Remarks of Luis Marti

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Good morning, Chairman Bay, Commissioners, FERC staff, and fellow panelists.

My name is Luis Marti and I am the Director of Reliability Studies Standards and Compliance at Hydro One Networks, Ontario Canada. I received my PhD degree in Electrical Power Systems from the University of British Columbia in 1986 and have over 30 years of experience in the modelling and simulation of electromagnetic transients and other power system phenomena. I have served as adjunct professor at the Universities of Toronto, Western Ontario, Ryerson and Waterloo and I am an IEEE Fellow. I greatly appreciate the opportunity to participate in today's technical conference.

Ontario Hydro (and Hydro One) has been involved in the assessment of the effects of GIC in power systems since the early 1980's. In 2012, a real-time GMD management system was put in service at the Ontario Grid Control Centre. This eXtreme Space Weather (XSW) management tool assesses GIC flows, transformer hot spot heating, reactive power absorption and harmonic stresses in shunt capacitor banks in every part of the Ontario 500 kV and 230 kV networks using measurements from 18 GIC monitors and geomagnetic field measurements from the Ottawa magnetic observatory. By the end of 2016 measurements from 6 additional utility-grade magnetometers in addition to the effects of 7 distinct physiographic regions (non-uniform geoelectric fields) will be integrated into this application. Pre-planned operational measures to manage GMD events are informed/triggered by the eXtreme Space Weather application.

Thermal effects during half-cycle saturation

Power transformers are designed to operate in the linear region of their magnetizing characteristic. When zero-sequence quasi-dc currents such as GIC flow into a transformer winding, the operating point is shifted and can cause asymmetric or half-cycle saturation of the core depending on both the level of GIC current as well as the transformer's core configuration. It is generally accepted that 3-limbed core-type units tend to be the least susceptible, while all other core configurations including single-phase and 3-phase shell-type or 5-limbed core types may exhibit similar vulnerability [1-2].

When half-cycle saturation takes place a greater share of flux leaks out beyond the core, inducing additional eddy currents in various parts of the core and winding assembly including metallic structural parts such as the tie plate and tank walls. The consequence is additional heating at these locations, potentially causing gassing or simply resulting in accelerated ageing of the cellulosic insulation due to thermal degradation. Heating of the tank walls due to eddy currents can also cause the interior paint to be peeled off, liberating contaminants into the oil. The end result is that, at best, some of the useful life of the cellulosic insulation is lost, and at worst, the unit is at a greater risk of incurring an imminent failure due to the gassing causing dielectric strength to be compromised, especially on units whose design is more susceptible to GIC or whose condition is already suspect.

IEEE Standard C57.91-1995 [3] offers some guidance on temperature limits that should not be exceeded at either winding or structural hot spots on operating transformers to avoid undue aging of the winding insulation as well as to limit the risk of an imminent dielectric failure from gassing (at winding or structural hot spots). Since both of these hazards increase with the duration of exposure, the Standard recommends graded limits depending on planned needs (i.e. higher limit for shorter exposure, classified according to normal loading, planned overloading beyond nameplate rating, or long and short time emergency loading; see Table 1).

The heating mechanisms contemplated by the Standard are associated with sinusoidal load currents in the windings and symmetrical core excitation, whereas those associated with GIC currents are due to asymmetrical currents and a more distorted leakage flux distribution.

TABLE 1:
Excerpt from maximum temperature limits suggested in IEEE C57-91 1995.

	Normal life expectancy loading	Planned loading beyond nameplate rating	Long-time emergency loading	Short-time emergency loading
Insulated conductor hottest-spot temperature °C	120	130	140	180
Other metallic hot-spot temperature (in contact and not in contact with insulation), °C	140	150	160	200
Top-oil temperature °C	105	110	110	110

Nevertheless, given that the mechanisms responsible for insulation aging or gas generation depend only on temperature, and not its cause, we assume that the temperature limits prescribed by the Standard remain relevant for GIC. The location of these hot spots though may indeed differ from those in normal service.

Arguably, the suggested limits need not be interpreted too rigidly, since risks associated with exceeding these thresholds are difficult to quantify with certainty. Furthermore, they vary with the mechanical and dielectric condition of individual units, which in turn depends on the operating history. Thus a measured deviation from the prescribed limits could perhaps be justified at times, taking into account the potential consequences of dong so relative to immediate operating needs.

