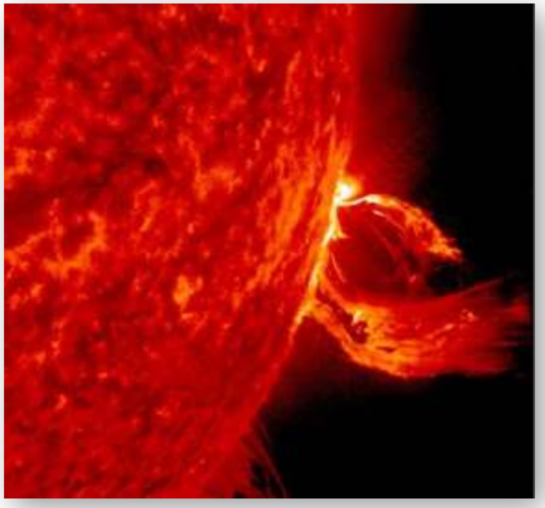
Both GMD and E3 HEMP induce GIC in the ground

GMD



E3 HEMP

Earth/Ground

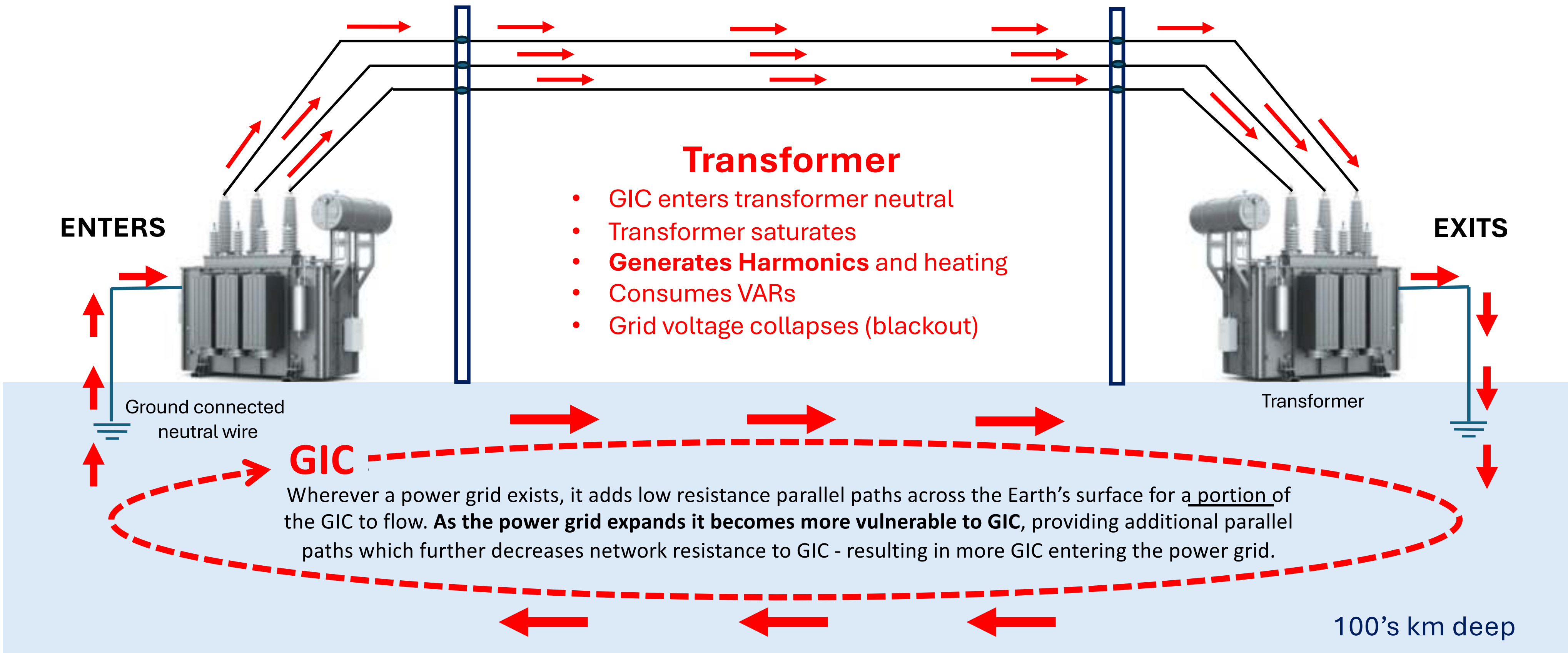
GIC

GMD & **E3 HEMP** events induce a quasi-DC current across the surface of the Earth in one direction with a return loop deep in the Earth in the opposite direction - traveling the paths of least resistance. The electric power grid ties into this “GIC circuit" via the ground connected neutral wire of transformers.

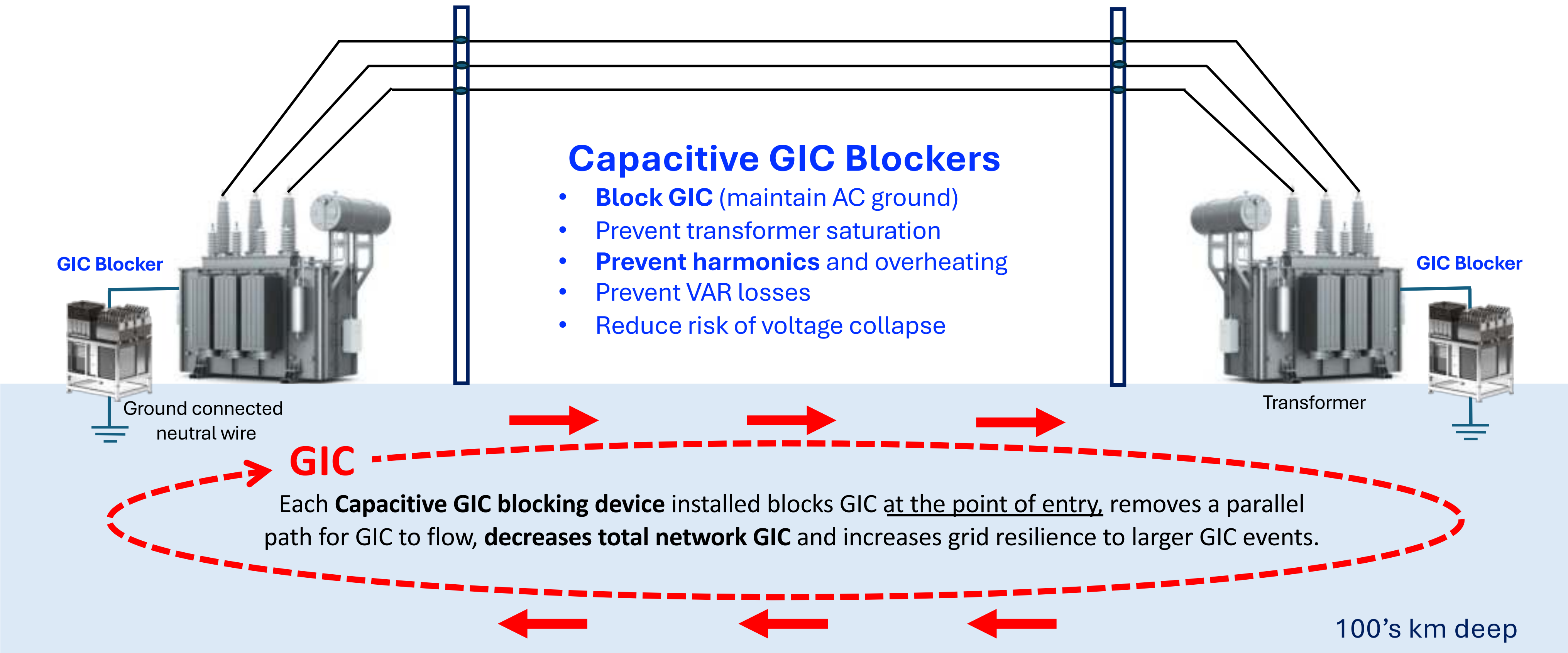
GIC: Geomagnetically/Ground induced current
GMD: Geomagnetic Disturbance
E3 HEMP: late-time portion of high-altitude nuclear detonation

