NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Transformer Thermal Impact Assessment White Paper (Draft)

Project 2013-03 (Geomagnetic Disturbance Mitigation)

TPL-007-1 Transmission System Planned Performance during Geomagnetic Disturbances

Background

On May 16, 2013, FERC issued Order No. 779, directing NERC to develop Standards that address risks to reliability caused by geomagnetic disturbances (GMDs) in two stages:

- Stage 1 Standard(s) that require applicable entities to develop and implement Operating Procedures. The Stage 1 Standard, EOP-010-1 is pending at FERC in Docket No. RM14-1-000.
- Stage 2 Standard(s) that require applicable entities to conduct assessments of the potential impact of benchmark GMD events on their systems. If the assessments identify potential impacts, the Standard(s) will require the applicable entity to develop and implement a plan to mitigate the risk.

TPL-007-1 is a new Reliability Standard to specifically address the Stage 2 directives in Order No. 779.

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-007-1 will require owners of such transformers to conduct thermal analyses of their transformers to determine if the transformers will be able to withstand the thermal transient effects associated with the Benchmark GMD event. This paper discusses methods that can be employed to conduct such analyses, including example calculations.

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 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.

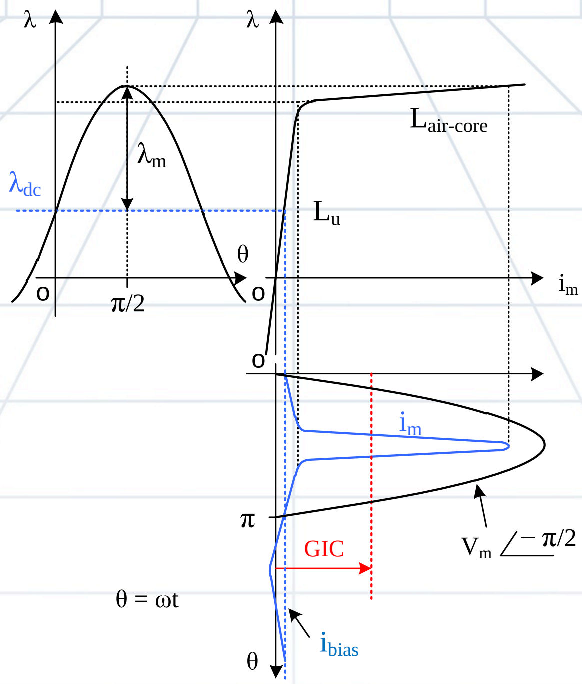


Figure 1: Mapping Magnetization Current to Flux through Core Excitation Characteristics

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 and that "pass" means that GIC in a particular transformer is so low that a detailed study is unnecessary. Such threshold would have to be technically justifiable and sufficiently low to be considered a conservative value within the scope of the benchmark.

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 standard [1] for hot spot heating during short-term emergency operation. 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 "waveshape" 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]

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

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

There are two different ways to carry out a detailed thermal impact screening:

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 waveshape 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** [3], a square pulse of 900 A/phase with a duration of 2 minutes would reach a temperature of 180 °C at full load. While GIC capability curves are relatively simple to use, a fair amount of engineering judgment is necessary to ascertain what portion of a GIC waveshape is equivalent to, for instance, a 2 minute pulse. Also, manufacturers generally maintain that in the absence of transformer standards defining thermal duty due to GIC, such capability curves have to be developed for every transformer design and vintage.

