# EPRI GMD Research Status Update:

## GMD Harmonic Assessment

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ERCOT Planning Geomagnetic Disturbance Task Force
Austin, Texas
16 May 2019

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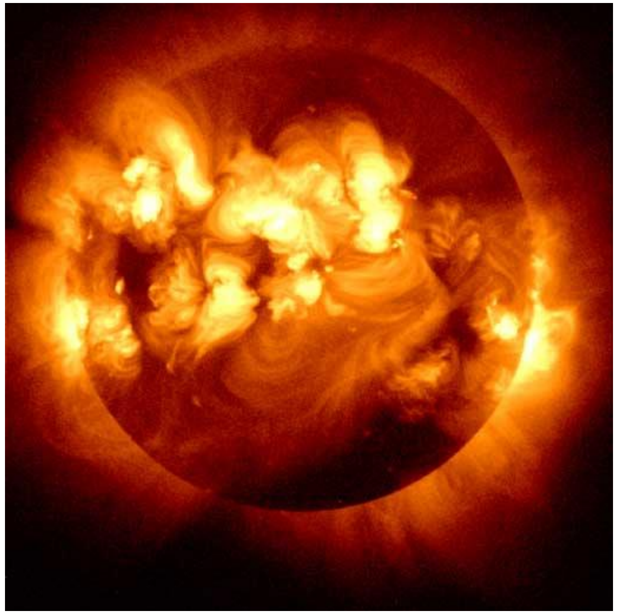
# GMD Research Portfolio

**GMD Supplemental Project - FERC/NERC GMD Project**

- Benchmark GMD Event
- Transformer Assessment
- GMD Harmonics Assessment



**ARP – GMD Vulnerability Assessments**

- GMD Assessment Guidelines
- Commercial Planning Tools
- Road Map for Future Assessment Methods/Tools

**SUNBURST & Adv. Sensors**

- GIC Monitoring (neutral and line)
- Magnetometers
- Data Analytics

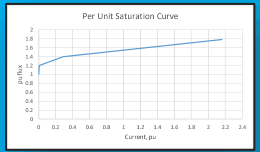
# Why the GMD Supplemental Project?

- FERC Order 830 addressed NERC TPL-007-1 (GMD Vulnerability Assessment)
- GMD Research Work Plan
- October 19th, 2017 FERC Order
- Will inform future revisions of TPL-007

Highest Priority

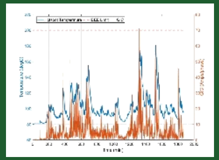
**Improved Earth Conductivity Models**

**Improved Harmonic Analysis Capability**




**Harmonic Impacts**

**Transformer Thermal Impacts**



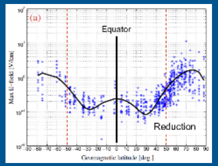
**Spatial Averaging**

$E_{peak} = 8 \times \alpha \times \beta$ (V/km)

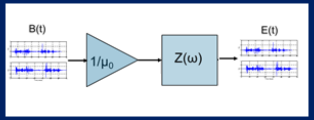
α= Geomagnetic Latitude Scaling Factors

β= Conductivity Scaling Factor

**Latitude Scaling Factor**




**Geoelectric Field Evaluation**




Lowest Priority

# Newly Released Material

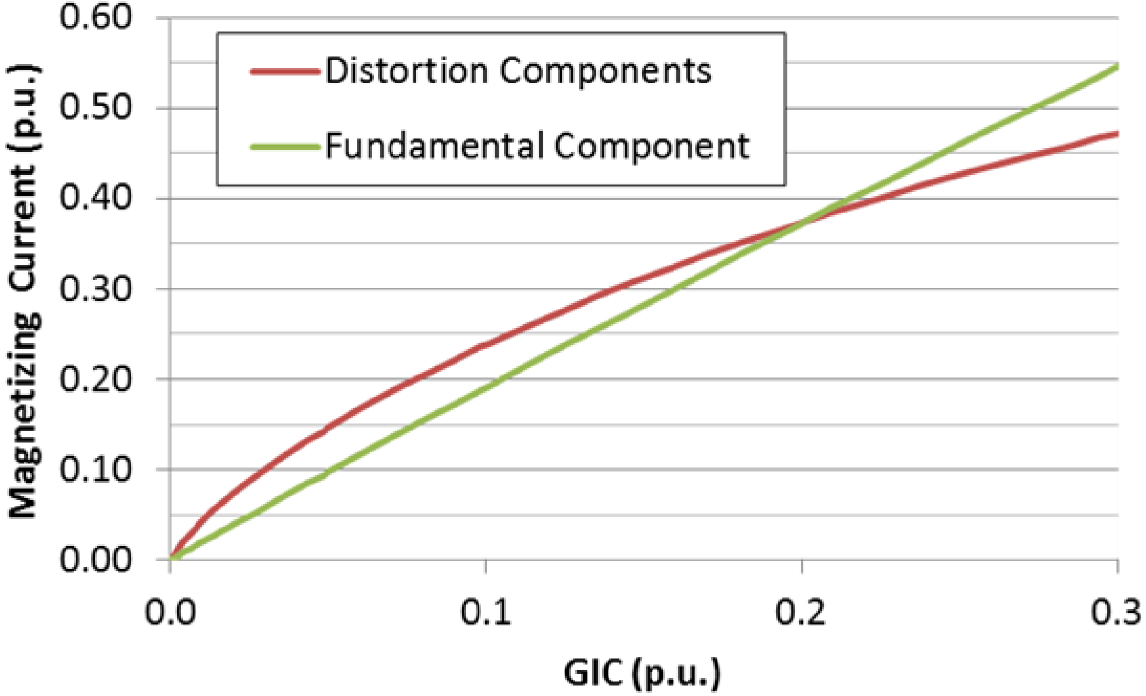
- Improve Harmonics Analysis Capability Tool Product ID# 3002014854
- Tool Evaluation and Electric Field Estimate Benchmarking Results Product ID# 3002014853
- Use of Magnetotelluric Measurement Data to Validate/Improve Existing Earth Conductivity Models Product ID# 3002014856
- Transformer Vibration Analysis Product ID# 3002014855

# Potential Harmonic Distortion – Scale of Magnitude

- Severe GMD is recognized to create a risk of voltage instability
- The harmonic current injected by a GIC-saturated transformer is of similar magnitude as the fundamental-frequency reactive current demand

$$V(h) = Z(h) \cdot I(h)$$

- System impedance *Z(h)* generally increases with frequency
- For fundamental reactive demand to be so severe as to risk voltage collapse, how severe could harmonic voltage distortion be?




**Harmonic distortion during a severe GMD is far more than a "power quality" issue, harmonic impacts can substantially accelerate system voltage collapse**

# March 1989 Event

*"GICs caused the saturation of many power transformers, causing them to draw more reactive power while turning them into strong sources of harmonics. The extra reactive power could have been supplied by special static var compensators (SVCs) connected to the network, but, just when they were needed most, the SVCs were tripped out of service due to the high harmonic currents. Seven large SVCs were lost in one minute." – IEEE Spectrum November/December 2016*

