001	0.0011	0.0025	0.0001	**0.3077**	0.0012

TABLE II
TBDF COEFFICIENTS AT TRANSFORMER τ FOR BLOCKING TRANSFORMER t WITH T5 BLOCKED

t \ τ	T1	T2	T3	T6	T8	T10	T14	T15
T5	0.0027	0.0009	0.0028	0.0081	0.0052	0.0007	0.0011	**0.6567**
T15 (with T5 blocked)	0.0647	0.0206	0.0678	**0.1931**	**0.1251**	0.0176	0.0257	∼
T12	0.0014	**0.2445**	0.0002	0.0004	0.0009	0.0000	**0.2253**	0.0004
T12 (with T5 blocked)	0.0014	**0.2445**	0.0002	0.0004	0.0009	0.0000	**0.2253**	0.0007

Substation Blocking Problem

- Using the sensitivity based approximation, problem (GBD) becomes

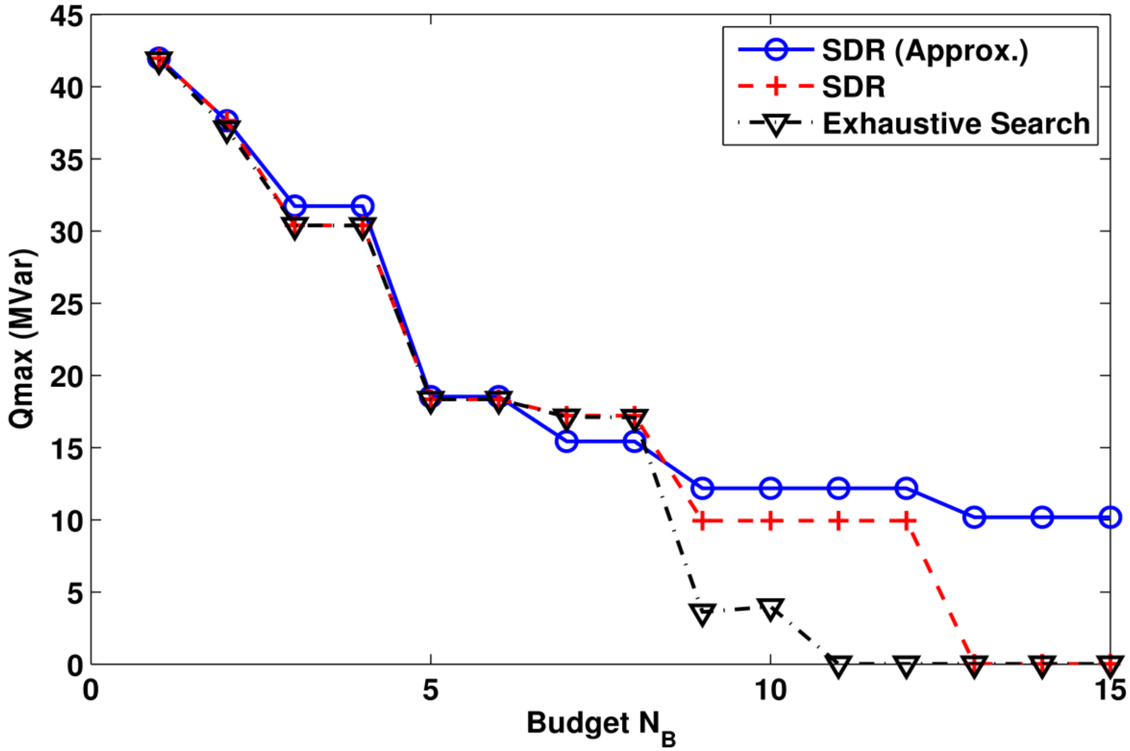
$$\begin{aligned} \min_{\{x_s\},Q^{\max}} \quad & Q^{\max} \\ \text{s.t.} \quad & \left\| \mathbf{C}_t + \textstyle\sum_s x_s \tilde{\mathbf{C}}_{s,t} \right\|_2^2 \le Q^{\max}, \quad \forall t \\ & x_s \in \{0,1\}, \text{ and } \textstyle\sum_s w_s x_s \le N_B \end{aligned} \qquad \textbf{(max-Q)}$$

$$\begin{aligned} \min_{\{x_s\}} \quad & \left\| \mathbf{C} + \sum_s x_s \tilde{\mathbf{C}}_s \right\|_F^2 \\ \text{s.t.} \quad & x_s \in \{0,1\}, \text{ and } \textstyle\sum_s w_s x_s \le N_B \end{aligned} \qquad \textbf{(ss-Q)}$$

