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Benchmarking the GICharm Tool against EMT Simulation

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SUMMARY

The part-cycle saturation of power transformers caused by the flow of Geomagnetically-Induced Currents (GIC) through power transformers is the root cause of GIC-related harmonic issues on the bulk power system. [1][2] EPRI has developed the GICharm tool for analysis of power systems experiencing harmonic distortion from transformer saturation due to GIC. [3]

The power system analysis in GICharm is performed by the EPRI OpenDSS program, which solves electric power circuits in the phasor domain. [5][6][7] The circuit modeling and solution methods evolved from power system harmonics analysis tools utilizing nodal admittance formulations. This is a good fit to analyzing harmonic flows due to GIC-induced transformer saturation.

OpenDSS can model detailed multi-phase circuits consisting of multiple voltage levels. Actual values of voltage, current, and impedance are used. OpenDSS requires detailed transformer models to correctly represent circuits with multiple voltage levels in full multi-phase detail, complete with correct winding connections. While in the rms steady-state domain, this model is more like electromagnetic transients (EMT) models that also use actual values and represent transformers in detail than typical power flow models, which may represent only the positive-sequence circuit in per unit values.

Previous benchmarking for validation of the tool involved matching staged laboratory tests such as the Fingrid test. [8] It is sometimes difficult to obtain adequate model data from the published descriptions of such tests. This paper describes benchmarking against an EMT simulation of GIC found documented in the nuclear power industry literature. [9] An excellent match to the EMT simulation was achieved.

KEYWORDS
Geomagnetic Disturbance (GMD), Geomagnetically-induced Currents (GIC), Harmonics, Transformer Saturation

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INTRODUCTION

Solar disturbances, such as coronal mass ejections, can result in a geomagnetic disturbance (GMD) when charged particles emitted from the sun interact with the earth's magnetic field. During GMD events, variations in the magnetic field drive low-frequency, quasi-dc electric currents along transmission lines and through wye-connected transformer windings to ground. The dc offset bias of these geomagnetically-induced currents (GIC) produce part-cycle saturation in the transformers. Figure 1 shows a typical magnetizing current waveforms for one of the phases in a bank of three single-phase transformers having GIC in each phase. In this case the transformer sees about 10% of the peak of the transformer winding's rated peak (or crest) current, i.e., 0.1 p.u. GIC.

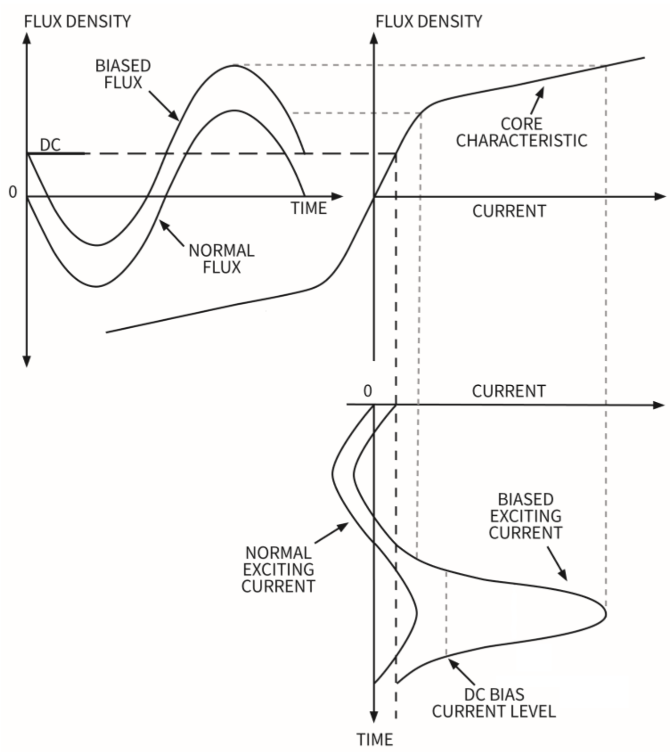

Figure 1. Relationship between the magnetic flux and the exciting current for normal operation and bias operation.

