Transformer Thermal Impact Assessment White Paper

TPL-007-2–Transmission System Planned Performance for Geomagnetic Disturbance Events

Background

Proposed TPL-007-2 includes requirements for entities to perform two types of GMD Vulnerability Assessments to evaluate the potential impacts of GMD events on the Bulk Electric System (BES):

- The benchmark GMD Vulnerability Assessment is based on the benchmark GMD event associated with TPL-007-1 which was approved by the Federal Energy Regulatory Commission (FERC) in Order No. 830 in September 2016. The benchmark GMD event is derived from spatially-averaged geoelectric field values to address potential wide-area effects that could be caused by a severe 1-in-100 year GMD event.[1]
- The supplemental GMD Vulnerability Assessment, based on the supplemental GMD event, is used by entities to evaluate localized peaks in geomagnetic field during a severe GMD event that "could potentially affect the reliable operation of the Bulk-Power System."[2] Localized enhancements of geomagnetic field can result in geoelectric field values above the spatially-averaged benchmark in a local area.

The standard requires transformer thermal impact assessments to be performed on BES power transformers with high side, wye-grounded windings with terminal voltage greater than 200 kV. Large power transformers connected to the EHV transmission system can experience both winding and structural hot spot heating as a result of GMD events. TPL-007-2 requires owners of such BES transformers to conduct thermal analyses to determine if the BES transformers will be able to withstand the thermal transient effects associated with the GMD events. BES Transformers must undergo a thermal impact assessment if the maximum effective geomagnetically-induced current (GIC) in the transformer is equal to or greater than:[3]

- 75 A per phase for the benchmark GMD event
- 85 A per phase for the supplemental GMD event

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[1] See *Benchmark Geomagnetic Disturbance Event Description* white paper, May 12, 2016. Filed by NERC in RM15-11 on June 28, 2016.

[2] See Order No. 830 P. 47. On September 22, 2016, FERC directed NERC to develop modifications to the benchmark GMD event, included in TPL-007-1, such that assessments would not be based solely on spatially averaged data. The characteristics of a GMD event for this assessment are in the Supplemental GMD Event Description white paper.

[3] See *Screening Criterion for Transformer Thermal Impact Assessment* for technical justification.

This white paper discusses methods that can be employed to conduct transformer thermal impact assessments, including example calculations. The first version of the white paper was developed by the Project 2013-03 GMD Standards Drafting Team (SDT) for TPL-007-1 and was endorsed by the Electric Reliability Organization (ERO) as implementation guidance in October 2016. The SDT has updated the white paper to include the supplemental GMD event that is added in TPL-007-2 to address directives in FERC Order No. 830.

The primary impact of GMDs on large power transformers is a result of the quasi-dc current that flows through wye-grounded transformer windings. This geomagnetically-induced current (GIC) results in an offset of the ac sinusoidal flux resulting in asymmetric or half-cycle saturation (see **Figure 1**).

Half-cycle saturation results in a number of known effects:

- Hot spot heating of transformer windings due to harmonics and stray flux;
- Hot spot heating of non-current carrying transformer metallic members due to stray flux;
- Harmonics;
- Increase in reactive power absorption; and
- Increase in vibration and noise level.

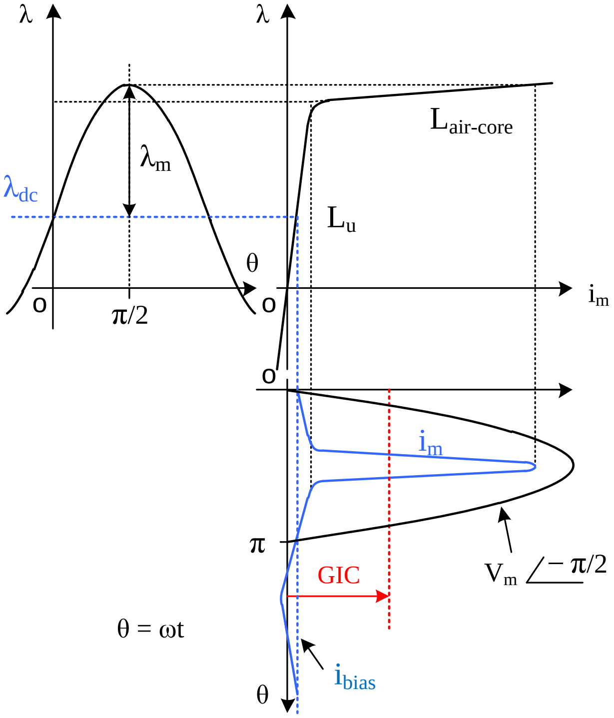

Figure 1: Mapping Magnetization Current to Flux through Core Excitation Characteristics

This paper focuses on hot spot heating of transformer windings and non current-carrying metallic parts. Effects such as the generation of harmonics, increase in reactive power absorption, vibration, and noise are not within the scope of this document.

Technical Considerations

The effects of half-cycle saturation on HV and EHV transformers, namely localized "hot spot" heating, are relatively well understood, but are difficult to quantify. A transformer GMD impact assessment must consider GIC amplitude, duration, and transformer physical characteristics such as design and condition (e.g., age, gas content, and moisture in the oil). A single threshold value of GIC cannot be justified as a "pass or fail" screening criterion where "fail" means that the transformer will suffer damage. A single threshold value of GIC only makes sense in the context where "fail" means that a more detailed study is required. Such a threshold would have to be technically justifiable and sufficiently low to be considered a conservative value of GIC.