Finally, while IEEE C57-91 also defines algorithms for estimating hot-spot temperatures, it only models thermal mechanisms associated with normal loading, as described above, which is inadequate for estimating temperature rise from GIC.

A key aspect of hot spot heating caused by GIC is its time-dependence. To be able to estimate whether hot spot temperatures will approach or exceed IEEE C57-91 thresholds, it is necessary to estimate the magnitude and duration of GIC in the transformer windings during a GMD event. In real-time calculations, the “waveshape” of GIC in a transformer is known either by direct GIC measurements, or indirect magnetic field measurements used to estimate GIC. In the case of steady-state GIC studies, there is no “waveshape”, therefore it is necessary to make assumptions regarding the amplitude and duration. Some manufacturers assume (square) GIC pulses of a given duration and then plot the permissible GIC as a function of loading. This type of curve is often referred to as “GIC capability curve”.

An example of such a capability curve for the tie plate hot spot of a 500/16.5 kV, 400 MVA single-phase transformer is shown in Fig. 1.

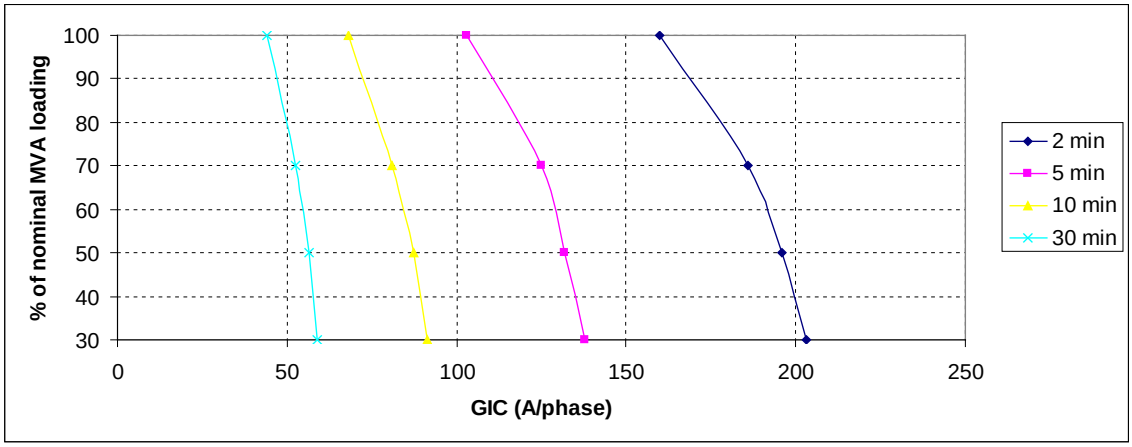

Fig. 1: Metallic hot spot capability curve calculated for a 500/16.5 kV, 400 MVA single-phase transformer.

With a reference geoelectric field, a "reference" GIC waveshape can be calculated and scaled according to the results of steady-state GIC calculations. This GIC waveshape can then be used to obtain the thermal response of a transformer hot spot without directly measuring the temperature, so long as the thermal step response input is known, either through manufacturer's calculations or measurements [4]. The temperature as a function of GIC for a waveshape based on the March 1989 GMD event for a transformer with the same capability curve shown in Fig.1 is shown in Fig.2.