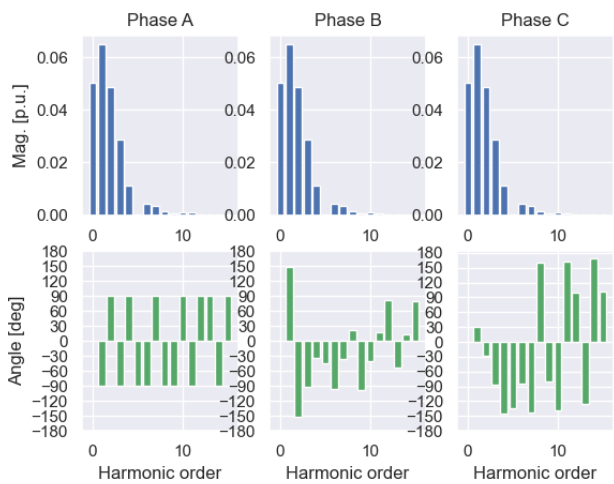

Figure 2. Harmonic magnitudes and phase angles for a bank of 1-phase transformers excited with 0.05 pu of GIC in each phase.

Figure 2 shows typical harmonic current spectra for a bank of similar transformers impacted by 0.05 pu GIC. The harmonic current injections are over a range of harmonic frequencies and include both even and odd orders. It is important to highlight that the spectrum is dependent on the core topology of the transformer as well as on the harmonic content of the voltage and the level of GIC flowing into the transformer terminals. EPRI has developed the GICharm tool [3] to analyze power systems containing one or more power transformers subjected to GIC. Figure 3 shows some of the core topologies GICharm is able to represent in its current version.

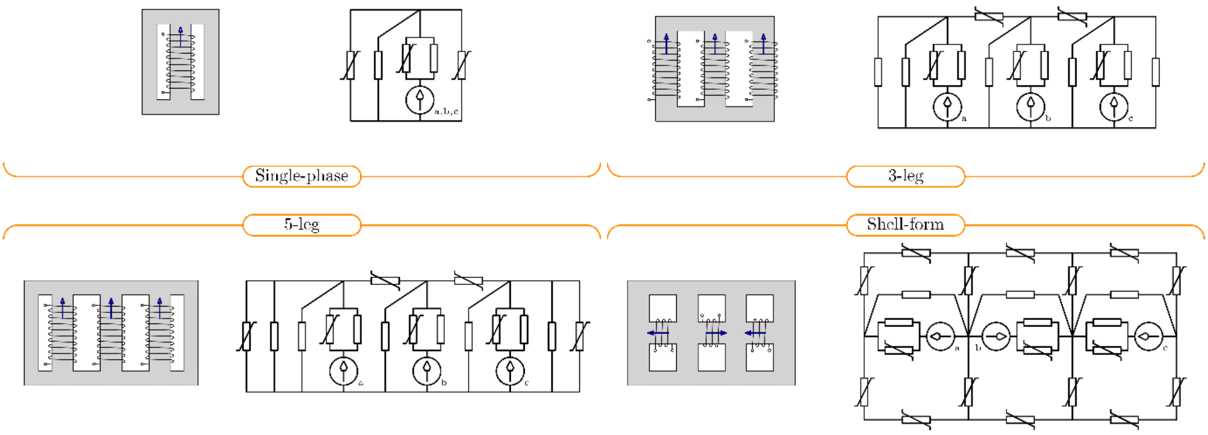

Figure 3. Core-Topologies and Magnetic Circuit Models in GICharm

This paper describes part of a continuing effort to validate the GICharm tool against the output of other tools and measurements. The first and most complete benchmarking was performed against the Fingrid laboratory tests of back-to-back 400 MVA, 410-kV transformers reported by Lahtinen and Elovaara. [8] The GICharm match to these test results is reported by the authors in [6].

The Fingrid tests were described in sufficient detail that the authors were able to easily construct a suitable model in GICharm and achieve good results. That has not always been the case. It has been difficult to find published results with sufficient circuit model data to validate the GICharm model. The authors were frustrated several times by incomplete or apparently erroneous data in candidate benchmark cases.

In this paper we compare the GICharm results with a computer simulation reported in 1994 using the venerable original EMTP program. The circuit is simple (Figure 5) and the complete EMTP model is provided in the source document, Ref. [9]. This eliminates much of the guesswork for constructing the system models in OpenDSS.