The following considerations should be taken into account when assessing the thermal susceptibility of a transformer to half-cycle saturation:

- In the absence of manufacturer specific information, use the temperature limits for safe transformer operation such as those suggested in the IEEE Std C57.91-2011 (IEEE Guide for Loading Mineral-oil-immersed Transformers and Step-voltage Regulators) for hot spot heating during short-term emergency operation [1]. This standard does not suggest that exceeding these limits will result in transformer failure, but rather that it will result in additional aging of cellulose in the paper-oil insulation and the potential for the generation of gas bubbles in the bulk oil. Thus, from the point of view of evaluating possible transformer damage due to increased hot spot heating, these thresholds can be considered conservative for a transformer in good operational condition.
- The worst case temperature rise for winding and metallic part (e.g., tie plate) heating should be estimated taking into consideration the construction characteristics of the transformer as they pertain to dc flux offset in the core (e.g., single-phase, shell, 5 and 3-leg three-phase construction).
- Bulk oil temperature due to ambient temperature and transformer loading must be added to the incremental temperature rise caused by hot spot heating. For planning purposes, maximum ambient and loading temperature should be used unless there is a technically justified reason to do otherwise.
- The time series or "waveform" of the reference GMD event in terms of peak amplitude, duration, and frequency of the geoelectric field has an important effect on hot spot heating. Winding and metallic part hot spot heating have different thermal time constants, and their temperature rise will be different if the GIC currents are sustained for 2, 10, or 30 minutes for a given GIC peak amplitude.
- The "effective" GIC in autotransformers (reflecting the different GIC ampere-turns in the common and the series windings) must be used in the assessment. The effective current $I_{dc,eq}$ in an autotransformer is defined by [2].

$$I_{dc,eq} = I_H + (I_N / 3 - I_H) V_X / V_H \quad (1)$$

where

I_H is the dc current in the high voltage winding;
I_N is the neutral dc current;
V_H is the rms rated voltage at HV terminals;
V_X is the rms rated voltage at the LV terminals.

Transformer Thermal Impact Assessment Process

A simplified thermal assessment may be based on the appropriate tables from the "Screening Criterion for Transformer Thermal Impact Assessment" white paper [3].[4] Each table below provides the peak metallic hot spot temperatures that can be reached for the given GMD event using conservative thermal models. To use each table, one must select the bulk oil temperature and the threshold for metallic hot spot heating, for instance, from reference [1] after allowing for possible de-rating due to transformer condition. If the effective GIC results in higher than threshold temperatures, then the use of a detailed thermal assessment as described below should be carried out.[5]

Table 1: Upper Bound of Peak Metallic Hot Spot Temperatures Calculated Using the Benchmark GMD Event

Effective GIC (A/phase)	Metallic hot spot Temperature (°C)	Effective GIC (A/phase)	Metallic hot spot Temperature (°C)
0	80	100	182
10	107	110	186
20	128	120	190
30	139	130	193
40	148	140	204
50	157	150	213
60	169	160	221
70	170	170	230
75	172	180	234
80	175	190	241
90	179	200	247

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[4] Table 1 in the *Screening Criterion for Transformer Thermal Impact Assessment* white paper provides upper bound temperatures for the benchmark GMD event. Table 2 in the *Screening Criterion for Transformer Thermal Impact Assessment* white paper provides upper bound temperatures for the supplemental GMD event.

[5] Effective GIC in the table is the peak GIC(t) for the GMD event being assessed. Peak GIC(t) is not steady-state GIC.

Table 2: Upper Bound of Peak Metallic Hot Spot Temperatures Calculated Using the Supplemental GMD Event

Effective GIC (A/phase)	Metallic hot spot Temperature (°C)	Effective GIC(A/phase)	Metallic hot spot Temperature (°C)
0	80	120	188
10	107	130	191
20	124	140	194
30	137	150	198
40	147	160	203
50	156	170	209
60	161	180	214
70	162	190	229
75	165	200	237
80	169	220	248
85	172	230	253
90	177	250	276
100	181	275	298
110	185	300	316

Two different ways to carry out a detailed thermal impact assessment are discussed below. In addition, other approaches and models approved by international standard-setting organizations such as the Institute of Electrical and Electronic Engineers (IEEE) or International Council on Large Electric Systems (CIGRE) may also provide technically justified methods for performing thermal assessments.[6] All thermal assessment methods should be demonstrably equivalent to assessments that use the GMD events associated with TPL-007-2.

1. Transformer manufacturer GIC capability curves. These curves relate permissible peak GIC (obtained by the user from a steady-state GIC calculation) and loading, for a specific transformer. An example of manufacturer capability curves is provided in **Figure 2**. Presentation details vary between manufacturers, and limited information is available regarding the assumptions used to generate these curves, in particular, the assumed waveshape or duration of the effective GIC. Some manufacturers assume that the waveform of the GIC in the transformer windings is a square pulse of 2, 10, or 30 minutes in duration. In the case of the transformer capability curve shown in **Figure 2**, a square pulse of 900 A/phase with a duration of 2 minutes would cause the Flitch plate hot spot to reach a temperature of 180°C at full load [5]. While GIC capability curves are relatively simple to use, an amount of engineering judgment is necessary to ascertain which portion of a GIC waveform is equivalent to, for example, a 2 minute pulse. Also, manufacturers generally maintain that in the absence of transformer standards defining thermal duty due to GIC, such capability curves must be developed for every transformer design and vintage.

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[6] For example, C57.163-2015 – IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances. [4]

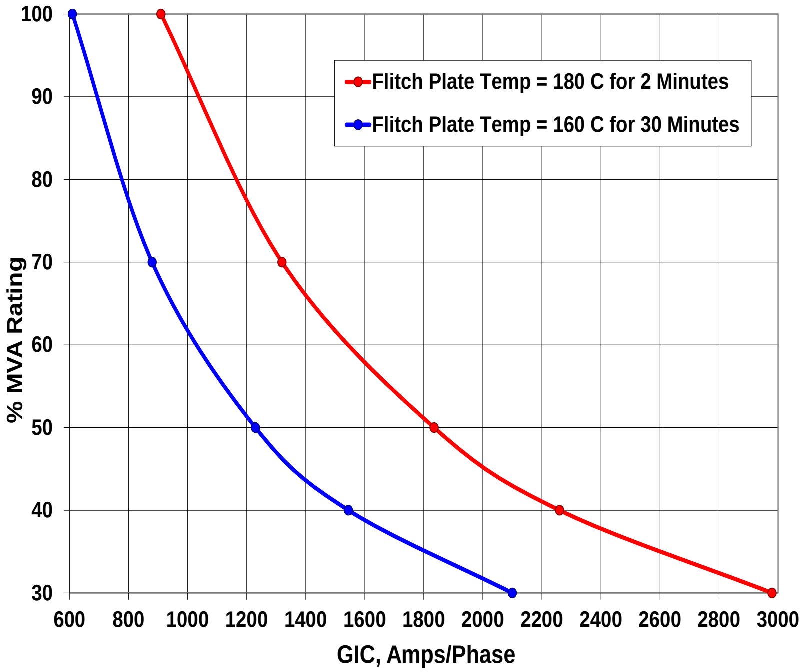

Figure 2: Sample GIC Manufacturer Capability Curve of a Large Single-Phase Transformer Design using the Flitch Plate Temperature Criteria [5]