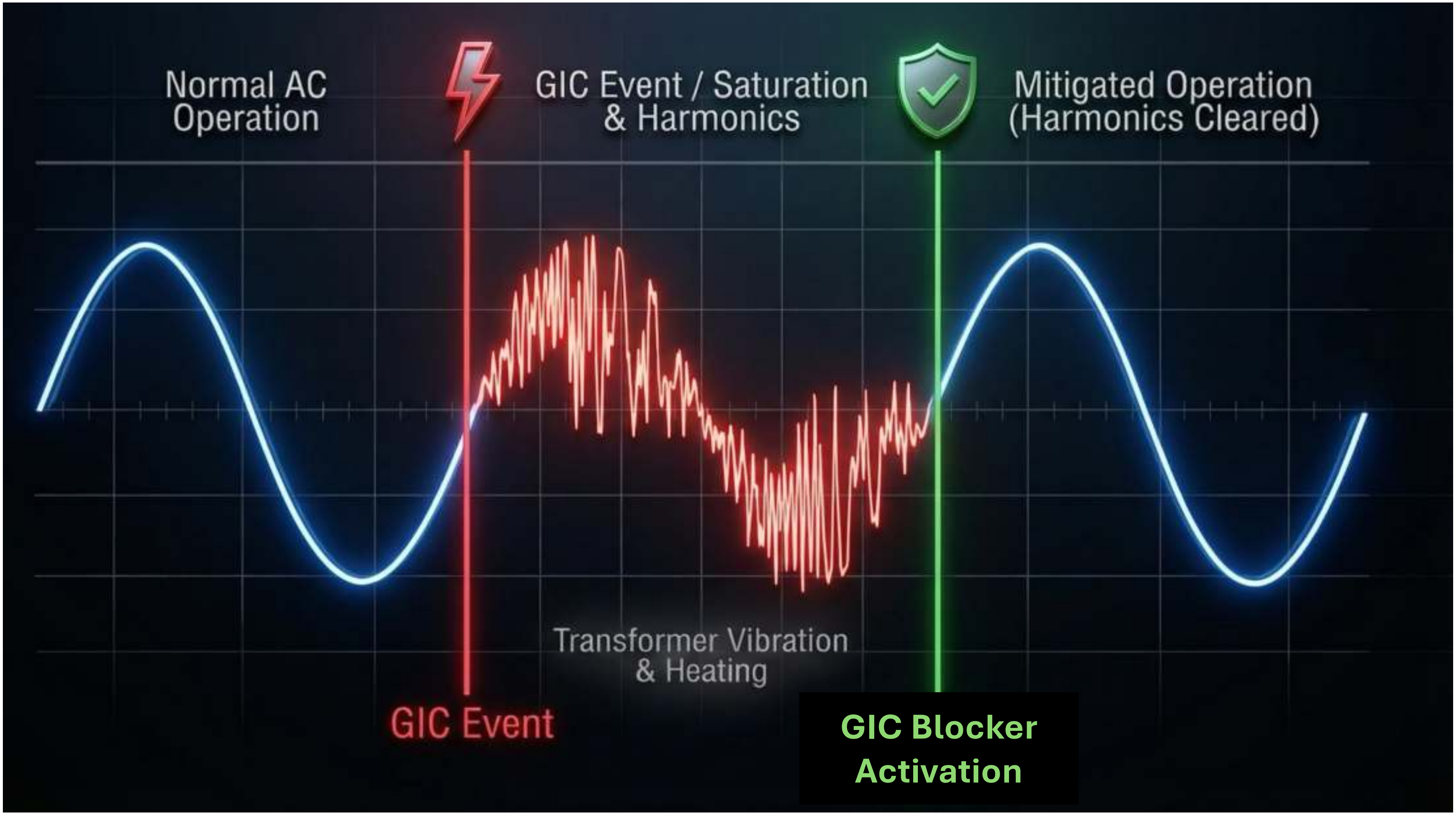
100’s km deep

The power grid provides low resistive paths in parallel to the Earth's surface for GIC to travel. **GIC enters** and **exits** the power grid through the **ground connected neutral wire of transformers**.



GIC Blockers installed on the ground connected neutral wire of large power transformers - protects transformers *and* - **protects the rest of the power grid *from* those transformers**.




Normal AC Operation
GIC Event / Saturation & Harmonics
Mitigated Operation (Harmonics Cleared)
Transformer Vibration & Heating
GIC Event
GIC Blocker Activation

The U.S. power grid is not designed for GIC

- **TODAY:** when common low level solar storms occur, small amounts of ground induced currents (**GIC**) enter the electric power grid through the grounded neutral connections of high voltage transformers, saturating them and generating **harmonics** which is estimated to cause ***$Billion(s)** in economic loss each year* in the U.S. ***This is happening – and can be stopped....***

  - Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment, Zurich/Lockheed/NOAA, Space Weather Journal, 2014
  - Electrical Claims and Space Weather – Measuring the Visible Effects of an Invisible Force, Zurich, June 2015

- **RISK:** in 2013 **Lloyd's of London** estimated the economic loss of a large Carrington-class solar storm (**GMD**) on the North American grid today would be between ***$0.6 and $2.6 trillion*** *based solely on the value of lost load (not including equipment damage and immense loss of human life).* ***Statistically, this will happen again – and the risk can be largely removed.***

  - Solar Storm Risk to the North American Electric Grid, Lloyd's, 2013

The power grid is vulnerable to large GICs and Harmonics from major GMD events (statistical) and E3 HEMP (intentional)

Comparing the magnitude of GMD/E3 HEMP events

The electric field strength of a **GMD/E3 HEMP** event is measured in *volts per kilometer* (**V/km**) and directly relates to how large the ground induced currents (**GIC**) and the resulting **harmonics** will be.

If: **1 V/km = 100 Amps GIC**
at a specific location,

then: **85 V/km = 8,500 Amps GIC**
at that same location.

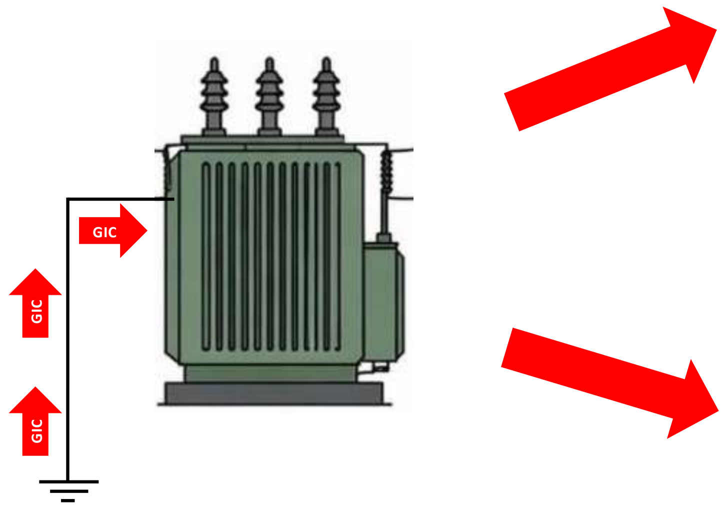
Larger **V/km** = larger **GIC** = higher **<u>harmonics</u>**

"Thermal Damage" to Transformers is <u>not</u> the main GIC threat to the power grid.

"Misconception in the electric power industry - Paying more attention to thermal effects in transformers and not to the ***true issue*** *of increased VAR Demand and* ***effect of harmonics on power system components****."*

CIGRE, "**Susceptibility of TVA's 500 kV Fleet of Power Transformers to Effects of GIC**"
-Dr. Ramsis Girgis, G. Burden, M. Bernesjo, Ian Grant, Gary Kobet - October 23, 2017

When GIC enters a Large Power Transformer the Transformer is at risk and saturates, **becoming an Active Threat to the rest of the grid**



Generate HARMONICS (injecting them into the grid)

- **Harmonics grow as they travel into lower voltage towards load.** Largest increase occurs at GIC saturating Step-Down Transformers.
- **At the Greatest risk: Data Centers and VAR supply**
- Harmonics damage transformers, large power generators, HV circuit breakers, power supplies, unexpectedly trip protective relays
- **EMP E1 filters exacerbate harmonics by 50%** (Idaho National Labs)
- GIC induced Harmonics cause an estimated $10 billion in economic loss each year in the U.S. (Zurich)

Consume reactive power (VAR losses)

- Grid voltage drops (if severe enough = blackout)

It is the GIC saturated Transformers that collapse a power grid

Operating Procedures cannot block GIC (and resulting harmonics) from entering an operating grid.
Protection against **GIC** and the induced **Harmonics** requires the installation of hardware: **capacitors in the grounded neutral** of large power transformers - to **block GIC** while maintaining an AC ground.

Misconception: Large Transformers are more resilient to GIC

Level of GIC at which Half-Cycle Saturation and induced Harmonics begin:

Source: ABB, Inc.

"Highest-Risk" Design:
These large transformers begin to saturate and generate harmonics with **GIC** as low as **5 Amps per phase** (**or less**). **MVA size does <u>not</u> matter.**

1. Shell Single-Phase, 1 Limb
2. Shell 3 Phase, conventional (2 Limb or "D")
3. Shell 3 Phase, 7 Limb
4. Core Single-Phase, 2 Limb
5. Core Single-Phase, 3 Limb
6. Core Single-Phase, 4 Limb
7. Core 3 Phase, 5 Limb

U.S. High Voltage Transformer Fleet:

500kV to 765kV – almost 100% of the largest transformers are "Highest-Risk" Design (~ 2,000)

230kV to 345kV – 20%+ are "Highest-Risk" Design (up to 4,000)

Highest-Risk Design = ~ 6,000 Large Power Transformers

Only one design requires slightly more **GIC** to saturate: large 200 MVA size begins to generate harmonics at **~ 8 Amps per phase**.

8. Core 3 Phase, 3 Limb

The largest power transformers (Single-Phase) are the most vulnerable

1989 - Minnesota Power (**EPRI RP1770-1**) <u>injected DC into the neutrals</u> of **3 Large Transformer Designs** in their power system **(200+ MVA)** to analyze half cycle saturation and the **GIC induced <u>harmonics</u>**.

Single Phase Shell Form
500/230kV Autotransformer

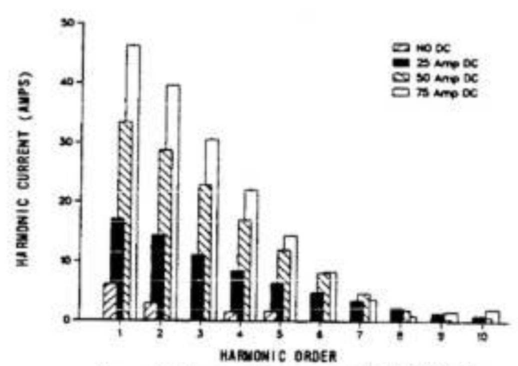


Figure 2. Harmonic Currents on the 500kV Side of Transformer (8T) With 75 Amp DC Injection (Test #1)

Three Phase Three-Legged Core Form
230/115kV Autotransformer (**200 MVA**)

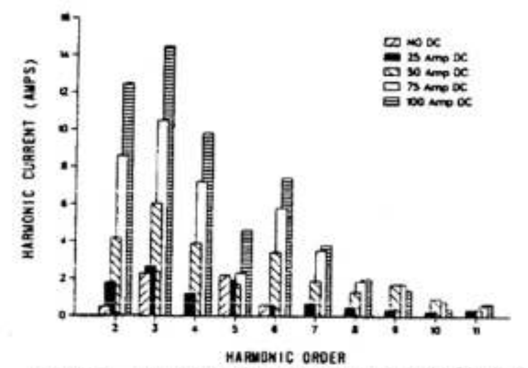


Figure 8. Harmonic Current on the 230kV Side of Transformer (3T) With DC Injection (Test #2)

Three Phase Shell Form
230/115kV Autotransformer (**200 MVA**)