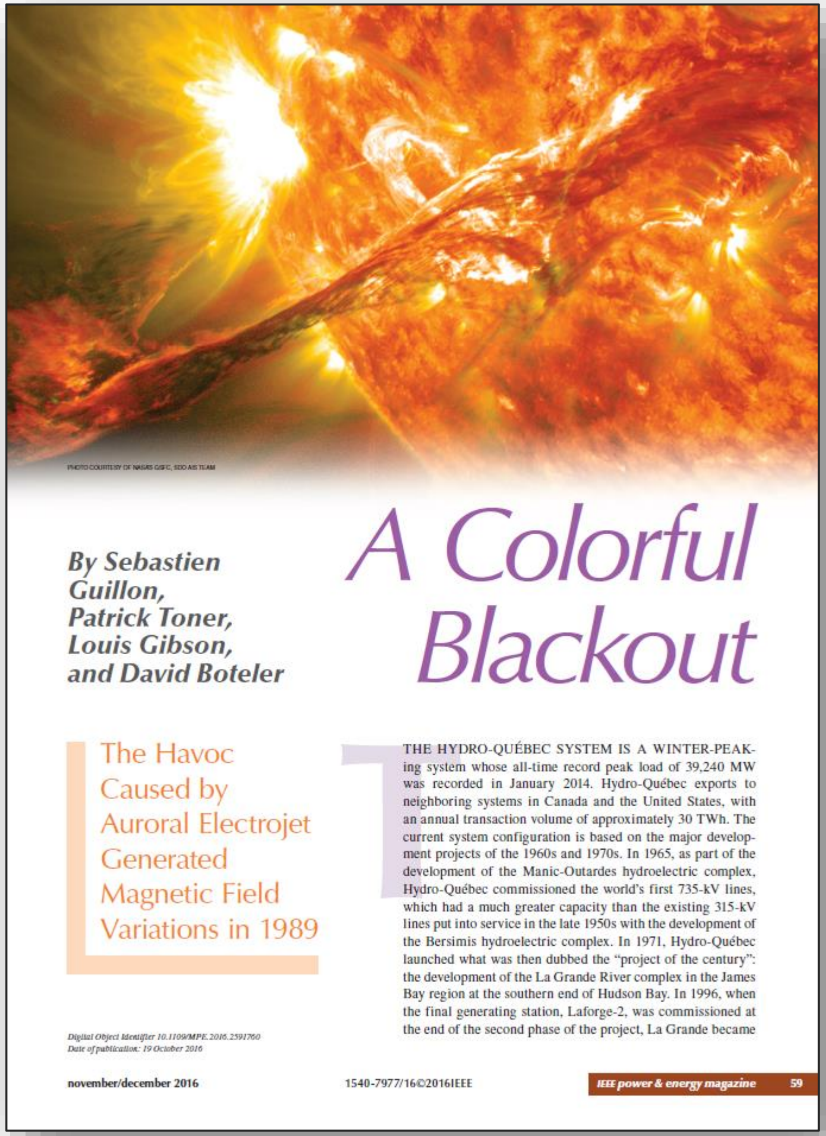


PHOTO COURTESY OF NASA'S GSFC, SDO AIS TEAM

# A Colorful Blackout

By Sebastien Guillon, Patrick Toner, Louis Gibson, and David Boteler

## The Havoc Caused by Auroral Electrojet Generated Magnetic Field Variations in 1989

THE HYDRO-QUÉBEC SYSTEM IS A WINTER-PEAKing system whose all-time record peak load of 39,240 MW was recorded in January 2014. Hydro-Québec exports to neighboring systems in Canada and the United States, with an annual transaction volume of approximately 30 TWh. The current system configuration is based on the major development projects of the 1960s and 1970s. In 1965, as part of the development of the Manic-Outardes hydroelectric complex, Hydro-Québec commissioned the world's first 735-kV lines, which had a much greater capacity than the existing 315-kV lines put into service in the late 1950s with the development of the Bersimis hydroelectric complex. In 1971, Hydro-Québec launched what was then dubbed the "project of the century": the development of the La Grande River complex in the James Bay region at the southern end of Hudson Bay. In 1996, when the final generating station, Laforge-2, was commissioned at the end of the second phase of the project, La Grande became

*Digital Object Identifier 10.1109/MPE.2016.2591760*
*Date of publication: 19 October 2016*



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# March 1989 Event

- Seven static var compensators (SVCs) tripped in rapid succession in the Hydro Quebec system, resulting in system instability and total blackout of that system. Post-event analysis revealed that harmonic distortion was the direct cause of the SVC trips.
- Widespread capacitor banks trips, including 16 bank trips in the Virginia Power system, 12 in the New York Power Pool (predecessor to NYISO), four at Bonneville Power, seven in the Allegheny Power system, and at least three in the PJM system (including 500 kV capacitor banks).
- Generator trips due to negative sequence or phase imbalance protection in the Manitoba Hydro and Ontario Hydro systems (including one major nuclear unit).
- Static var compensator trip in the WAPA system.
- HVDC system trip at the WAPA Miles City station and an HVDC filter trip at the Comerford converter station in the New England system.
- Transmission line trips at Manitoba Hydro and WAPA.

# How Do GMD Harmonics Threaten Grid Security?

- During a severe GMD, the grid is under great stress due to GIC-saturated transformer reactive demand
- Harmonics can take out critical grid facilities:
  - False tripping due to protection issues with distortion
  - Possible damage and failure of grid equipment
  - Correct tripping of facilities to protect from harmonic damage
- Reactive power sources are particularly vulnerable
- Loss of facilities can allow the grid to collapse at a less severe GMD intensity than predicted using intact grid

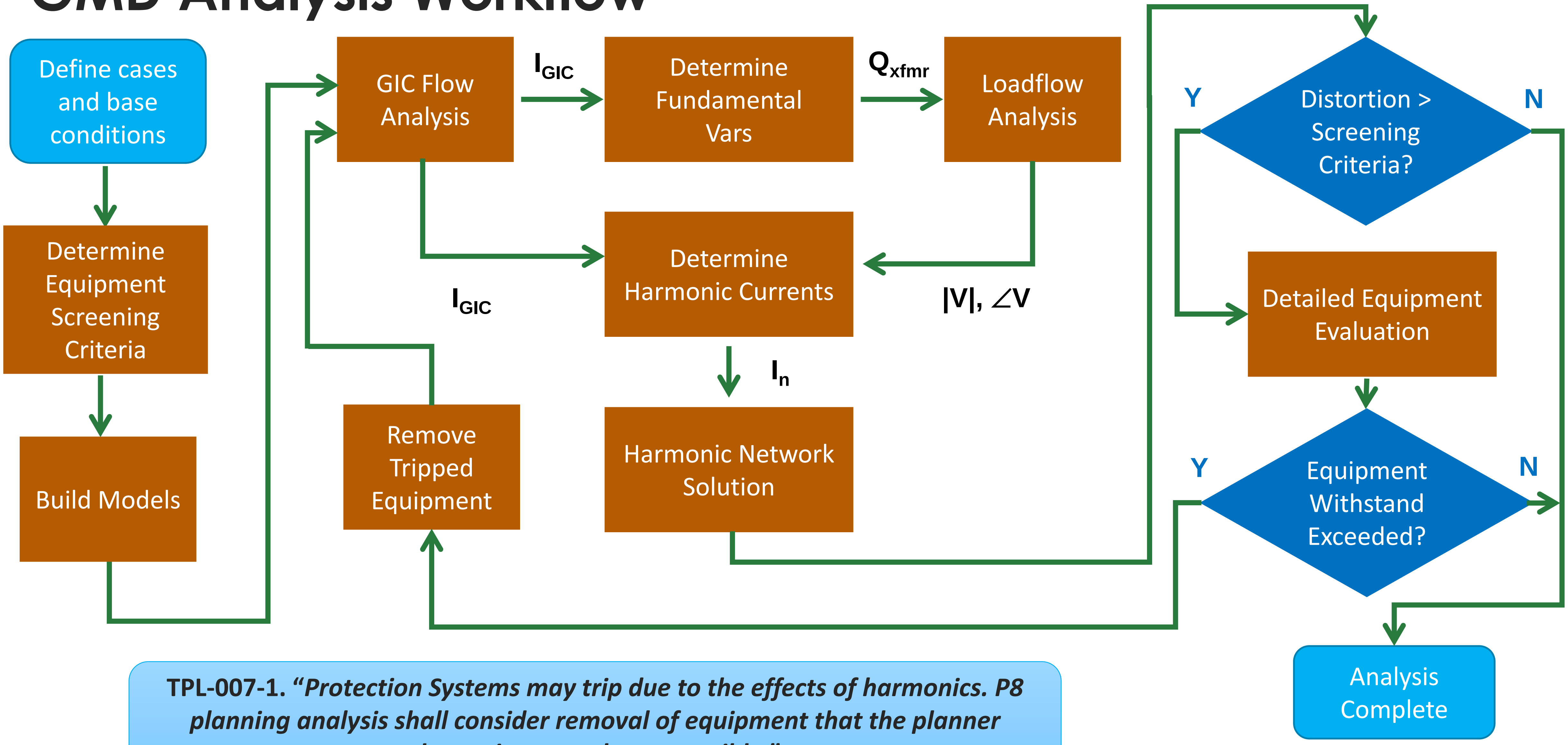
**Harmonic analysis is an essential and integral part of grid GMD impact assessment**

# What Needs to be Examined in an Harmonic Analysis?

- Determine harmonic currents and voltages applied to equipment throughout the transmission grid
- Evaluate equipment and protection systems to identify:
  - Protection systems that are likely to falsely trip
  - Equipment in danger of possible failure during GMD
  - Operation of protection systems in proper response to the harmonic stress

**Analysis of harmonics caused by a GMD presents unique challenges and the need for specialized tools and skills not used in conventional transmission planning**