2. Thermal response simulation.[7] The input to this type of simulation is the time series or waveform of effective GIC flowing through a transformer (taking into account the actual configuration of the system), and the result of the simulation is the hot spot temperature (winding or metallic part) time sequence for a given transformer. An example of GIC input and hotspot temperature time series values from [6] are shown in **Figure 3**. The hot spot thermal transfer functions can be obtained from measurements or calculations provided by transformer manufacturers. Conservative default values can be used (e.g., those provided in [6]) when specific data are not available. Hot spot temperature thresholds shown in **Figure 3** are consistent with IEEE Std C57.91-2011 emergency loading hot spot limits. Emergency loading time limit is usually 30 minutes.

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[7] Technical details of this methodology can be found in [6].

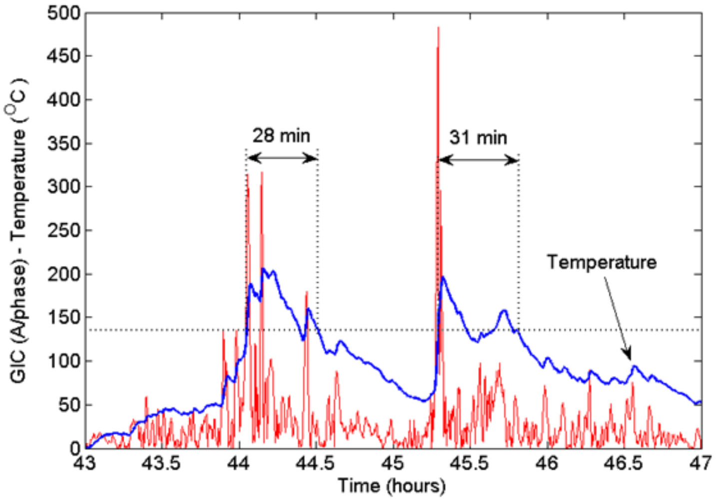

Figure 3: Sample Tie Plate Temperature Calculation

Blue trace is incremental temperature and red trace is the magnitude of the GIC/phase [6]

It is important to reiterate that the characteristics of the time sequence or “waveform” are very important in the assessment of the thermal impact of GIC on transformers. Transformer hot spot heating is not instantaneous. The thermal time constants of transformer windings and metallic parts are typically on the order of minutes to tens of minutes; therefore, hot spot temperatures are heavily dependent on GIC history and rise time, amplitude and duration of GIC in the transformer windings, bulk oil temperature due to loading, ambient temperature and cooling mode.

Calculation of the GIC Waveform for a Transformer

The following procedure can be used to generate time series GIC data (i.e., GIC(t)) using a software program capable of computing GIC in the steady-state. The steps are as follows:

1. Calculate contribution of GIC due to eastward and northward geoelectric fields for the transformer under consideration;
2. Scale the GIC contribution according to the reference geoelectric field time series to produce the GIC time series for the transformer under consideration.

Most available GIC–capable software packages can calculate GIC in steady-state in a transformer assuming a uniform eastward geoelectric field of 1 V/km (GIC_E) while the northward geoelectric field is zero. Similarly, GIC_N can be obtained for a uniform northward geoelectric field of 1 V/km while the eastward geoelectric field is zero. GIC_E and GIC_N are the normalized GIC contributions for the transformer under consideration.

If the earth conductivity is assumed to be uniform (or laterally uniform) in the transmission system of interest, then the transformer GIC (in A/phase) for any value of $E_E(t)$ and $E_N(t)$ can be calculated using (2) [2].

$$GIC(t) = |E(t)| \cdot \{GIC_E \sin(\varphi(t)) + GIC_N \cos(\varphi(t))\} \tag{2}$$

where

$$|E(t)| = \sqrt{E_N^2(t) + E_E^2(t)} \tag{3}$$

$$\varphi(t) = \tan^{-1}\left(\frac{E_E(t)}{E_N(t)}\right) \tag{4}$$

$$GIC(t) = E_E(t) \cdot GIC_E + E_N(t) \cdot GIC_N \tag{5}$$

GIC_N is the effective GIC due to a northward geoelectric field of 1 V/km, and GIC_E is the effective GIC due to an eastward geoelectric field of 1 V/km. The units for GIC_N and GIC_E are A/phase per V/km)

The geoelectric field time series $E_N(t)$ and $E_E(t)$ is obtained, for instance, from the reference geomagnetic field time series (from [7] and/or [8]) after the appropriate geomagnetic latitude scaling factor α is applied.[8] The reference geoelectric field time series is calculated using the reference earth model. When using this geoelectric field time series where a different earth model is applicable, it should be scaled with the appropriate conductivity scaling factor β.[9] Alternatively, the geoelectric field can be calculated from the reference geomagnetic field time series after the appropriate geomagnetic latitude scaling factor α is applied and the appropriate earth model is used. In such case, the conductivity scaling factor β is not applied because it is already accounted for by the use of the appropriate earth model.

Applying (5) to each point in $E_N(t)$ and $E_E(t)$ results in GIC(t).

GIC(t) Calculation Example

Let us assume that from the steady-state solution, the effective GIC in this transformer is GIC_E = -20 A/phase if E_N=0, E_E=1 V/km and GIC_N = 26 A/phase if E_N=1 V/km, E_E=0. Let us also assume the geomagnetic field time series corresponds to a geomagnetic latitude where α = 1 and that the earth conductivity corresponds to the reference earth model in [7]. The resulting geoelectric field time series is shown in **Figure 4**. Therefore:

$$GIC(t) = E_E(t) \cdot GIC_E + E_N(t) \cdot GIC_N \text{ (A/phase)} \tag{6}$$

$$GIC(t) = -E_E(t) \cdot 20 + \cdot E_N(t) \cdot 26 \text{ (A/phase)} \tag{7}$$

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[8] The geomagnetic factor α is described in [2] and is used to scale the geomagnetic field according to geomagnetic latitude. The lower the geomagnetic latitude (closer to the equator), the lower the amplitude of the geomagnetic field.

