Comparative Study of the Reactive Power Consumption of a Dominion Energy Virginia Autotransformer due to Geomagnetically-induced Current

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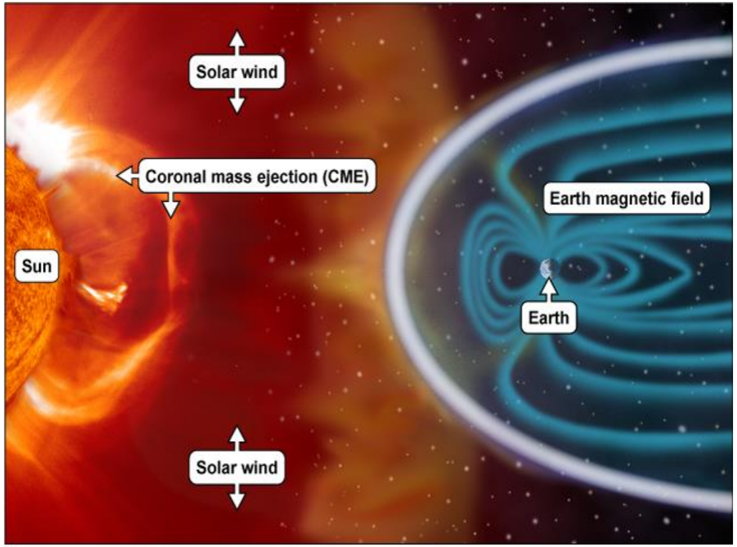
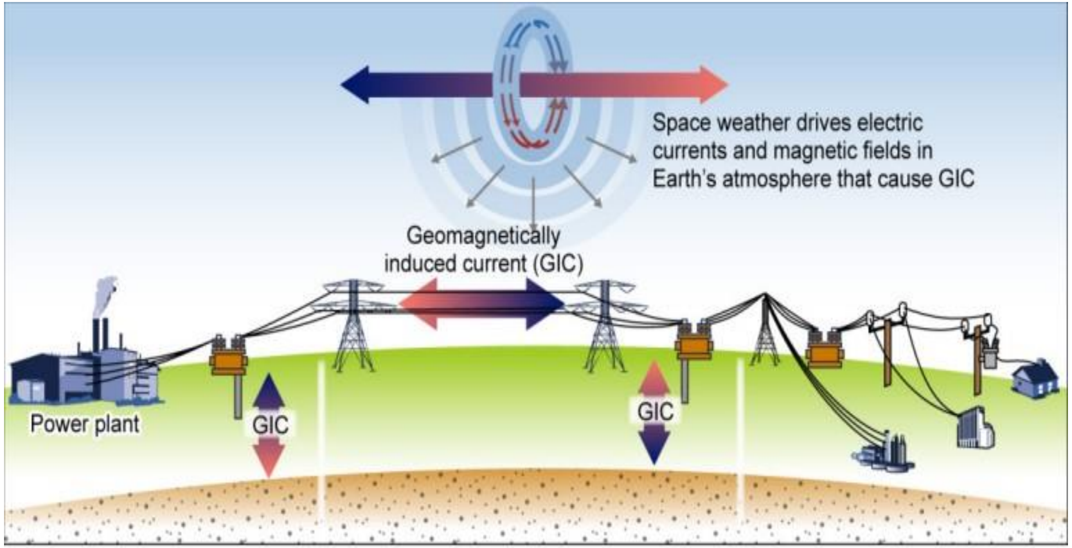
Dominion Energy

GIC and Its Effects on Power Systems

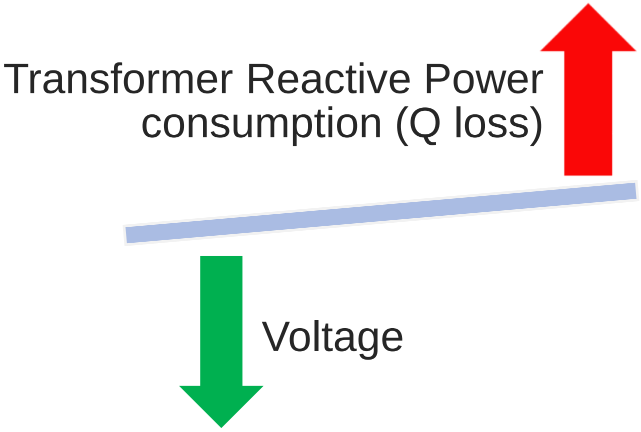


Source: National Aeronautics and Space Administration (illustration). | GAO-19-98



