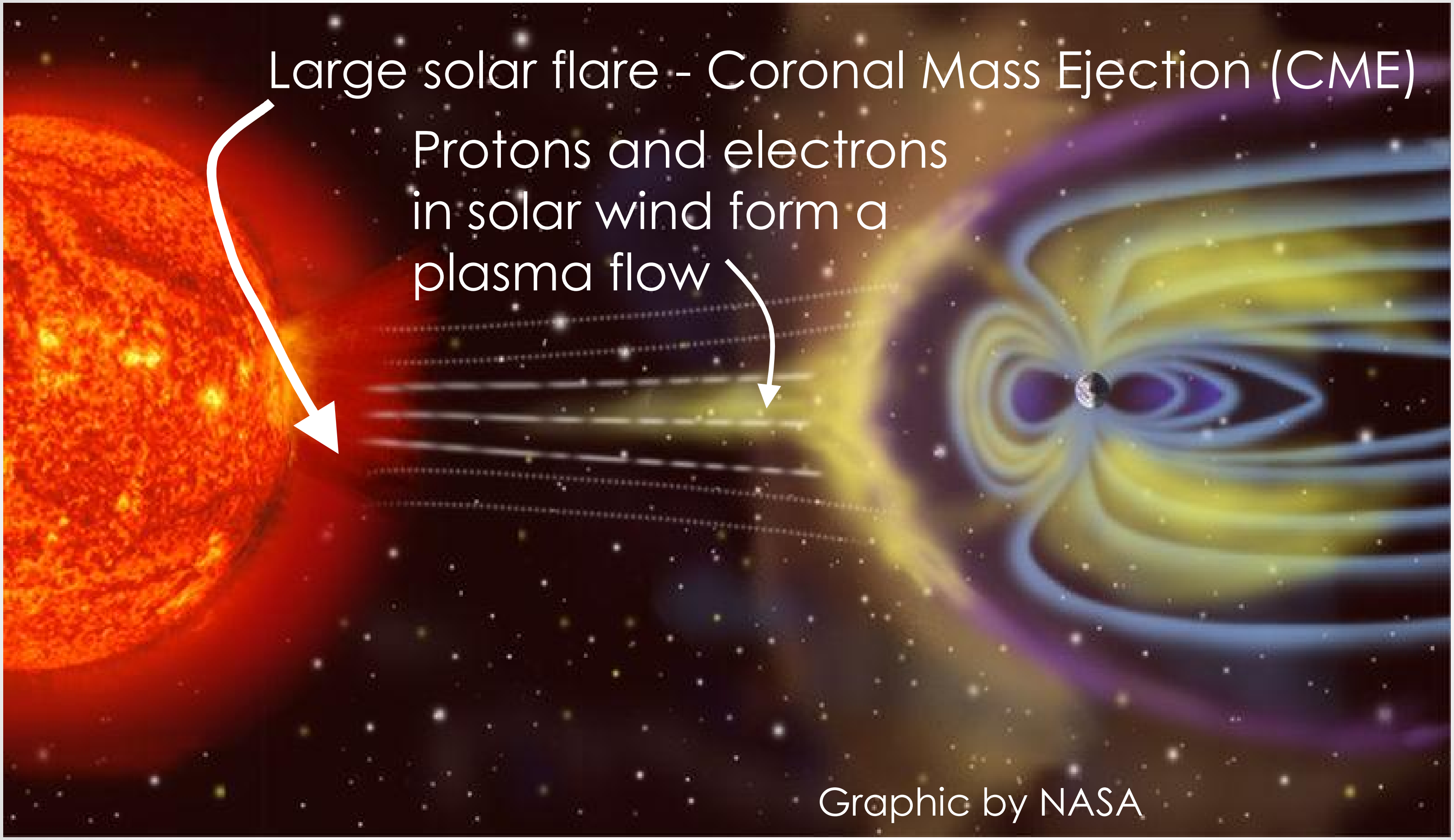
Walling Energy Systems Consulting, LLC

GMD Impacts on Generators

Reigh Walling

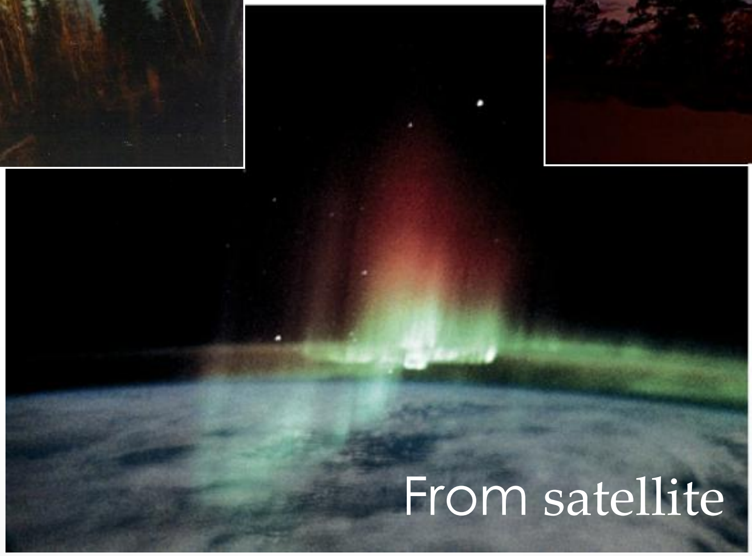