[9] The conductivity scaling factor β is described in [2], and is used to scale the geoelectric field according to the conductivity of different physiographic regions. Lower conductivity results in higher β scaling factors.

The resulting GIC waveform GIC(t) is shown in **Figures 5 and 6** and can subsequently be used for thermal analysis.

It should be emphasized that even for the same reference event, the GIC(t) waveform in every transformer will be different, depending on the location within the system and the number and orientation of the circuits connecting to the transformer station. Assuming a single generic GIC(t) waveform to test all transformers is incorrect.

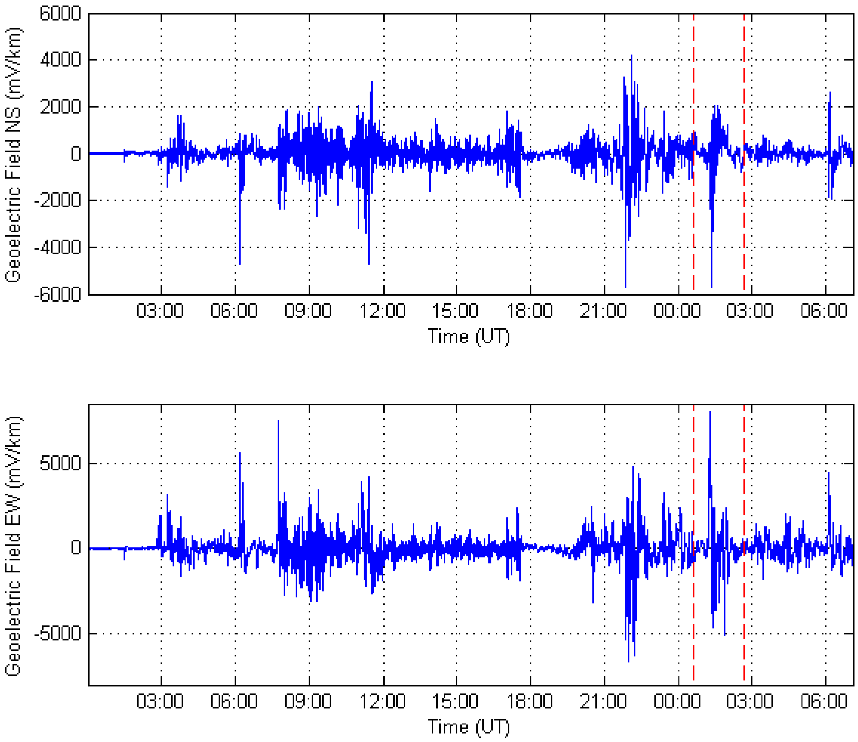

Figure 4: Calculated Geoelectric Field $E_N(t)$ and $E_E(t)$ Assuming $\alpha=1$ and $\beta=1$ (Reference Earth Model).
Zoom area for subsequent graphs is highlighted.
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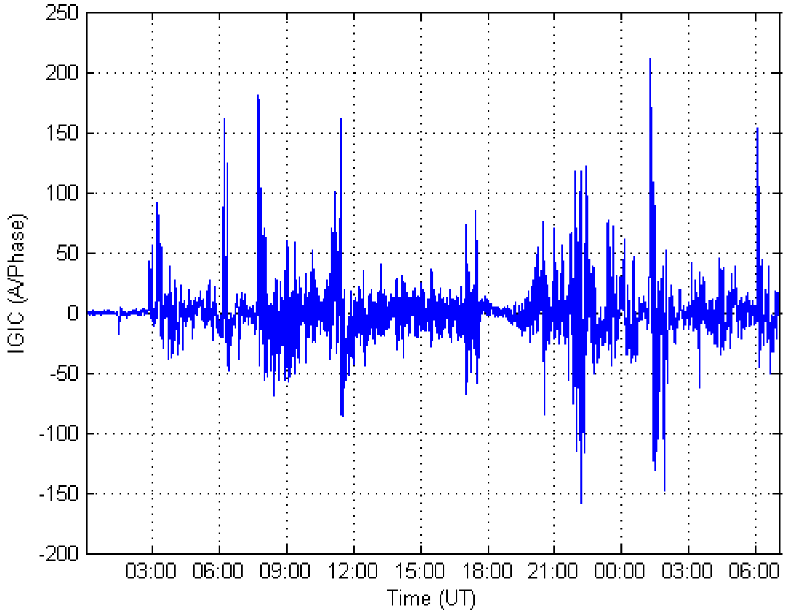

Figure 5: Calculated GIC(t) Assuming α=1 and β=1
Reference Earth Model

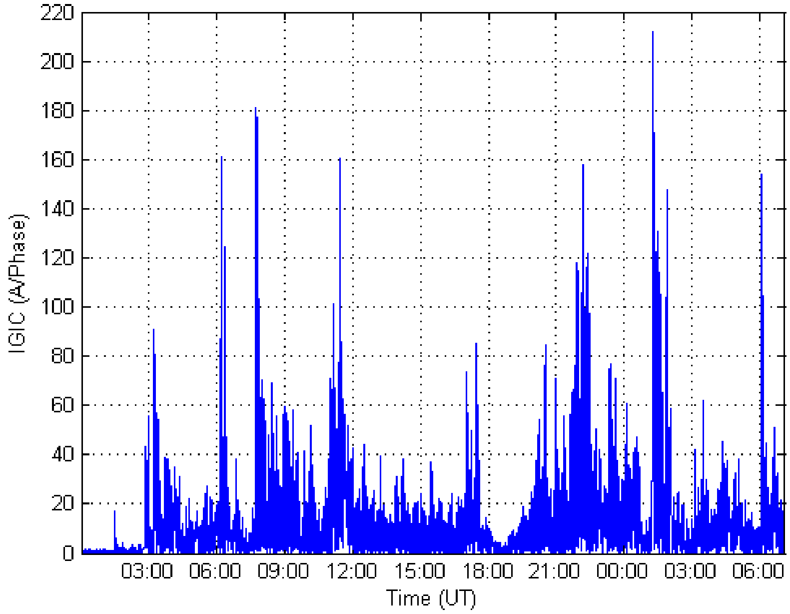

Figure 6: Calculated Magnitude of GIC(t) Assuming α=1 and β=1
Reference Earth Model

Transformer Thermal Assessment Examples

There are two basic ways to carry out a transformer thermal analysis once the GIC time series GIC(t) is known for a given transformer: 1) calculating the thermal response as a function of time; and 2) using manufacturer's capability curves.