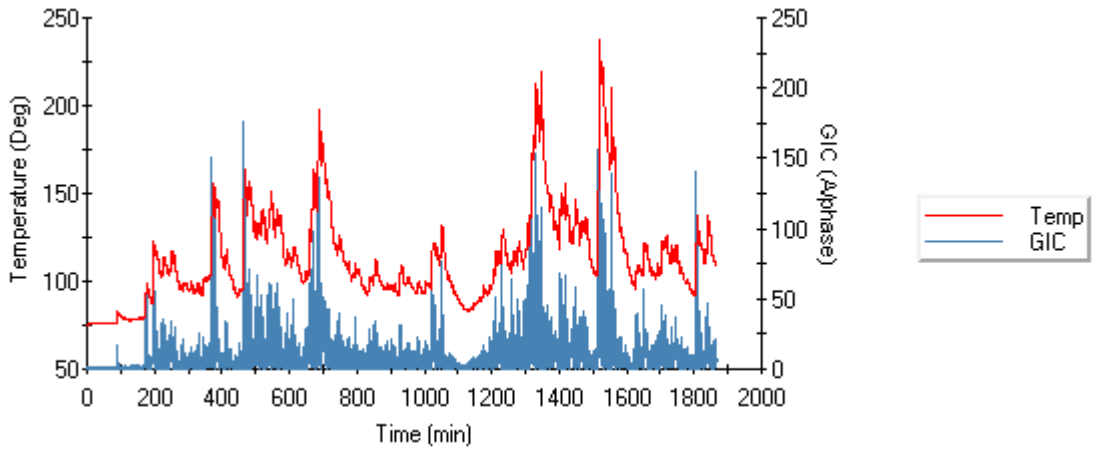

Fig. 2: Metallic hot spot temperature for a GIC waveshape derived from the March 1989 GMD event.

Selection of the benchmark 75 A/phase threshold

The methodology for the selection of the screening threshold is explained in [5-6]. The following remarks are intended to emphasize the rationale as well as some important points that are sometimes poorly understood.

In the early days of NERC's GMD Task force, there was a lot of discussion over what is the duration of a GIC peak/pulse in connection to transformer hot spot heating caused by half-cycle saturation. Should it be 1, 2 or 5 minutes, or continuous? The discussion was probably driven by the analytical tools of transformer manufacturers that could only calculate temperature rise due to a GIC step. Tools to calculate the temperature rise due to an arbitrary GIC waveshape were published in 2013 [4]. They can calculate the temperature rise due to an arbitrary GIC(t) waveform and only require either the measured or calculated thermal step responses for different values of GIC.

The results obtained using these tools match measurements very well. An example from measurements of a large 400 kV 400 MVA transformer in the Fingrid system [7] is shown in Fig. 3. Highest dc current injected was 66.7 A/phase for approximately 10 minutes. Both heating and cooling are captured. In this case the thermal step response was obtained directly from measurements.

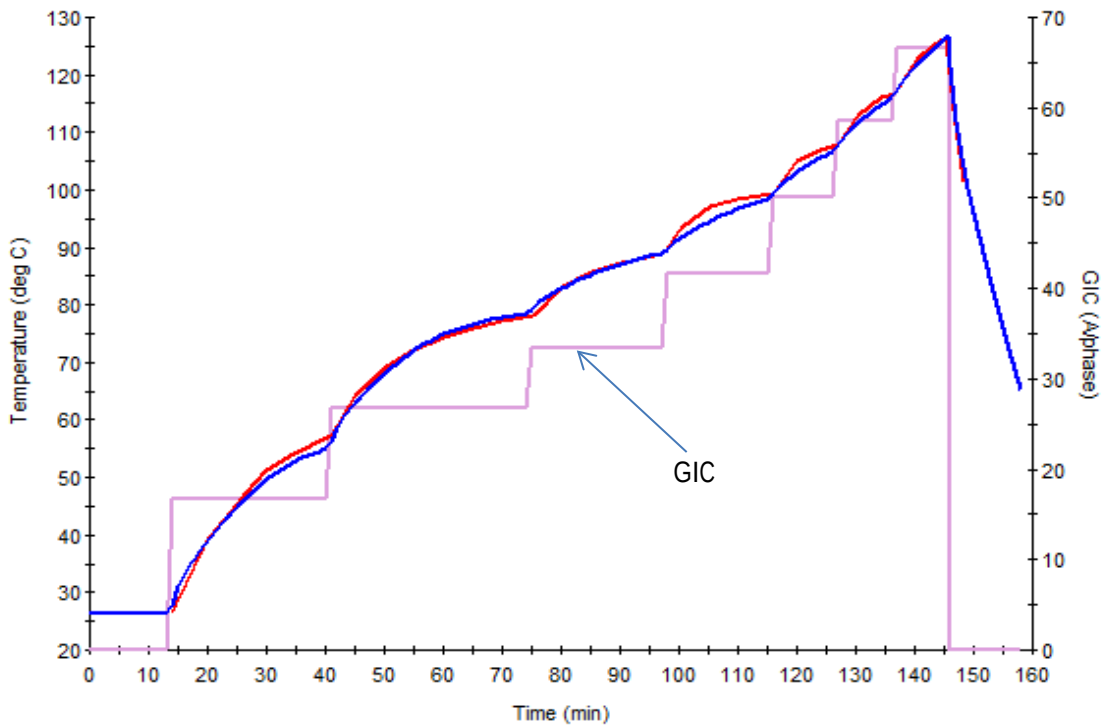

Fig. 3: Fingrid GIC injection tests. Measured values (red trace) and simulated values (blue trace). 400 kV, 400 MVA, 3-phase, 5-limb core.