Sources: GAO (presentation); Art Explosion (images). | GAO-19-98

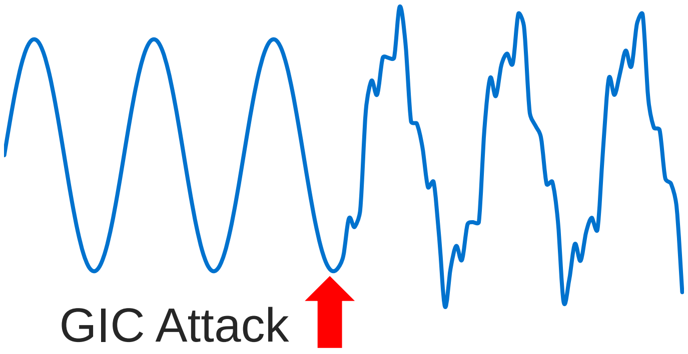
GIC and Its Effects on Power Systems



Transformer Reactive Power consumption (Q loss)

Voltage

Generation of Harmonics



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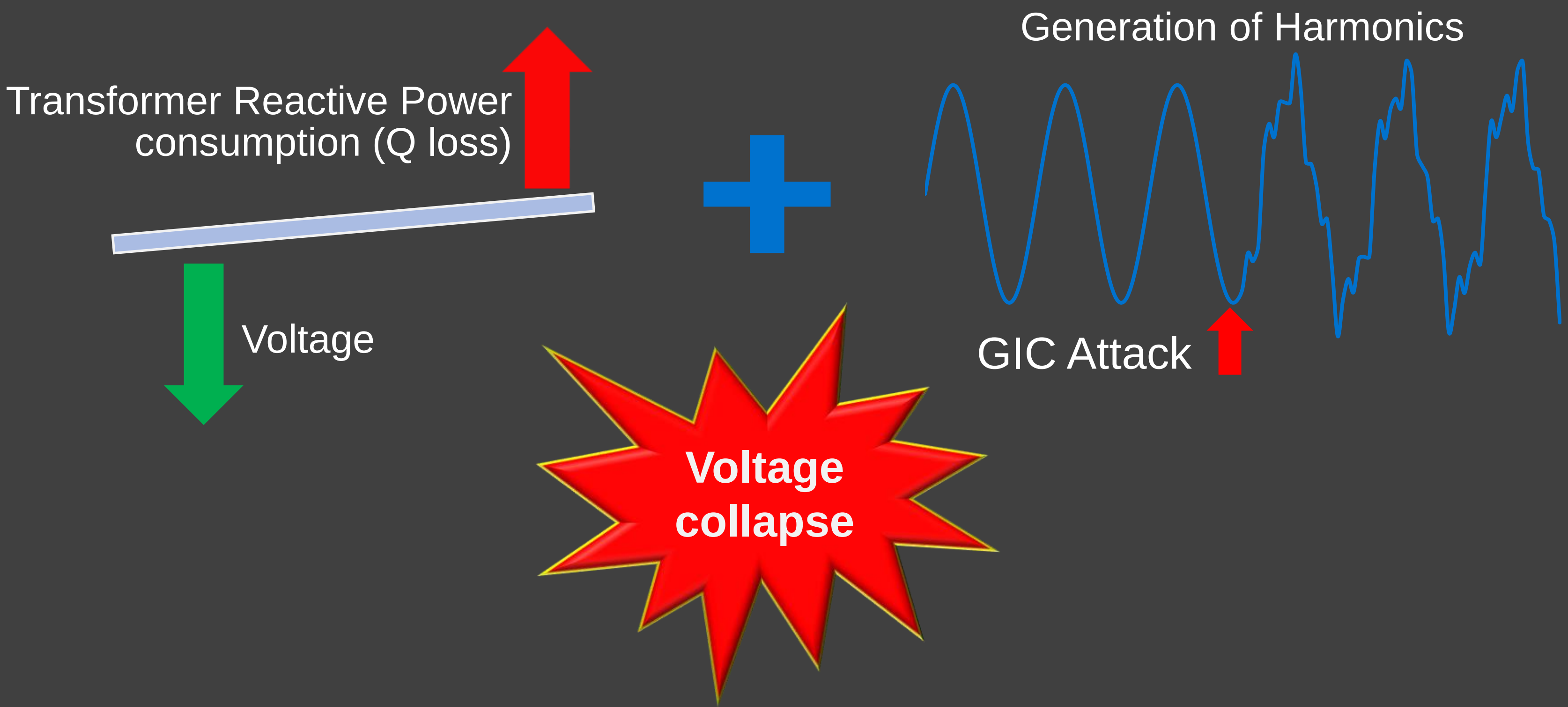