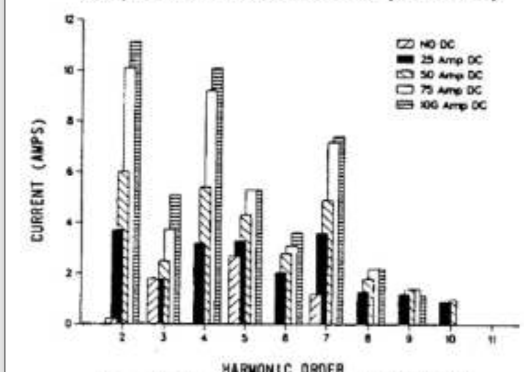


Figure 11. Harmonic Current on the 230kV Side of Transformer (6T) With DC Injection (Test #3)

<u>All</u> transformer designs generated harmonics with the <u>lowest level of DC</u> (8.3 Amps/phase)

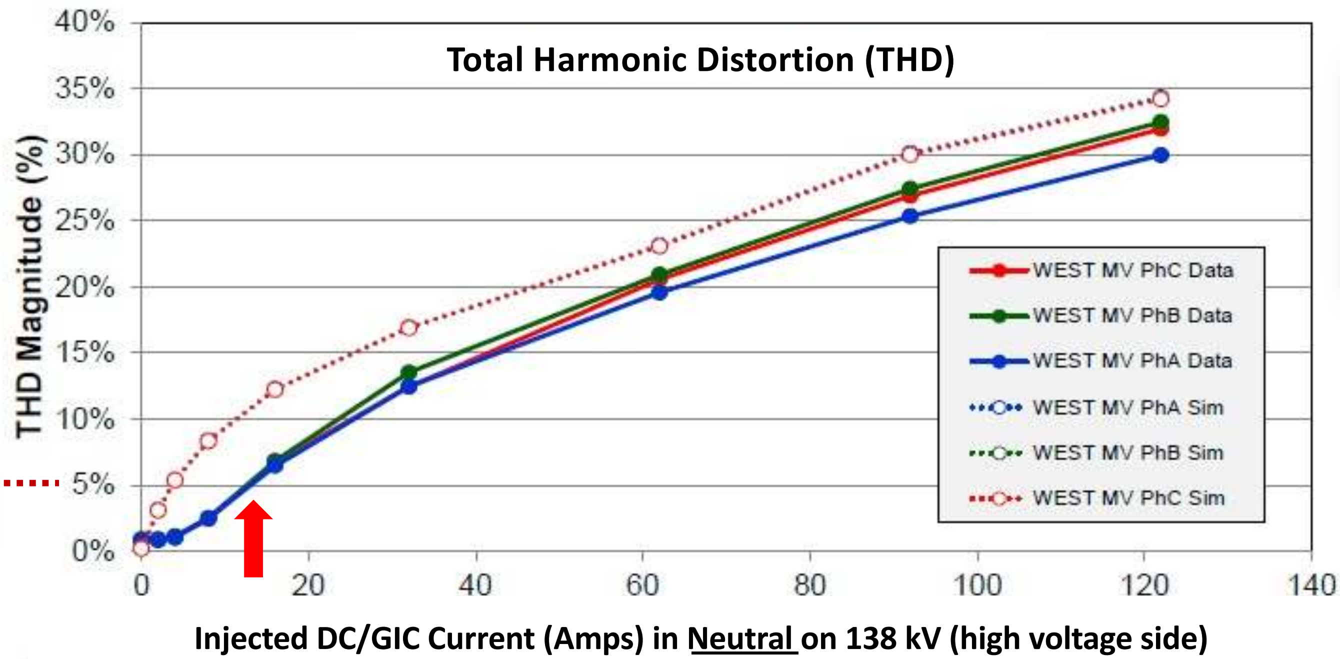
*"In spite of reduced saturation effects...three phase core-form transformer **produced substantial half-cycle saturation effects**."*

*"In **<u>all</u>** cases...transformer...produced **increased harmonic currents with an increase of direct current**...both even and odd harmonics..."*

*"**Geomagnetic disturbances**...over an entire continent...**turn nearly every transformer...into harmonic current generators.**"*

These tests *only measured harmonics on the high voltage side* – **Harmonics amplify on the low "Secondary" side**

Secondary Harmonic Trends



DTRA/INL Testing was stopped at **40 Amps/phase** over concerns of harmonic damage to power system

IEEE HARMONIC Limit 5%

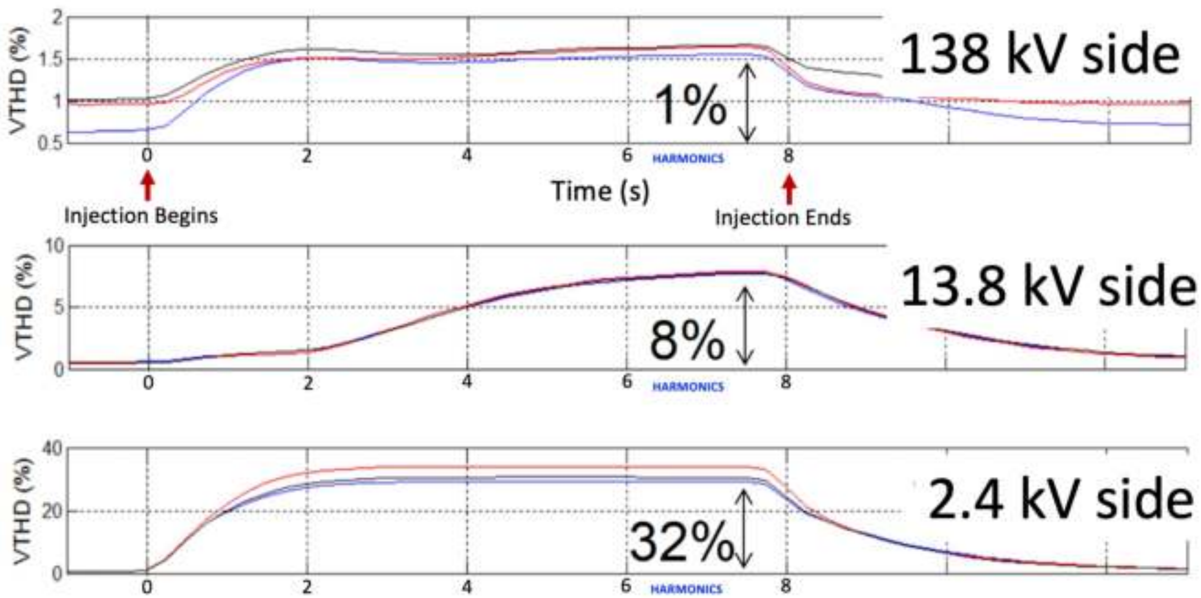
***U.S. Defense Threat Reduction Agency** (DTRA) test results measured during the **Idaho National Laboratory** E3 HEMP Live Grid experiment in 2012.

GIC less than **5 Amps per phase** (15 Amps neutral) on the high side, generated enough harmonics on the low "secondary" side to **exceed the IEEE 519 Standard** for **Total Harmonic Distortion**. This data explains how **harmonics from low-level GIC** entering the neutrals of large power transformers from common GMD events **amplify** and cause est. $Billion(s) in economic loss *each year* (Zurich/Lockheed/NOAA).

As GIC increases, Harmonics increase – severe **GMD/E3** events can induce **GIC** of **100**(s) to **1,000(s) of Amps per phase**

GIC induced Harmonics amplify at Step-Down Transformers

DC (GIC) was injected into the neutrals of two 138kV Transformers for 8 seconds on **Idaho National Labs** live grid. Transformers begin saturating within 1 second and generated harmonics.



Harmonics generated on the high side **grow significantly as the voltage steps down: 1% ➡ 32%**

High power users and equipment located on the low side and in close proximity to Step-Down Transformers are at the greatest harmonic risk: Data Centers and SVCs (VAR Supply)

TODAY: est. $billion(s) in economic loss for high power users located on the low side of and in close proximity to Step-Down Transformers

Common solar storms produce low-levels of **GIC** which invade the power grid through ground connected neutral wires causing high voltage transformers to **half-cycle saturate** and **generate harmonics** which propagate and **amplify** as they travel into the lower voltage side of Step-Down Transformers.

- *est. **$10 Billion** in economic loss **each year** in the United States **due to GIC induced harmonics***

AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE

10.1002/2014SW001066

Key Points:
- We present a first analysis of the effects of space weather on insurance claims
- Geomagnetic variability couples into the low-voltage power network
- GIC effects lead to malfunctions in electrical and electronic devices

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Schrijver, C. J., R. Dobbins, W. Murtagh, and S. M. Petrinec (2014), Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment, *Space Weather*, *12*, 487–498, doi:10.1002/2014SW001066.

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Published online 8 JUL 2014

Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment

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[1]STAR Labs, Lockheed Martin Advanced Technology Center, Palo Alto, California, USA, [2]Risk Engineering Technical Strategies Team, Zurich Services Corporation, Schaumburg, Illinois, USA, [3]Space Weather Prediction Center, NOAA, Boulder, Colorado, USA

Abstract Geomagnetically induced currents are known to induce disturbances in the electric power grid. Here we perform a statistical analysis of 11,242 insurance claims from 2000 through 2010 for equipment losses and related business interruptions in North American commercial organizations that are associated with damage to, or malfunction of, electrical and electronic equipment. We find that claim rates are elevated on days with elevated geomagnetic activity by approximately 20% for the top 5% and by about 10% for the top third of most active days ranked by daily maximum variability of the geomagnetic field. When focusing on the claims explicitly attributed to electrical surges (amounting to more than half the total sample), we find that the dependence of claim rates on geomagnetic activity mirrors that of major disturbances in the U.S. high-voltage electric power grid. The claim statistics thus reveal that large-scale geomagnetic variability couples into the low-voltage power distribution network and that related power-quality variations can cause malfunctions and failures in electrical and electronic devices that, in turn, lead to an estimated 500 claims per average year within North America. We discuss the possible magnitude of the full economic impact associated with quality variations in electrical power associated with space weather.