Once GIC(t) is known, temperature rise as a function of time can be calculated as illustrated in Fig. 4

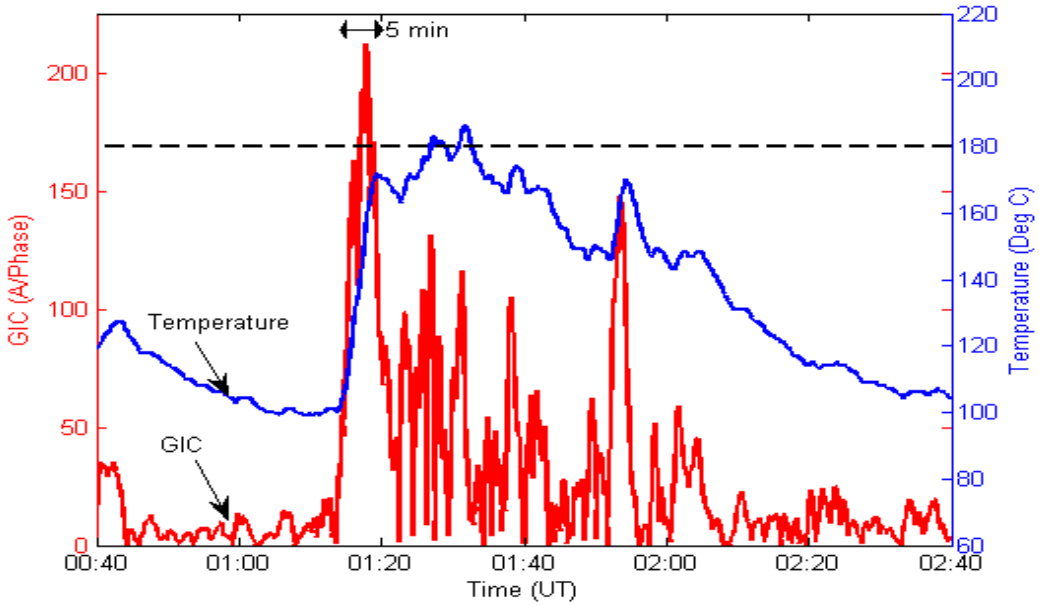

Fig 4: Metallic hot spot temperature for a GIC waveshape derived from the March 1989 GMD event.

The proposed TPL-007-1 Standard requires that GIC(t) be calculated for any given transformer. This GIC(t) is based on the scaled waveshape of the benchmark event. Scaled waveshapes from other recorded GMD events and different observatories were considered but yielded lower temperatures (see, for example Fig. 5). With temperature rise as a function of time the suggested limits in IEEE Std C57.91 can be applied (see Table 1). In the example shown in Fig 4, the hot spot temperature limits for metallic parts (200 ^{o}C and short term emergency loading (typically 30 min) would not be exceeded.

