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Experiences with NERC TPL-007-4 Geomagnetic Disturbances (GMD) Vulnerability Assessments in Ontario

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SUMMARY

Severe geomagnetic disturbances (GMDs), commonly referred to as solar storms, may affect Bulk Power System reliable operation. Ontario is addressing planning related reliability risks of instability, uncontrolled separation and cascading by implementing North American Electric Reliability Corporation (NERC) Reliability Standard TPL-007-4, Transmission System Planned Performance for Geomagnetic Disturbance Events [1]. This standard defines the planning performance requirements, the assessment risk level, the technical methodology and GMD events for assessments. This standard allows Canadian entities to refine assessment parameters for performing GMD vulnerability studies.

Ontario is undergoing its first implementation of TPL-007-4. Thus far, Ontario has addressed the standard's technical requirements on system modeling (Requirement R2), Geomagnetically Induced Current (GIC) flow assessments (Requirements R5 and R9), and thermal impact assessments on applicable transformers (Requirements R6 and R10). Additionally, the paper describes regionally specific modeling through application of the Canadian Variance. This work shares the joint experience by Hydro One Networks Inc. (HONI) and Independent Electricity System Operator (IESO). This information may help other jurisdictions in preparation for TPL-007-4 assessments.

The unique contributions of this paper are in sharing considerations for Ontario's "Firsts". First system modeling experience includes decision-making on assessment software, reviewing data challenges and determining model assumptions. This resulted in a DC equivalent of the network model and process for model maintenance. First Canadian variance implementation resulted in advancement and application of Ontario's geoscience models for GIC studies. First assessment experience includes decision-making where the standard allows for flexibility and in performing results validation. This resulted in improved understanding of GIC flow patterns into applicable transformers in the planning area when undergoing severe GMD events. Based on observing that all applicable transformers experience worst case GICs below standard defined screening thresholds, it is concluded that there are no transformer thermal vulnerabilities that needs to be addressed.

KEYWORDS

Geomagnetic Disturbances, GMD, Geomagnetically Induced Currents, GIC, NERC Standard TPL-007-4, Vulnerability Assessments, Reliability

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I. INTRODUCTION

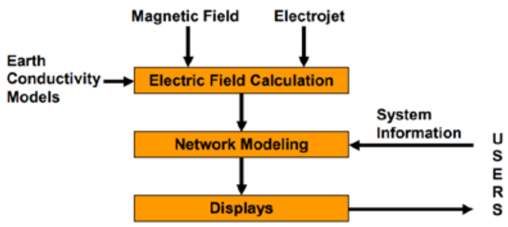
GMDs are naturally occurring phenomena. During a GMD event, magnetic field variations induce an electromotive force that results in induced electric currents on long conductors, such as pipelines and transmission circuits. In power systems, these induced quasi-DC currents, referred to as GICs, flow along circuits, through transformer windings and down the transformer grounded neutral. The amount of induced GIC on circuits depends on network properties, such as circuit orientation in relation to the GMD storm orientation, as well as geological characteristics in the area. In transformers, the additional DC offset as a result of GICs, could push the transformer core into saturation [2].

GICs could result in risks to assets and system reliability [3]. From an asset perspective, leakage magnetic flux could result in potential hot spot heating and reduced life of the transformer. From a system perspective, half-cycle saturation of transformers could increase reactive power absorption as well as cause high harmonics in magnetization currents that could result in protection mis-operations. This may be impactful to system voltage performance should it cause significant loss of reactive power support during a time of increased reactive power demand. This could cause loss of voltage stability, which could subsequently lead to voltage collapse and blackout [4].

NERC standard TPL-007-4 addresses planning reliability risks from GMDs [1]. This standard defines transmission system steady state performance expectations during severe 1-in-100 year GMD planning events. It applies to planning coordinators, transmission planners, as well as transmission and generator owners with high side, wye grounded transformers with terminal voltage above 200 kV. Currently, Ontario is undergoing its first standard cycle implementation [5].

Figure 1 simplifies the steps in calculating GIC flow and reference [2] describes the theory for electric field and GIC calculations. Section II of this paper describes related tools and modelling considerations for Ontario. The standard allows for defining alternate assessment events to leverage existing research and measurements in Canada. Section III of this paper discusses Ontario's experience in defining and applying alternate electric field and earth conductivity models to leverage research by Natural Resources Canada (NRCan). These components influence GIC flow and affects the assessment results.