1. Introduction

Large explosions that expel hot, magnetized gases on the Sun can, should they eventually envelop Earth, effect severe disturbances in the geomagnetic field. These, in turn, cause geomagnetically induced currents (GICs) to run through the surface layers of the Earth and through conducting infrastructures in and on these, including the electrical power grids. The storm-related GICs run on a background of daily variations associated with solar (X)(E)UV irradiation that itself is variable through its dependence on both quiescent and flaring processes.

The strongest GIC events are known to have impacted the power grid on occasion [see, e.g., *Kappenman et al.*, 1997; *Boteler et al.*, 1998; *Arslan Erinmez et al.*, 2002; *Kappenman*, 2005; *Wik et al.*, 2009]. Among the best known of such impacts is the 1989 Hydro-Québec blackout [e.g., *Bolduc*, 2002; *Béland and Small*, 2004]. Impacts are likely strongest at middle to high geomagnetic latitudes, but low-latitude regions also appear susceptible [*Gaunt*, 2013].

The potential for severe impacts on the high-voltage power grid and thereby on society that depends on it has been assessed in studies by government, academic, and insurance industry working groups [e.g., *Space Studies Board*, 2008; *FEMA and NOAA*, 2010; *Kappenman*, 2010; *Hapgood*, 2011; *JASON*, 2011]. How costly such potential major grid failures would be remains to be determined, but impacts of many billions of dollars have been suggested [e.g., *Space Studies Board*, 2008; *JASON*, 2011].

Noncatastrophic GIC effects on the high-voltage electrical grid percolate into financial consequences for the power market [*Forbes and St. Cyr*, 2004, 2008, 2010] leading to price variations on the bulk electrical power market on the order of a few percent [*Forbes and St. Cyr*, 2004].

Schrijver and Mitchell [2013] quantified the susceptibility of the U.S. high-voltage power grid to severe, yet not extreme, space storms, leading to power outages and power-quality variations related to voltage sags and frequency changes. They find, "with more than 3σ significance, that approximately 4% of the

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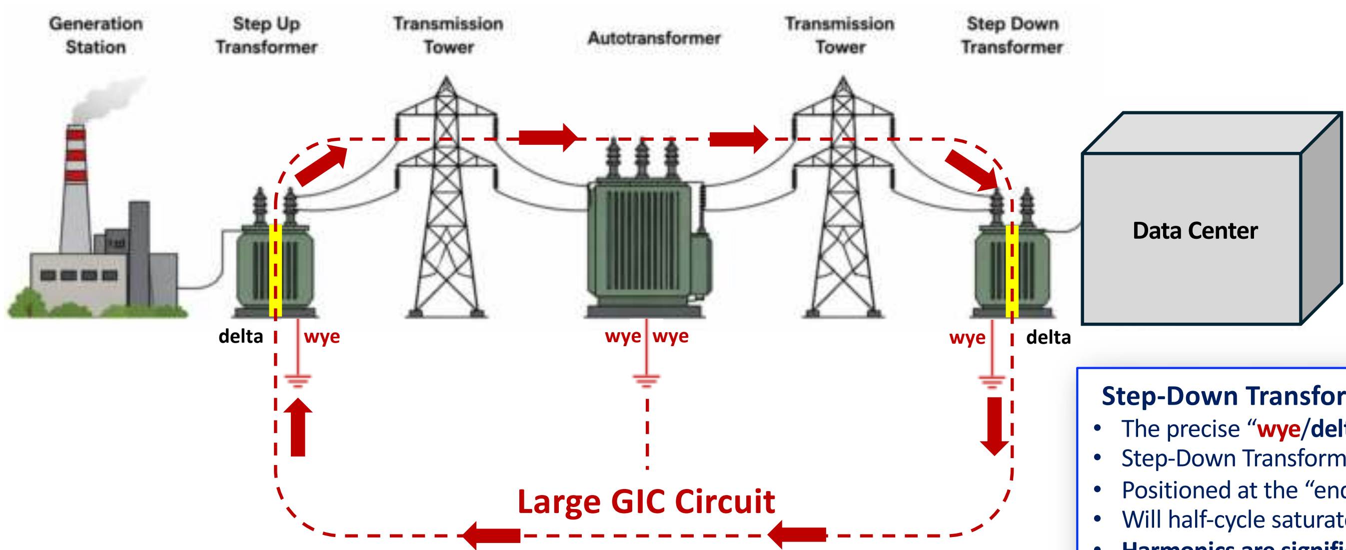
SCHRIJVER ET AL. ©2014. The Authors. 487

Electrical Claims and Space Weather: Zurich, June 2015

Insurance Study By Lockheed/Zurich/NOAA:
C. J. Schrijver, R. Dobbins,
W. Murtagh, and S.M. Petrinec
Space Weather Journal, 2014

Large Power Transformer Design (**wye grounded**)

In general, **any wye grounded transformer** installed on the power grid – increases grid vulnerability to GIC events becoming an <u>additional</u> **harmonic current generator/amplifier** and **VAR consumer** during large GIC events.



Step-Down Transformers: Wye grounded on the **high side:**

- The precise "**wye/delta**" design **tested by INL/DTRA**
- Step-Down Transformer is tied directly into the large **GIC circuit**
- Positioned at the "end" of line = experiences the highest GIC
- Will half-cycle saturate, consume VARs and generate harmonics
- **Harmonics are significantly amplified on low side**
- Capacitive GIC blockers installed on any wye grounded connection of transformers removes these GIC vulnerabilities

Data Centers and high-power users requiring large Step-Down Transformers: **Larger MVA = less resistive windings = Higher GIC**.
Data Centers and voltage support equipment (VAR supply) are **vulnerable to harmonics,** and both are installed on the low side of and in close proximity to Step-Down transformers – **precisely where harmonics are amplified**. VAR Supply does <u>not</u> have a good track record of being available when needed the most (during GIC events) – due to harmonics tripping them offline (1989 Quebec, 2024 Gannon).

March 1989 – **GIC induced harmonics** from a moderate **2 V/km** solar storm event

tripped out VAR supply and collapsed Quebec's power grid in 92 seconds (**6 million people without power**)

Document C-15

NPCC, Inc.

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Document C-15 was created in reaction to the Quebec grid collapse due to GIC impact

Procedures for Solar Magnetic Disturbances
Which Affect Electric Power Systems

Approved by the Task Force on Coordination of Operation on April 10, 1989

Revised:	May 23, 1989
Revised:	September 1, 1989
Revised:	February 10, 1993
Revised:	January 21, 1997
Reviewed:	March 25, 1998
Revised:	November 7, 2000
Revised:	October 15, 2003
Reviewed:	August 18, 2005
Revised:	January 11, 2007

Many revisions over the following 18 years

1.0 Introduction

Solar Magnetic Disturbances (SMD) are events that occur on the sun which can ultimately affect man-made systems on earth, including power systems. Voltage potentials are induced in the earth's crust which in turn cause geomagnetically induced currents (GIC) to flow in transmission lines. The resulting GICs are predominantly direct currents in nature and are typically more prevalent in the more northerly latitudes and in those regions in which the resistivity of the earth's crust is high to a considerable depth. This is notably the case in areas of igneous rock deposits.

Those utilities most affected by solar activity since 1989 have developed procedures which establish a safe operating posture and which are initiated by criteria for their respective systems.

A detailed technical description of SMDs may be found Appendix F.

2.0 Impacts on Power Systems

The flow of GICs in the transmission system may affect the following equipment:

2.1 General Effects

2.1.1 Power Transformers

The presence of GIC produces off-setting dc excitation in a transformer, resulting in some degree of core saturation. This can cause the production of **harmonic currents** which can distort system voltages and cause **protective relay** operation due to the flow of neutral current to ground. Core saturation can also result in internal localized heating of the core and windings, and degradation of winding insulation. Saturated transformers are **reactive power** sinks, using up system reactive capacity, resulting in voltage depression.

2.1.2 HVdc Systems and **Static VAR Compensators**

Operations at or near the minimum or maximum current **rating** of HVdc circuits increases the potential for **commutation failures**, jeopardizing continuity of service.

These systems require a sinusoidal voltage to properly commutate current transmission. Voltage distorted by **harmonics** may be severe enough to cause **commutation failures** and result in shutdown of such systems.

Filter banks, including capacitor banks, associated with these systems will tend to overload due to harmonic current and may result in tripping.

2.1.3 Shunt Capacitor Banks

Shunt capacitor banks will tend to overload due to **harmonic current**, typically the third **harmonic**.

2.1.4 Generators

Automatic voltage regulators (AVR) associated with generators require representative voltage signals to control the dc field current on generators. Distorted ac voltage input to the AVR may result in uncertain translation of the ac signals for control, possibly resulting in a cyclical level of excitation on the generator, and hence real and **reactive power** output may vary in an abnormal manner.

Overheating may occur in large generators due to imbalances in phase currents and **harmonic** distortion in voltages which result from the saturation of power transformers. Turbine mechanical vibration may be excited by the presence of increased **harmonic** rotor current.