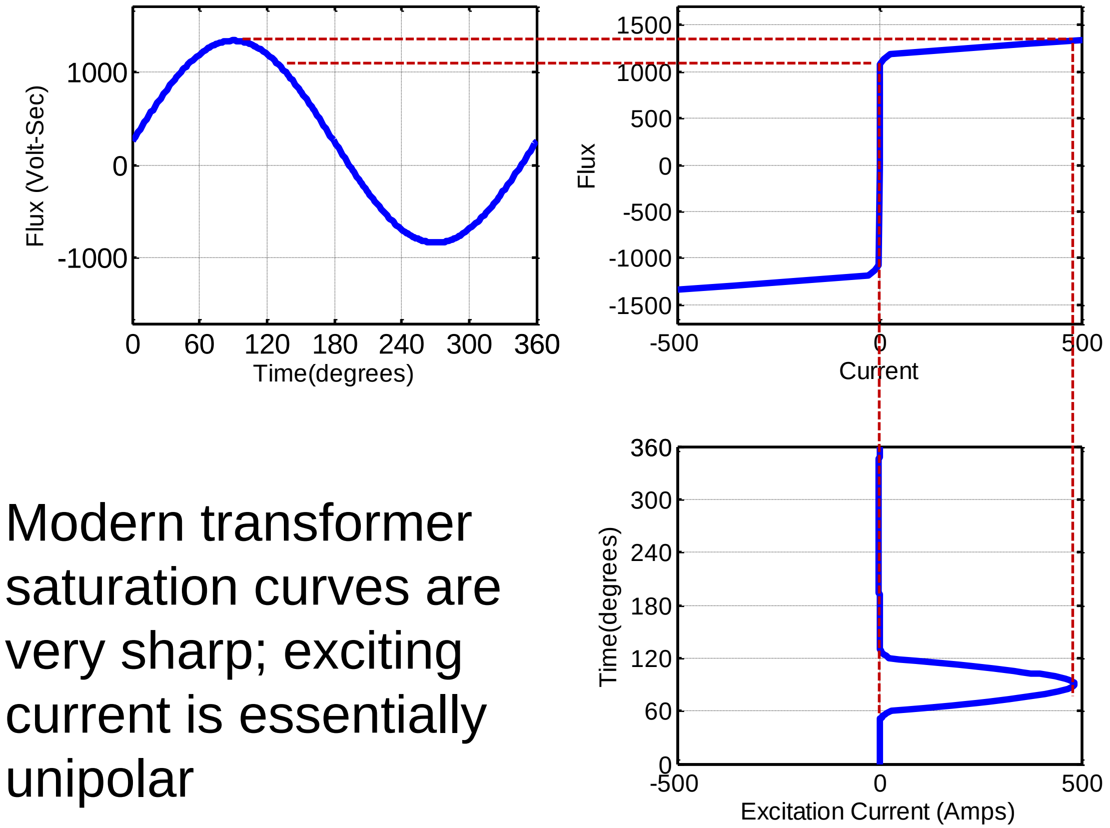
# GMD Analysis Workflow



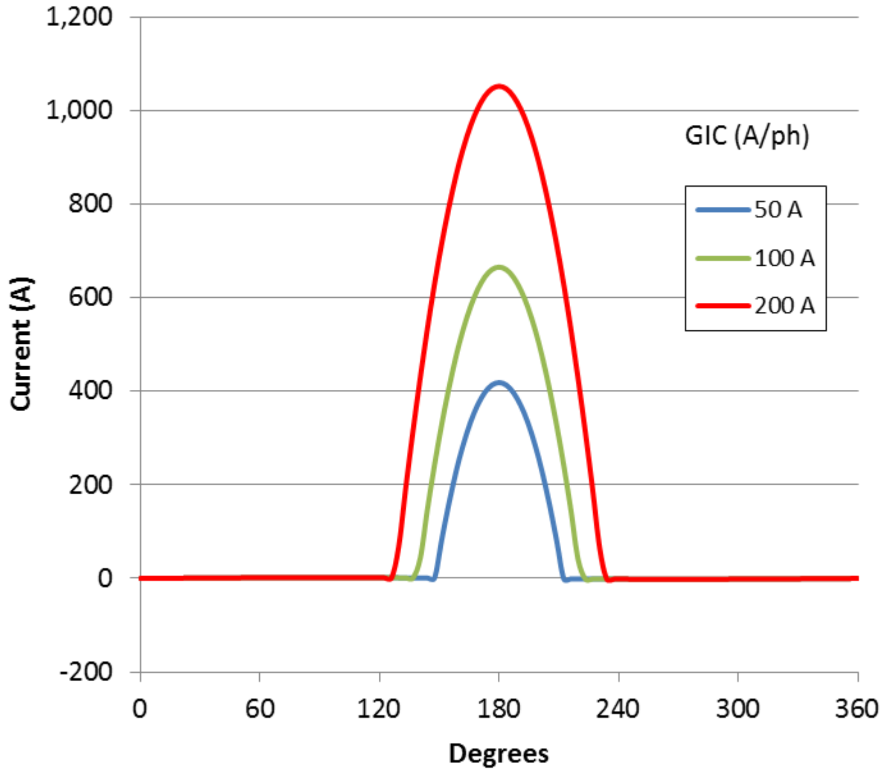

**TPL-007-1. “*Protection Systems may trip due to the effects of harmonics. P8 planning analysis shall consider removal of equipment that the planner determines may be susceptible.*”**

# Part-Cycle Saturation

- Amount of GIC determines the flux off-set
  - Line Current Supplying Single-Phase Auto-Bank

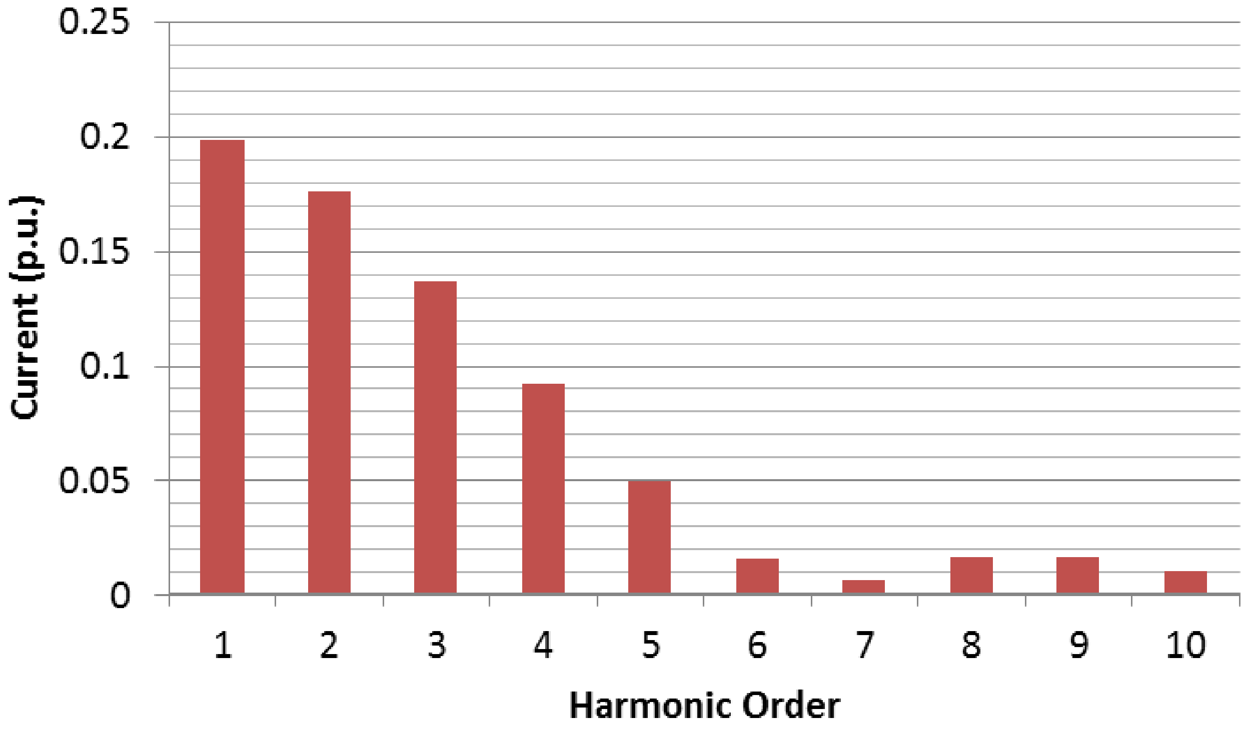



Modern transformer saturation curves are very sharp; exciting current is essentially unipolar



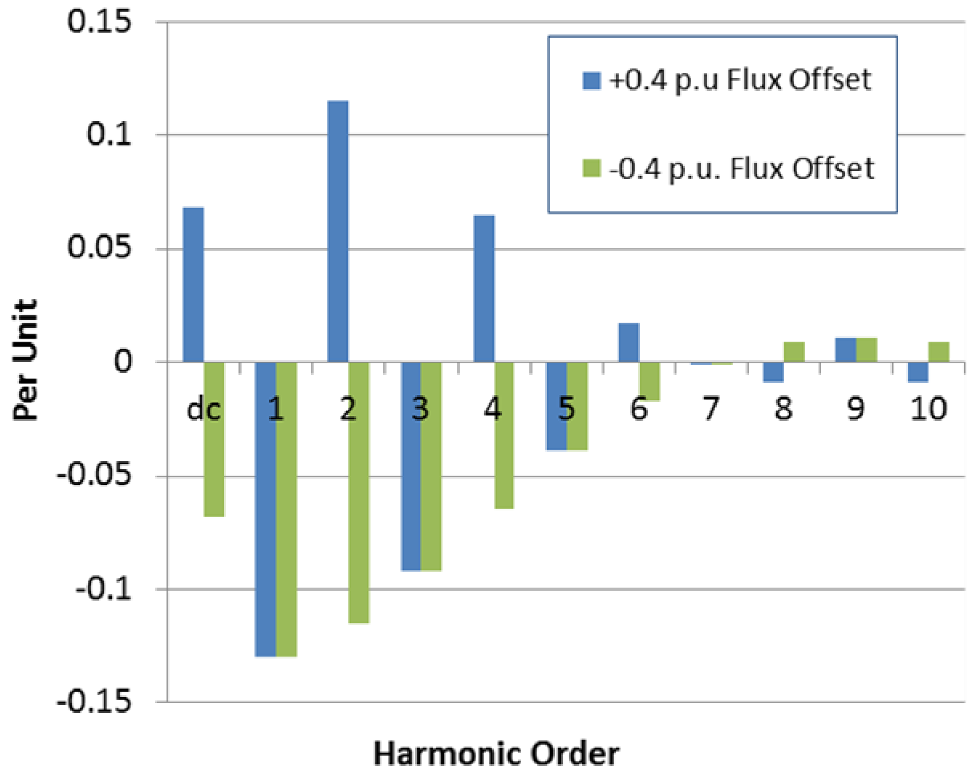
# Harmonic Spectrum

- Exciting current is highly distorted
  - Even- and odd-order harmonics
  - 2nd harmonic nearly as large as fundamental reactive current
  - Magnitude generally decreases with harmonic order
  - Harmonics of concern < 11th order