Example 1: Calculating thermal response as a function of time using a thermal response tool

The thermal step response of the transformer can be obtained for both winding and metallic part hot spots from: 1) measurements; 2) manufacturer's calculations; or 3) generic published values. **Figure 7** shows the measured metallic hot spot thermal response to a dc step of 16.67 A/phase of the top yoke clamp from [9] that will be used in this example. **Figure 8** shows the measured incremental temperature rise (asymptotic response) of the same hot spot to long duration GIC steps.[10]

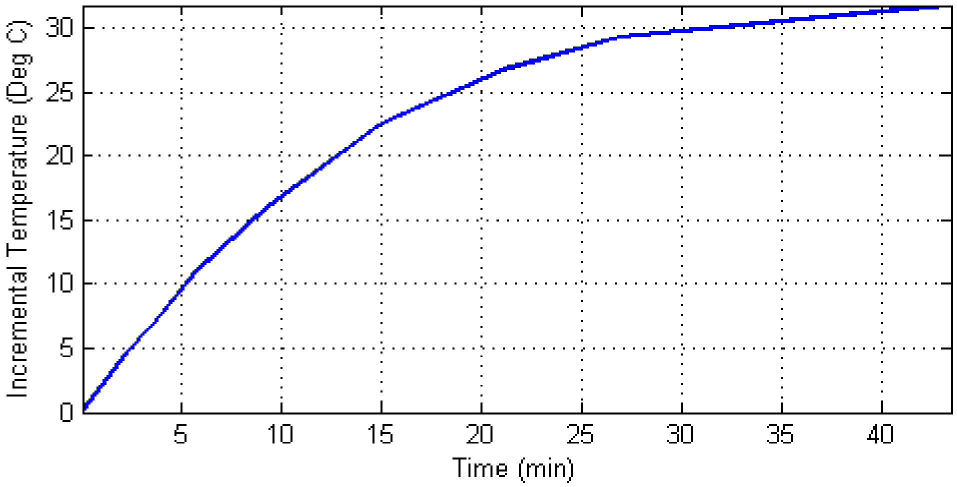

Figure 7: Thermal Step Response to a 16.67 Amperes per Phase dc Step
Metallic hot spot heating

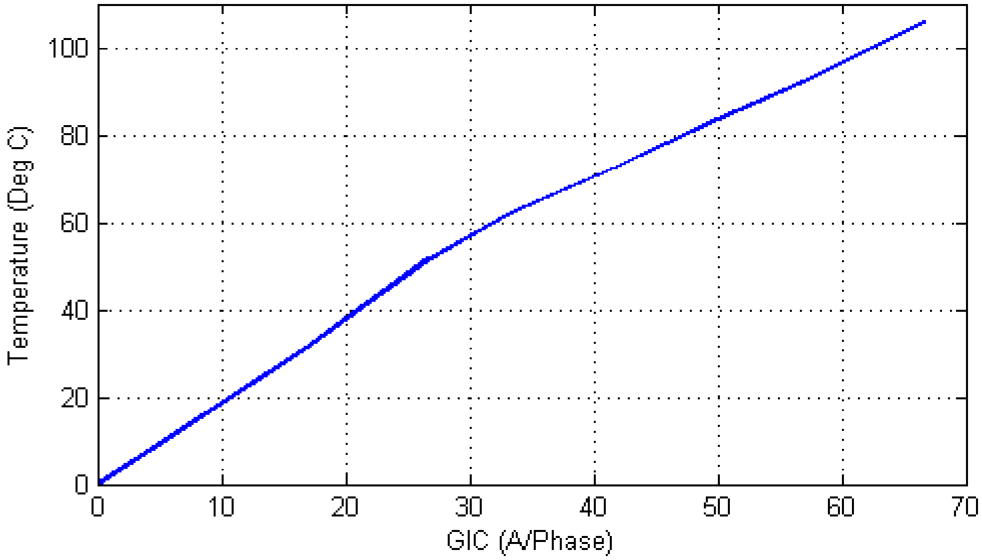

Figure 8: Asymptotic Thermal Step Response
Metallic hot spot heating

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[10] Heating of bulk oil due to the hot spot temperature increase is not included in the asymptotic response because the time constant of bulk oil heating is at least an order of magnitude larger than the time constants of hot spot heating.

The step response in **Figure 7** was obtained from the first GIC step of the tests carried out in [6]. The asymptotic thermal response in **Figure 8** was obtained from the final or near-final temperature values after each subsequent GIC step. **Figure 9** shows a comparison between measured temperatures and the calculated temperatures using the thermal response model used in the rest of this discussion.

