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DECOUPLED, DECENTRALIZED, LQR-BASED CONTROLS FOR E3 HEMP/GMD MITIGATION ON THE POWER GRID

CONNOR A. LEHMAN (SNL), TIM J. DONNELLY (SNL), WAYNE W. WEAVER (MTU), DAVID G. WILSON (SNL), RUSH D. ROBINETT III (MTU)

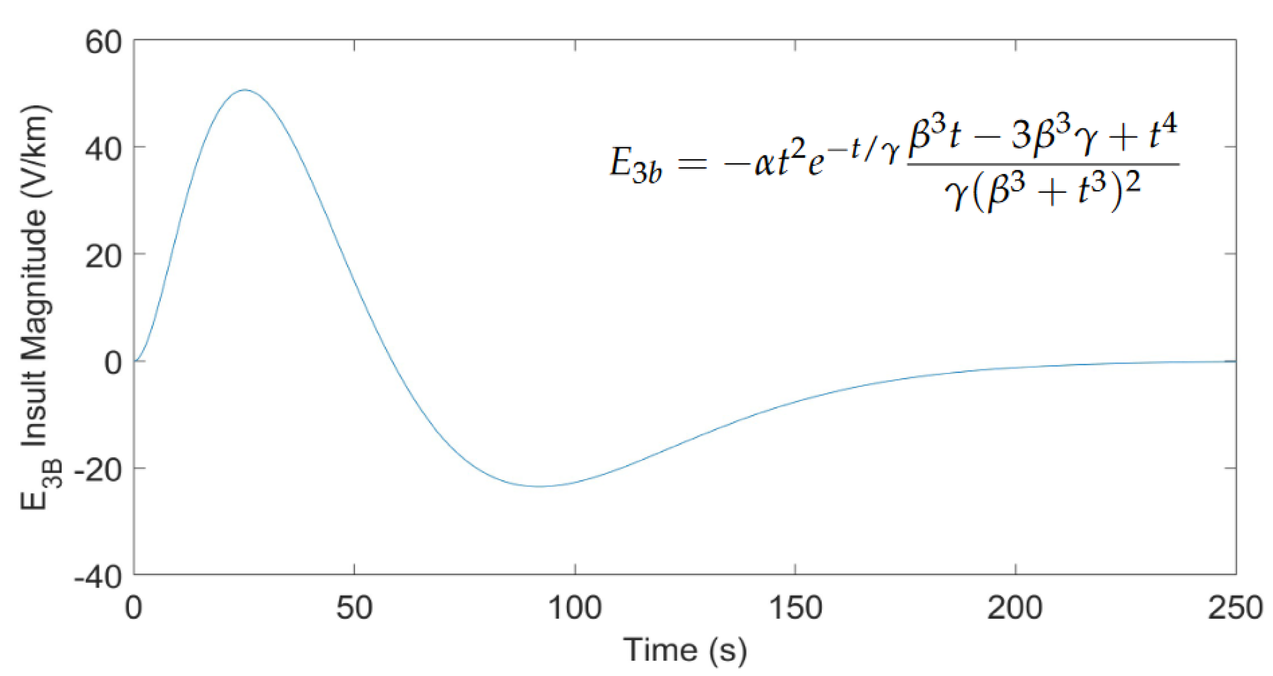
Introduction

Objective of Study:

Prevent magnetic core saturation of transformers during an E3b high altitude electromagnetic pulse (HEMP) insult