Figure 1: Steps in GIC calculation [2]



The standard defines two types of GMD vulnerability assessments to evaluate different effects of GMDs as two planning events, namely wide-area and localized enhancements of GMD events. Wide-area, also known as benchmark assessment, assumes uniform storm characteristics, i.e. electric field intensity and storm orientation, throughout the planning area [6]. Conversely, localized enhancements, also known as supplemental assessment, assumes spatially non-uniform electric field characteristics in the planning area [7]. While benchmark event definition is uniform, the standard allows flexibility to determine methodology and assessment parameters for studying supplemental event. Section IV highlights these areas of flexibility and discusses Ontario's choice of parameters with supporting rationale.

Section V discusses the GIC flow assessments for benchmark and supplemental assessments. When GIC flow at specific transformers exceed standard defined threshold levels, it implies that these transformers could be at risk of thermal damage and owners are required to further assess and propose mitigating actions.

Currently, Ontario has fulfilled technical requirements for system models, GIC flow assessments and transformer thermal impact assessments. The next steps include voltage criteria definition and system impact assessments. To prepare, IESO and HONI are participating in Northeast Power Coordinating Council's (NPCC) task force in system studies to discuss studies approach.

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II. GIC System Model

In 2019, HONI provided available asset data to create Ontario's first GIC model. This was integrated with IESO's 2024 planning load flow base case, to study the IESO connected grid 5 years in the planning horizon. As the model is based on best available data and there are uncertainties from extending into the future, the model will be improved as new information become available. Further, IESO has implemented new GIC reporting requirements for entities in the planning area to report related data for ongoing model maintenance [8].

Amongst the commercially available GIC modeling software packages, Ontario selected Siemens PTI PSS/E as the power system modeling software to perform TPL-007-4. This builds on current load flow tools used in Ontario and is consistent with neighboring entities. The PSS/E Program Operation Manual [9] is the basis of the GIC model construction, and NERC's application guide provides the background on calculations and GIC DC model fundamentals [2]. The sections below highlight assumptions and notable data treatment of substation, transformer and branch as well as boundary system in the model. The model includes all facilities 200 kV and greater contributing GIC flow.

II.A. Substation Data

This section describes three topics: substations, GPS coordinates and stations grounding resistances.

Substations in the model include artificial and real stations. Artificial nodes, modelled as ungrounded substations, are used for a line tap or the turn point, i.e. orientation change, of line sections. For real stations, the following buses are assumed to be at the same substation.

- buses connected by zero length branches with no GMD induced voltage,
- buses connected by a transformer, and
- buses or transformers connected to the same station ground grid. This required manual adjustment as PSS/E may not detect this if not electrically connected.

The direction of geoelectric field to network orientation affects the resulting GIC. GPS coordinates of each modeled substation are used by PSS/E to account for these impacts. It is verified that the assessments are not sensitive to the GPS position within the station. For the turn/end points of lines, the corresponding coordinates is modeled as the GPS location for the artificial station.

The station grounding resistance represents an interconnected station ground impedance rather than an isolated station ground resistance. This includes the impact of grounding system connections to distribution neutrals and overhead ground wires on transmission lines. This data is usually obtained from station grounding surveys, which may not have been conducted for every station. Where unavailable, the model assumes a value of 0.1 ohms. The artificial substations are modeled as ungrounded.

II.B. Transformers Data

Most transformer winding resistance values are available from manufacturers' test reports. For Step-Up or Step-Down transformers, winding resistance values are the per phase DC resistance of associated windings. For Auto-transformers, values for Bus I and J represent the series and common winding data resistances. It is observed that some test sheets may provide combined winding data resistance, which required adjustments to ensure correct modelling.

Where transformer test reports are unavailable, PSS/E estimates DC winding resistances from the AC load flow base case model. As indicated below, R_{PU} equals the total per-unit copper loss resistance for the specified winding, in ohms.

1. For Auto-transformers, the series winding resistance is the product of R_{PU} at V_H winding base and $(1-V_L/V_H)$; the common winding resistance is the product of R_{PU} at V_H winding base and (V_L/V_H),
2. For Step-Up or Step-Down transformers, the winding resistance values are 50% of R_{PU} at winding bases.

The remaining parameters including vector group, core type and grounding resistance are modeled based on PSS/E requirements.

II.C. BRANCH DATA

The DC resistance of a conductor is a function of conductor type, dimension, construction, temperature and resistivity characteristics, expressed as equation (1).

$$R = R_{20}\,[1 + \rho\,(T\text{-}20)] / N_B * L \qquad (1)$$

, where R = resistance of each sections of a circuit, in ohms
R_{20} = conductor resistance at 20°C, in ohms, from conductor data sheet
T = operating temperature of the conductor, in °C
ρ = temperature coefficient of resistivity
N_B = number of conductors in the bundle
L = length of the branch

Notable modeling considerations include:

- T, at 50°C, to study a stressed and loaded system, which is more susceptible to GICs.
- The DC resistance of underground cables are calculated individually.
- Explicitly identify pipe-type underground cables to not induce GIC voltage.
- Calculate each connected section separately for different conductor segments, and account for corresponding bundled conductor composition and length.