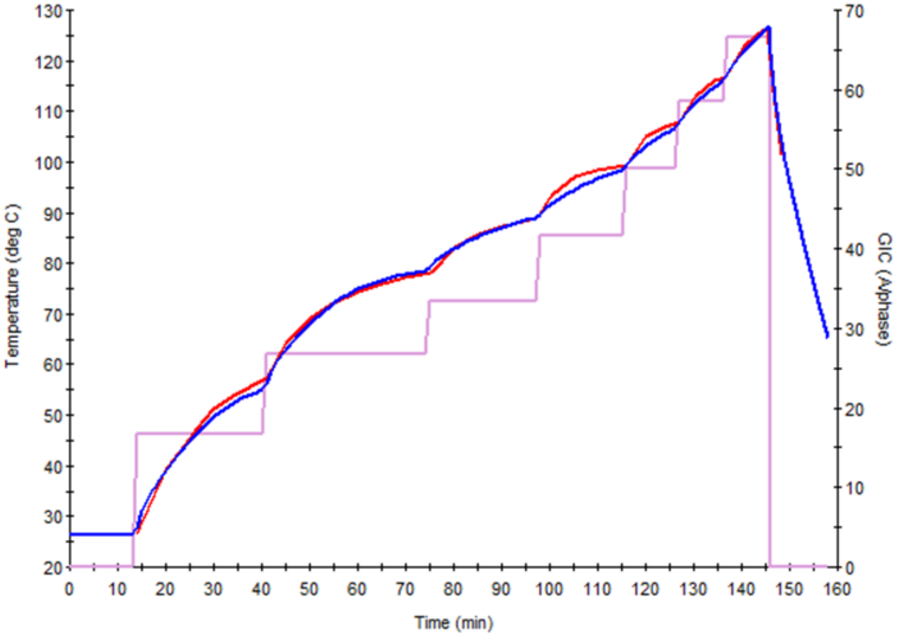

Figure 9: Comparison of measured temperatures (red) and simulation results (blue).
Injected current is represented by magenta.

To obtain the thermal response of the transformer to a GIC waveform such as the one in **Figure 6**, a thermal response model is required. To create a thermal response model, the measured or manufacturer-calculated transformer thermal step responses (winding and metallic part) for various GIC levels are required. The GIC(t) time series or waveform is then applied to the thermal model to obtain the incremental temperature rise as a function of time $\theta(t)$ for the GIC(t) waveform. The total temperature is calculated by adding the oil temperature, for example, at full load.

Figure 10 illustrates the calculated GIC(t) and the corresponding metallic hot spot temperature time series θ(t). **Figure 11** illustrates a close-up view of the peak transformer temperatures calculated in this example.

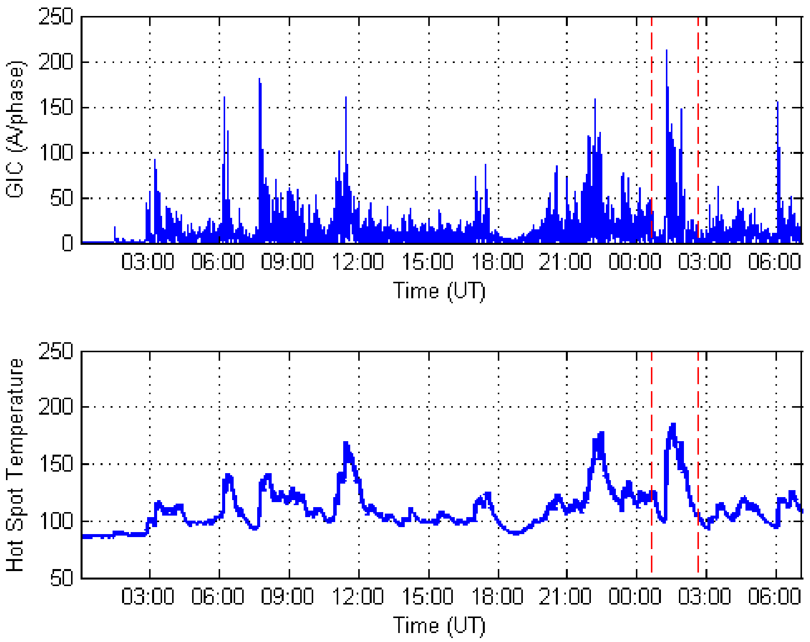

Figure 10: Magnitude of GIC(t) and Metallic Hot Spot Temperature θ(t) Assuming Full Load Oil Temperature of 85.3°C (40°C ambient).

Dashed lines approximately show the close-up area for subsequent figures

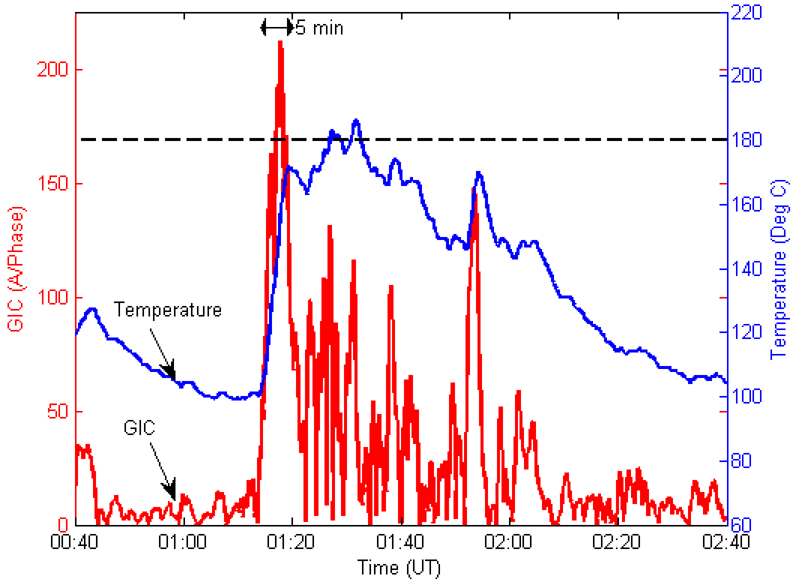

Figure 11: Close-up of Metallic Hot Spot Temperature Assuming a Full Load

Blue trace is θ(t). Red trace is GIC(t)

In this example, the IEEE Std C57.91-2011 emergency loading hot spot threshold of 200°C for metallic hot spot heating is not exceeded. Peak temperature is 186°C. The IEEE standard is silent as to whether the temperature can be higher than 200°C for less than 30 minutes. Manufacturers can provide guidance on individual transformer capability.

It is not unusual to use a lower temperature threshold of 180°C to account for calculation and data margins, as well as transformer age and condition. **Figure 11** shows that 180°C will be exceeded for 5 minutes.

At 75% loading, the initial temperature is 64.6°C rather than 85.3°C, and the hot spot temperature peak is 165°C, well below the 180°C threshold (see **Figure 12**).

If a conservative threshold of 160°C were used to account for the age and condition of the transformer, then the full load limits would be exceeded for approximately 22 minutes.