# Harmonic component polarities

- Even-order harmonic polarities reverse with change in GIC polarity
- Odd-order harmonic polarities do not reverse
- Important to system analysis because harmonic currents at any location are the aggregate of contributions from many transformers over a wide area

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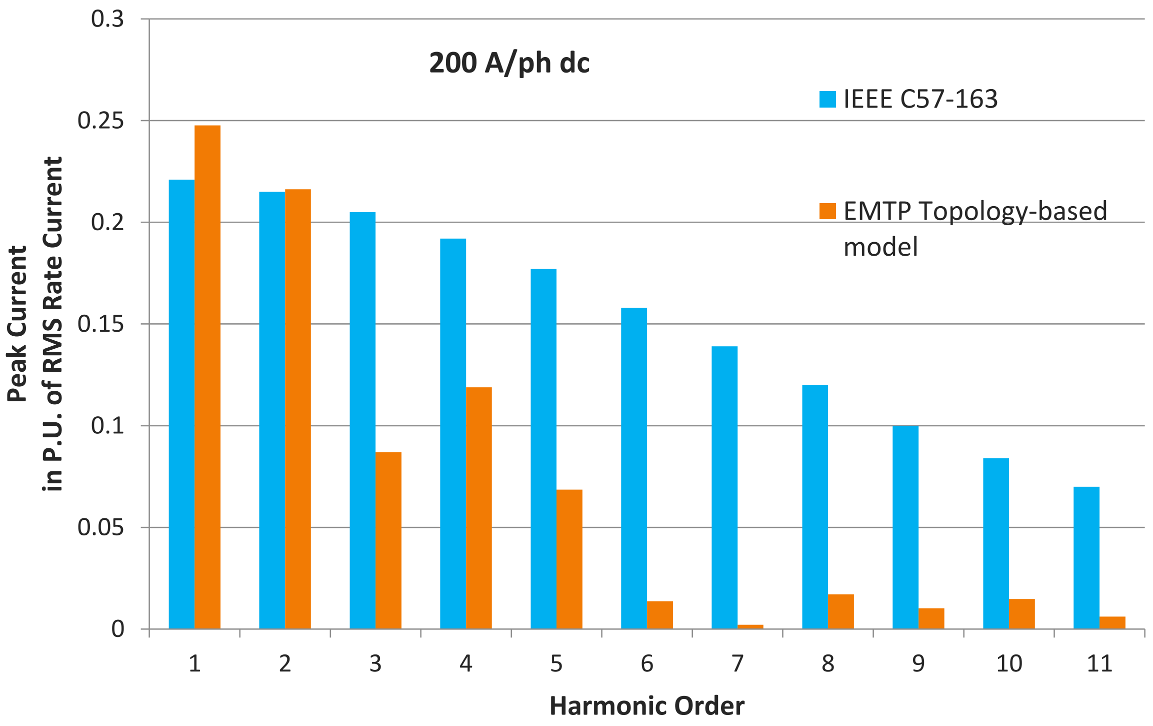
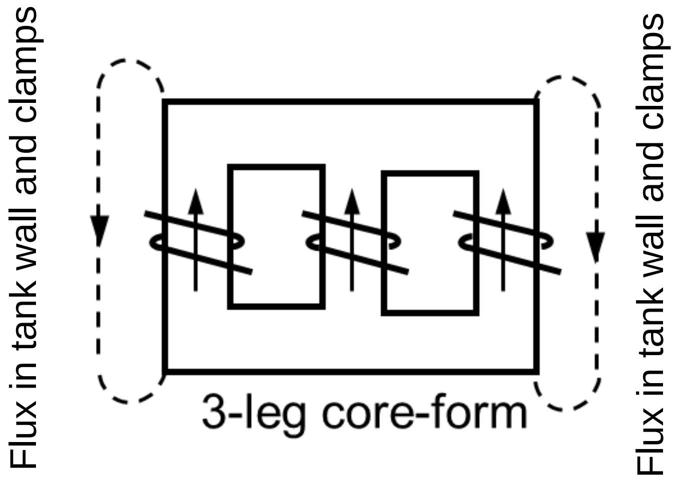
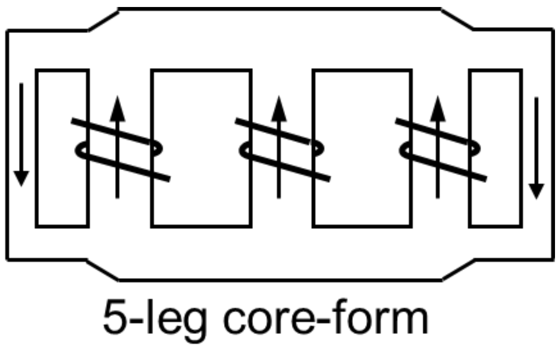
# Harmonic Spectrum

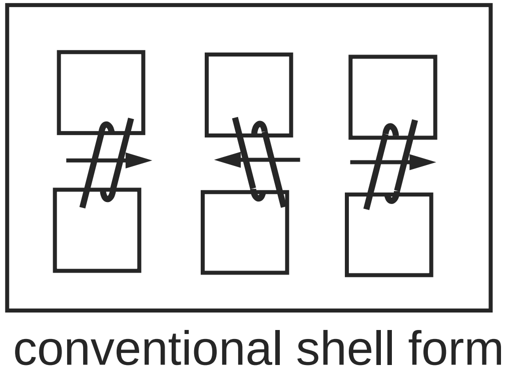
- Take into account the resulting harmonic spectrum to provide a more accurate assessment



# Three-Phase Transformers

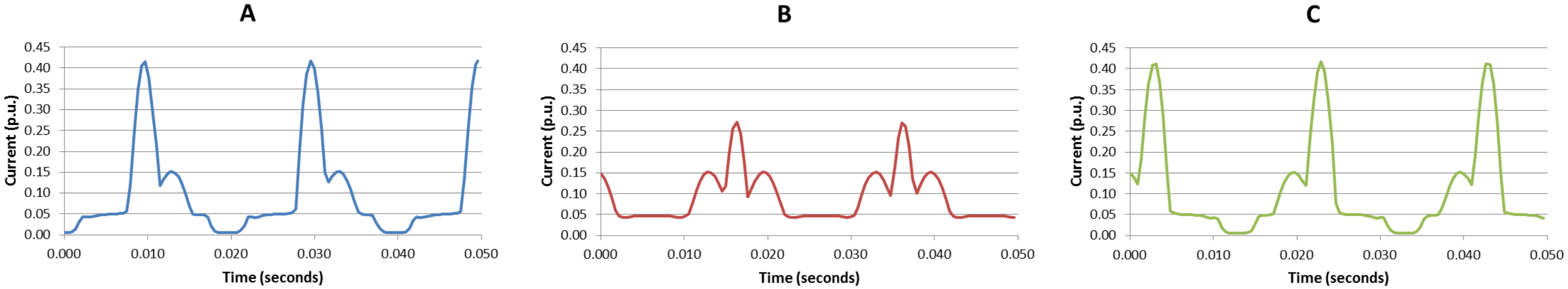


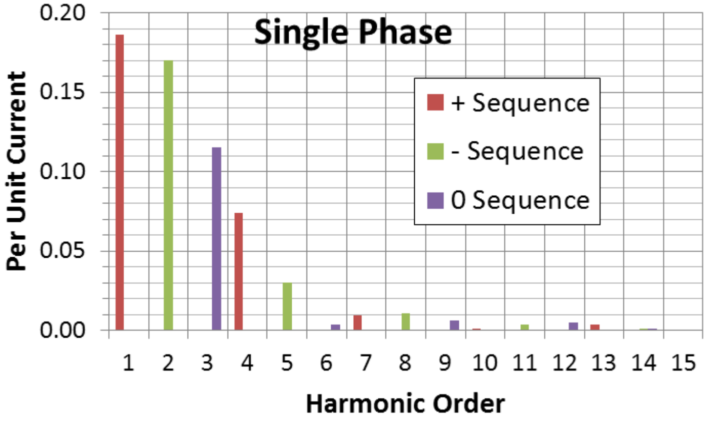



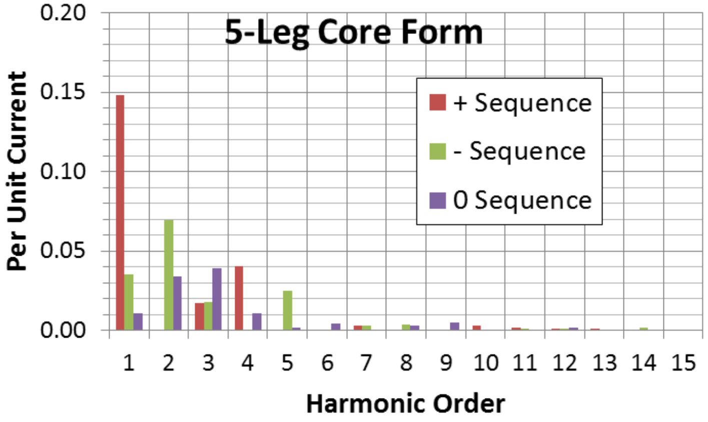

- Magnetic circuits have branches in common between phases
- Results in very different exciting currents in each phase during GIC saturation