2.1.5 Transmission Lines

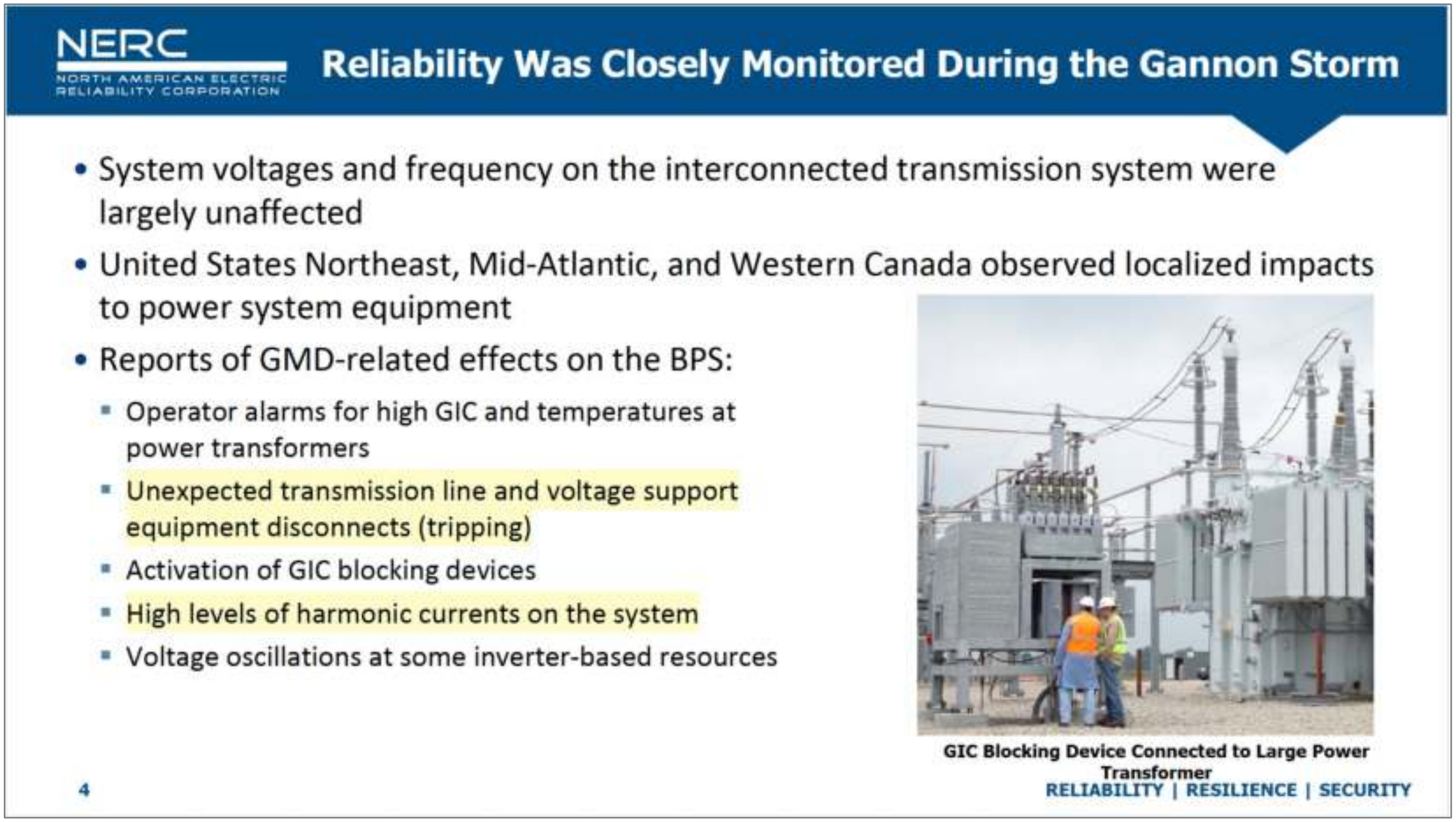
Harmonic frequencies in the system voltage can increase the magnitude of the voltage required to be switched by circuit breakers. **Harmonics** increase transmission losses and cause interference to communications systems.

2.1.6 Overall System Impact

Transformer saturation results in increased VAR consumption and **harmonic** injection into the system. These **harmonic currents** can result in capacitor bank overloading and their tripping, generator tripping and misoperation of **static VAR compensators**. This could further deplete the system of reactive VAR support and impact the overall system performance and security. The power systems are becoming more vulnerable to GIC effects due to longer transmission lines, decreased reactive margins and greater dependence on **static VAR compensators** and high voltage dc control.

Conclusion: Primary impact of **GIC** entering the power grid → **HARMONICS**

May 2024, **GIC** from a **smaller** **1 V/km** event (“Gannon Storm”) induced ***“high levels of harmonic currents on the system”*** that unexpectedly **tripped out VAR Supply**. VAR losses during this smaller event were not enough to collapse the grid. Capacitive GIC blocking devices (**pictured below**) activated several dozen times during this event - blocking GIC, preventing the generation of harmonics and reducing VAR losses.



July 2012, a large solar eruption shot through Earth's orbit and **narrowly missed Earth**. STEREO A Satellite was in the direct path and took measurements – the event was estimated by NASA to be larger than "Carrington" (**> 20 V/km**). **This was a warning shot.**

A major solar eruptive event in July 2012: Defining extreme space weather scenarios

*"This is **considerably larger than** estimates for the famous **Carrington** storm of 1859"*

*"We argue that **this extreme event should immediately be employed** by the space weather community **to model severe space weather effects on** technological systems such as **the electric power grid**."*

This event has **not** been factored into the NERC standard

*"In my view the **2012 storm** was in all respects **at least as strong as the 1859 Carrington**"* (Dr. Baker, NASA)

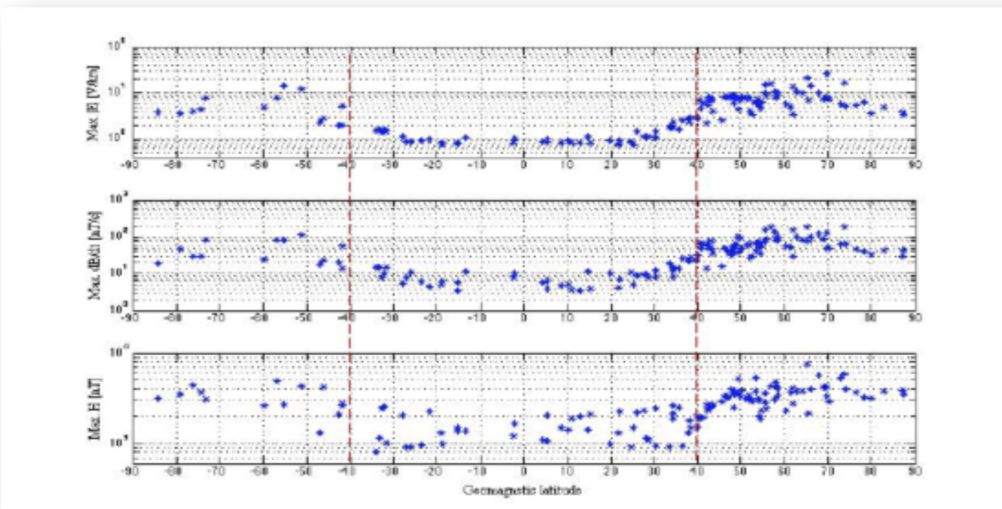
Had this event hit Earth, the GIC induced harmonics and VAR losses would have been catastrophic.

2013, a **NERC** committee of 8 respected space weather scientists estimated a reference **GMD** storm, preliminary results were determined - max. geoelectric field of **30 - 40 V/km**

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

NASA/CUA

- We are getting 30-40 V/km max. fields (preliminary results)



- Current Science Team composition includes:
  - A. Pulkkinen (NASA/CUA),
  - W. Murtagh (NOAA),
  - C. Balch (NOAA),
  - J. Gannon (USGS),
  - D. Boteler (NRCan),
  - R. Pirjola (NRCan),
  - D. Baker (U. of Colorado), and
  - A. Thomson (BGS/EURISGIC).

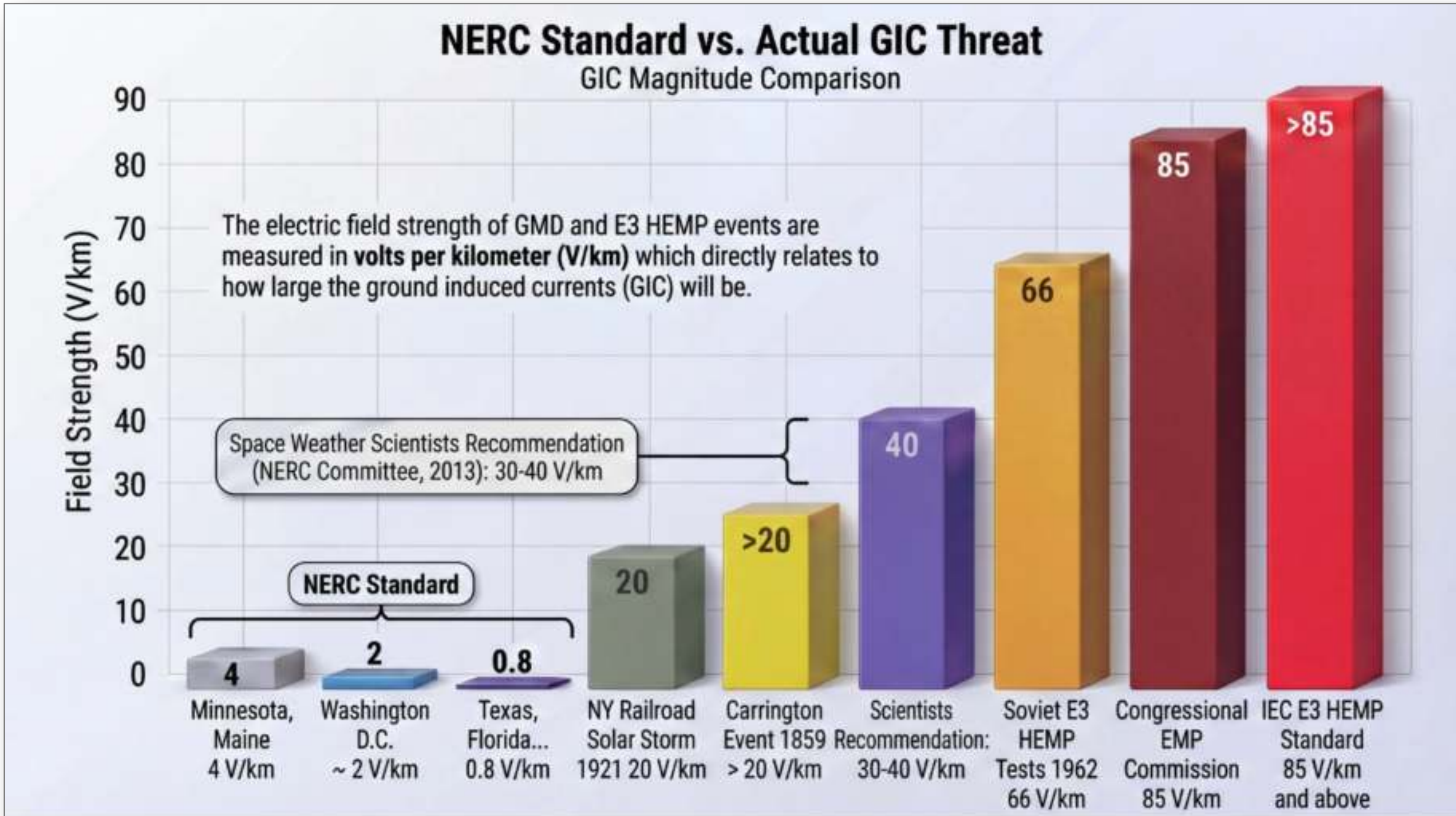
Adding a 25% safety margin

= 50 V/km (GMD storm)