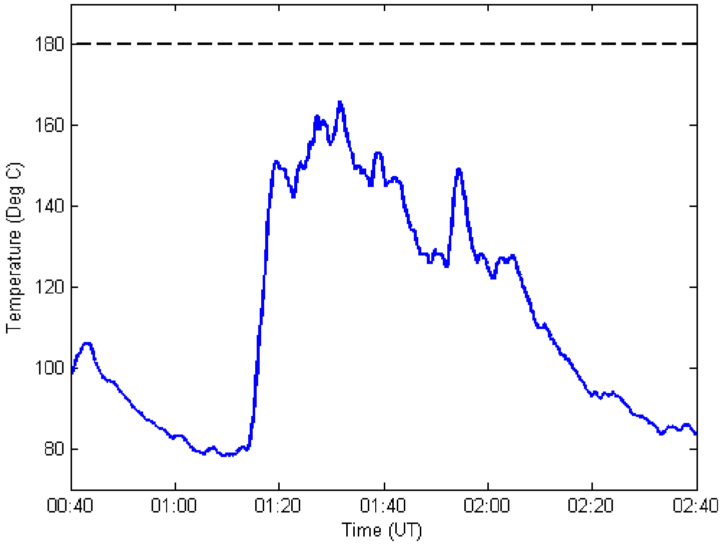

Figure 12: Close-up of Metallic Hot Spot Temperature Assuming a 75 % Load
Oil temperature of 64.5°C

Example 2: Using a Manufacturer's Capability Curves

The capability curves used in this example are shown in **Figure 13**. To maintain consistency with the previous example, these particular capability curves have been reconstructed from the thermal step response shown in **Figures 7** and **8**, and the simplified loading curve shown in **Figure 14** (calculated using formulas from IEEE Std C57.91-2011).

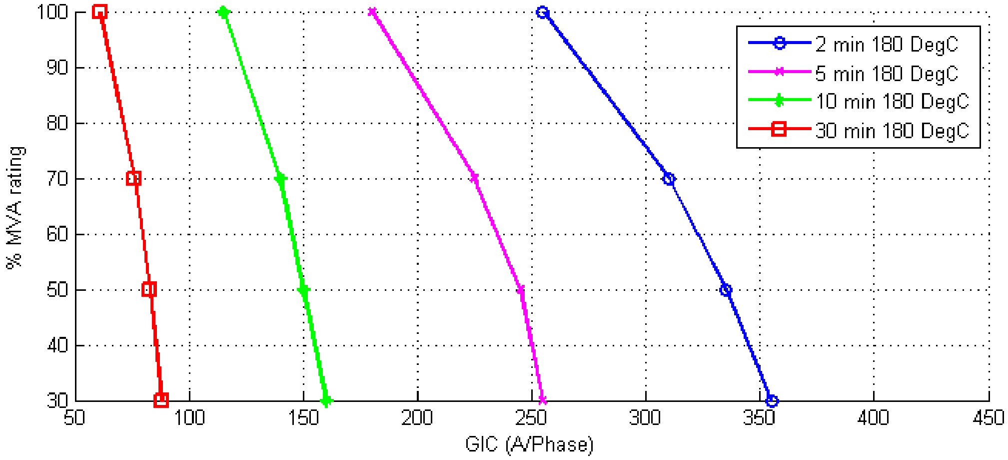

Figure 13: Capability Curve of a Transformer Based on the Thermal Response Shown in Figures 8 and 9.

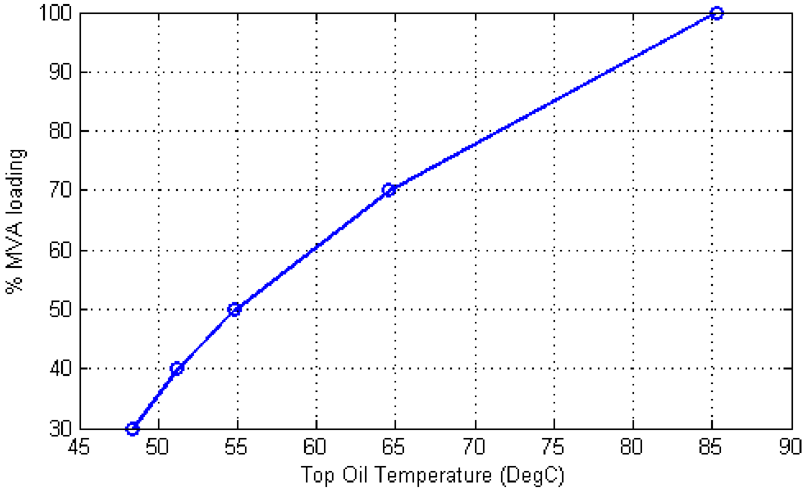

Figure 14: Simplified Loading Curve Assuming 40°C Ambient Temperature.

The basic notion behind the use of capability curves is to compare the calculated GIC in a transformer with the limits at different GIC pulse widths. A narrow GIC pulse has a higher limit than a longer duration or wider one. If the calculated GIC and assumed pulse width falls below the appropriate pulse width curve, then the transformer is within its capability.

To use these curves, it is necessary to estimate an equivalent square pulse that matches the waveform of GIC(t), generally at a GIC(t) peak. **Figure 15** shows a close-up of the GIC near its highest peak superimposed to a 255 Amperes per phase, 2 minute pulse at 100% loading from **Figure 13**. Since a narrow 2-minute pulse is not representative of GIC(t) in this case, a 5 minute pulse with an amplitude of 180 A/phase at 100% loading has been superimposed on **Figure 16**. It should be noted that a 255 A/phase, 2 minute pulse is equivalent to a 180 A/phase 5 minute pulse from the point of view of transformer capability. Deciding what GIC pulse is equivalent to the portion of GIC(t) under consideration is a matter of engineering judgment.