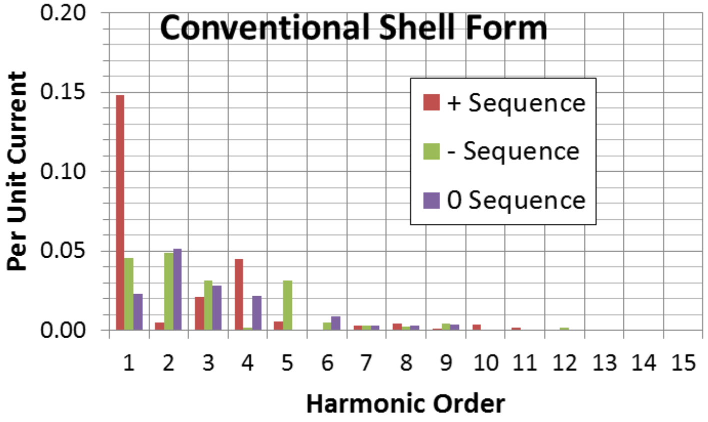
5-leg core form transformer exciting currents



# Harmonic Sequence Components



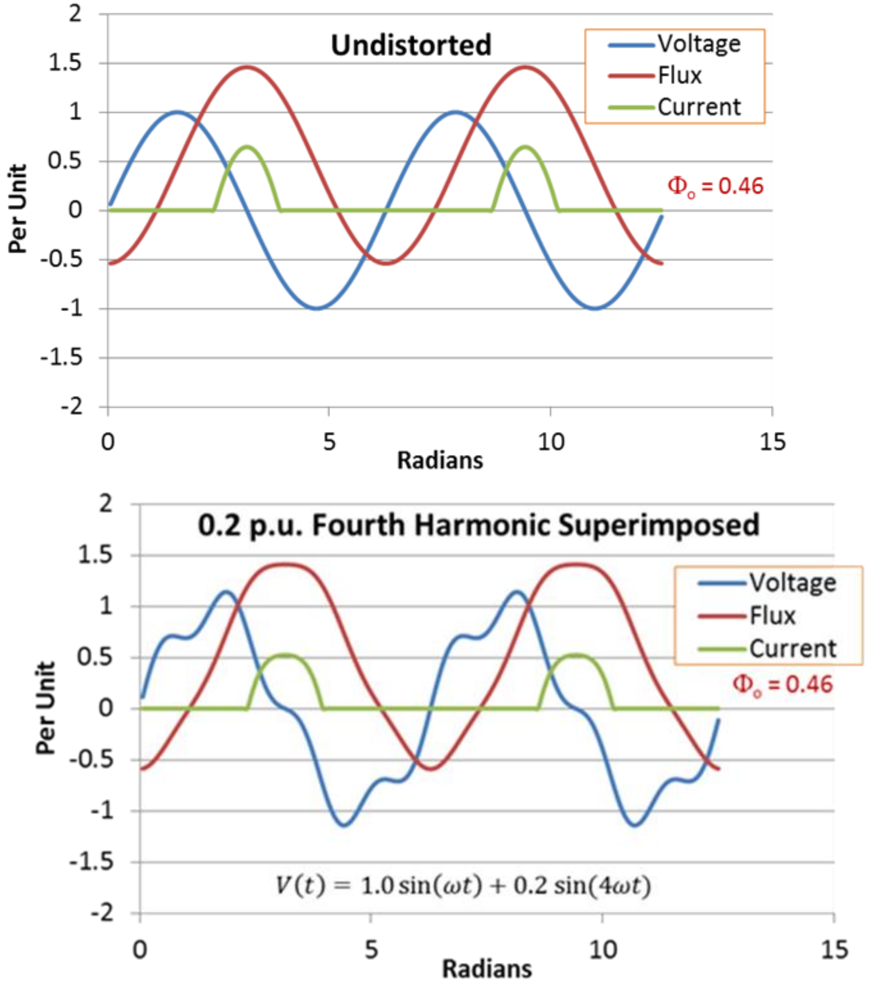




- Banks of 1-ph transformers follow conventional sequence component pattern
- Three-phase transformers do not follow this familiar pattern
  - Triplen (multiples of $3^{rd}$ order) harmonics not all zero sequence
  - Zero sequence has harmonic orders that are not triplens

GMD harmonic analysis must model all sequence components
(or three-phase model with all mutual couplings)

# Distortion Interaction with Saturation

- Injected harmonic currents produce voltage distortion
- Flux = ∫Vdt, so flux wave is also distorted
- Injected exciting currents are changed
  - Harmonics near system impedance resonances generally are decreased
  - Total distortion tends to decrease
  - Other harmonics may actually increase



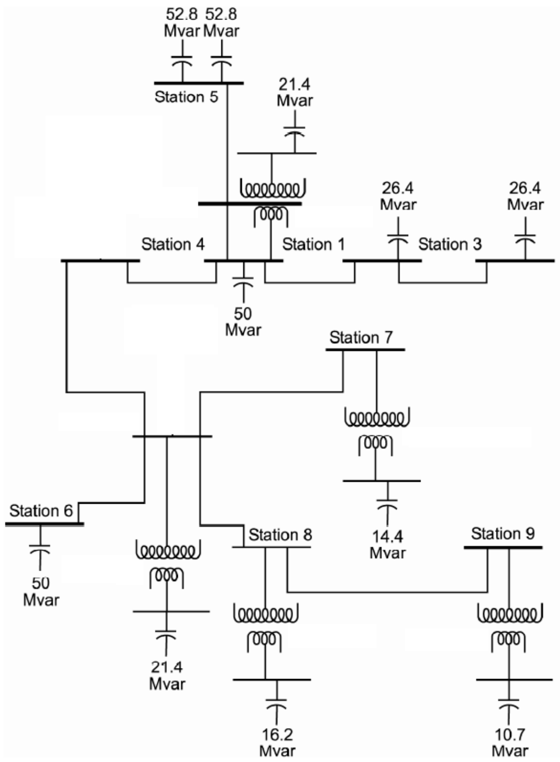

New harmonic analysis tools is being developed to incorporate this complex closed-loop interaction

# EPRI GMD Harmonic Tool

# Challenges of Harmonic Analysis

- Large number of *coherent* harmonic sources distributed throughout the transmission grid.
- Very large system models are needed.
- Considerable engineering judgement required to estimate typically unavailable parameters
  - Transformer characteristics
  - Characteristics of system equipment at harmonic frequencies
- Injection and propagation in both the ground mode (zero sequence) and line modes (positive and negative sequence).
- The harmonic source characteristics of three-phase transformers are complex, requiring magnetic modeling.
- Harmonic voltage distortion interacts with the transformers to alter the injected current

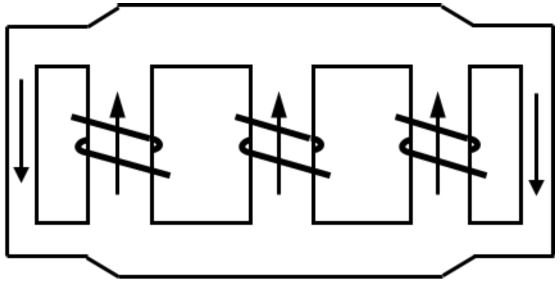
When the results of a properly performed harmonic assessment are performed a much more accurate evaluation of grid security during GMD events can be obtained.



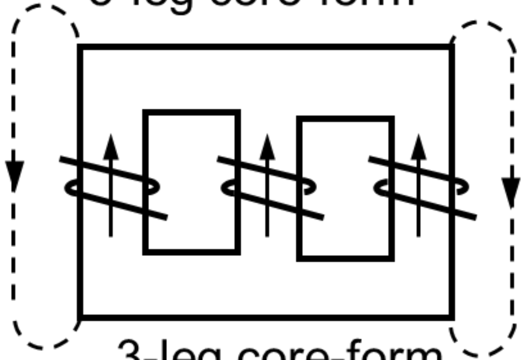
# Software Requirements – OpenDSS Platform

- ☑ The tool must be capable of extensive system modeling, accepting models with a large number of buses.
- ☑ Provide full three-phase representation of the system including mutual couplings.
- ☑ Accept data from other sources such as loadflow, stability, and short-circuit databases.
  - Converts fundamental-frequency data from these data sources to appropriate parameters for harmonic analysis.
- ☑ The tool should provide accurate representation of harmonic sources (saturated transformers) based on the results of GIC flow analysis. These sources are also dependent on fundamental-frequency voltage and angle, so it is desirable for the tool to accept loadflow results with minimum user intervention.
- ☑ Representation of GIC-saturated three-phase transformers requires the capability within the tool to perform nonlinear magnetic circuit analysis of transformers.
- ☑ Tool to represent closed-loop interaction to take in to account voltage distortion.
- ☑ The tool should facilitate parametric analysis of a variety of system conditions and configurations.
- ☑ The tool must be able to accommodate a large number of simultaneous harmonic current injections.