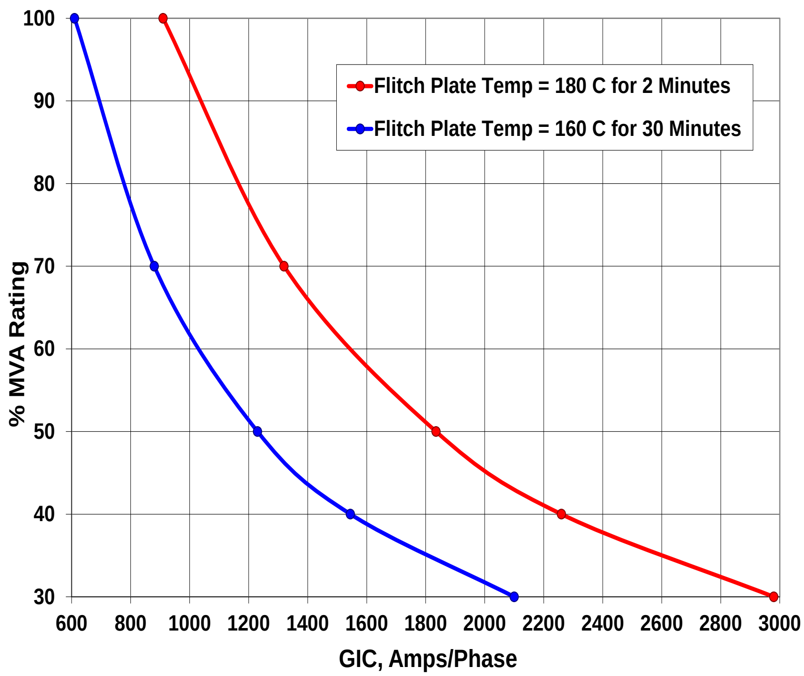


Figure 2: Sample GIC manufacturer capability curve of a large single-phase transformer design using the Flitch plate temperature criteria [3]

2. Thermal response simulation[1]. The input to this type of simulation is the time series or waveshape 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 [4] are shown in **Figure 3**. The hot spot thermal transfer functions can be obtained from measurements or calculations provided by transformer manufacturers. Default values can be used (e.g. those provided in [4]) when specific data are not available. Hot spot temperature thresholds shown in **Figure 3** are consistent with IEEE Std. C57.91 emergency loading hot spot limits. Emergency loading time limit is usually 30 minutes.

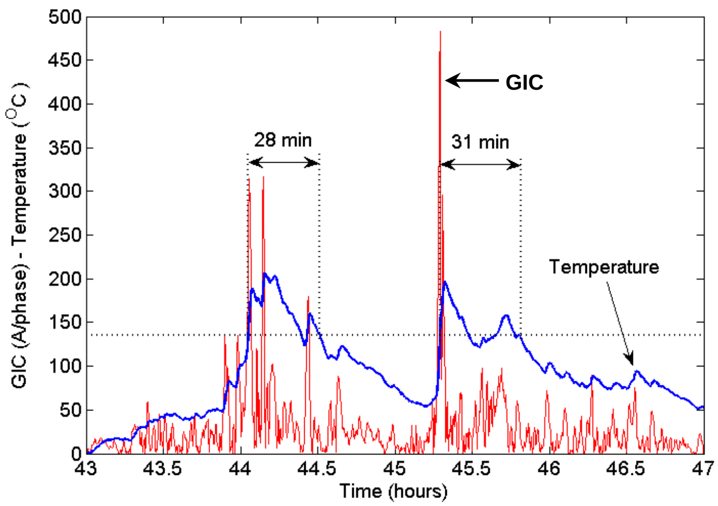


Figure 3: Sample Tie Plate Temperature Calculation

Blue trace is incremental temperature and red trace is the magnitude of the GIC/phase [4]

It is important to reiterate that the characteristics of the time sequence or "waveshape" 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 waveshape 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

[1] Technical details of this methodology can be found in [4].

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 when 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/V/km) 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_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 geoelectric field time series E_N(t) and E_E(t) is obtained, for instance, from the reference geomagnetic field time series [5] after the appropriate geomagnetic latitude factor α is applied[2]. Applying (2) 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 = -6A/phase if E_N=0, E_E=1 V/km and GIC_N = 9.6A/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 [5]. The resulting geoelectric field time series is shown in **Figure 4**. Therefore,