This modeling task is intended to move the industry towards a complete, near real-time simulation of GIC flow along with its effects on system assets and performance. Presently the GIC and harmonics analyses are conducted on different platforms. The effort described here will work to provide a seamless interface between these platforms. The integration of these platforms will lead to more effective real-time impact mitigation decisions and a reduction in the likelihood of ending with equipment damage and widespread power blackouts due to a major GMD event.

As explained in [5], to characterize the behavior of transformers exposed to GIC, the GICharm program uses the magnetic circuit models of Figure 3, for 3-legged core, 5-legged core, shell-form and banks of 3 single-phase core transformers, as well as some additional models in the v4.0 version. The detailed parameter values of the models depend on the user input.

GICharm makes use of a magnetic circuit solver algorithm in and a “DC-flux finder” algorithm [6] to produce time-domain waveforms for the excitation currents drawn by a GIC exposed transformer. These algorithms take advantage of the fact that the magnetic circuits of interest fall in the category of “Networks of nonlinear monotone resistors”, which have a unique solution for each unique combination of inputs. [10] The algorithms in GICharm are based on the ones proposed in [11]and [12]

The overall GIC harmonics approach implemented in the EPRI GICharm program is illustrated in the flow chart in Figure 4. The software is based on the EPRI OpenDSS program with Python-language auxiliary programs for time-domain solution and for importing data from other sources. The main network model is first constructed in the OpenDSS program. The GIC values are either computed using the OpenDSS model or imported from other computer tools in the industry capable of computing the GIC values given the GMD electric field values. A basic power flow calculation at fundamental frequency is then made. This may also be imported from another computer program’s power flow results. This initializes the process. Subsequent iterations consider voltage harmonic distortion and refine the harmonics solution.

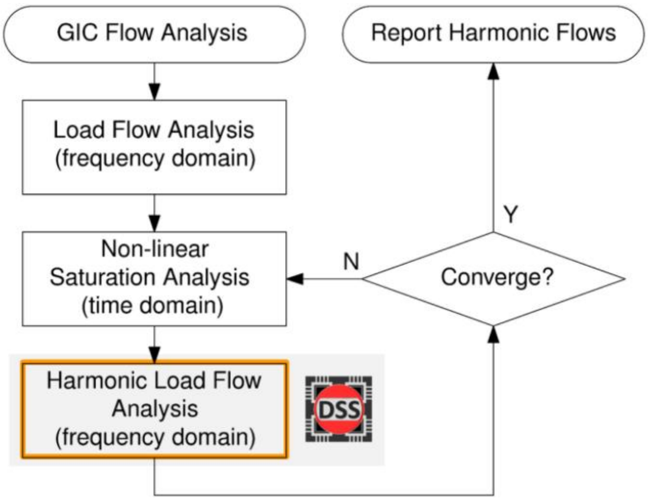

Figure 4. GICharm Software Solution Approach [6].

THE BENCHMARK CIRCUIT

The circuit chosen for benchmarking is the 50-mile 500 kV line from the Salem 1 generating station to the New Freedom bus (Figure 5). The main transformer in the benchmark is the generator step-up (GSU) at Salem 1.

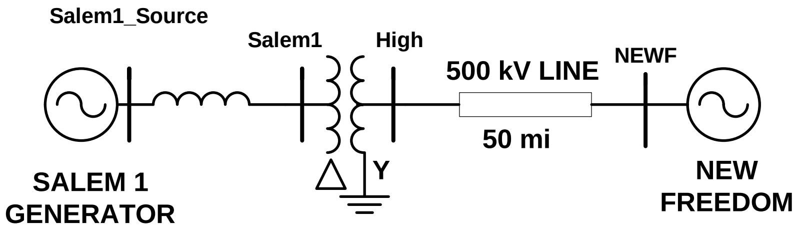

Figure 5. One-Line Diagram for Salem 1 Circuit [9]

The complete OpenDSS script for the Salem 1 circuit described in [9] is given in Figure 6. It follows the EMTP model for the most part where it is possible. Since OpenDSS is a steady-state phasor-domain model, it is not possible to model the nonlinear saturation characteristic of the GSU transformer in exactly the same way as in the EMTP model. GICharm handles this by defining a third wye-connected 24-kV winding on the 1080-MVA GSU to represent the magnetizing impedance (see the definition for "New Transformer.1_2_3_1_1" in Figure 6). GICharm utilizes this impedance to simulate the nonlinear saturation analysis block shown in Figure 4.