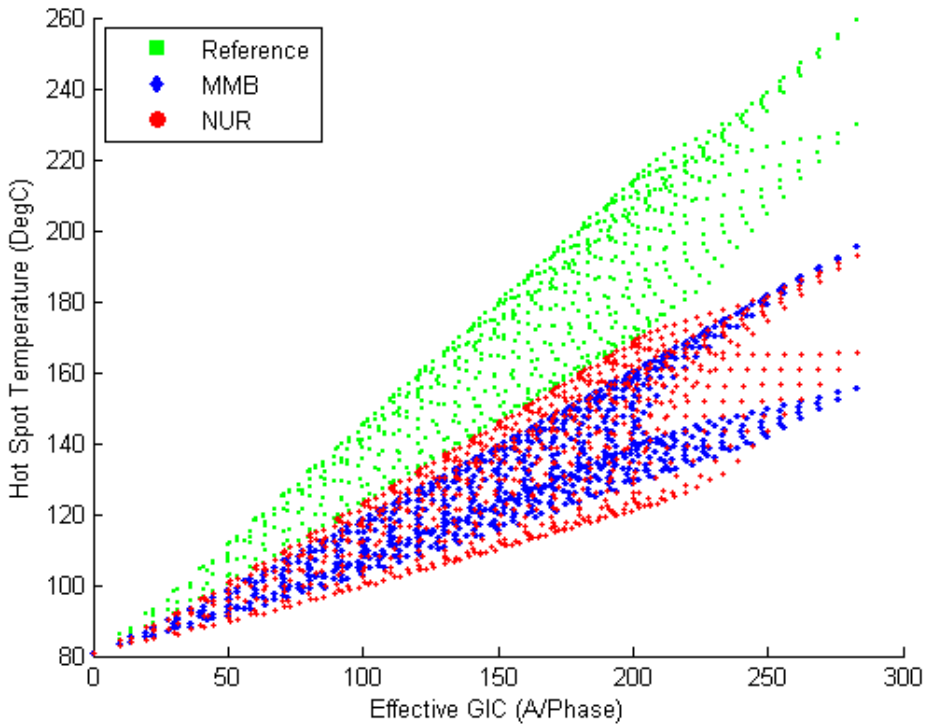

Fig 5: Metallic hot spot temperature for a GIC waveshape derived from the March 1989 GMD event (reference) and the Halloween event.

To obtain a threshold a number of models and measurements collected by the GMD Task Force were examined. Of note:

- Theoretical models from manufacturers. Both published and commissioned by Hydro One.
- Measurements from
  - Hydro Quebec tests
  - Fingrid tests
  - SoCo tests
  - Hydro One tests (1-ph Static Var Compensator and a 3-phase, 3-leg core-type units)

Of these, the measurements/models that produced the highest temperatures were selected:

- Every possible combination of GIC(t) from the benchmark event waveshape was applied to the thermal models (thousands of simulations).
- Peak temperature was recorded and plotted as shown in Fig. 6.
- Since every possible peak temperature (using these conservative models) is captured in these simulations, the Table 2 was created. Any calculated temperature on any given system using the benchmark waveshape must be less than or equal to these values.