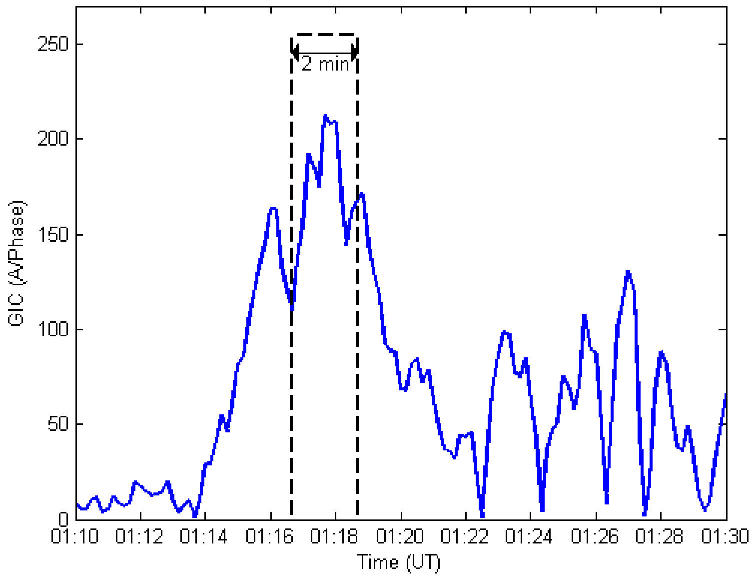

Figure 15: Close-up of GIC(t) and a 2 minute 255 A/phase GIC pulse at full load

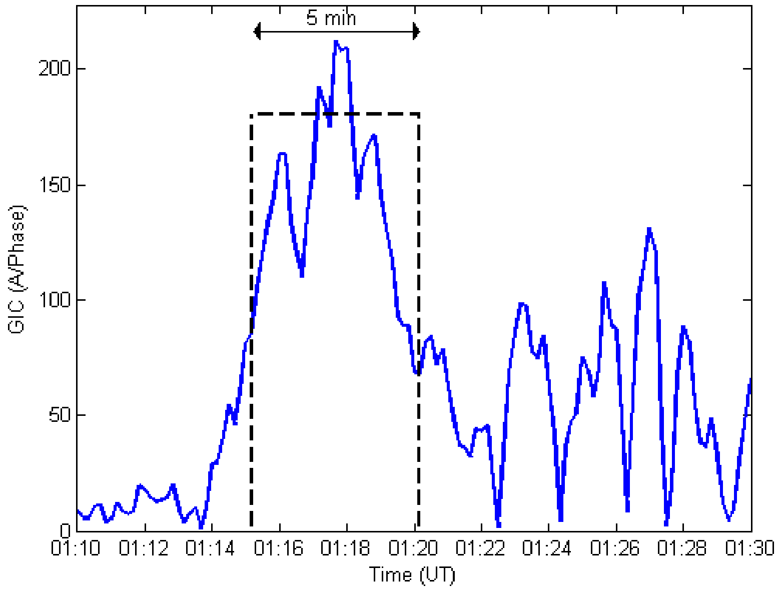

Figure 16: Close-up of GIC(t) and a Five Minute 180 A/phase GIC Pulse at Full Load

When using a capability curve, it should be understood that the curve is derived assuming that there is no hot spot heating due to prior GIC at the time the GIC pulse occurs (only an initial temperature due to loading). Therefore, in addition to estimating the equivalent pulse that matches GIC(t), prior metallic hot spot heating must be accounted for. From these considerations, it is unclear whether the capability curves would be exceeded at full load with a 180°C threshold in this example.

At 70% loading, the two and five minute pulses from **Figure 13** would have amplitudes of 310 and 225 A/phase, respectively. The 5 minute pulse is illustrated in **Figure 17**. In this case, judgment is also required to assess if the GIC(t) is within the capability curve for 70% loading. In general, capability curves are easier to use when GIC(t) is substantially above, or clearly below the GIC thresholds for a given pulse duration.

If a conservative threshold of 160°C were used to account for the age and condition of the transformer, then a new set of capability curves would be required.

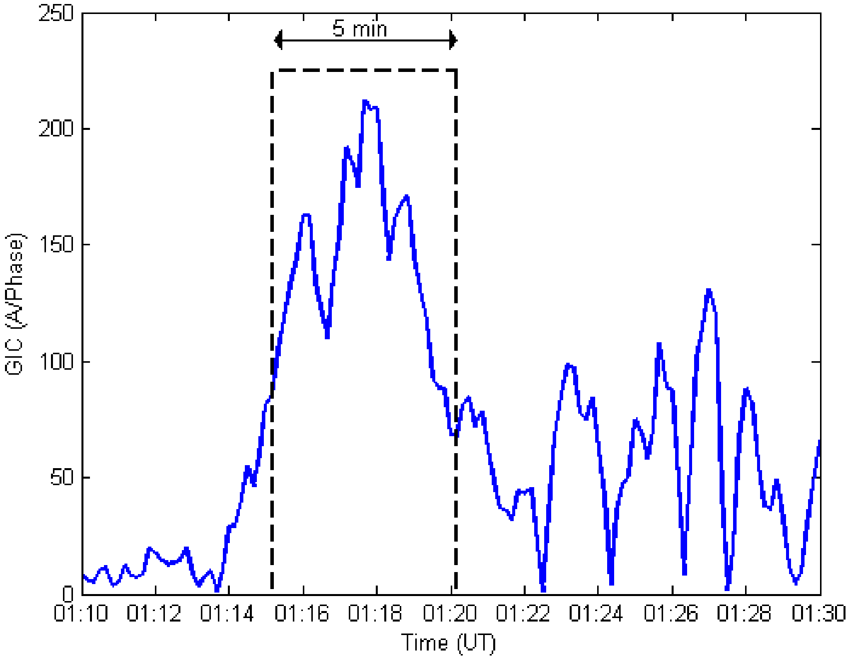

Figure 17: Close-up of GIC(t) and a 5 Minute 225 A/phase GIC Pulse Assuming 75% Load

References

[1] "IEEE Guide for loading mineral-oil-immersed transformers and step-voltage regulators." IEEE Std C57.91-2011 (Revision of IEEE Std C57.91-1995).

[2] Application Guide: Computing Geomagnetically-Induced Current in the Bulk-Power System, NERC. Available at: http://www.nerc.com/comm/PC/Geomagnetic%20Disturbance%20Task%20Force%20GMDTF%202013/GIC%20Application%20Guide%202013_approved.pdf

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[5] Girgis, R.; Vedante, K. “Methodology for evaluating the impact of GIC and GIC capability of power transformer designs.” IEEE PES 2013 General Meeting Proceedings. Vancouver, Canada.

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