CME interacts with earth magnetic field



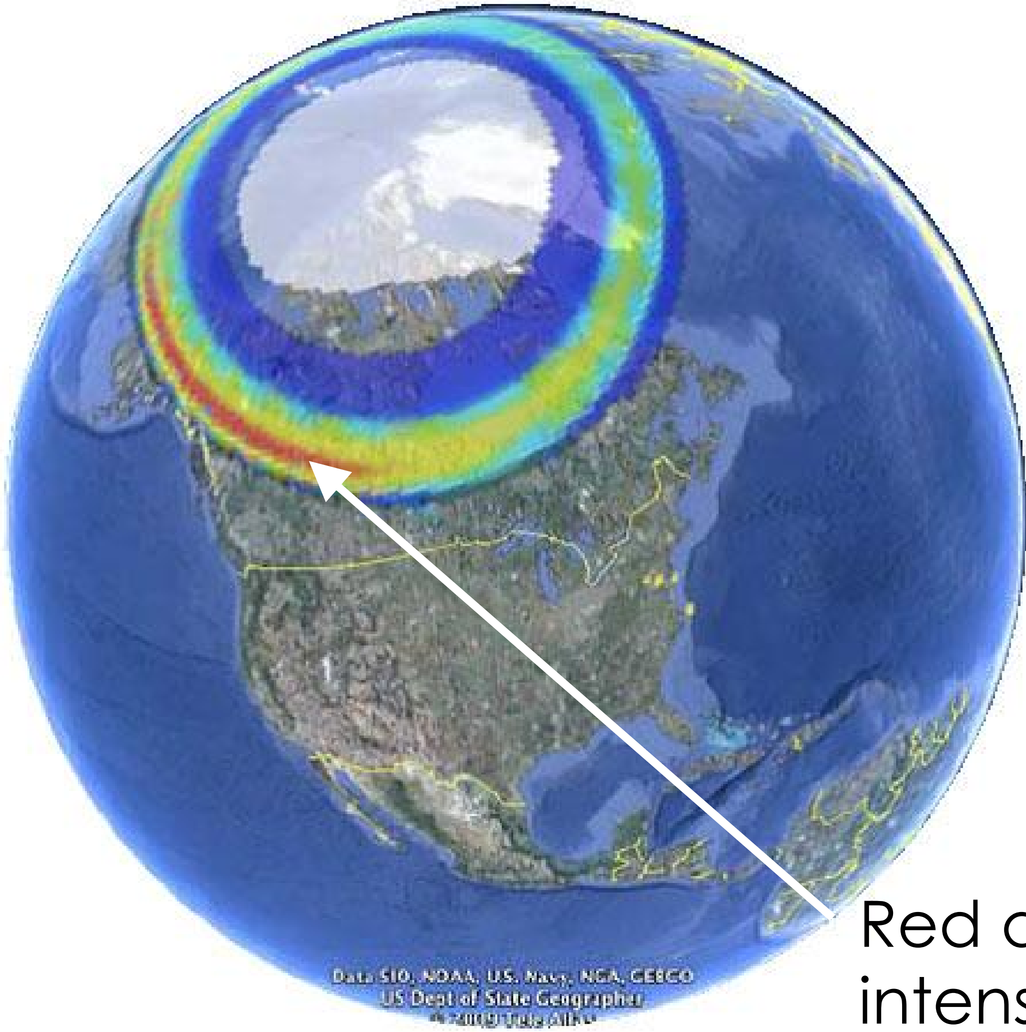
Auroras are the result of this interaction