- To solve this mixed-integer program, we develop an efficient *semidefinite relaxation* based solver to relax the binary constraint

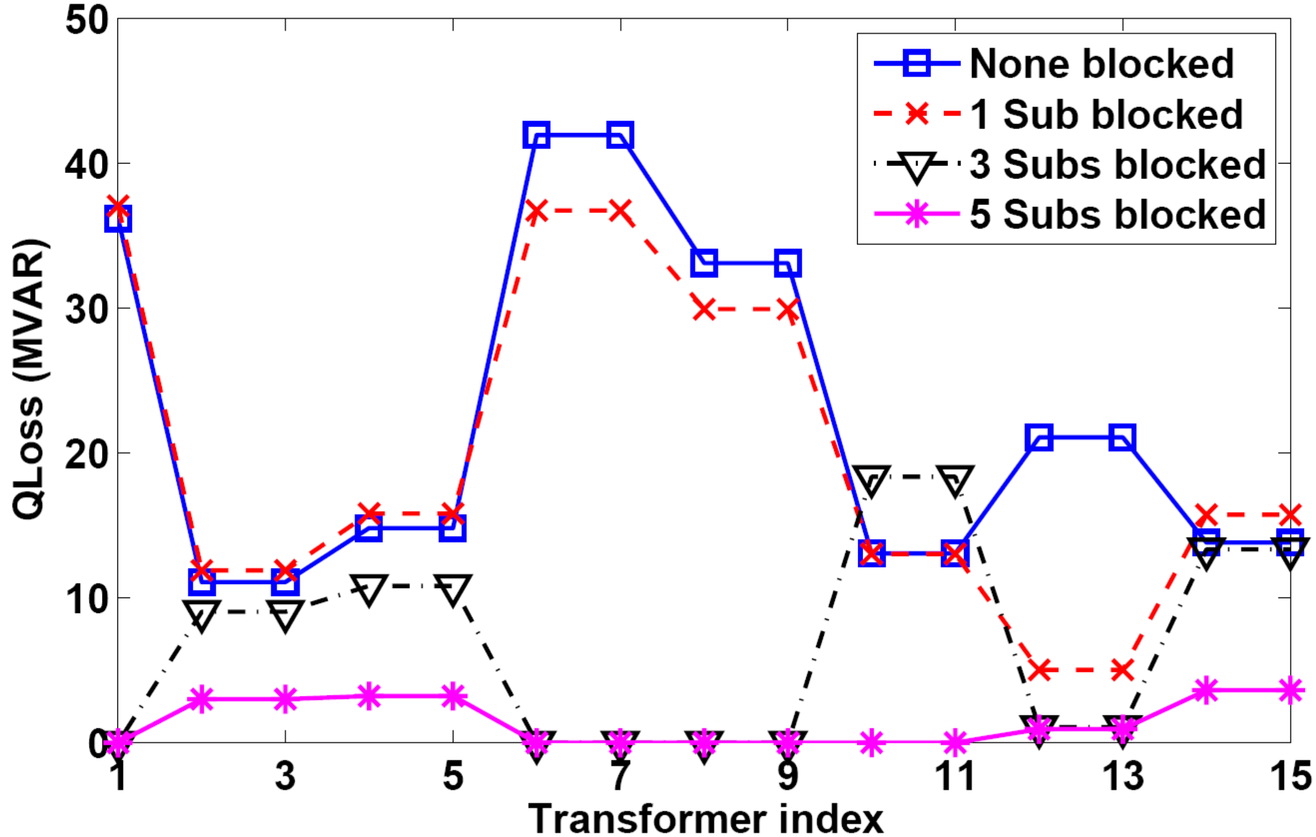
Qmax Minimization

- For < 8 GBDs, the SDR approach is very competitive to the benchmark exhaustive search (ES) method
- The approx. cost attained by SDR approaching the actual cost
- Max G …)s



GIC Redistribution Effects

- Blocking more substations does not decrease Qloss uniformly at every transformer



Conclusions

- GIC hazard mitigation crucial for power grid reliability and stability
- GIC blocking device placement to block power network GIC flow
  - Semidefinite relaxation (SDR) to tackle the binary selection constraint
- Numerical tests show the effectiveness of the SDR-based approach

- Future research directions
  - Test the proposed methods on large real cases at high-latitude regions
  - Investigate the GBD effects to neighboring areas
  - Extend to other GIC operational mitigation strategies