Transformer Reactive Power consumption (Q loss)

Voltage

Generation of Harmonics

GIC Attack

Voltage collapse

GIC and its effects on Power Systems

Previous GIC-related efforts by DEV

Grid Study and Modeling [1], [2]

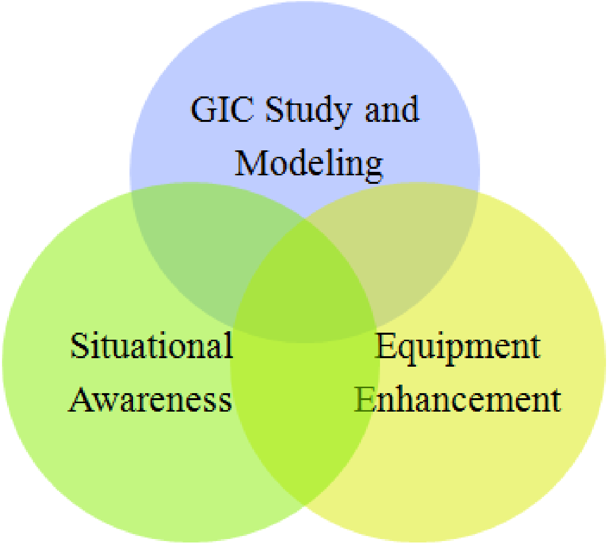
- On-site test on HV transformer
- Modeling of DVP system under extreme GMD events

Situational Awareness [1]

- Installation of GIC monitors and visualization tool
- Risk assessment of NOAA storm forecasts

Equipment Enhancement [1]

- Improved EHV transformer design
- Improved Capacitor bank protection scheme



Research Aim

To establish a relationship between GIC and reactive power consumption for a transformer that is generalizable across multiple operating conditions and network topologies

Motivation

- With a GIC monitor, effects of a measured GIC level at a transformer will be easily computed online.
- Without a GIC monitor, observation of abnormal reactive power consumption at a transformer may be used to quantify possible GIC level online.

Previous Work

$$Q_{GIC} = Q - Q_0 = K \cdot I_{eff} \tag{1}$$

$$I_{eff} = \frac{(N-1)I_s + I_c}{N}, \qquad N = \frac{N_s + N_c}{N_c}$$

Where, Q is the total reactive power consumption,

Q_0 is the reactive power consumption during normal operation without GIC, and

I_{eff} is the effective GIC flowing in the transformer windings

I_c, I_s, N_c, and N_s, are the currents and number of turns in the autotransformer common and series windings respectively