Scientist's estimates have **not** been factored into the NERC standard

U.S. NERC Standard (TPL-007-4) is explicitly "Geomagnetic Disturbance" (GMD)

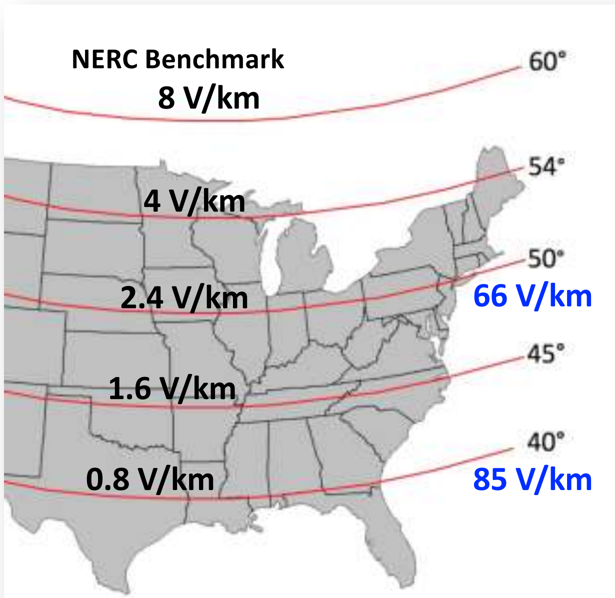
and does <u>not</u> consider GIC Harmonic Impact, scientist's recommendations, large GMD events in recent history or E3 HEMP



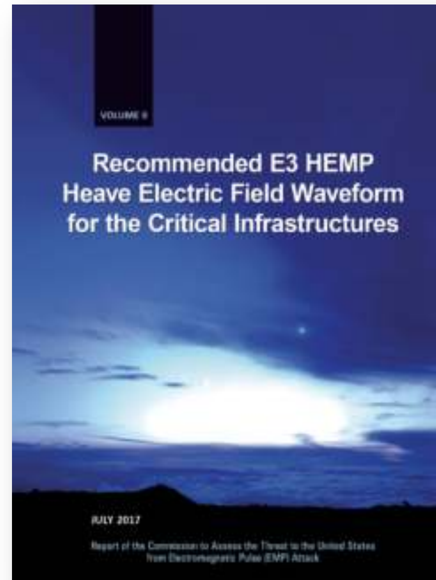
Source: Secure the Grid Coalition

U.S. NERC GMD Standard vs. E3 HEMP (1962 Soviet Test Data)

Field Strength ("V/km") scaled per <u>geomagnetic</u> latitude below, directly relates to how large the ground induced currents ("GIC") and induced harmonics will be.



NERC GMD standard is dangerously low:
0.8 V/km vs. 85 V/km @ 40° geo-latitude

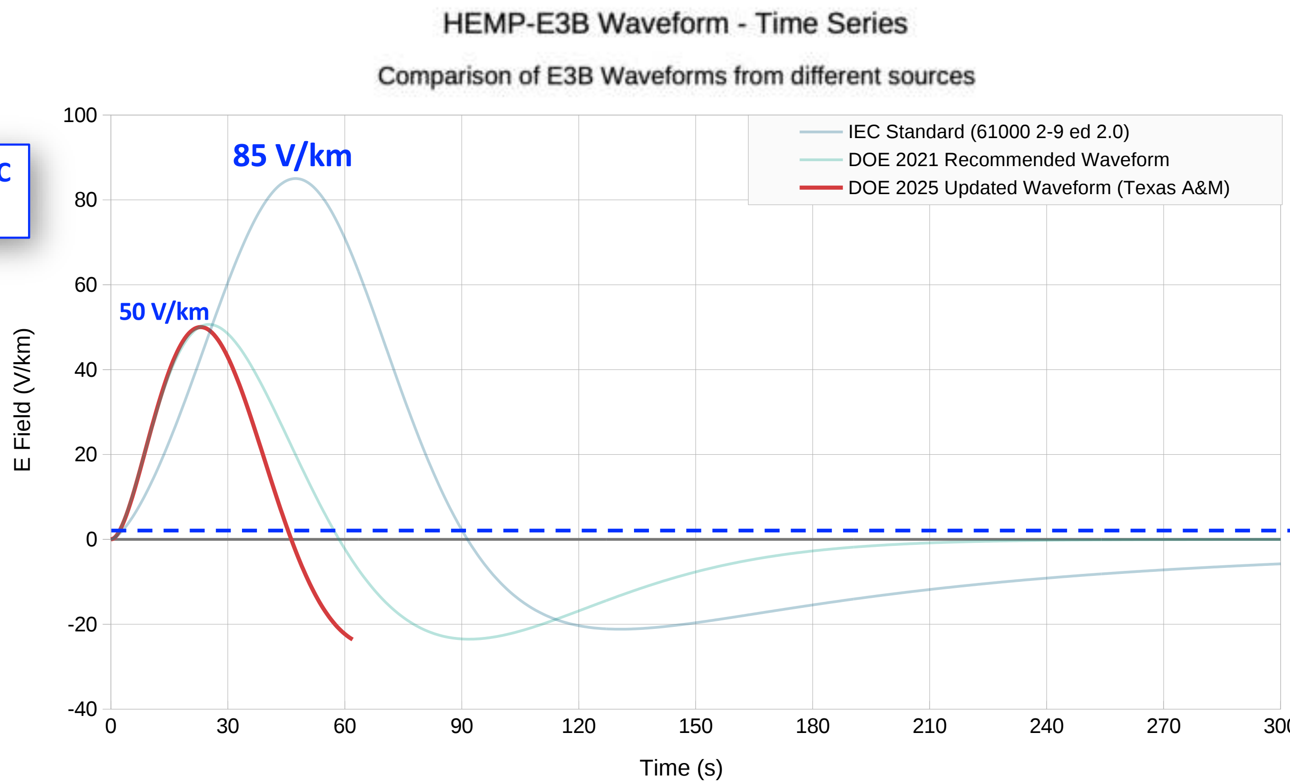


DOD: *"… **E3 HEMP** … **<u>increases</u>** for burst points closer to the geomagnetic equator … **85 V/km** for locations **<u>in the southern part</u> of the continental U.S.**…"*

GIC and induced Harmonics from E3 HEMP will be the most extreme <u>in the south</u>

United States is <u>not</u> using the Standard E3 HEMP Waveform

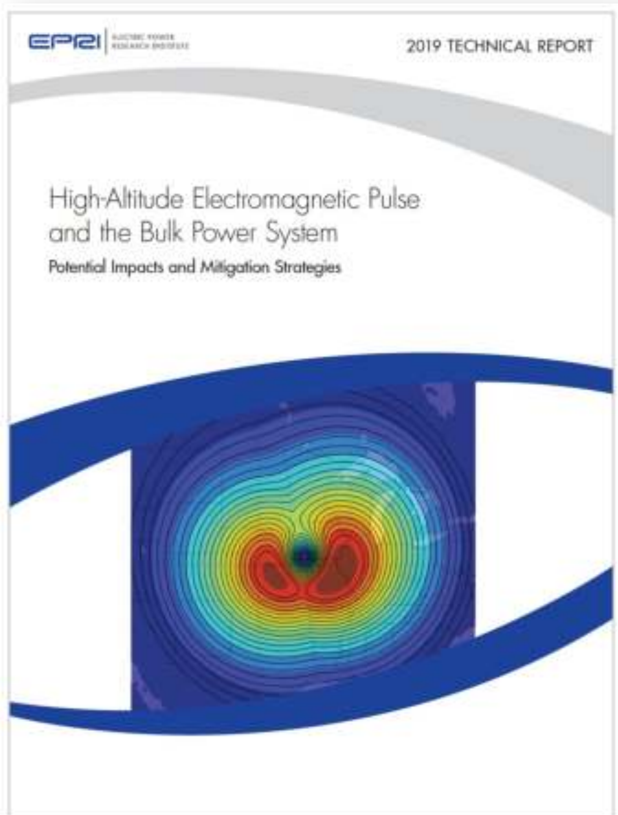
Larger **V/km** = larger **GIC** = higher **Harmonics**



GIC induced **<u>Harmonics</u>** from a **2 V/km** event: **collapsed Quebec's grid** in 92 seconds

United States is using a **much-reduced waveform** (**shown in red**) – lower peak and progressively shorter durations minimize transformer "***thermal***" damage <u>in models.</u> This does not appear to be "Defense Conservative" and **does <u>not</u> consider GIC harmonic damage or catastrophic damage to breakers** as they attempt to OPEN (with severe **GIC + harmonic currents** across them) at many locations across the grid as voltage collapses. **If breakers are damaged - the grid will <u>not</u> restart**.

As GIC increases, harmonics increase. GIC induced harmonics due to E3 HEMP will be catastrophic, yet the analysis does not include harmonics.



"As with the previous study, ***the effects of harmonics were not included****."* p. 4-21

"The effects of harmonics were not included in the analysis*."* p. 4-25

"As ***high-voltage circuit breakers*** *begin to trip due to the effects of voltage collapse* ***there is considerable uncertainty regarding their ability to interrupt the significant levels of GIC*** *that can be generated by E3 EMP. This is of particular concern if circuit loading is low such that the combined waveform* ***(fundamental frequency + harmonics + GIC)*** *does not contain a zero crossing."* p. 4-26

Blocking GIC protects high-voltage circuit breakers

U.S. Senate Committee on Homeland Security & Governmental Affairs:

Perspectives on Protecting the Electric Grid from an Electromagnetic Pulse or Geomagnetic Disturbance

February 19, 2019

"I would like to stress that in addition to these extreme events, smaller but more frequent GMDs are estimated to cause an average of $10 billion in damage each year. **Address the major GMDs and we can also protect us from these smaller events**."