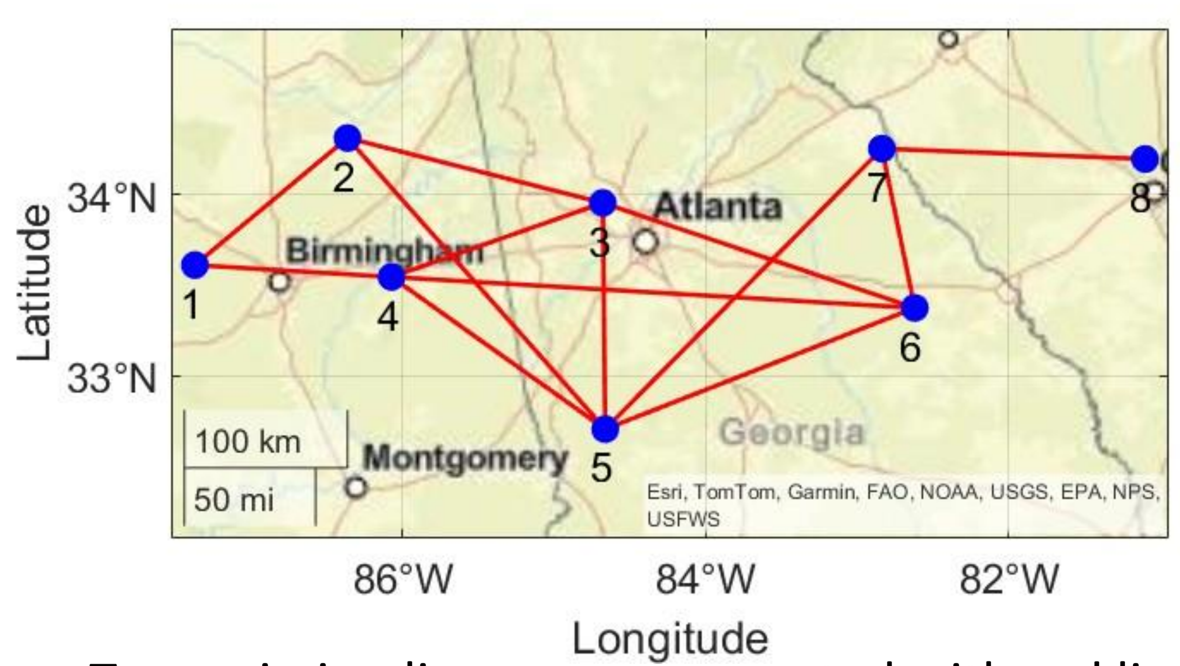
- Long-term exposure to high common mode currents cause distortion and overheating of transformers

Field Strength of Simulated HEMP Insult

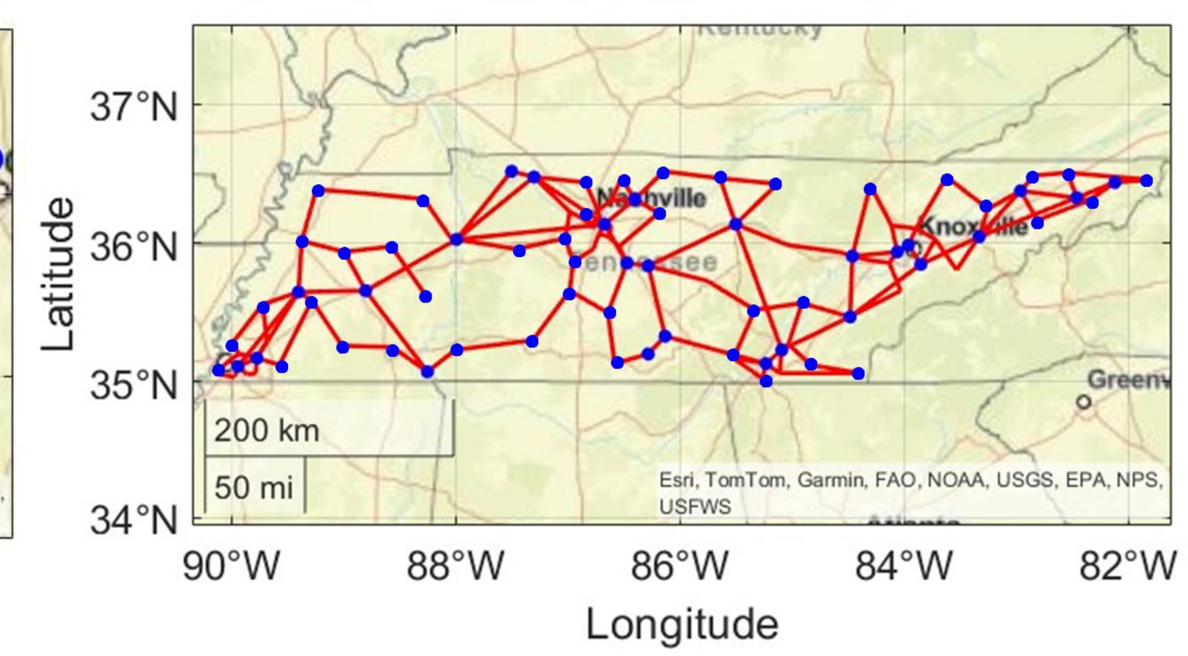


Grid Models

Horton et al. Model [1]:



Birchfield et al. Model [2]:

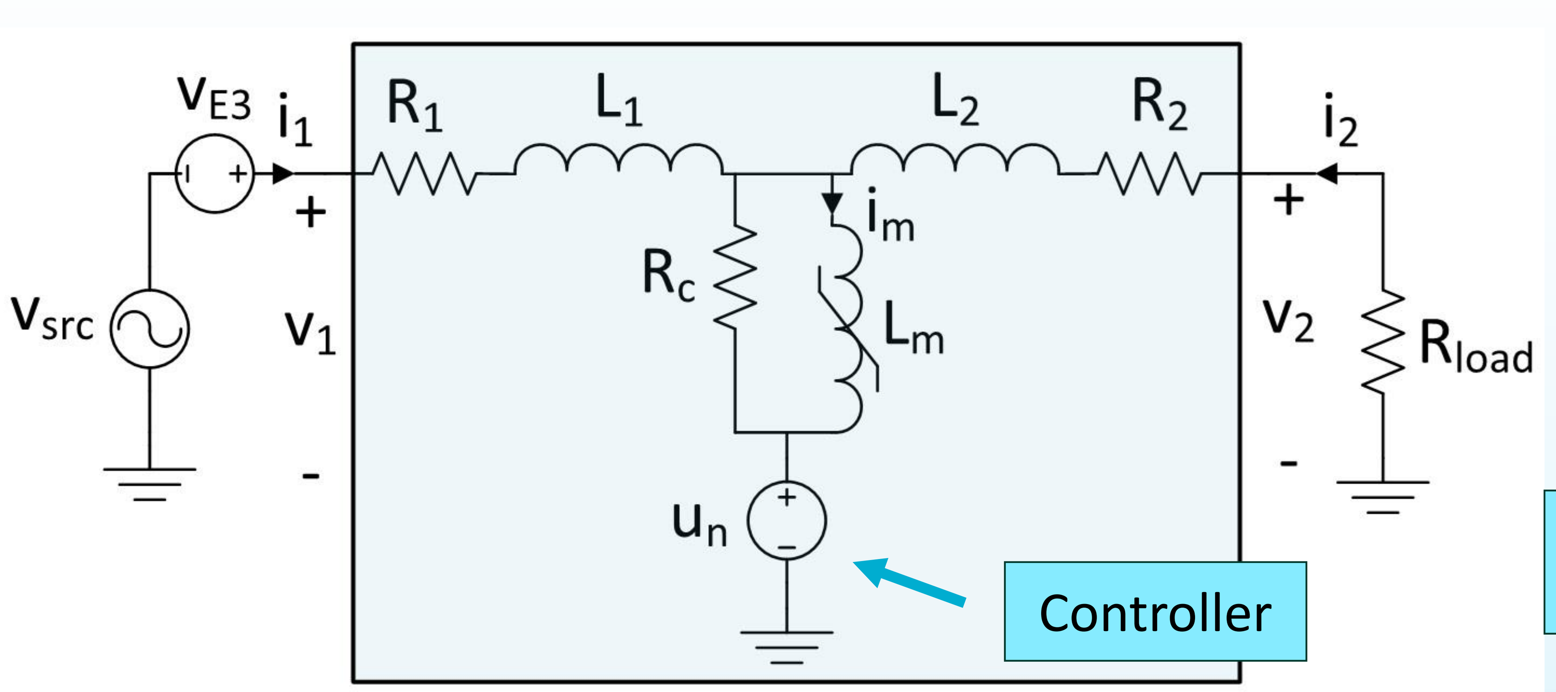


- Transmission lines are represented with red lines and substations are represented with blue dots
- Substations house between 0-4 transformers, with details present in [1,2]
- The π-model is used to represent the transmission lines in the system
- HEMP coupled to grid: $V_j = E3b(t) * cos\delta_j$, where V_j is the voltage source on the j-th transmission line and δ_j is the angle between the field and the j-th transmission line

Transformer Model

Per-Phase Transformer:

- Per-phase model simulates the dynamics of the 0 axis in the stationary frame of reference using dq0 coordinates
- Blocking controller is placed on neutral path of transformers and provides voltage as control effort



Theoretical Framework

Magnetic Saturation:

- Saturation occurs when the magnetic core will no longer store additional magnetic flux and magnetic flux begins to be stored in the air
- Saturation in this study's models is defined as any value of magnetic flux below -1.2 pu and above 1.2 pu
- A transformer with a saturating core is inherently nonlinear, but will act linearly when the transformer's magnetic core remains unsaturated

The Local Linear Quadratic Regulator (L-LQR):

- LQR is an optimal feedback controller when acting within the system's linear regime
- L-LQR is a decentralized, decoupled feedback controller designed for each transformer with power flowing in and out of primary and secondary sides of transformer treated as disturbances
- Optimal feedback gains for each transformer as individual subsystems are found from