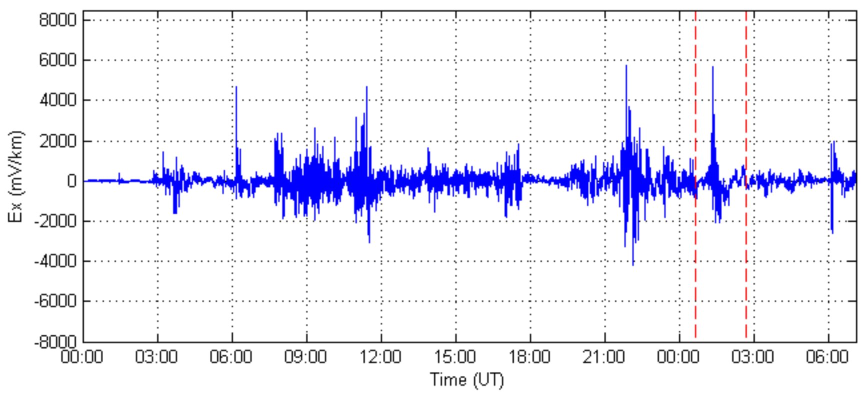
[2] The geomagnetic factor α is described in [2] and is used to scale the geomagnetic field according to geomagnetic latitude. The lower the geomagnetic latitude (closer to the equator) the lower the amplitude of the geomagnetic field.

$$GIC(t) = \sqrt{E_N^2(t) + E_E^2(t)} \cdot \{GIC_E \sin\varphi(t) + GIC_N \cos\varphi(t)\}$$

$$GIC(t) = \sqrt{E_N^2(t) + E_E^2(t)} \cdot \{-16 \cdot \sin\theta(t) + 9.6 \cdot \cos\theta(t)\}$$

The resulting GIC waveshape 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) waveshape 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) waveshape to test all transformers is incorrect.



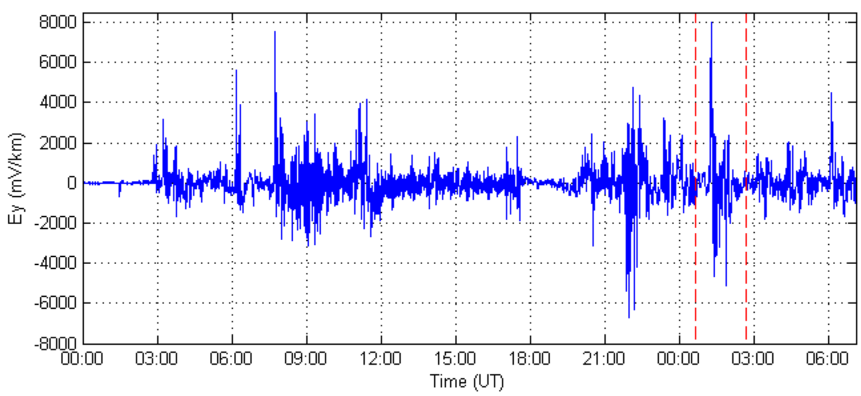


Figure 4: Calculated geoelectric field $E_N(t)$ and $E_E(t)$ assuming $\alpha=1$ and $\beta=1$ (Reference Earth Model)

Zoom area for subsequent graphs is highlighted.

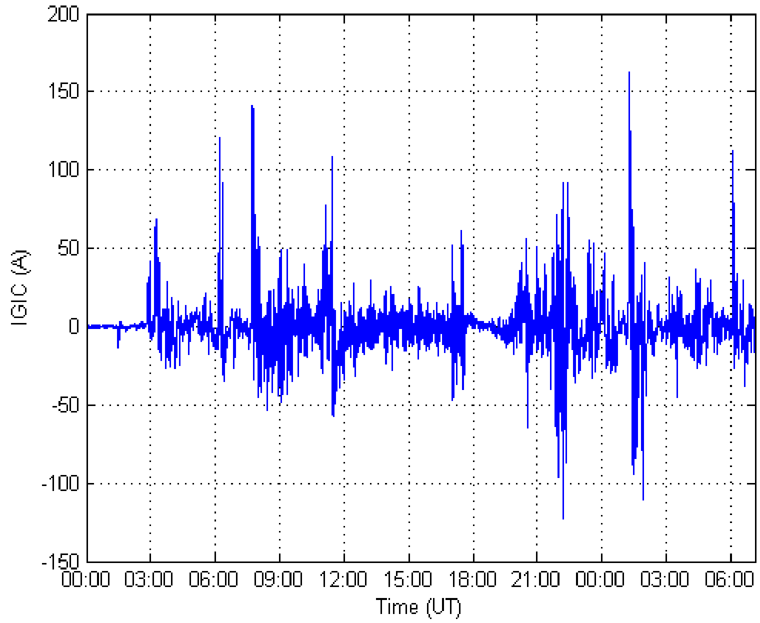


Figure 5: Calculated GIC(t) Assuming $\alpha=1$ and $\beta=1$ (Reference Earth Model)