A simple two-point saturation curve was assumed for the saturable element as was done in the EMTP model. The values are shown in Table I. Note that the quantities are given in peak values.

Table I. Transformer Saturation Characteristic at 24 Kv

Current (peak amps)	Flux (Wb)	Per Unit Flux
120.83	90.031	1.0
771.94	99.035	1.1

The load at the New Freedom bus is modelled using a voltage source – as it was in the EMTP model: a 1.0 pu 500 kV source with a phase angle of 31 degrees.

Comparing Figure 7 to Figure 8, it can be seen that a good match for the GSU magnetizing current was achieved between the GICharm model and the EMTP model.

The computed transformer neutral current is also reported for the EMTP model (Figure 9). The time-domain waveform exhibits some high frequency components that do not appear in the waveform produced by GICharm (Figure 10). These components are likely due to reflections appearing on the 50-mile transmission line model. However, the general shape of the waveform produced by GICharm clearly follows the same pattern as the waveforms produced by the time-domain simulations.

CIRCUIT DESCRIPTION SCRIPT

```
Clear

! From BNL-NUREG-52359
! January 1994
! The Effects of Solar-geomagnetically Induced
! Currents on Electrical systems in Nuclear Power Stations

! Adapted from EMTP case in Appendix D in the report

! Revised May 2023

redirect env_variables.dss

New circuit.Salem1Case

!***** ~ angle=4.23  pu=1.002731796381894 Basekv=24 puZ1=[ 0.0003  0.3]  puZ0=[0.0003 0.3 ] BaseMVA=1000  Bus1=Salem1_source
~ angle=20.3 pu=1.0662 Basekv=24  Model=Ideal puZideal= [1E-007, 0.0001] BaseMVA=1080 Bus1=Salem1_source   !_source

! Generator impedance 0.3 pu reactance @24 kV according to report
New Reactor.Zs Bus1=Salem1_Source Bus2=Salem1 Z1=[0.0   0.0576]   ! in Ohms  0.3 pu @ 24 kV ???
New monitor.source_gv_md0 vsource.source 1 mode = 0

! Don't have the exact conductor in the database, but this should be close.
! 2-conductor bundle of 1272 ACSR at 1.5 ft spacing -- from Wiredata.txt on the Examples folder in OpenDSS
New Wiredata.Bundle2 GMR=0.264386 DIAM=1.5 Rac=0.03755 Normamps=2400 caprad=[1.382000 12 / 2 / 1.5 * sqrt ] Runits=mi
~ Radunits=ft GMRUnits=ft   !1272 MCM
New Wiredata.SKYWIRE GMR=0.0044600 DIAM=0.3980000 RAC=2.6 NormAmps=100.0000 Runits=mi radunits=in gmrunits=ft

New LineGeometry.SalemNewF nconds=5 nphases=3
~ cond=1 wire=Bundle2 x=-20   h=50 units=ft
~ cond=2 wire=Bundle2 x=0.0   h=50 units=ft
~ cond=3 wire=Bundle2 x=20    h=50 units=ft
~ cond=4 wire=SKYWIRE x=-12.9 h=98.5 units=ft
~ cond=5 wire=SKYWIRE x=12.9  h=98.5 units=ft
~ reduce=y

! GSU model with extra Y winding for Magnetizing branch
New Transformer.1_2_3_1_1 Phases=3 windings=3 buses=[High, Salem1, Isat_Salem] conns=[wye Delta wye]
~ kVs=[500 24 (24 3 sqrt *)]
~ kVAs=[1080000 1080000 1080000] ! 360 MVA/phase
~ X12=16.185  X23=4  X13=4     ! 3rd winding at mid point, XH = XL =6%  XT=1%
~ %rs=[0.08 0.08 0.0009]
~ core = 1-phase

// Magnetizing
New Load.Isat_1_2_3_1_1_a phases=1 bus1=Isat_Salem.1.0 kV= 24 kW=0.01 kvar=0.01 model=1 spectrum=Linear
New Load.Isat_1_2_3_1_1_b phases=1 bus1=Isat_Salem.2.0 kV= 24 kW=0.01 kvar=0.01 model=1 spectrum=Linear
New Load.Isat_1_2_3_1_1_c phases=1 bus1=Isat_Salem.3.0 kV= 24 kW=0.01 kvar=0.01 model=1 spectrum=Linear

! monitors T1
New Monitor.1_2_3_1_1_v_md10  Transformer.1_2_3_1_1 1 Mode=10
New Monitor.1_2_3_1_1_i_md08  Transformer.1_2_3_1_1 1 Mode=8
New Monitor.1_2_3_1_1_vi_md11 Transformer.1_2_3_1_1 1 Mode=11

! 500 kV Line
New Line.TL1  bus1=High bus2=NEWF Geometry=SalemNewF length=50 units=mi
!/*** GIC Source for TL1
New GICSource.TL1  Lat1=61.493246 Lon1=22.969592 Lat2=60.493246 Lon2=22.969592 EE=@EE0 EN=@EN0 !fictitious coordinates
new monitor.TL1_li1_md11 line.TL1 1 Mode=11
!*/

! Load at NEWF modeled as quasi-ideal Voltage source
New vsource.Load3
~ angle=31.0   Basekv=500 pu=1.0 Model=Ideal  BaseMVA=1000  Bus1=NEWF

Set VoltageBases=[500 24]
CalcVoltageBases
```