Aurora Borealis in the northern hemisphere

Aurora Australis in the southern hemisphere



Aurora during "modest" solar wind conditions

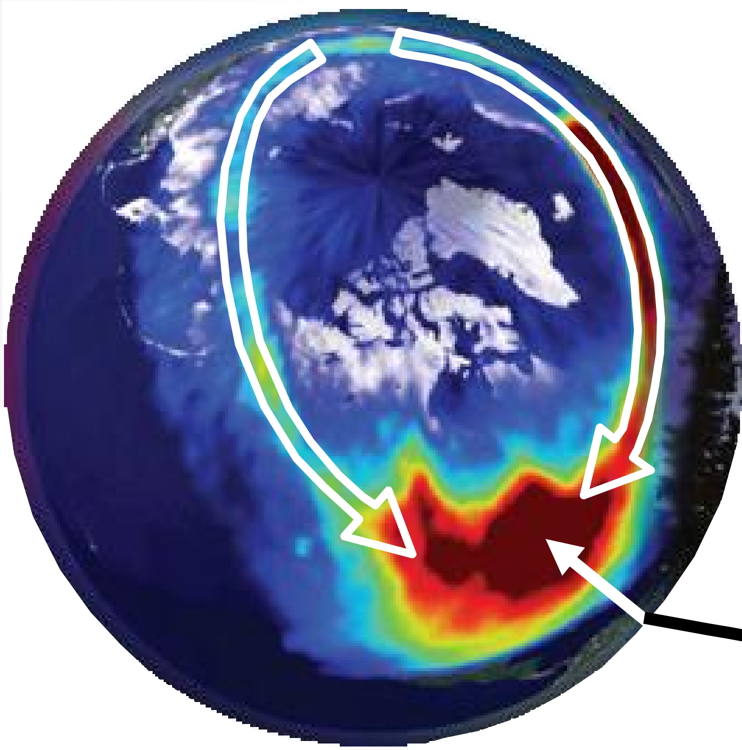


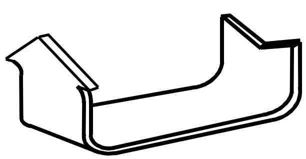
Typically, the northern *auroral oval* covers only higher latitudes of North America

Red area indicates greatest intensity of the aurora

When solar wind is disturbed, the northern auroral oval is deflected southward on the night side of earth, causing intense auroral displays even at low latitudes