Testimony of Dr. Justin Kasper – University of Michigan

It is not reasonable to expect grid operators to respond to common solar storms which occur many times each year.

"If we responded to every K alert of level 5 or greater, PJM would have spent over $100 million in excess incremental operating costs… **The ultimate protection against GMD is mitigation**."

-Solar Magnetic Disturbance: **An Operator's Wish List**, Greg A. Gucchi, EPRI TR-100450

GIC and Harmonic Analysis, prediction, detection and VAR supply (voltage support) are not protection.

Without GIC Blocking Devices, GIC will continue to invade the power grid through the ground connected neutral wires of large power transformers, causing them to consuming VARs and **generating harmonics which amplify** causing cumulative stress/pre-mature aging of equipment. $Billion(s) in economic losses will continue each year in the U.S. **and our grid will remain extremely vulnerable to severe GIC events.**

U.S. Department of Energy

Electromagnetic Pulse (EMP) Resilience Action Plan Meeting – July 21, 2016

Attendees: DOE, EMP Commission, DOD, INL, LANL, ABB, Siemens, Dominion, EPRI, MITRE, STRATCOM, NATF...

Objective: identify specific actions to protect the electric power grid

#1 Prevent Grid Failure

#2 Expedite recovery (should the grid fail)

*"**Best policy is to protect the grid** - Fight to the last breath to keep the system running."*

"Shutting down grid is very risky...completely unrealistic."

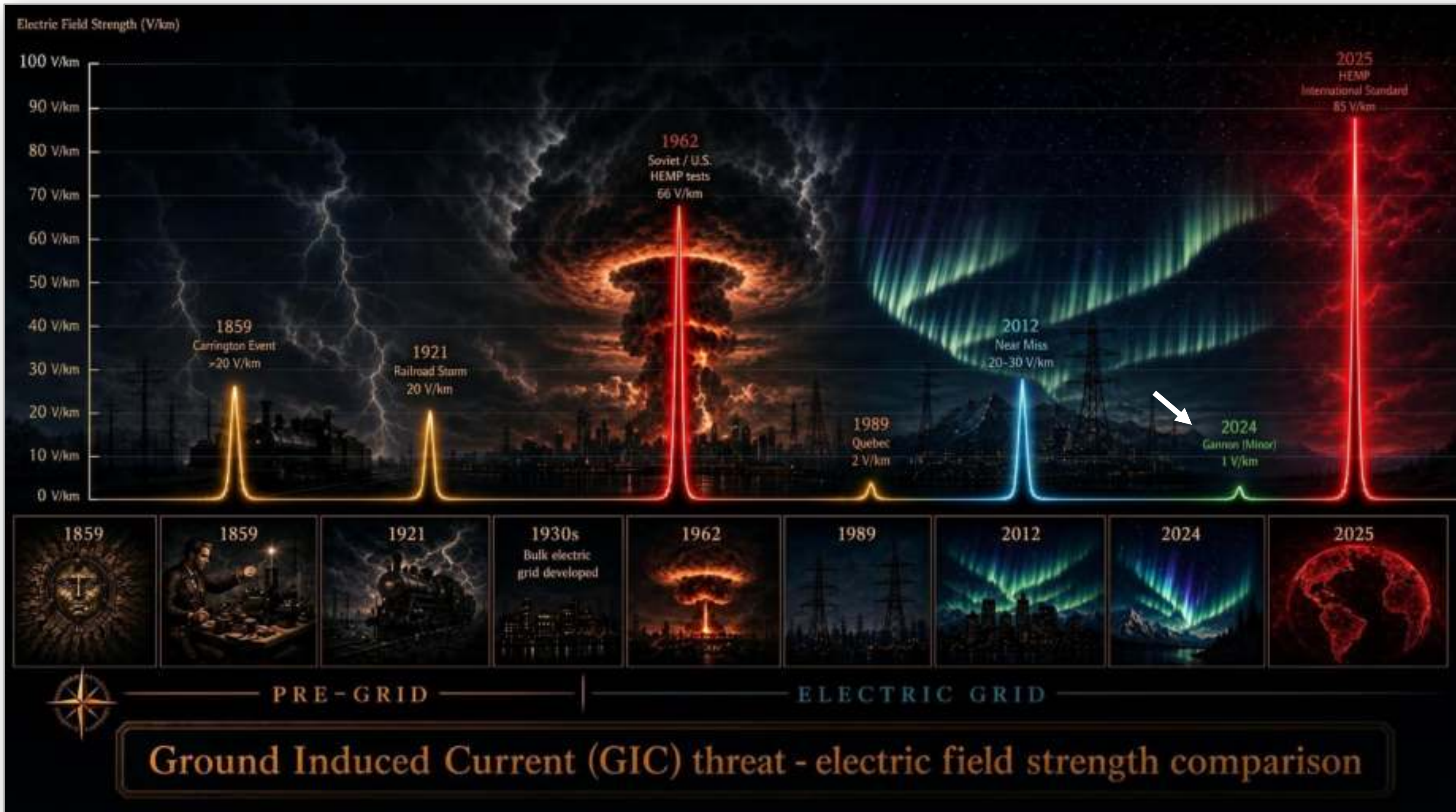
*"**Transformers will need E3/GMD protection.**"*

"neutral blocking device"

"High value quick fix:
Transformer protection is a low hanging fruit."

GIC grid protection hardware must be "Defense Conservative"

able to handle historic GIC events and threat levels of modern warfare.



Source: Secure the Grid Coalition

The industry has been consistent on capacitive GIC Neutral Blocking Devices (NBDs) as the solution for over 40 years

1983: "...capacitor in the neutral of transformers was determined to be the most effective and practical blocking device."
- "Mitigation of Geomagnetically Induced and DC Stray Currents", **Electric Power Research Institute,** EL-3295, Project 1770-1

1992: "...inserting blocking devices in the neutral...most logical and effective means of preventing GIC flow...capacitors is the best option."
-"Proceedings: Geomagnetically Induced Currents Conference" **Electric Power Research Institute,** TR-100450

2017: "Installation of blocking devices in the neutral to ground connection of transformers will significantly reduce the probability of damage from solar storms and ... EMP E3."
-Risk-Based National Infrastructure Protection Priorities for EMP and Solar Storms, **Report to the Commission to Assess the Threat to the United States from EMP Attack**, Baker, July 2017

2018: "Recommendations For Further Action...protect existing EHV transformers...neutral ground blockers..."
-**Electromagnetic Defense Force**, 2018 Report, Stuckenberg, Woolsey, DeMaio...

2019: "...capacitors in the neutral...effective means of blocking the flow of GIC..."
- "High-Altitude Electromagnetic Pulse and the Bulk Power System...Mitigation Strategies", **Electric Power Research Institute**, 3002014979, 2019

2023: "At present, most neutral grounding transformers of 220kV and above substations in China are mostly considered to install capacitor DC blocking devices"
-Research Summary on Transformer DC Magnetic Bias and Suppression Technology, **North China Electric Power University**, Zhou, Hui, Zhu, Xia, 2023

Neutral Resistors do not prevent GIC half-cycle saturation or harmonics

U.S. Department of Homeland Security

May 11, 2015

What can be done? (part 2)

- **Need to protect key power grid elements in USA and Canada**
  - **Over 2,000 Extra High Voltage (EHV) Transformers**
  - **Tens of thousands of other Large Power Transformers (over 100 MVAs)**
  - **About 6,000 power plants (100 nuclear reactors and large hydro plants are key)**
  - **About 50,000 electric substations in the USA**
  - **Experts have recommended protecting neutrals in LPTs from GICs**
    - Large resistors in neutrals could work but may increase problem for non-protected equipment and resistors don't effectively mitigate harmonics
    - Capacitors in the neutrals can protect equipment from both GICs and harmonics (appears to be a better solution than resistors)
    - Neutral disconnect switch during times of major storm (but leaves LPTs vulnerable to ground faults)
    - One hybrid solution, the Emprimus SolidGround™ neutral DC blocking system, has been tested and proved to be effective by the U.S. government

Utility Operating Procedures are <u>not</u> sufficient

Operating Procedures

- *Do **<u>not</u>** block **GIC** (**DC Current**) from entering an operating grid*
- *Do **<u>not</u>** prevent half-cycle saturation, do **<u>not</u>** prevent harmonics, do **<u>not</u>** prevent VAR losses or GIC heating and aging of transformers*
- ***Decreasing load** on vulnerable transformers **<u>increases risk</u> to HV Circuit Breakers** (GIC bias)*
- *Susceptible to human error – likely **<u>no warning</u>** prior to an **E3 HEMP attack***
- ***VAR Supply** is vulnerable to harmonics and is a **dangerous approach** during severe GIC events exposing critical grid equipment to **<u>severe GIC</u>** and **<u>harmonics</u>** over a **<u>longer period of time</u>***
- *Harmonics from low-level GIC events currently cause **<u>$Billion(s) in economic loss each year</u>***

Vs.