Figure 6. GICharm/OpenDSS Script for the Salem 1 Circuit Model

RESULTS WAVEFORMS

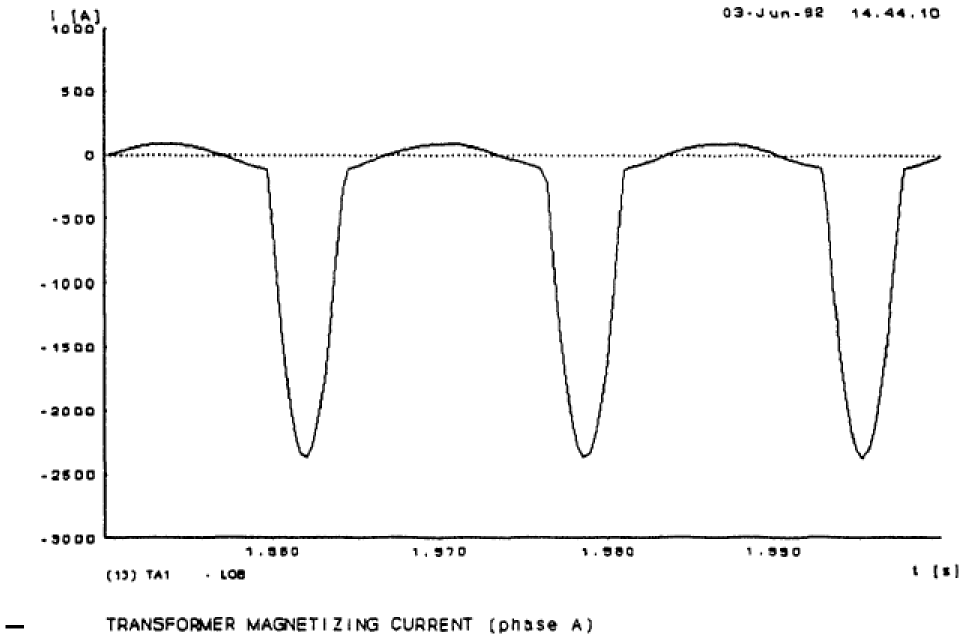

Figure 7. Transformer Magnetizing Current Waveform from Appendix D of Reference [9].