Napa Valley, CA

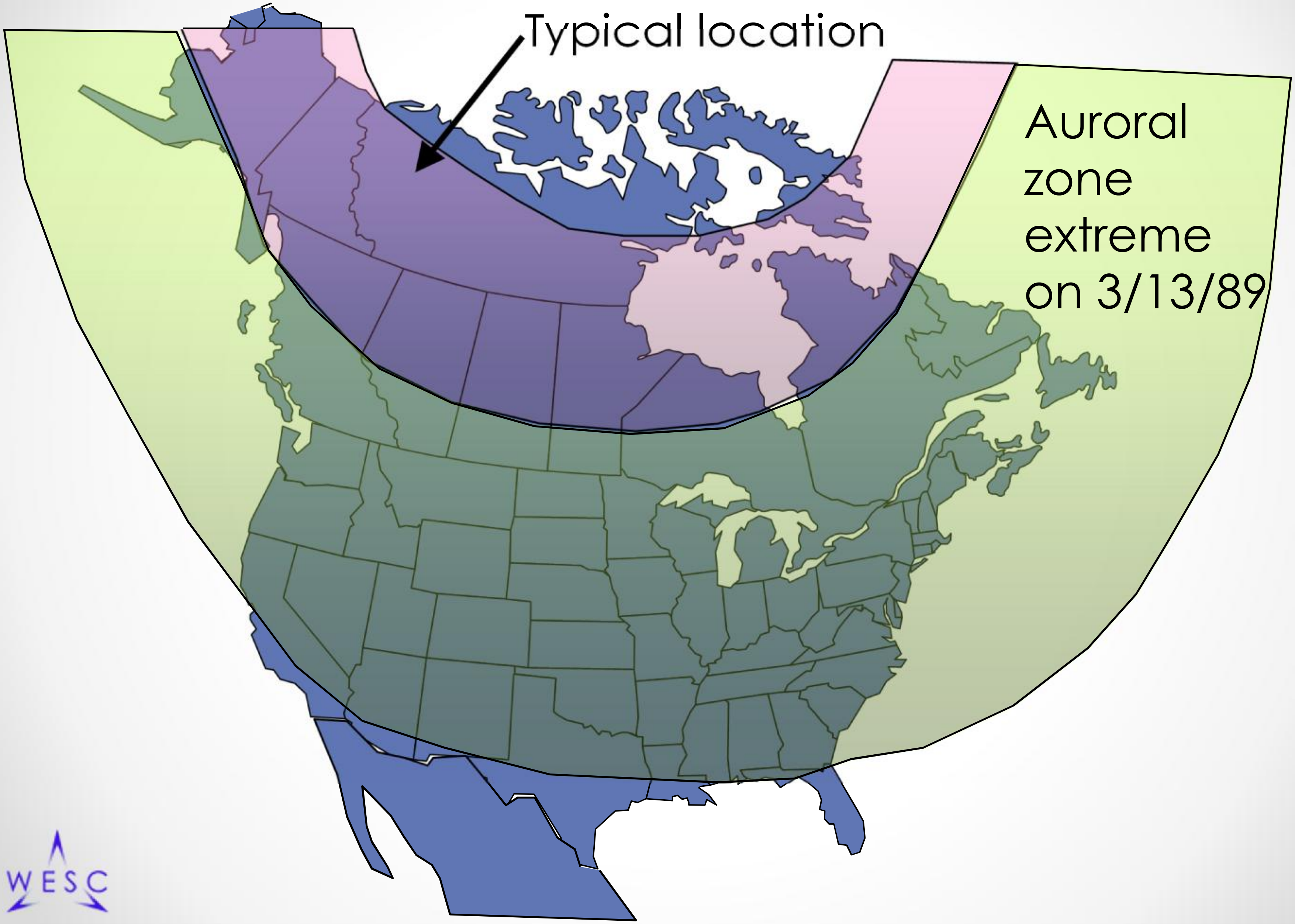




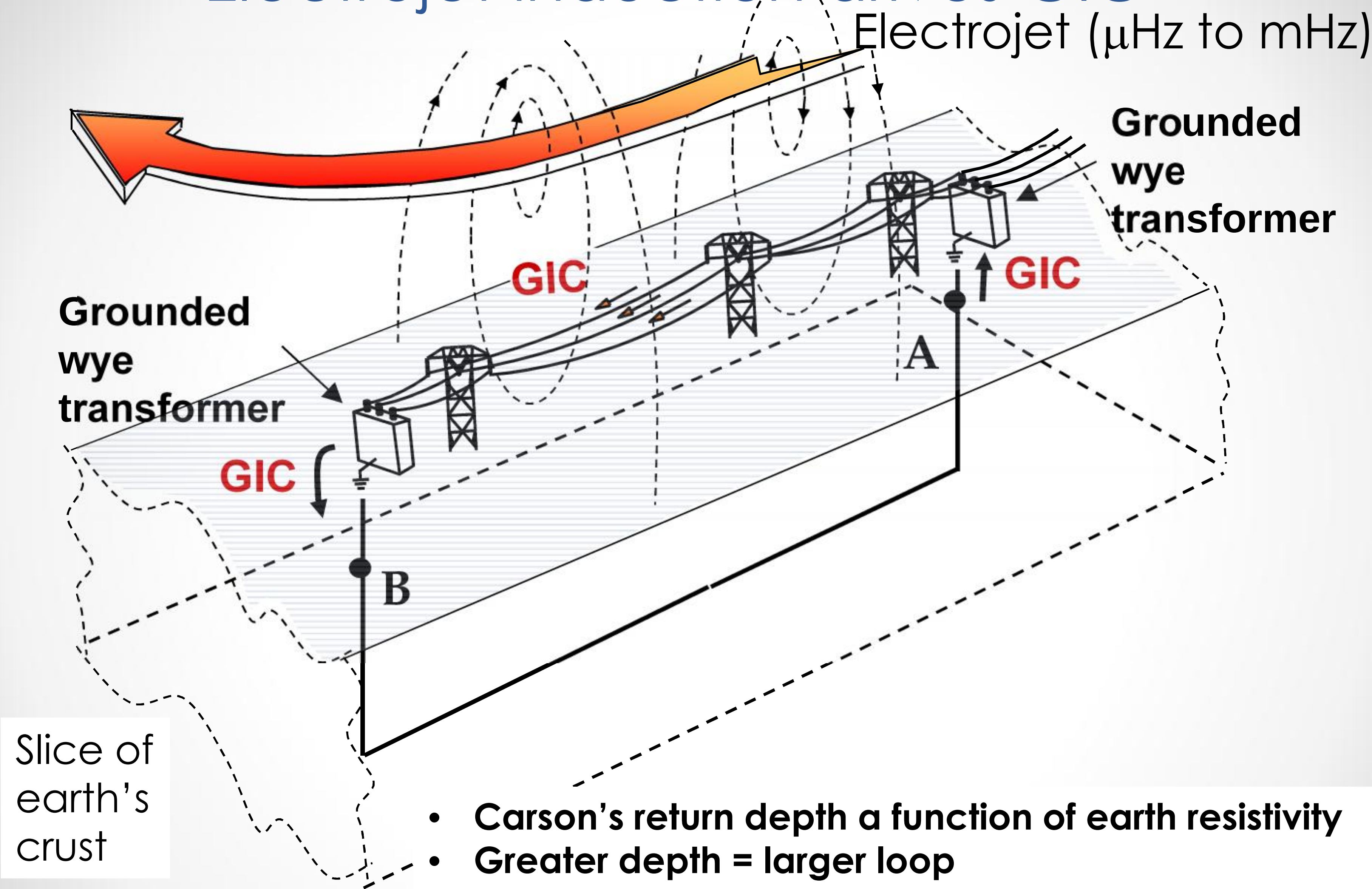
Ionospheric electrojets dip into low levels of the Ionosphere

Area of auroral sub-storms

Auroral zone expansion on March 13, 1989



Electrojet induction drives GIC



- Carson's return depth a function of earth resistivity
- Greater depth = larger loop
- Larger loop captures more induction