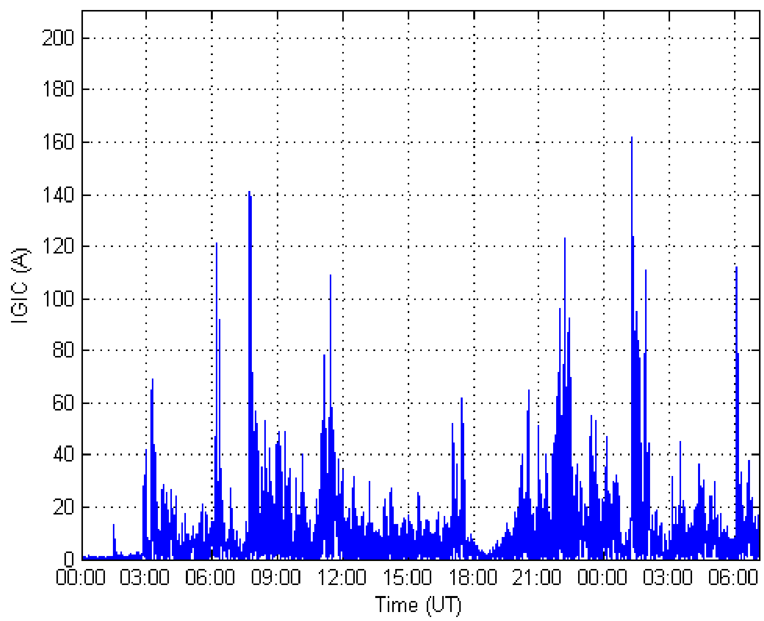


Figure 6: Calculated Magnitude of GIC(t) Assuming $\alpha=1$ and $\beta=1$ (Reference Earth Model)

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) using manufacturer's capability curves, and 2) calculating the thermal response as a function of time.

Example 1: Using a thermal response tool

The thermal step response of the transformer can be obtained for both winding and metallic part hot spots from: (a) measurements; (b) manufacturer's calculations; or (c) generic published values. **Figure 7** shows the measured metallic hot spot thermal response from [4] that will be used in this example. **Figure 8** shows the estimated incremental temperature rise (asymptotic response) of the hot spot to long duration GIC steps.[3] The asymptotic response in **Figure 8** is extrapolated linearly from relatively low magnitude dc measurements. This is a conservative approximation for illustration purposes. In the Fingrid transformer tests reported in 2002 [6], the measured maximum value of the asymptotic response of the inside of the yoke clamp (highest hot spot temperature) is 15% lower than the value obtained using linear extrapolation. The linear extrapolation results in a calculated temperature peak 9% higher than the measured asymptotic behavior when the GIC(t) time series in **Figure 6** is used.

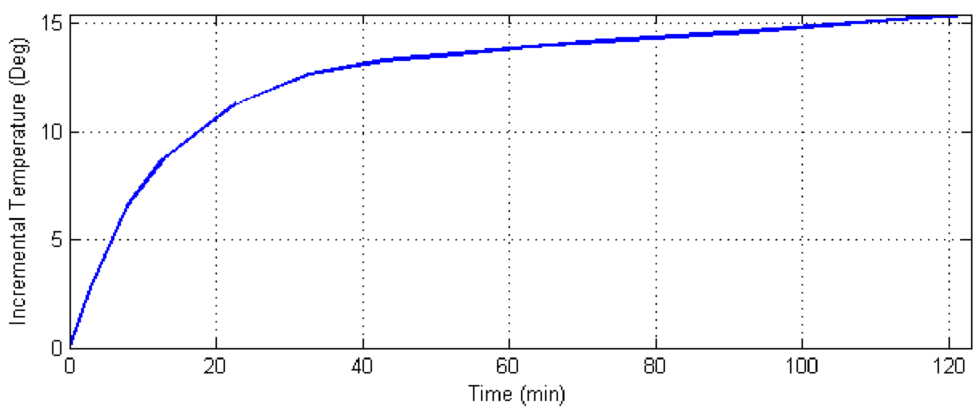


Figure 7: Thermal Step Response to a 5 A/phase dc Step [3]
Metallic hot spot heating.