Previous Work

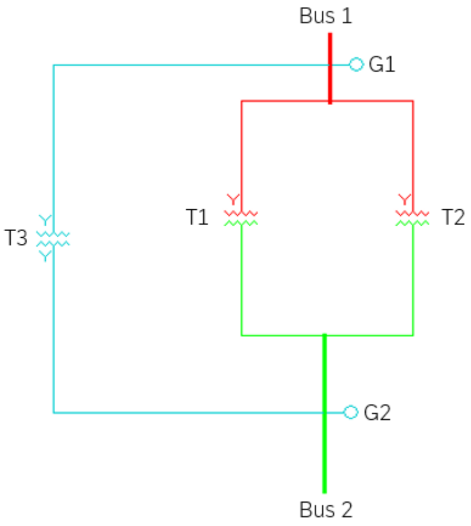
- K linearly maps I_{eff} into Q_{GIC}
- Accurate determination of K values requires measurement tests during transformer pre-commissioning [3].
- Previous studies have either used generic K values based on transformer core design [4], or simulated DC injection tests to estimate its value for a particular transformer [3].

Core design	**K**
Single-phase	1.18
Three-phase, shell form	0.33
Three-phase, 3-legged, core form	0.29
Three-phase, 5-legged, core form	0.66

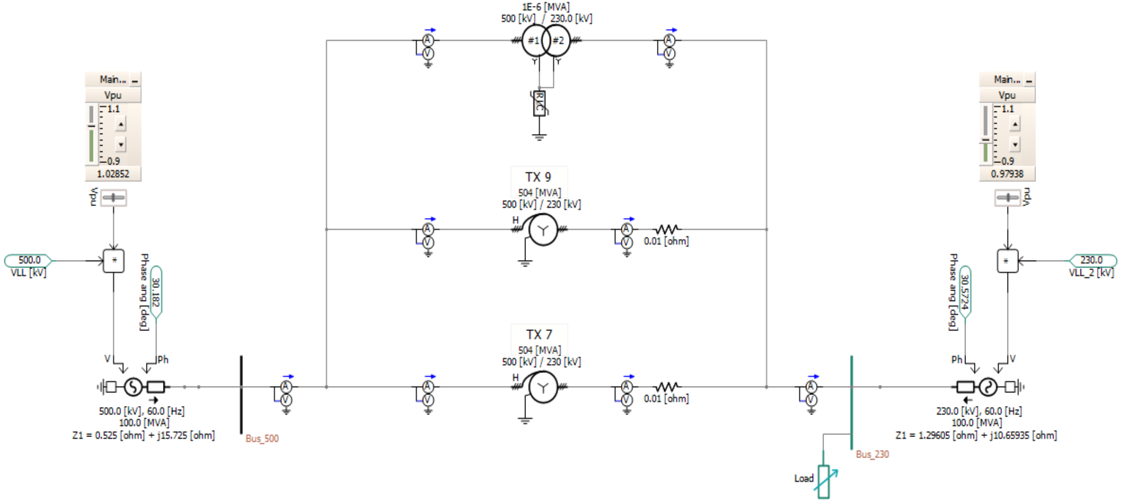
Gaps in Previous Works

- These works did not consider the possible changes in K values under different grid operating conditions as posited in Ref [5].
- Little consideration of transient interaction between GIC and Q_{GIC} [6].

Modeling of DEV substation in PSCAD/EMTDC



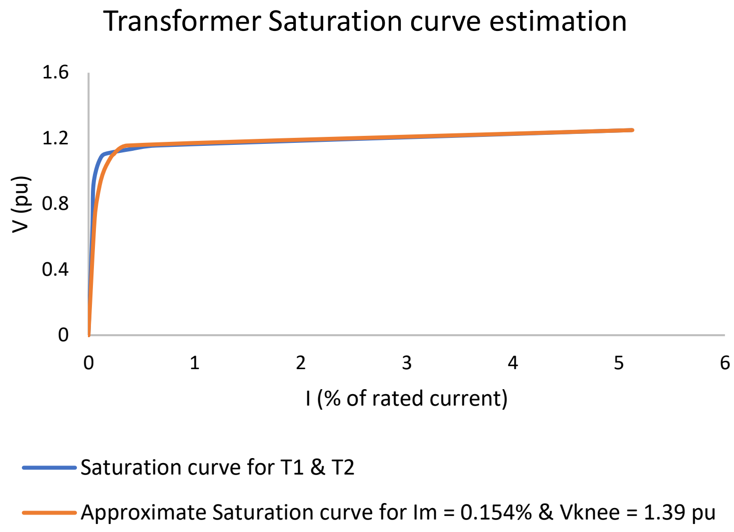
Thevenin equivalent of the DEV substation in Aspen OneLiner