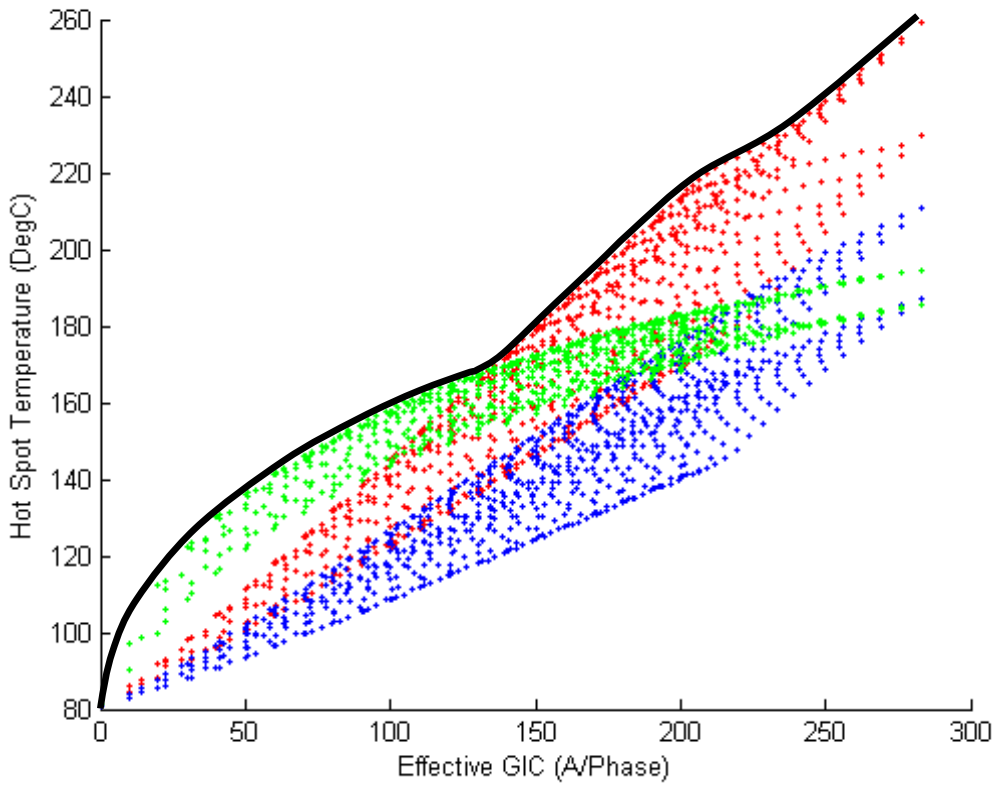

Fig 6: Metallic hot spot temperature for a GIC waveshape derived from the March 1989 GMD event. Red trace from [4], green trace from SoCo tests, blue trace from [7].

TABLE 2

Maximum temperatures (envelope in Fig. 6)

Effective GIC (A/phase)	Metallic hot spot Temperature (°C)	Effective GIC(A/phase)	Metallic hot spot Temperature (°C)
0	80	140	172
10	106	150	180
20	116	160	187
30	125	170	194
40	132	180	200
50	138	190	208
60	143	200	214
70	147	210	221
75	150	220	224

80	152	230	228
90	156	240	233
100	159	250	239
110	163	260	245
120	165	270	251
130	168	280	257

75 A/phase was selected since it represents a 70° C incremental temperature rise and provides ample margin with respect to the short term emergency overloading limits of IEEE Std C57.91. The duration of short-term emergency overloading is typically 30 minutes.

75 A/phase is the instantaneous peak value of GIC(t). This means that this value of GIC would not be maintained or exceeded for any length of time, therefore it does not take into account the 30 minute short-term emergency loading guidelines of IEEE Std C57.91, thus providing another layer of conservatism.

The 75 A per phase screening threshold was determined using single-phase transformers, but for the purpose of TPL-007-1 is applicable to all types of transformer construction. While it is known that some transformer types such as three-limb, three-phase transformers are intrinsically less susceptible to GIC, it is not known by how much, on the basis of experimentally-supported models.

An additional layer of conservatism was added by not taking into account local oil viscosity changes with hot spot temperature.

Concluding remarks

The state-of-the-art of transformer thermal modelling needs more experimental validation of analytical models (e.g., FEM). However, several measurement-based models are currently available and were used to develop the 75 A/phase screening criterion. The criterion includes a large degree of margin.

Publicly-available tools can be used by asset owners to carry out thermal assessments. The thermal response can be obtained from the manufacturer or from conservative defaults.

The screening threshold is based on known transformer thermal behaviour. It contains a number of conservative layers and it is not based on anecdotal evidence.

Going forward it will be important to obtain measurements or models supported by measurements of a larger sample of transformers. Equally important will be having internally-instrumented transformers so that the thermal response can be obtained directly during a GMD event.

As more thermal responses (either measured or from measurement supported calculations) are known, the threshold can be modified.

References

[1] R.A. Walling, and A.H. Khan, “Characteristics of Transformer Exciting-Current during Geomagnetic Disturbances.” *IEEE Trans. Power Del.*, vol. 6, no 4, pp. 1707-1714, 1991.

[2] P.R. Price, "Geomagnetically Induced Current Effects on Transformers", *IEEE Trans. Power Del.*, vol. 17, no 4, pp. 1002-1008, 2002.

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

[4] Marti, L.; Rezaei-Zare, A.; Narang, A., "Simulation of transformer hot-spot heating due to Geomagnetically Induced Currents," in *Power and Energy Society General Meeting (PES), 2013 IEEE* , vol., no., pp.1-1, 21-25 July 2013

[5] Transformer Thermal Impact Assessment White Paper. Project 2013-03 (Geomagnetic Disturbance Mitigation) TPL-007-1 Transmission System Planned Performance for Geomagnetic Disturbance Events

[6] Screening Criterion for Transformer Thermal Impact Assessment. Project 2013-03 (Geomagnetic Disturbance Mitigation) TPL-007-1 Transmission System Planned Performance for Geomagnetic Disturbance Events

[7] M. Lahtinen and J. Elovaara, "GIC occurrences and GIC test for 400 kV system transformer," Power Delivery, IEEE Transactions on, vol. 17, no. 2, pp. 555-561, 2002.