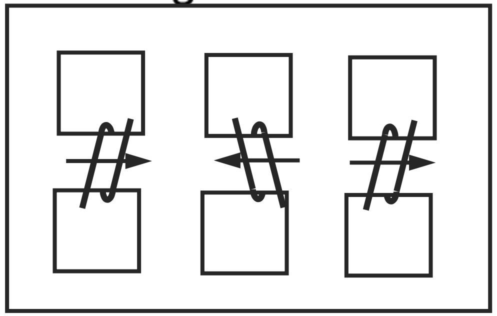
# Transformer level analysis



5-leg core-form

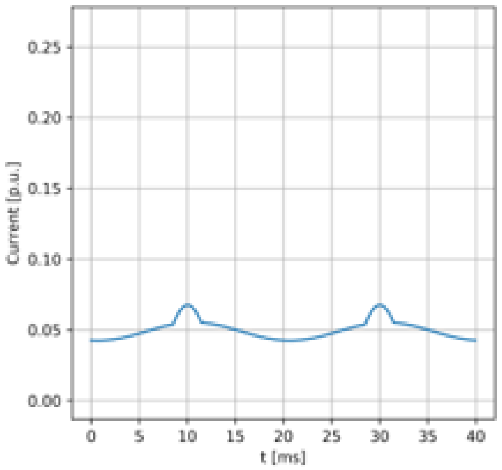


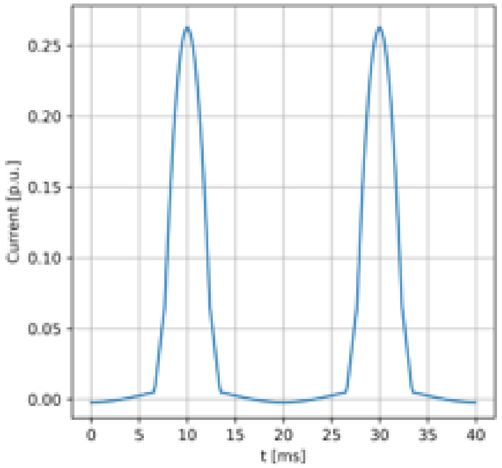
3-leg core-form

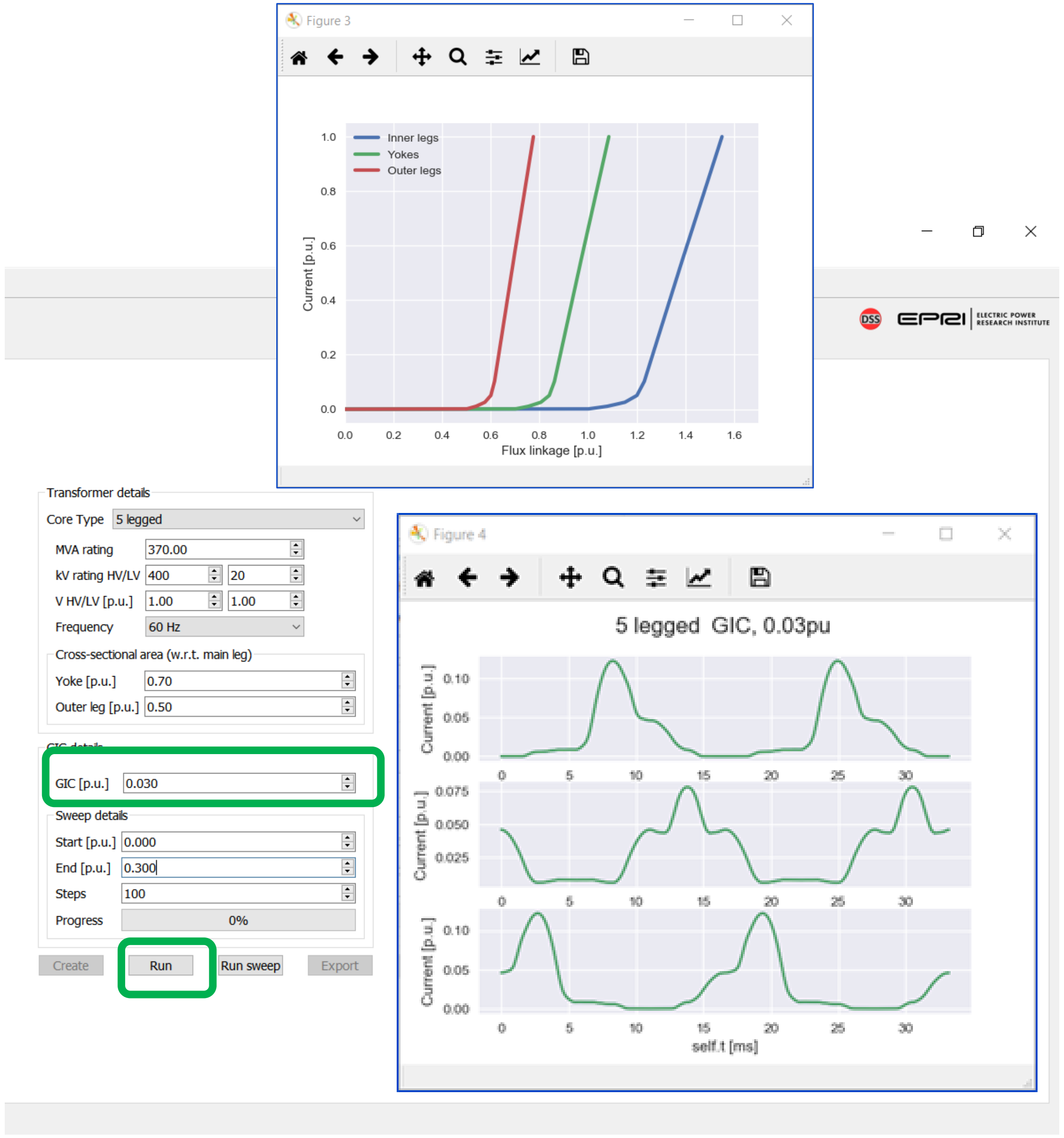


conventional shell form

Magnetizing Current 40A GIC