II.D. BOUNDARY SYSTEM

The ascertainment of equivalent network models to be used for neighboring systems in GIC calculations is under continued research. At present time, GIC models used for each jurisdiction may not have complete external models. Neighboring connections at Minnesota, Manitoba, Michigan and Quebec include up to four layers of external busses, based on the recommendation of the NERC Application Guide [2]. The entire NYISO GIC model is available and included to improve accuracy.

III. CANADIAN VARIANCE AND ONTARIO SPECIFIC MODEL

The TPL-007-4 standard reflects that higher geomagnetic latitudes have higher expected geomagnetic activity and different geological characteristics influence the peak local geoelectric fields, and allows for the use of specific GIC models in Canadian jurisdictions (“Canadian Variance”, TPL-007-4 Attachment 1-CAN). The standard captures the relationship that for an assessment location, the peak geoelectric field (E_{peak}) is equal to the product of three parameters [1]:

$$E_{peak} = E_{peak\_ref} \bullet \alpha \bullet \beta_{earth} \qquad (2)$$

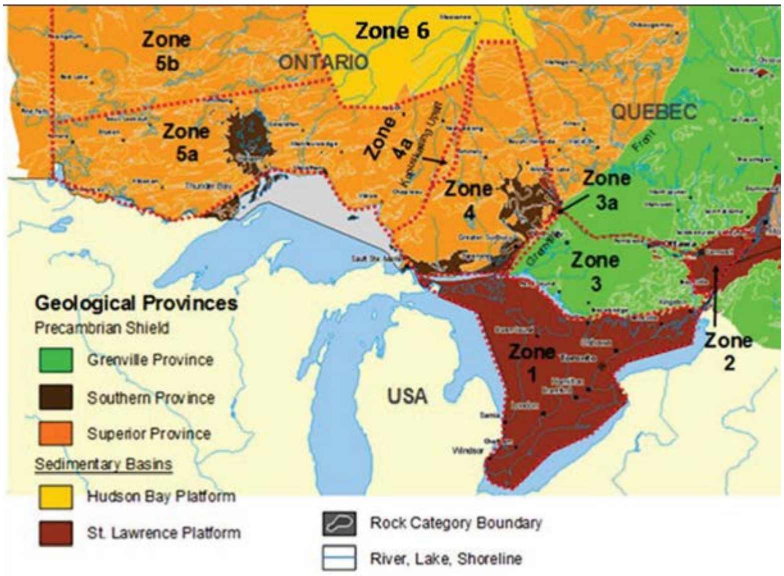
1) E_{peak_ref} = reference peak geoelectric fields, for benchmark and supplemental planning events of 1-in-100 year occurrence at 60N geomagnetic latitude, in V/km,
2) α = scaling factor relating the impact of assessment location’s geomagnetic latitude in comparison to reference geomagnetic latitude of 60N,
3) β_{earth} = scaling factor relating the impact of assessment location’s earth conductivity in comparison to reference Quebec earth conductivity model.

III.A. EARTH CONDUCTIVITY

Without applying the Canadian variance, the standard has generalizations of β_{earth}=1 across Shield provinces, equivalent to assuming uniform geological impact to E_{peak} all across Ontario and Quebec. However, Ontario is vast and captures multiple distinct geological characteristics [10]. To improve the accuracy of assessments, HONI retained Natural Resources Canada (NRCan) to refine the geological modeling of Ontario for GIC assessments. Figure 2 shows the identified eight distinct zones of geological characteristics in Ontario, on the basis of geophysical studies including magnetotelluric surveys. NRCan additionally provided one-dimensional (1D) earth resistivity models and the geographical boundaries of these zones [11]. Ontario’s transmission network of 200 kV and above lies on five of these zones.

The HONI Efield tool is available as a NERC GMD task force tool [12]. This tool takes a 1D earth conductivity model and determines its peak electric field induced when a magnetic field waveform is injected. When the standard reference waveform is injected into the standard reference earth model, the tool yields E_{peak_ref}. Equivalently, new peak-geoelectric fields are obtained with the standard waveform for each of the 5 earth models for Ontario. When divided by E_{peak_ref}, beta factor for each zone is obtained. These zonal β_{earth}, ranging from 0.6-0.8, are applied in PSS/E assessments as user-defined earth conductivity models, with each modeled substation connected by geographical location.