Capacitive GIC Blockers

- ✓ *Protect the electric power grid: **block GIC**, prevent half-cycle saturation, **<u>prevent harmonics</u>**, prevent VAR losses*
- ✓ *Provide Grid Operators with **reliable operation of HV Circuit Breakers** without severe GIC and harmonic currents across them*
- ✓ ***Automatic:** Operate in milliseconds when **GIC** or **E1** is detected. **Not** susceptible to human operational error or delays during an event*
- ✓ ***Reduce risk of voltage collapse** (**blackouts**) Decrease VAR consumption allowing utilities to safely **operate through** large Carrington level events with less exposure to GIC and harmonics*
- ✓ ***Perfect track record** over 10+ years blocking GIC from low-level GMD events. **No negative effects** to the power system*

It is critical to <u>block GIC</u> from entering the AC power grid

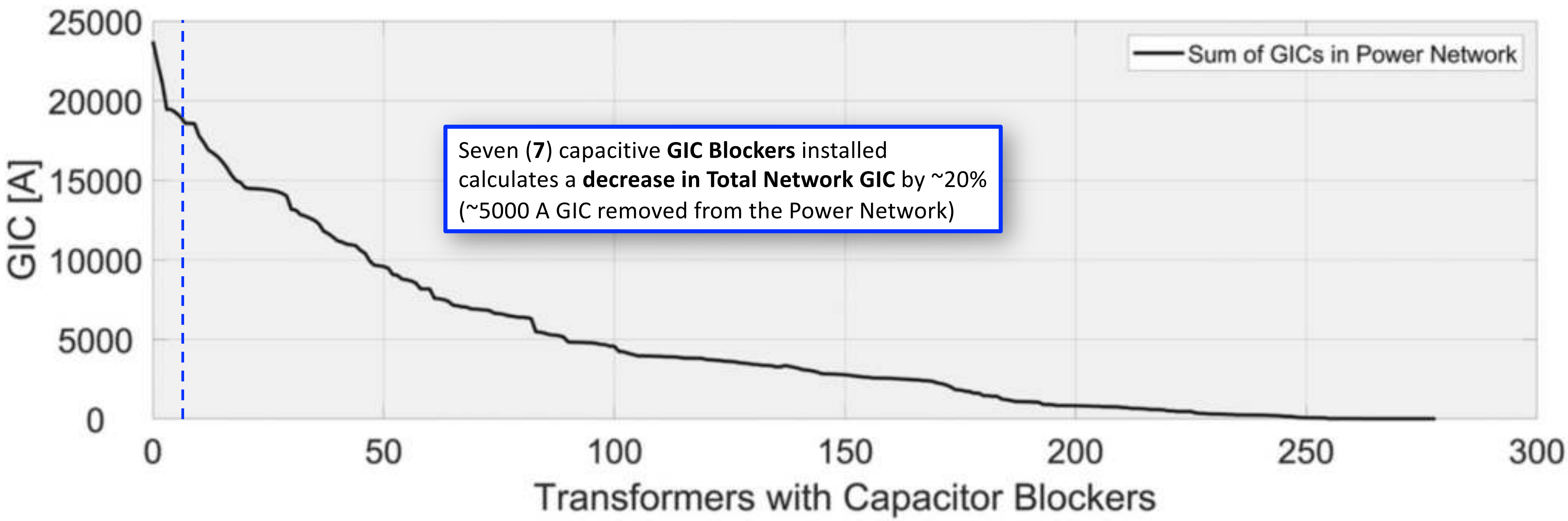
Capacitive GIC Neutral Blocking Devices have been designed in collaboration with the industry: **ATC**, **DOE**, **WAPA**, **TVA** and **EPRI**

High voltage circuit breakers are designed to break AC and can be catastrophically damaged in the arcing chamber when attempting to open with high GIC + harmonic currents across them. Damaged breakers = long term blackouts.
GIC blockers are designed to break extreme levels of GIC *without interrupting AC power* (**no load flows through device**).

It is clear from the size, cost, lead time and custom nature of these large power transformers that a “spare transformer program” is not an efficient or permanent solution. **Critical infrastructure should be protected with commercially proven hardware.**

First capacitive GIC blockers installed provide the greatest benefit

Not all GIC contribution points are equal. Prioritized installation of GIC blockers at the largest GIC entry points provides the greatest decrease in Network GIC (plug the largest "leaks" in the ship first).



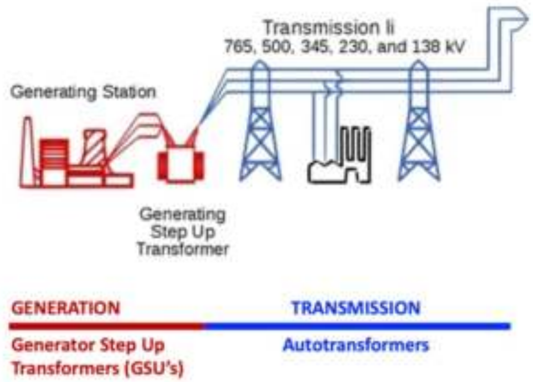
GIC in the New Zealand power network for the October 2003 ROGERS extreme storm scenario

D.H. Mac Manus, C.J. Rodger, A. Renton, J. Ronald, D. Harper, C. Taylor, M. Dalzell, T. Divett, and M.A. Clilverd, 2023, Geomagnetically Induced Current Mitigation in New Zealand: Operational Mitigation Method Development With Industry Input, *Space Weather*, 10.1029/2023SW003533

GIC is always traveling its preferred path (least resistance). When the GIC Blocker removes that path, GIC must travel a higher resistance path = **Network GIC decreases** as shown in modeling and verified in field measurements.

GIC induced Harmonics in transformers at the Generation/Transmission level – propagate and amplify as they travel into lower voltage Distribution

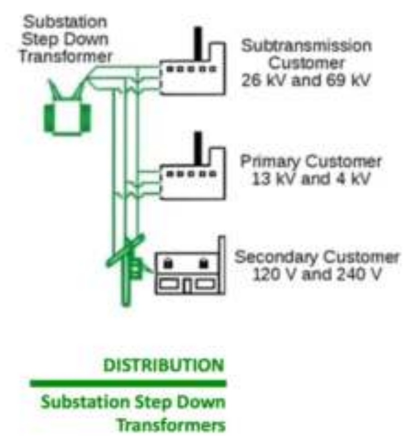
1st Priority to protect



Highest GIC Risk to the <u>entire</u> Power Grid

- Critical Infrastructure ("backbone of the power grid")
- Largest equipment (expensive, long lead times)
- Longer lines (greater voltage difference = higher GIC)
- Thicker lines (lower resistance = higher GIC)
- HV Circuit Breakers (vulnerable to harmonics and GIC bias)
- Large power generators (vulnerable to harmonics)

~6,000 large power transformers identified as "highest-risk" – generate harmonics with low-levels of GIC (5 Amps per Phase <u>or less</u>)



GIC blockers installed on High Voltage Transformers improves resilience at the Lower Voltage Distribution level

- **Low levels of GIC** at the Generation/Transmission level **saturate high voltage transformers** which **inject harmonics** into the grid that **propagate** and are **amplified by Step-Down transformers** as they step the voltage down for Distribution.
- **Step-Down Transformers with a wye grounded high voltage side should *also* be protected (Data Centers)**

2012 DTRA/INL Live Grid Tests – E1 filters make the GIC induced harmonic threat worse:

"When we do these [GIC] injection tests – the ***harmonics****... were about* ***50% higher with the EMP filter*** *in the circuit than they were without that filter in the circuit."*

"So now we've got a ***filter*** *designed to protect against one challenge [****E1 Pulse****] that* ***exacerbates the problem due to geomagnetic disturbances****."*

-**Dupont Summit:** Mitigating High Impact Threats to Critical Infrastructure, December 6, 2013
Scott McBride, Infrastructure Security Manager, National & Homeland Security, **Idaho National Laboratory**

Note: These HEMP filters are currently installed at many Data Centers, Call Centers, Critical DOD Mission Facilities, Hospitals and other critical loads.

GIC Protection should be addressed *prior to* E1 protection

U.S. Senate Committee on Homeland Security & Governmental Affairs

September 13, 2018

"...there must be a priority to protect the most critical large power transformers in place ... estimates are that this would cost less than **$4 billion if we made it a priority to install NBD's [neutral blocking devices]** at our most critical EHV substations..."

Idaho National Laboratory

Testimony of Scott McBride, Infrastructure Security Manager, National & Homeland Security, **Idaho National Laboratory**

Critical EMP Protection begins with commercially proven GIC Blocking Devices

Threat:	Probability:	Solution:	Cost:
Solar Storms (**GMD**)	**100%**, naturally occur, est. **~$10 billion in U.S. losses <u>each year</u>** (Zurich) Catastrophic event: est. **12% chance/decade** est. **$0.6 - 2.6 trillion in U.S. losses** (Lloyd's)	**Capacitive GIC Neutral Blocking Devices (NBDs)** Ground Induced Currents (**GIC**) *and* the induced **<u>harmonics:</u>** specifically **threaten the largest and most critical equipment** on the grid - transformers, circuit breakers, generators, data centers **Standardized, Proven**: Designed in conjunction with the utility industry and validated by ATC, ABB, DOE, INL, DTRA, ORNL, EPRI, TVA, WAPA…  **Blocks GIC <u>at the point of entry</u>**: preventing harmonics, transformer saturation, VAR losses, aging and thermal damage.	est. **$4 Billion** Protects the ~6,000 largest and "highest-risk" large power transformers on the U.S. grid **Protects the rest of the power grid <u>*from*</u> those transformers:** preventing them from generating harmonics *(est. $10 billion annual loss U.S.*) and consuming reactive power (*grid collapse*) Little to no maintenance costs in 10+ years of operating history on the U.S. grid
HEMP **E3** Pulse	unpredictable, intentional, strategic man-made		
HEMP **E2** Pulse	unpredictable, intentional, strategic man-made	Surge Arresters: existing surge arresters already installed on transformers for lightning protection, can protect against E2. **Note:** E2 Solutions will **<u>not</u>** protect grid against GMD or HEMP E3	NA
HEMP **E1** Pulse	unpredictable, intentional, strategic man-made	Faraday cage, waveguides, MOVs, grounding, power and signal line filters: to protect small vulnerable electronics **2012 INL/DTRA Tests - E1 filters exacerbate <u>harmonics</u> by 50%:** E1 filters increase grid vulnerability to GIC induced harmonics from GMD & EMP E3. ➡ Critical to install **NBD**s *prior to* E1 protection **Note:** E1 solutions will **<u>not</u>** protect grid against GMD or HEMP E3	est. **> $250 Billion** Protects portions of the grid **$billion(s)** ongoing annual maintenance costs