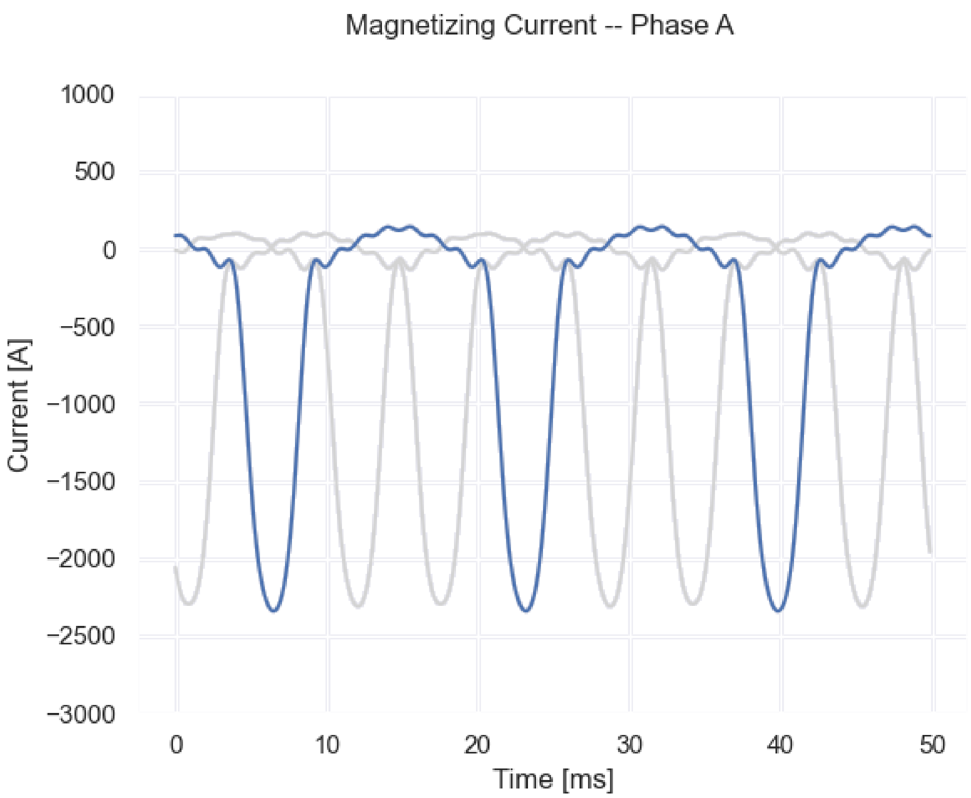

Figure 8. Magnetizing Currents Computed by GICharm (Phase A highlighted)

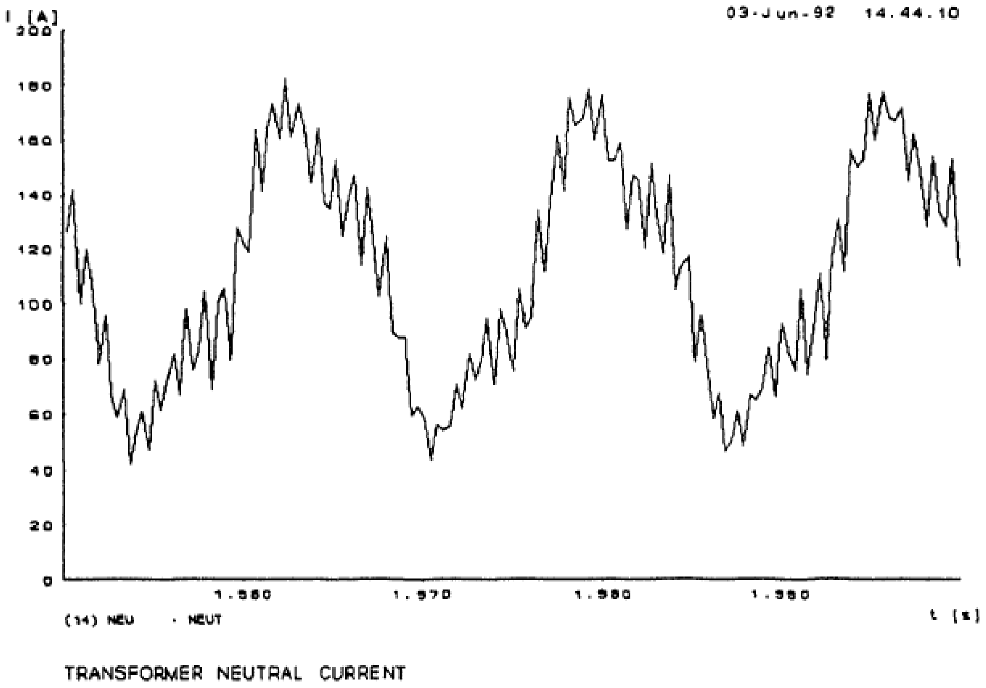

Figure 9. Transformer Neutral Current from Appendix D of Reference [9].