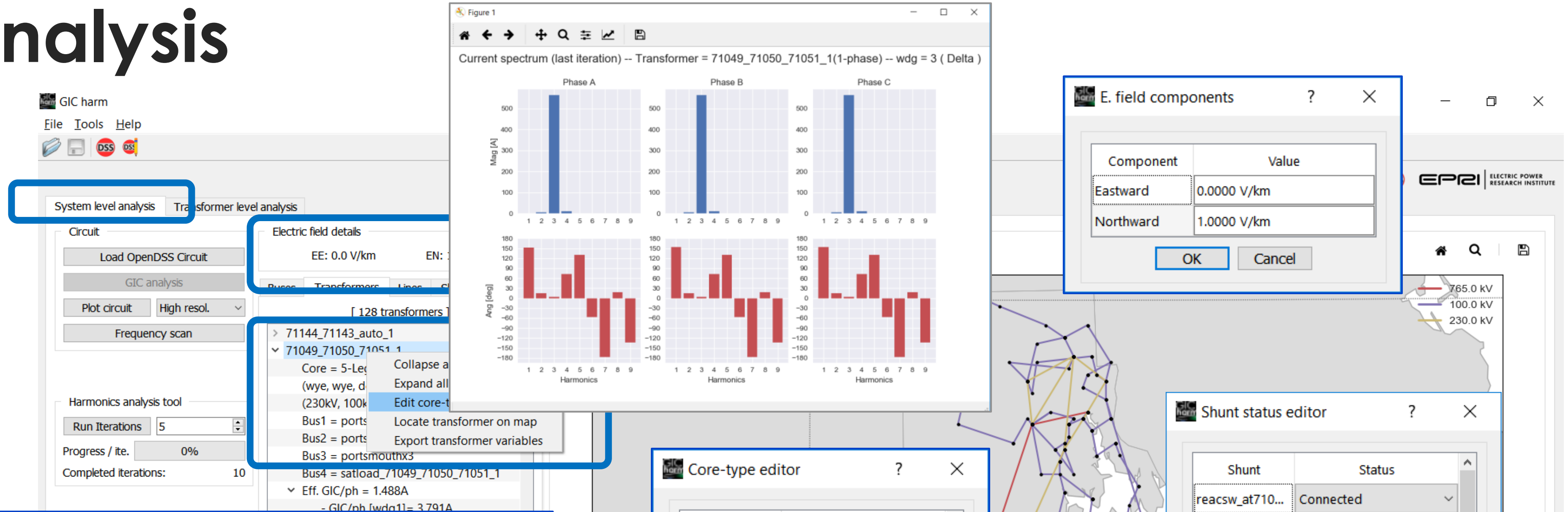


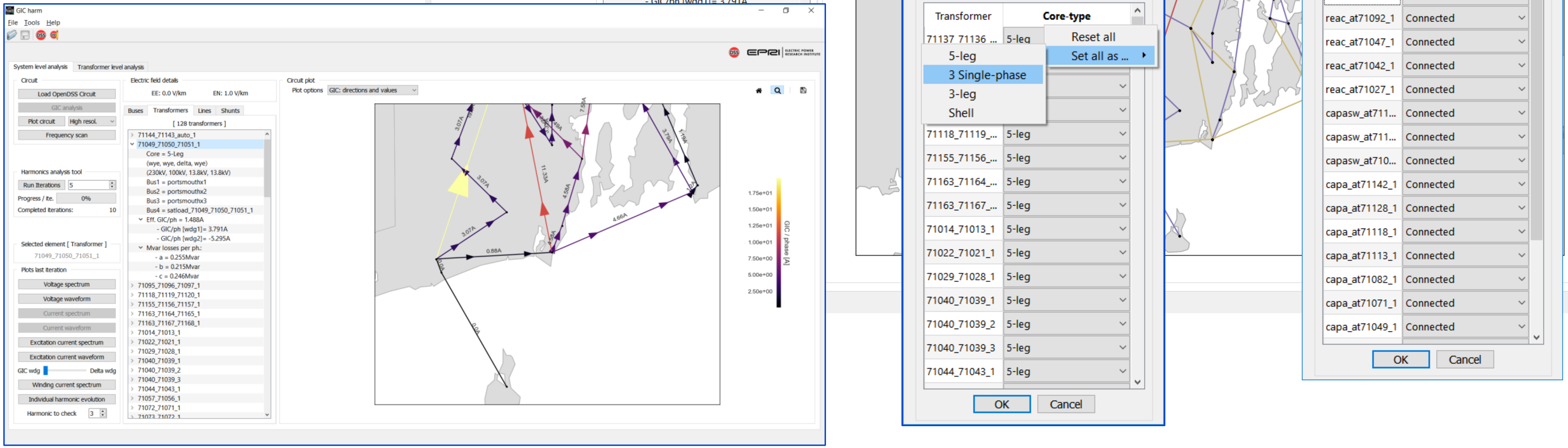



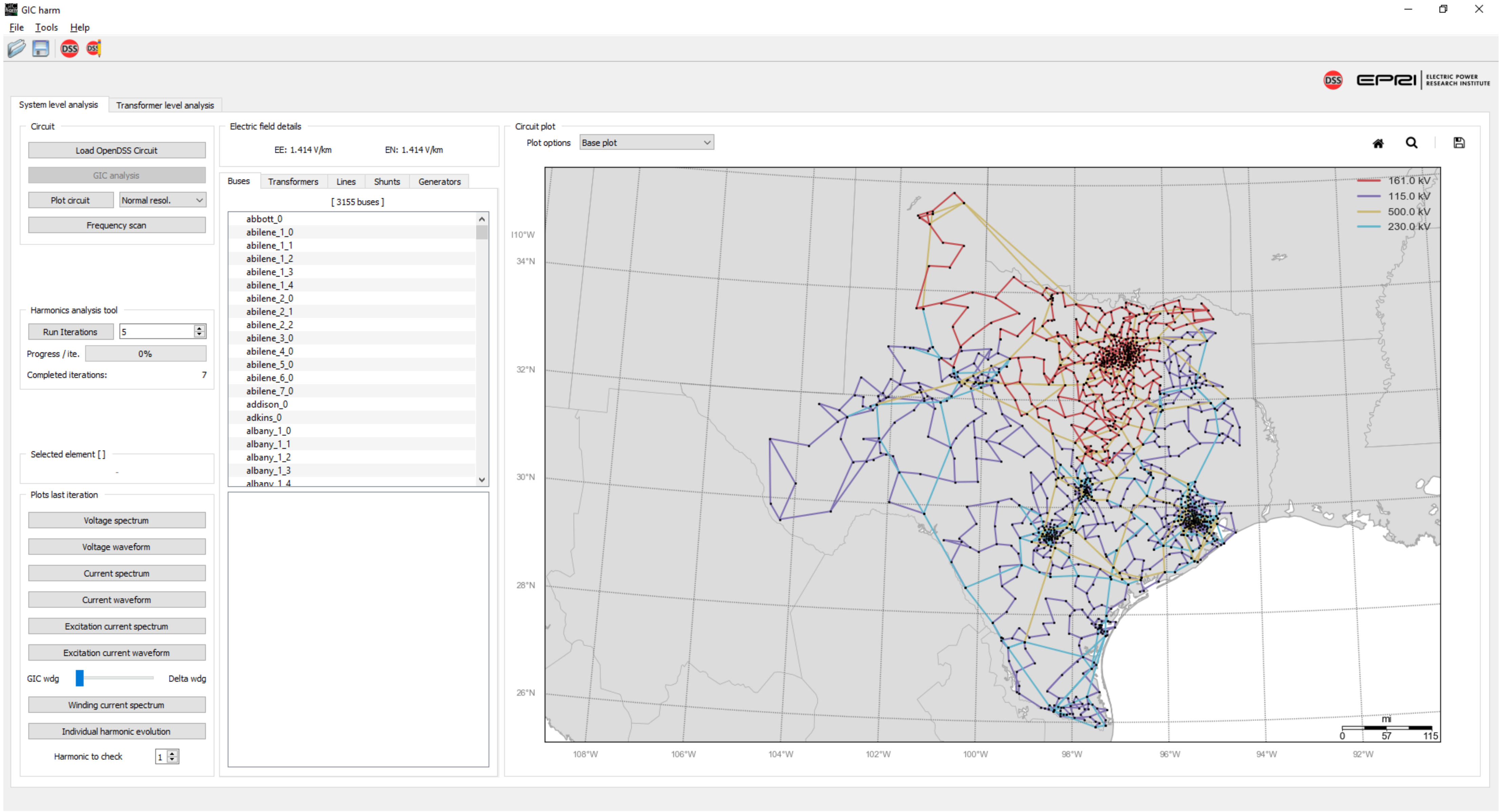
# System level analysis

- Relevant details for buses, elements, and electric field
  - Buses
  - Transformers
  - Capacitors
  - Reactors