Equivalent model of the DEV substation in PSCAD

Approximation of Transformers Saturation curve

- PSCAD curve-fitting optimization module [7] was used to estimate the knee voltage, V_{knee}, and magnetizing current, I_m, from the transformers' V-I data.
- Air core reactance was estimated as twice the transformer leakage reactance [8].



Model Validation

- The created model was validated by comparing its fault analysis result with that of the full model in Aspen OneLiner.

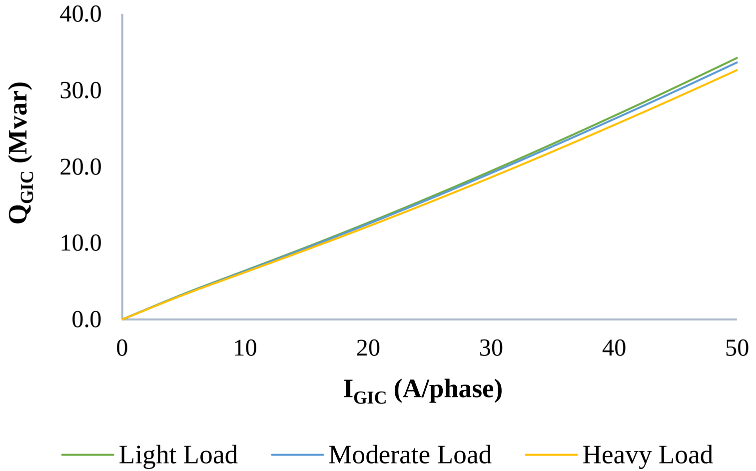
Fault Location	Fault Type	Original model fault current (kA)	Transient model fault current (kA)	% Absolute Error
Bus 1	3φ-to-ground	23.06∠-57.1	23.12∠-57.7	0.26%
	Line-to-Line	11.45∠-57.1	11.56∠-57.7	0.96%
Bus 2	3φ-to-ground	32.64∠-56.0	32.42∠-56.6	0.67%
	Line-to-Line	16.26∠-55.9	16.32∠-56.6	0.37%

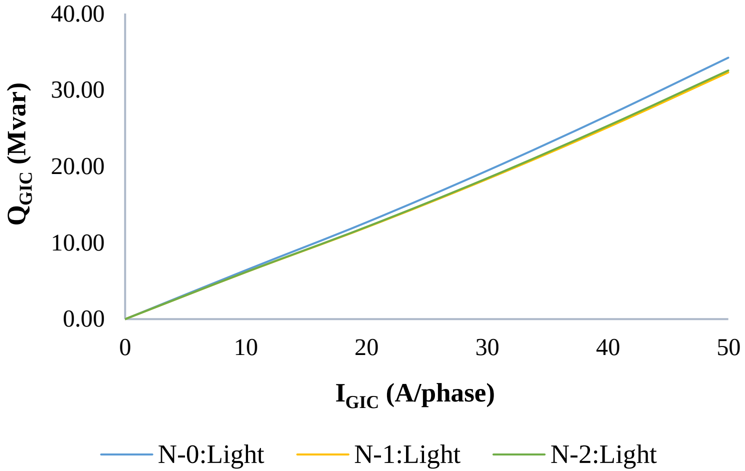
DC Injection Simulation

- GIC flow in the transformer was simulated by connecting a DC voltage source to the transformer neutral.
- A PI controller was used to control output DC current to reach desired values.
- Reactive power consumption in the transformer was measured and analyzed against simulated GIC in the neutral, I_{GIC}.
- The simulation was performed for different transformer loads and network topologies.