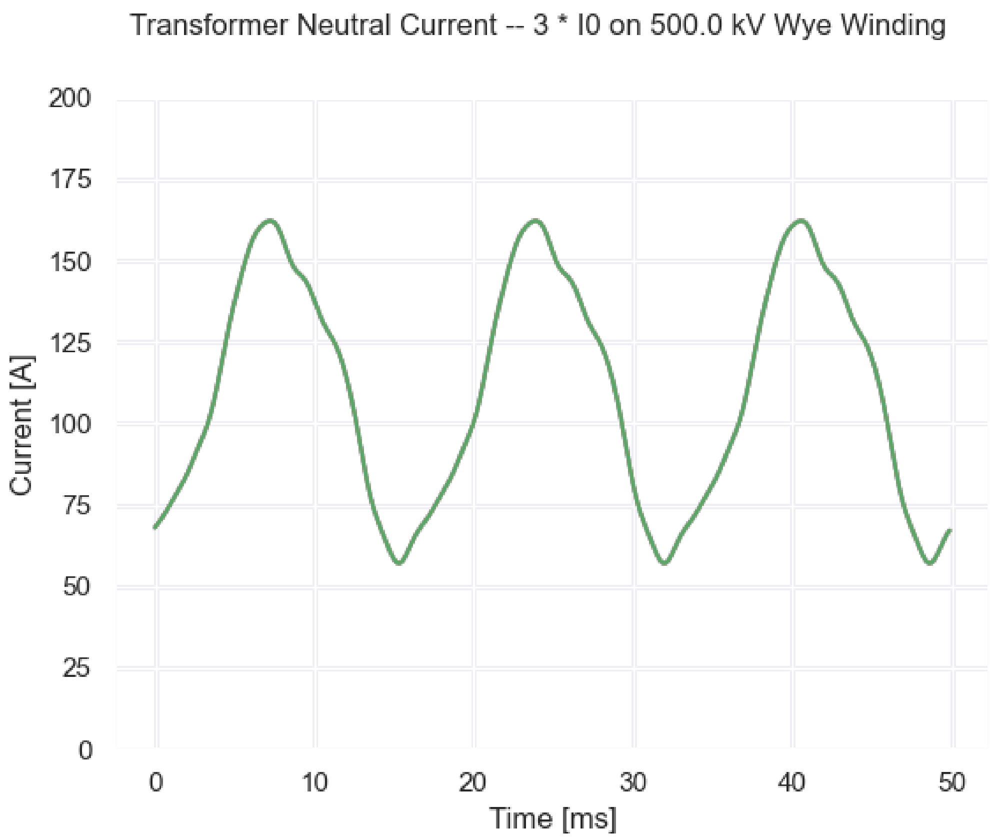

Figure 10. Neutral Currents Computed by GICharm

CONCLUSIONS

The close agreement between the simulation results produced by the EPRI GICharm program and a time-domain electromagnetic transients simulation validates the modeling approach taken by the EPRI team for this research. Of note, the high-frequency component of the transformer neutral current was not replicated in GICharm; however, the general shape of the waveform produced by GICharm clearly follows the same pattern as the waveforms produced by the time-domain simulations. It is suspected that is likely due to reflections appearing on the 50-mile transmission line model. It is of interest if an EMT simulation replicating this benchmark would produce this high-frequency component.

GIC-related harmonic analysis is a relatively new power system analysis compared to other transmission system studies. Benchmarking the GIC-related harmonic is valuable to ensure accuracy and consistency across software platforms. The results herein illustrate not only the accuracy, but also the similarities in an EMT-software platform. These results along with other benchmark efforts [6] provide further confidence in GIC-related harmonic analysis tools.

ACKNOWLEDGMENTS

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