Figure 2: Ontario's geological provinces [11]



III.B. Geo-electric Field Intensity for Alternative Planning Events

HONI retained NRCan to perform statistical analysis to determine the geoelectric field peaks from historical measurements at the Ottawa and Manitoba observatories. This is evaluated with extreme value statistics technique at occurrence of once per 100 years with the same confidence interval for estimation as the standard. This analysis is based on historical 1-minute magnetic field data, from up to 46 years of measurements. This is equivalent to the E_{peak} of equation (2) at each observatory [13].

$\alpha_{Observatory}$ considered historical average of geomagnetic latitude at the observatory and is evaluated with equation in the standard. $\beta_{earth\_observatory}$ is described in section III.A. Equation (2) can then be applied to derive equivalent alternative benchmark planning event's E_{peak_ref}. This is valid for wide area analysis, as confirmed by closely matching geoelectric field peaks from both observatories, i.e. spanning the east to west ends of Ontario. Further, the equivalent alternative supplemental planning event's E_{peak_ref} is obtained on the basis of maintaining same standard ratio between benchmark and supplemental assessment levels. These alternative parameters are applied in Ontario's assessments.

IV. Local Enhancement Assessment Approach

TPL-007-4 allows planners flexibility to determine the supplemental assessment approach in application of localized peak geoelectric field over the planning area. Acceptable approaches include: 1) uniformly applying enhanced peak geoelectric field for the planning area, 2) spatially limiting enhanced peak geoelectric field over a portion of the system with the rest studied with benchmark event, and 3) other methods to adjust [1]. TPL-007 implementation guidance further expresses that science has not determined the exact properties of local enhanced events, including spatial extent, occurrence, and geoelectric field characteristics inside and outside of the local area. The guide provides boundaries and approaches, consistent with approach 3, as other methods to adjust for local enhanced storms [14]. Considering the developing nature of the science and acceptable approaches, Ontario decided on the following assessment methodology for supplemental event.

The application of the peak geoelectric field in a localized area was studied iteratively using each station within Ontario as the box center. This allowed for the effects of the GMD event to be analyzed should the local enhancement occur anywhere within the planning area. The largest GIC per transformer accounting for all localized area and storm orientation simulations are determined as the worst case GIC flow into the transformer. It is recognized that the orientation of local enhancements are related to electrojet, and storm orientation may be refined in future assessments.

It is important to recognize the effect of the neighboring systems on these results and that the application of the localized enhancement area could at times be reaching hundreds of kilometers beyond the Ontario border, if a large spatial extent is applied and centered at transformer stations near the borders. In these instances, the results could be distorted by neighbouring systems and need to be considered carefully. It is due to these observations that the peak geoelectric field for supplemental GMD event was applied in 100 km x 100 km boxes across the large majority of the Ontario system. In a limited number of circumstances, a 250 km x 250 km box was used to assess a local enhancement area applied at transmission stations in Ontario with transmission circuits greater than 100 km between terminals. This method of analysis was used to ensure that the entire province was studied, while considering the impact of the external model.

V. Discussion of GIC Flow Assessment and Validation

Using PSS/E to conduct GIC assessments, the maximum GIC flowing into applicable transformers are evaluated and ranked for both benchmark and supplemental events. The corresponding worst-case storm orientation, representative of the direction of the peak electric field, per transformer are also obtained. From both assessments, simulations indicate that all applicable transformers in the planning area experience GIC under standard screening thresholds. Consequently, no transformers are identified as thermally vulnerable to GIC to require further actions.

The assessments are further validated by sanity checks against general expectations to gain confidence. Some examples are illustrated below.

Figure 3 illustrates a validation that the geographical orientation of the benchmark event resulting in worst case GIC on a transformer corresponds to the orientation of connected transmission circuits. For benchmark assessment, the worst case GIC orientation for transformers at Station A is when geoelectric field is oriented south.

Another effect confirmed is more GICs tend to flow to transformers at the boundary of the model. Figure 4 illustrates the stations with the top 10 transformers with highest effective GIC flow, noting locations at the northeast, north and south boundaries of the network model.