# Expanded Capabilities in Upcoming Release



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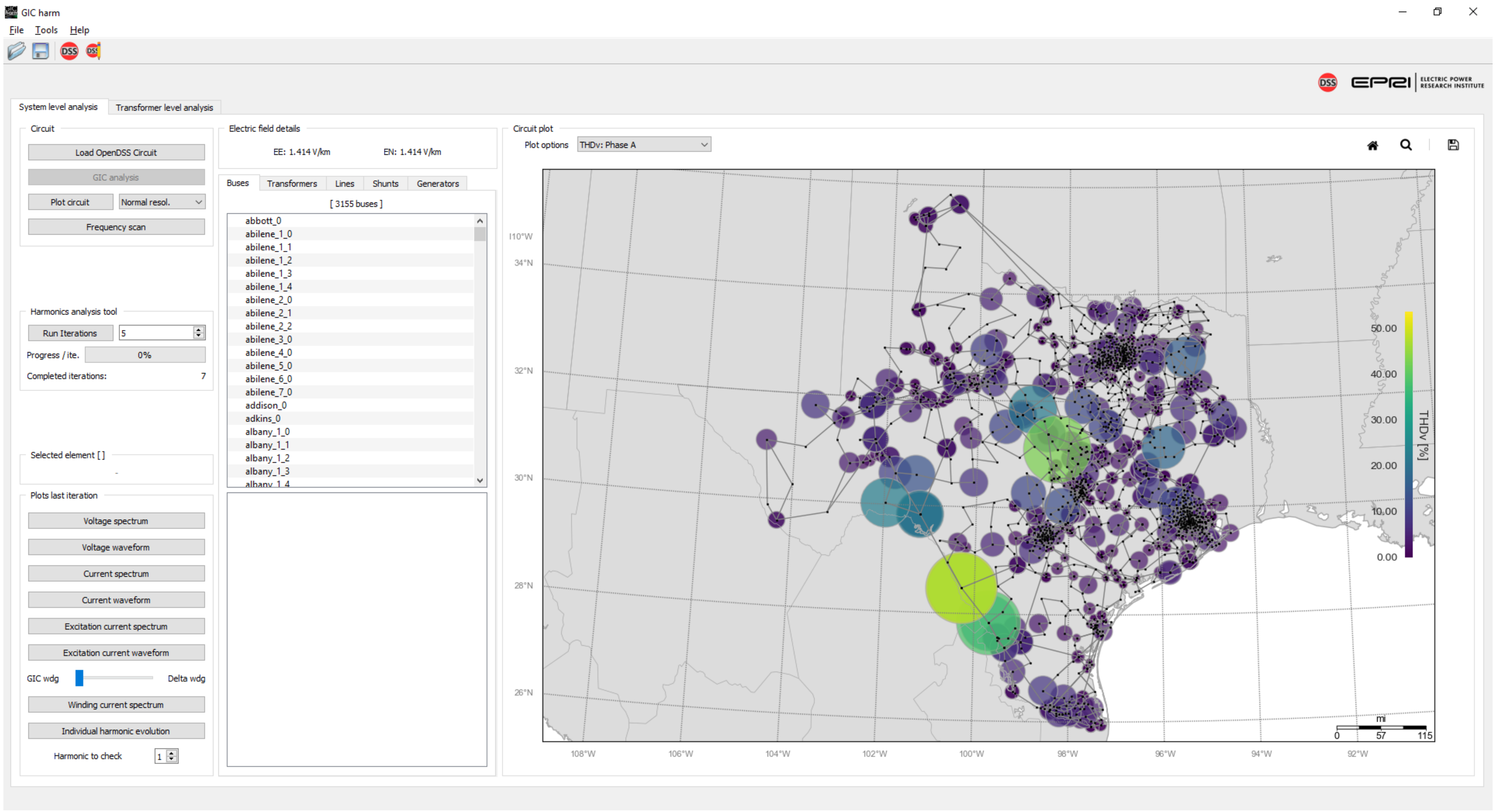
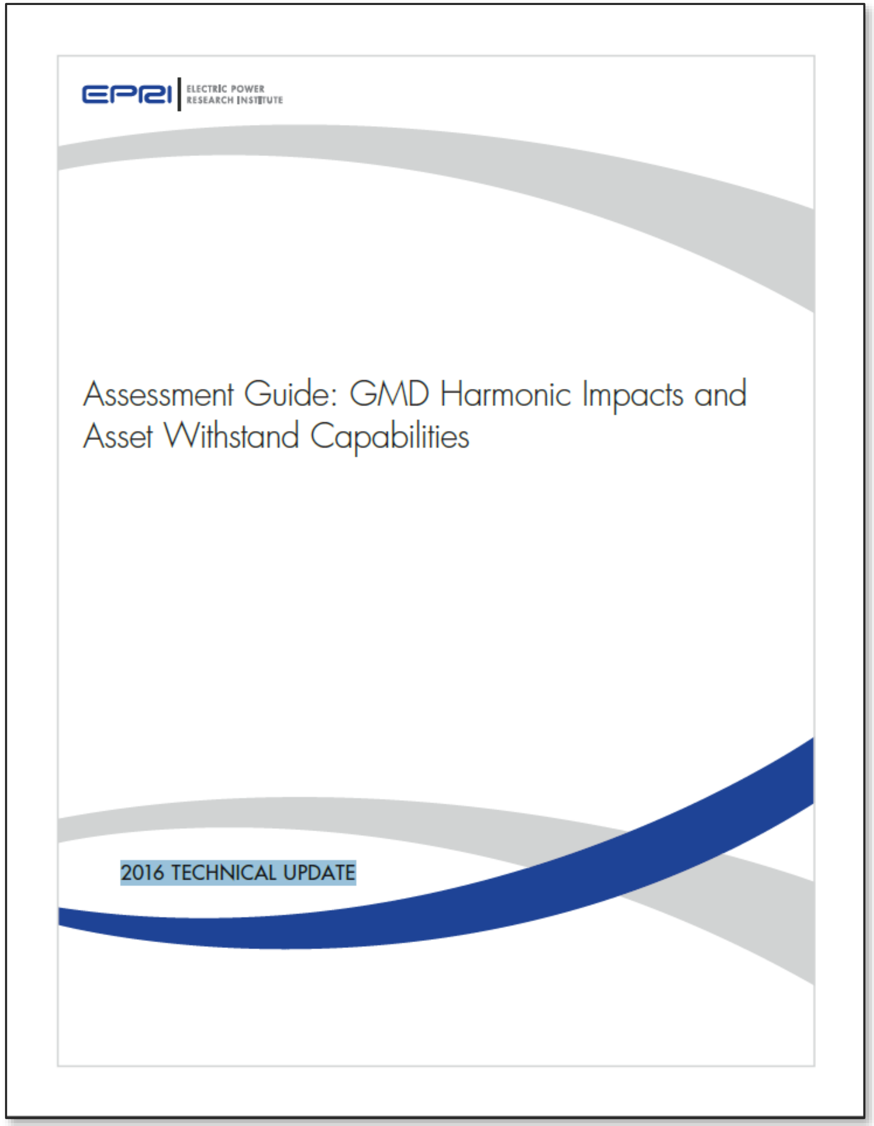


# Assessment Guide: GMD Harmonic Impacts and Asset Withstand Capabilities

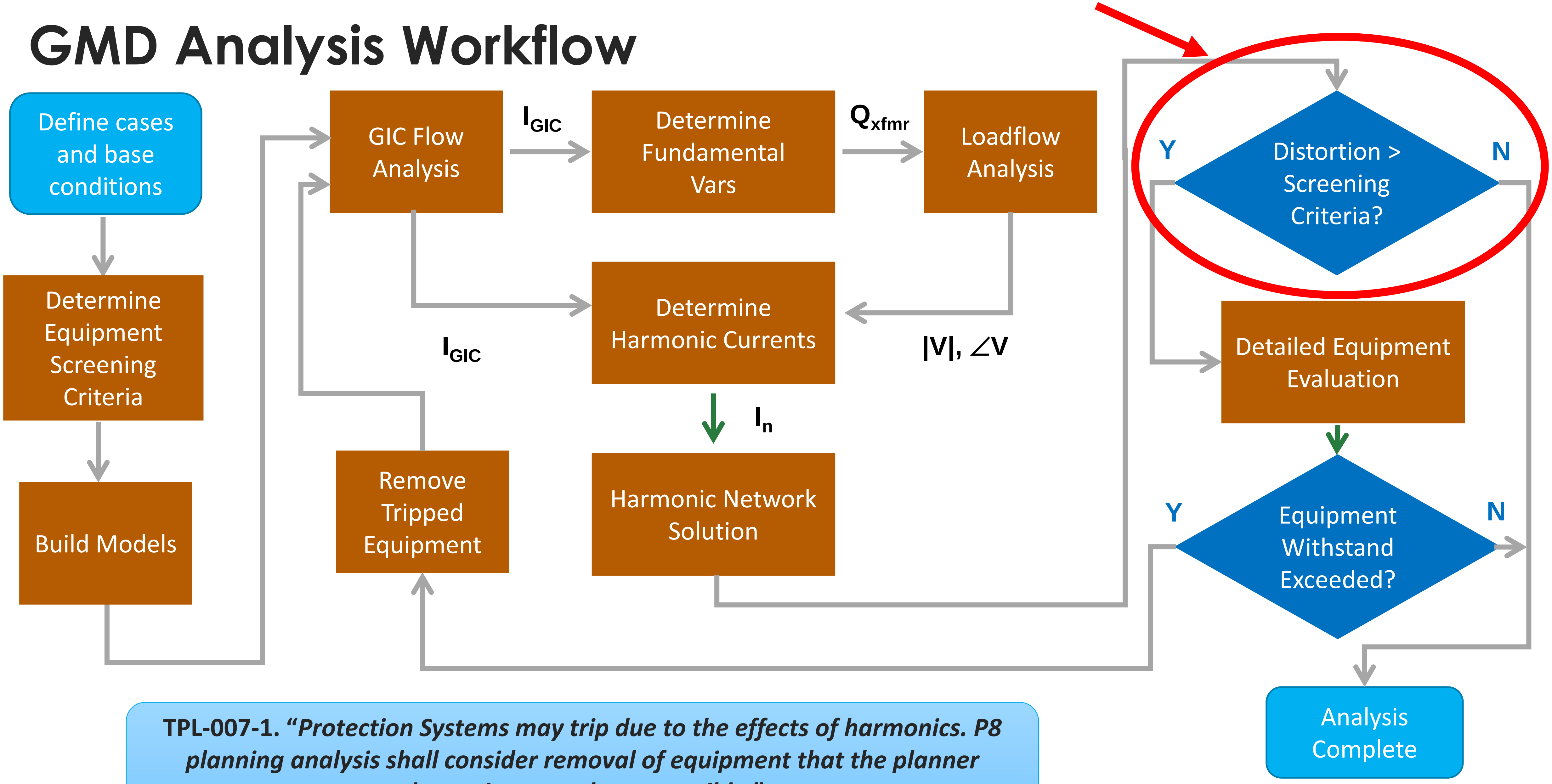
- 2016 Publically Available Report
- Report # 3002006444
  - www.epri.com
- This guide discusses the harmonic withstand and performance issues of major power system components:
  - transformers, shunt capacitor banks, generators, cables, overhead lines, high voltage direct current (HVDC) systems, flexible ac transmission system (FACTS) devices, surge arresters, distribution systems, consumer loads, relays, and protection systems.



# Scope and Organization of Guide

- Detailed evaluation of the harmonic impact on various types of equipment requires equipment data that are often not easily obtained and can require specialized calculations that commonly available harmonic analysis software typically does not perform.
- Therefore, for each type of equipment and where feasible, this guide suggests simplified screening criteria.
- These criteria are intentionally conservative.
- Harmonic values exceeding these criteria do not imply that the component will endure excessive duty, but rather indicate that more detailed evaluation of that component is prudent. The screening thresholds suggested in this guide incorporate ample safety factors depending on the uncertainty of the device parameters.

# GMD Analysis Workflow




**TPL-007-1. "*Protection Systems may trip due to the effects of harmonics. P8 planning analysis shall consider removal of equipment that the planner determines may be susceptible.*"**

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