[3] The heating of the 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.

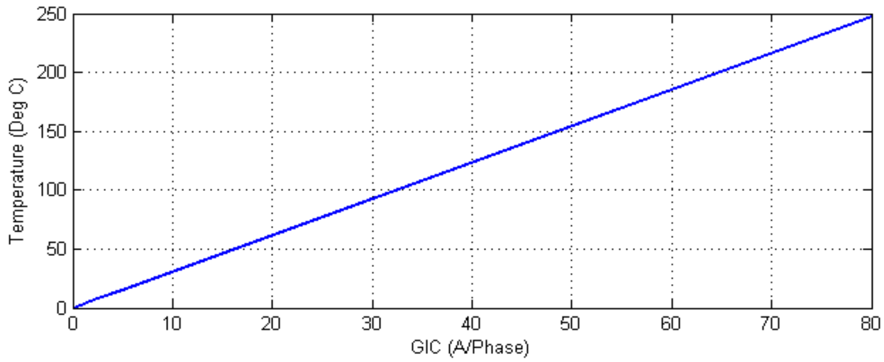


Figure 8: Asymptotic Thermal Step Response [4]
Metallic hot spot heating.

In order to obtain the thermal response of the transformer to a GIC waveshape 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 waveshape is then applied to the thermal model to obtain the incremental temperature rise as a function of time $\theta(t)$ for the GIC(t) waveshape. The total temperature is calculated by adding the oil temperature, for example, at full load.

Figure 9 shows the calculated GIC(t) and the corresponding hot spot temperature time series $\theta(t)$. **Figure 10** shows a close-up of the peak transformer temperatures calculated in this example.

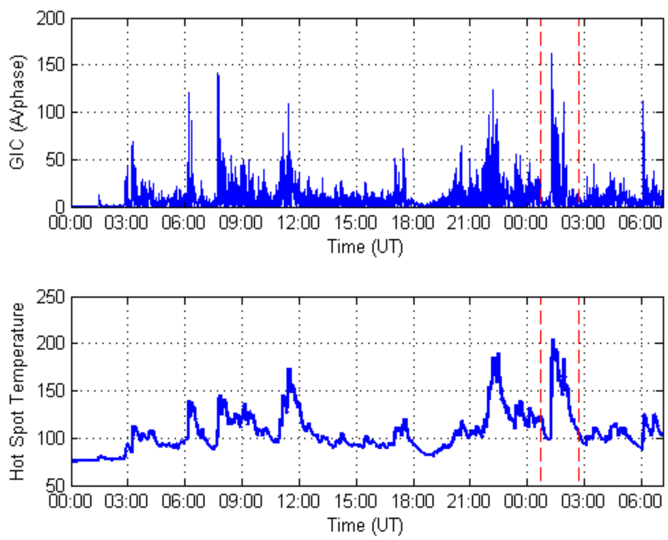


Figure 9: Magnitude of GIC(t) and metallic hot spot temperature $\theta(t)$ assuming full load oil temperature of 75.3°C (30°C ambient)