Results

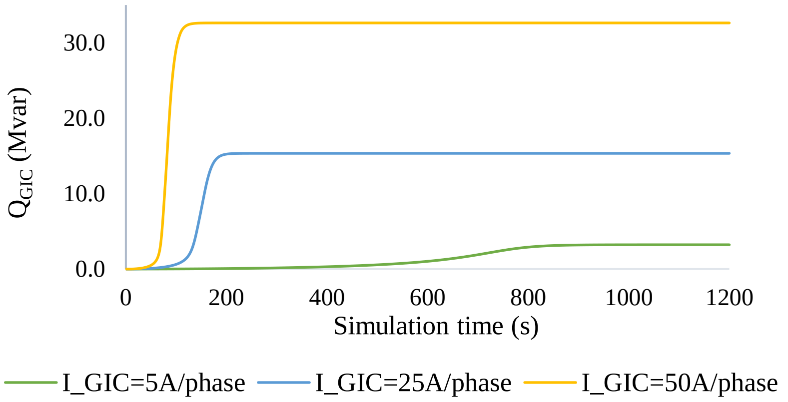
- Plot of Q_{GIC} after reaching equilibrium against I_{GIC} shows the expected linear relationship.
- K is within a narrow range of 0.64 – 0.66, showing that Q_{GIC} vs. I_{GIC} relationship is not significantly affected by load or network topology.

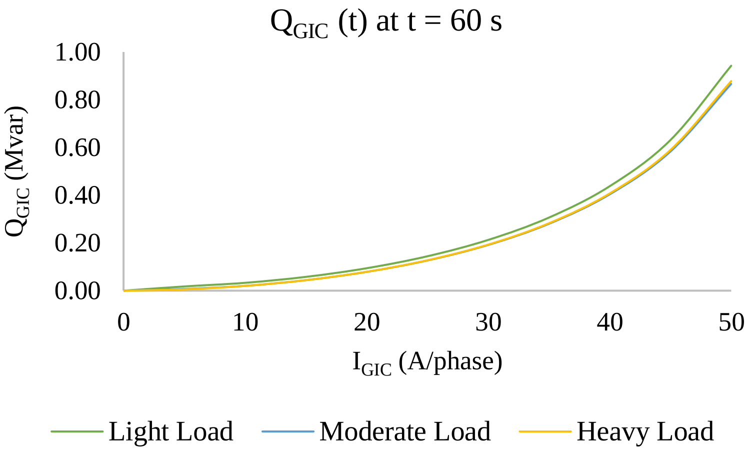




Results

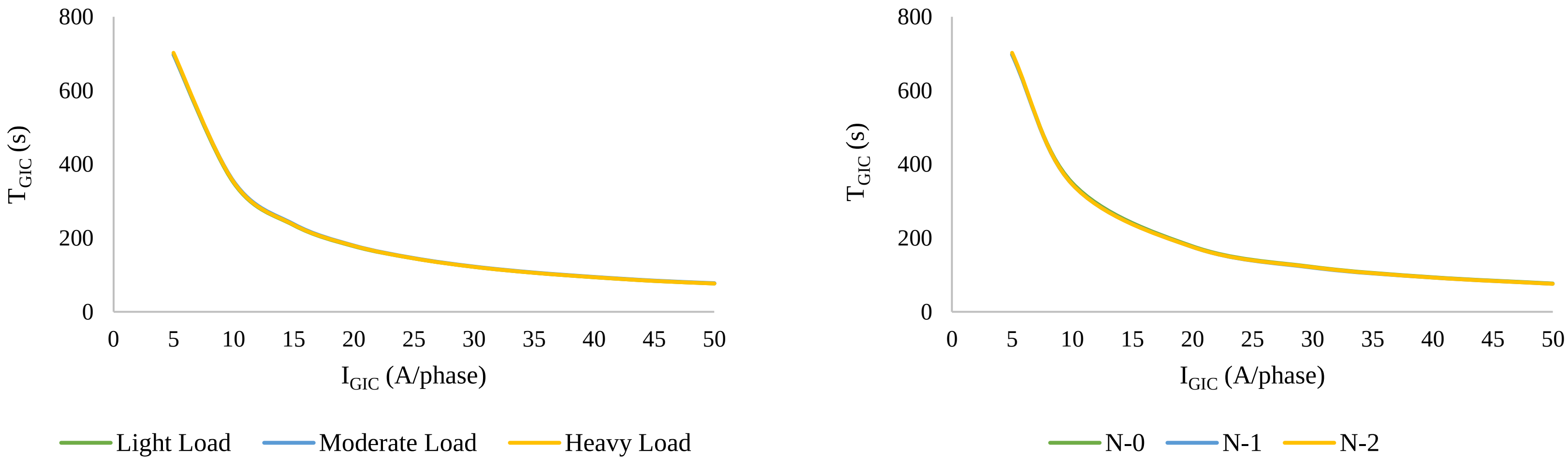
- Significant transient buildup period exist before Q_{GIC} reaches equilibrium.
- At time, t, before equilibrium, relationship between $Q_{GIC}(t)$ and I_{GIC} is non-linear, so Eq (1) cannot be used.
- $Q_{GIC}(t)$ is important to accurately evaluate the effect of short duration or relatively high frequency GIC (~0.1 Hz)