Figure 3: Example illustrating circuit orientation

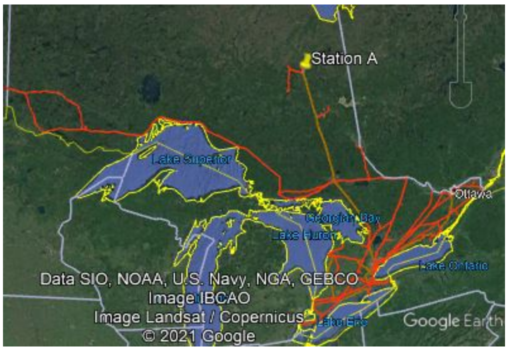
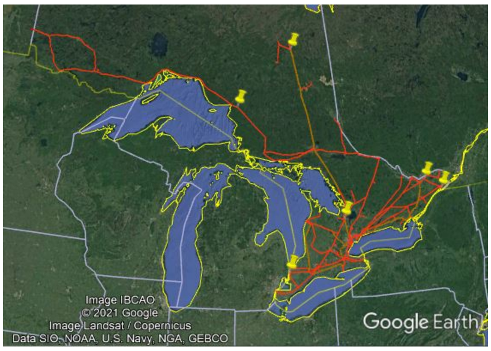


Figure 4: Higher GIC flows at model boundaries



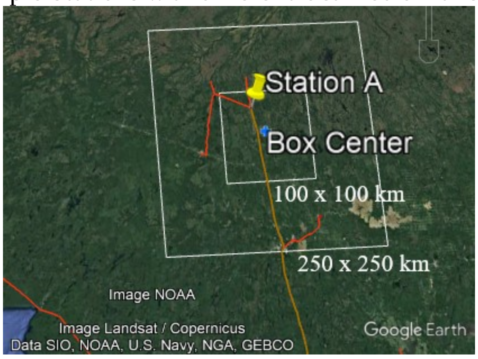
Earth conductivity modeling has impacts on transformer GIC flow. The refined β_{earth} reflect a 20-40% reduced impact on geo-electric field, resulting in lower geo-electric field and GIC flows, as demonstrated in Table 1 for an autotransformer at Station A for benchmark assessment.

The supplemental analysis was run systematically to apply the local enhancement over the entire province. This resulted in hundreds of simulations to confirm the validity of the effective GIC, while maintaining an approach that studied a GMD event with a 1-in-100 years occurrence. Figure 5 and table 2 demonstrates an example. Station A is connected to long circuits and is selected to be studied with local enhancements of 250 x 250 km. It can be noted that a higher GIC was observed in equipment within the localized area, which is consistent with applying a higher electric field. Table 2, in comparison to table 1, demonstrates the effect of the higher GIC of the localized area. Table 2 also demonstrates the differences in spatial considerations, where the bigger the area of localized enhancement, the higher the GIC flow. Table 3 demonstrates that the transformers at the edge of the localized enhancement box see higher GIC flow rather than center of the box, where GIC flows away.

Earth Model	Worst case GIC at Station A's auto-transformer
Shield	60 A
Refined Models	47 A

Table 1: Impact of earth model on transformer GIC flow

Figure 5: Example stations with different localized enhancement box size



Enhancement Size at Marked Box Center	Worst case GIC at Station A's auto-transformer
100 x 100 km	38 A
250 x 250 km	64 A

Table 2: Impact of enhancement box size on transformer GIC flow

250 x 250 km Enhancement Centered at	Worst case GIC at Station A's auto-transformer
Station A	53 A
Marked Box Center	64 A

Table 3: Impact of enhancement box position on transformer GIC flow

VI. CONCLUSION

Ontario is currently implementing NERC TPL-007-4 standard for the first time to address planning related GMD reliability risks. Thus far, Ontario has fulfilled key milestones in system modeling and GIC flow assessments to fulfill standard requirements.

The paper describes the construction of Ontario's first GIC model and maintenance plan. In addition, the paper reviews model assumptions and considerations. This paper highlights the flexible areas in determining assessment parameters and alternative methodology in the standard. Further, it summarizes these choices for Ontario assessments and the technical rationale to support these decisions. Considering NERC standard's implementation guidance, IESO connected grid's characteristics, and the ease of assessment with PSS/E, Ontario made decisions on spatial extent and the position of local enhancement for assessments. Additionally, through application of the Canadian variance of the standard and NRCan's research, Ontario leveraged historical measurements and local research to define Ontario specific planning event parameters for assessments. This included improved earth conductivity models and refined electric fields for Ontario. Lastly, the paper presents the results of the GIC flow assessments. It is concluded that there are no further requirements for transformer owners to assess and mitigate transformer thermal impacts due to GMDs.

The work in this paper contributes to an improved planning understanding of Ontario's transmission system on GMD risks with the most applicable and best available regional data. Amidst uncertainties of developing science, it demonstrates careful considerations and analysis to make effective and prudent decisions on necessary mitigation for reliability. In addition, it supports and furthers ongoing geo-science and research development in Canada.

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