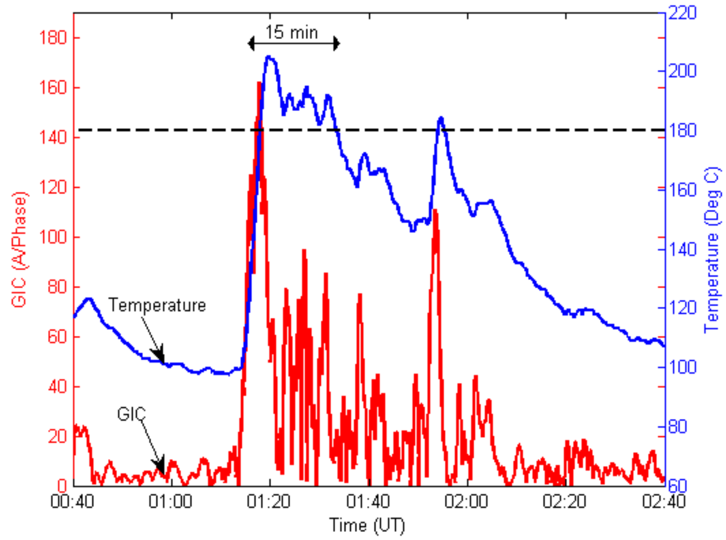


Figure 10: Close-up of Metallic hot spot temperature θ(t) assuming a full load (blue trace)

Red trace is GIC(t)

In this example the IEEE Std. C57.91 emergency loading hot spot threshold of 200°C for metallic hot spot heating is exceeded for 3 minutes (as opposed to 30 minutes for emergency overloading). Peak temperature is 204°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 to account for calculation and data margins as well as transformer condition. **Figure 10** shows that 180°C will be exceeded for 15 minutes.

At 70% loading, the initial temperature is 54.5 °C rather than 75.3 °C and the hot spot temperature peak is 183°C. In this case the 180 °C threshold is exceeded for 2 minutes (see **Figure 11**).

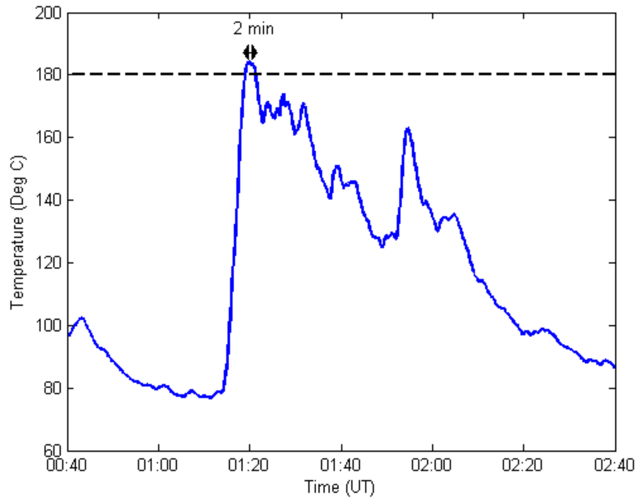


Figure 11: Close-up of Metallic hot spot temperature assuming a 70% load
(Oil temperature of 54.5°C)

Example 2: Using a manufacturer's capability curves

The capability curves used in this example are shown in **Figure 12**. To be consistent with the previous example, these particular capability curves have been reconstructed from the thermal step response shown in **Figures 8** and **9**, and the simplified loading curve shown in **Figure 14** (calculated using formula from IEEE Std. C57.91).