Results

- The time constant of $Q_{GIC}(t)$, T_{GIC}, also has a non-linear relationship with GIC, and is unaffected transformer load or network topology.
- Ongoing work to determine appropriate $Q_{GIC}(t) = f(I_{GIC}, T_{GIC}, K)$.



Conclusion

- Comparative study was performed to investigate the relationship between reactive power consumption, Q_{GIC}, and GIC flowing into the neutral of an autotransformer at a DEV substation.
- A linear relationship exist between the two parameters only after Q_{GIC} reaches steady-state.
- The relationship is neither considerably affected by transformer load or network topology, thus, value of K at one operating condition can be reliably used for other operating conditions.
- $Q_{GIC}(t)$ cannot be correctly estimated using the existing mathematical relationship. It requires non-linear function of I_{GIC}, T_{GIC}, and K.

Thank you

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References

[1] R. Sun, M. Mcvey, M. Lamb, and R. M. Gardner, "Mitigating Geomagnetic Disturbances: A summary of Dominion Virginia Power? efforts.," IEEE Electrification Magazine, vol. 3, no. 4, pp. 34-45, 2015-12-01 2015, doi: 10.1109/mele.2015.2480636.

[2] E. E. Bernabeu, "Modeling Geomagnetically Induced Currents in Dominion Virginia Power Using Extreme 100-Year Geoelectric Field Scenarios—Part 1," IEEE Transactions on Power Delivery, vol. 28, no. 1, pp. 516-523, 2013-01-01 2013, doi: 10.1109/tpwrd.2012.2224141

[3] L. Marti, J. Berge, and R. K. Varma, "Determination of Geomagnetically Induced Current Flow in a Transformer From Reactive Power Absorption," IEEE Transactions on Power Delivery, vol. 28, no. 3, pp. 1280-1288, 2013-07-01 2013, doi: 10.1109/tpwrd.2012.2219885

[4] X. Dong, Y. Liu, and J. G. Kappenman, "Comparative analysis of exciting current harmonics and reactive power consumption from GIC saturated transformers," in 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.01CH37194): IEEE, doi: 10.1109/pesw.2001.917055

[5] K. Shetye and T. Overbye, "Modeling and Analysis of GMD Effects on Power Systems: An overview of the impact on large-scale power systems.," IEEE Electrification Magazine, vol. 3, no. 4, pp. 13-21, 2015-12-01 2015, doi: 10.1109/mele.2015.2480356.

[6] L. Bolduc, A. Gaudreau and A. Dutil, "Saturation time of transformers under DC excitation," Electric Power Systems Research, vol. 56, pp. 95-102, 2000.

[7] PSCAD Knowledge Base. "Transformer Saturation Curve Matching in PSCAD™/EMTDC™." https://www.pscad.com/knowledge-base/article/561 (accessed July 13, 2021).

[8] PSCAD Knowledge Base, Applications of PSCAD/EMTDC, 2008. [Online]. Available: https://www.pscad.com/knowledge-base/download/application_20guide_202008_1.pdf.