Cost function at i-th transformer → $J_i = \int_0^{t_f} x_i^T Q_i x_i + u_i^T R_i u_i \, , \qquad u_i = -K_i x_i$ ← Control for cost minimization

- Values of Q are selected so that the system provides sufficient effort to keep the core magnetic flux within saturation bounds, ensuring that the system remains linear

Results

Horton et al. Model: *Saturated values are shown in red*

RESULTS FROM THE UNMITIGATED 20-BUS MODEL

Txfrmr	Peak Flux (pu)	Txfrmr	Peak Flux (pu)	Txfrmr	Peak Flux (pu)
1	1.975	6	-2.444	11	-1.620
2	-1.089	7	-2.444	12	1.290
3	1.171	8	1.385	13	-1.089
4	1.171	9	1.385	14	1.515
5	1.383	10	-1.620	15	1.383

RESULTS FROM THE MITIGATED 20-BUS MODEL

Txfrmr	Peak Flux (pu)	Txfrmr	Peak Flux (pu)	Txfrmr	Peak Flux (pu)
1	$5.599 \cdot 10^{-3}$	6	0.2814	11	0.6354
2	0.3839	7	-0.2814	12	0.3839
3	$4.020 \cdot 10^{-3}$	8	0.1631	13	0.3839
4	$4.020 \cdot 10^{-3}$	9	0.1631	14	0.3849
5	0.1614	10	-0.6354	15	0.1614

Birchfield et al. Model:

EXTREMAL PU VALUES OF UNMITIGATED TRANSFORMERS.

Txfrmr	Peak Flux (pu)	Txfrmr	Peak Flux (pu)	Txfrmr	Peak Flux (pu)
1	-1.640	21	1.427	41	-1.488
2	-1.873	22	1.427	42	-1.488
3	-1.321	23	-1.040	43	-1.488
4	1.802	24	-1.040	44	-1.283
5	0.8933	25	-0.9795	45	-1.283
6	-2.268	26	-0.9795	46	-1.283
7	1.457	27	1.183	47	1.592
8	2.041	28	1.183	48	1.592
9	2.041	29	-0.8466	49	1.592
10	-1.606	30	-0.8466	50	1.592
11	-0.1447	31	1.433	51	1.592
12	-0.1447	32	-1.587	52	-1.350
13	0.5280	33	-1.587	53	-1.350
14	-2.470	34	0.3204	54	-1.350
15	2.212	35	2.189	55	-1.350
16	-1.330	36	2.189	56	-1.250
17	0.8415	37	2.189	57	1.846
18	-1.525	38	2.189	58	-2.634
19	1.341	39	2.189	59	-2.634
20	-1.693	40	-1.488	60	-2.634

EXTREMAL PU VALUES OF MITIGATED TRANSFORMERS.

Txfrmr	Peak Flux (pu)	Txfrmr	Peak Flux (pu)	Txfrmr	Peak Flux (pu)
1	-0.6197	21	0.8434	41	-0.4825
2	-0.7918	22	0.8434	42	-0.4825
3	-0.2695	23	-0.4765	43	-0.4825
4	0.6878	24	-0.4765	44	0.0411
5	0.0598	25	0.0342	45	0.0411
6	-1.0203	26	0.0342	46	0.0411
7	0.3560	27	0.4641	47	0.4670
8	0.9923	28	0.4641	48	0.4670
9	0.9923	29	-0.3133	49	0.4670
10	-0.5937	30	-0.3133	50	0.4670
11	0.1099	31	0.5368	51	0.4670
12	0.1099	32	-0.8765	52	-0.3107
13	-0.0093	33	-0.8765	53	-0.3107
14	-1.1207	34	-0.0142	54	-0.3107
15	0.9530	35	0.8418	55	-0.3107
16	-0.1997	36	0.8418	56	-0.3107
17	-0.0431	37	0.8418	57	0.5375
18	-0.4911	38	0.8418	58	-0.8859
19	0.2958	39	0.8418	59	-0.8859
20	-0.6519	40	-0.4825	60	-0.8859

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[1] R. Horton, D. Boteler, T. J. Overbye, R. Pirjola, and R. C. Dugan "A Test Case for the Calculation of Geomagnetically Induced Currents" in IEEE Transactions of Power Delivery, vol. 27, no. 4, pp. 2368-2373, Oct. 2012
[2] Birchfield, Adam & Gegner, Kathleen & Xu, Ti & Shetye, Komal & Overbye, Thomas. (2016). Statistical Considerations in the Creation of Realistic Synthetic Power Grids for Geomagnetic Disturbance Studies. IEEE Transactions on Power Systems. 32. 1-1. 10.1109/TPWRS.2016.2586460.

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