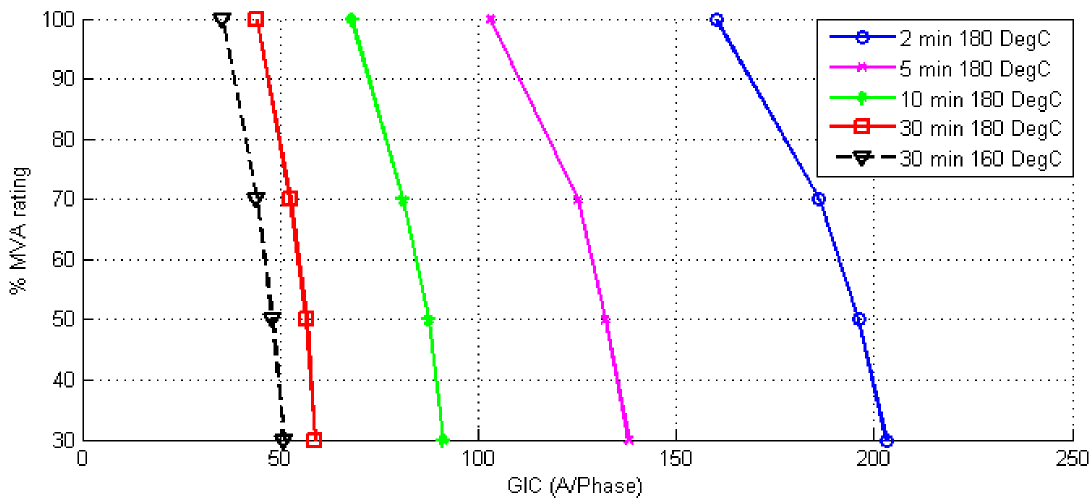


Figure 12: Capability curve of a transformer based on the thermal response shown in Figures 8 and 9

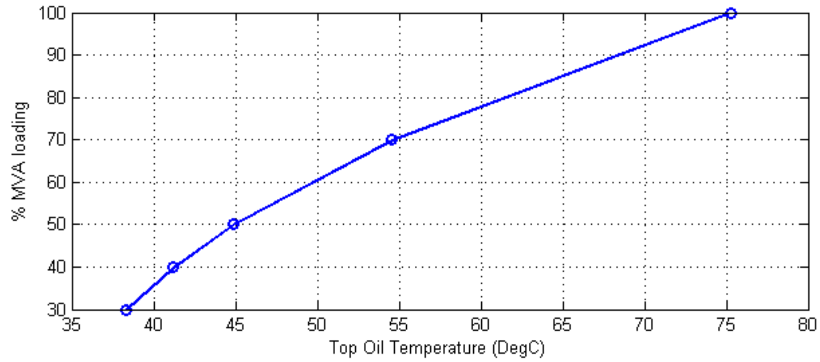


Figure 13: Simplified loading curve assuming 30°C ambient temperature

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 waveshape of GIC(t), generally at a GIC(t) peak. **Figure 14** shows a close-up of the GIC near its highest peak superimposed to a 160 A/phase, 2 minute pulse at 100% loading from **Figure 12**. Since a narrow 2-minute pulse is not representative of GIC(t) in this case, a 5 minute pulse with an amplitude of 103 A/phase at 100% loading has been superimposed on **Figure 15**. It should be noted that a 160 A/phase, 2 minute pulse is equivalent to a 103A/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.

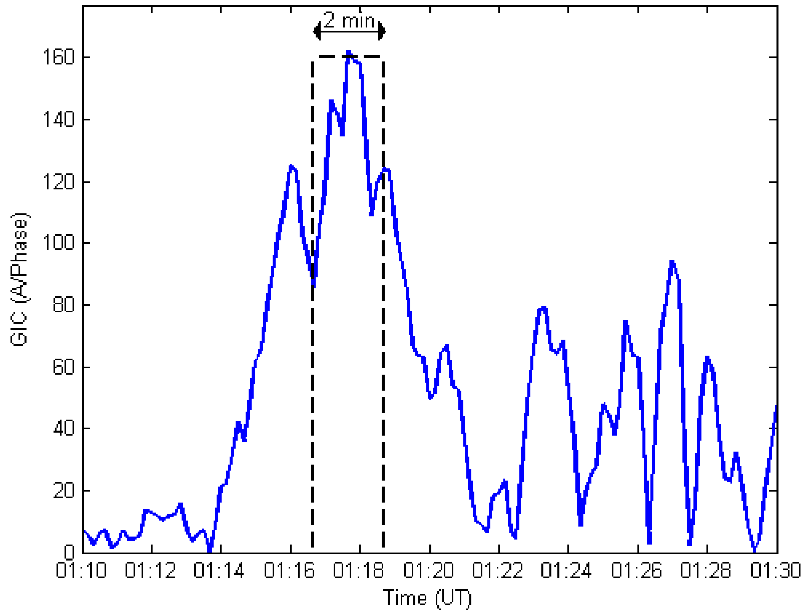


Figure 14: Close-up of GIC(t) and a 2 minute GIC pulse at full load

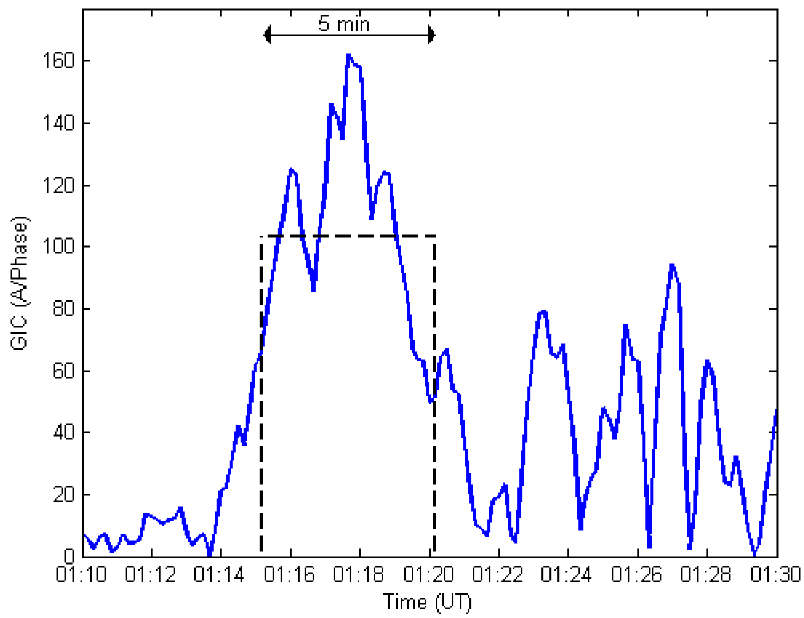


Figure 15: Close-up of GIC(t) and a 5 minute GIC pulse at full load

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), allowances have to be made in terms of prior hot spot heating. From these considerations it is apparent that the capability curves would be exceeded at full load with a 180 °C threshold.

At 70% loading, the two and five minute pulses from **Figure 12** would have amplitudes of 186 and 125 A/phase, respectively. The 5 minute pulse is illustrated in **Figure 16**. In this case, it is not easy 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.

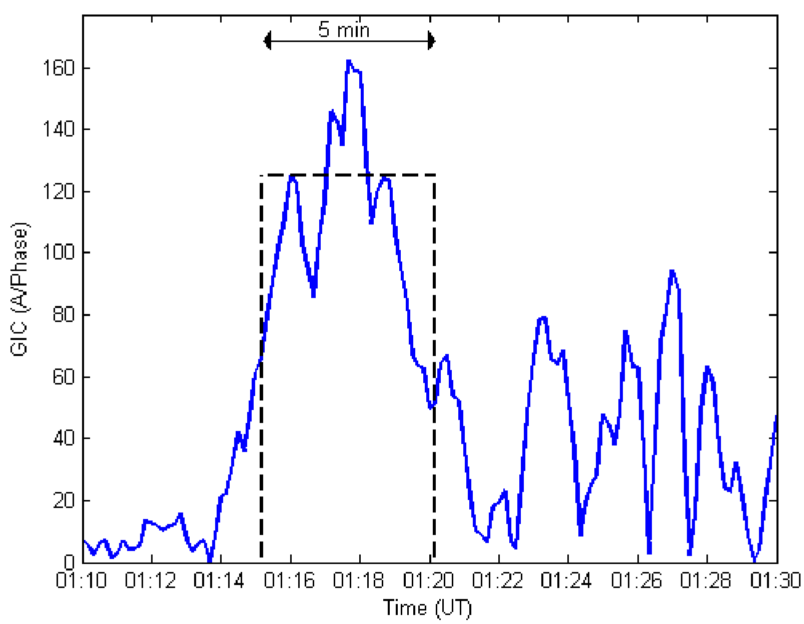


Figure 16: Close-up of GIC(t) and a 5 minute GIC pulse assuming 70% load

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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[4] Marti, L., Rezaei-Zare, A., Narang, A. "Simulation of Transformer Hotspot Heating due to Geomagnetically Induced Currents." IEEE Transactions on Power Delivery, vol.28, no.1. pp 320-327. January 2013.

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