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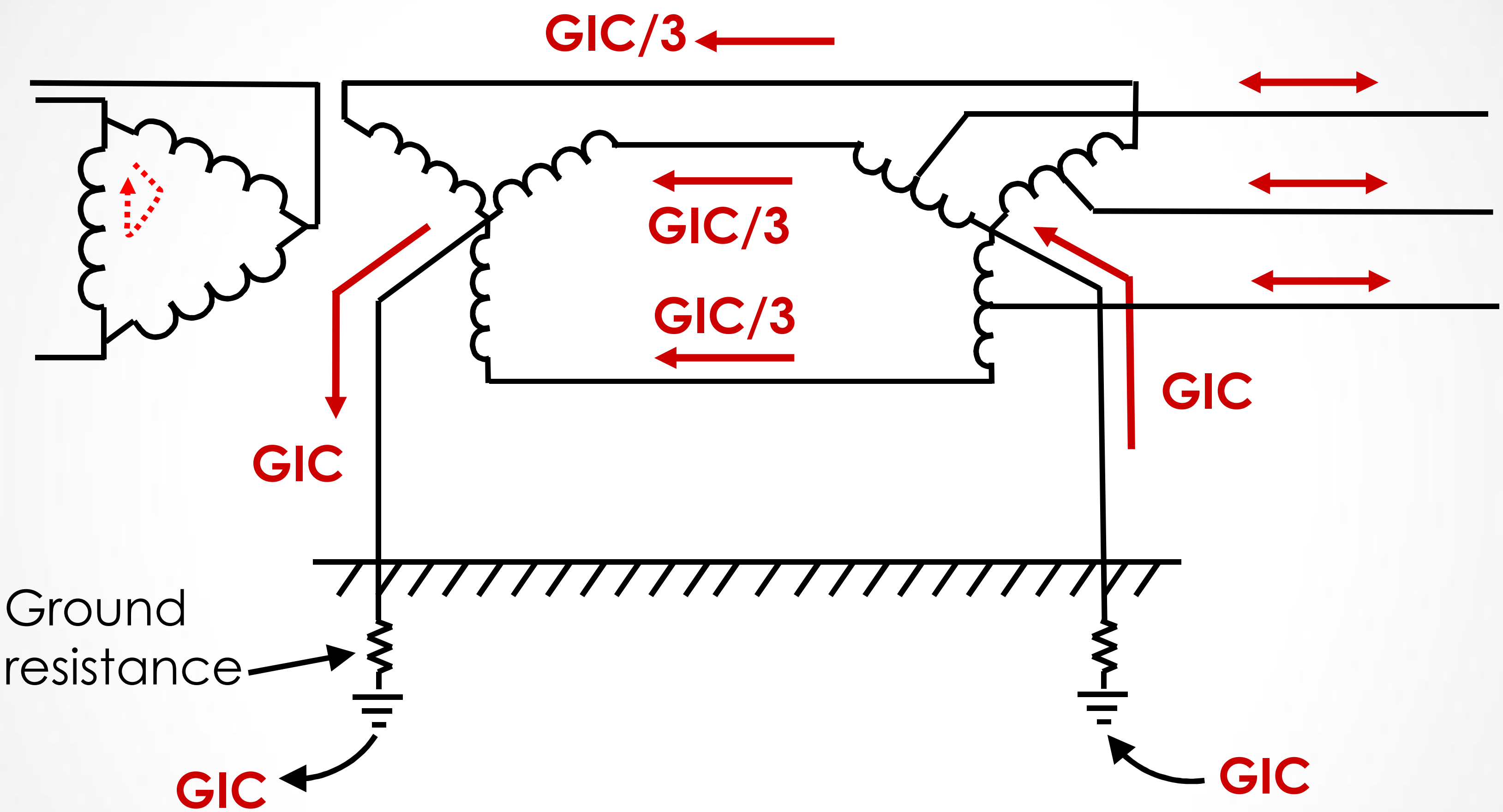
GIC Flow



- To/from ground via grounded-wye transformers
- Between voltage levels via autotransformer series windings

System Impacts During GMD

- Transformer heating – damage potential?
- Increase in reactive demand – potential for voltage collapse
- Protective relay system issues – false trips, failure to trip
- Loss of capacitor banks – protection issues and true overload
- Interactions with power-electronic systems – SVC, HVDC
- **Generator rotor heating** – are generators protected?

Generator Impact

- GIC does not flow through generator
    - o Isolated by the GSU transformer delta winding
- Predominate impact is rotor heating due to harmonic current flow into the stator
    - o Harmonic currents in stator create rotating magnetic fields that are not at synchronous speed
    - o Sources of harmonic current are transformers saturated by GIC
- Harmonic rotor heating might be aggravated by heavy reactive demand
- Possible stimulus of vibrations

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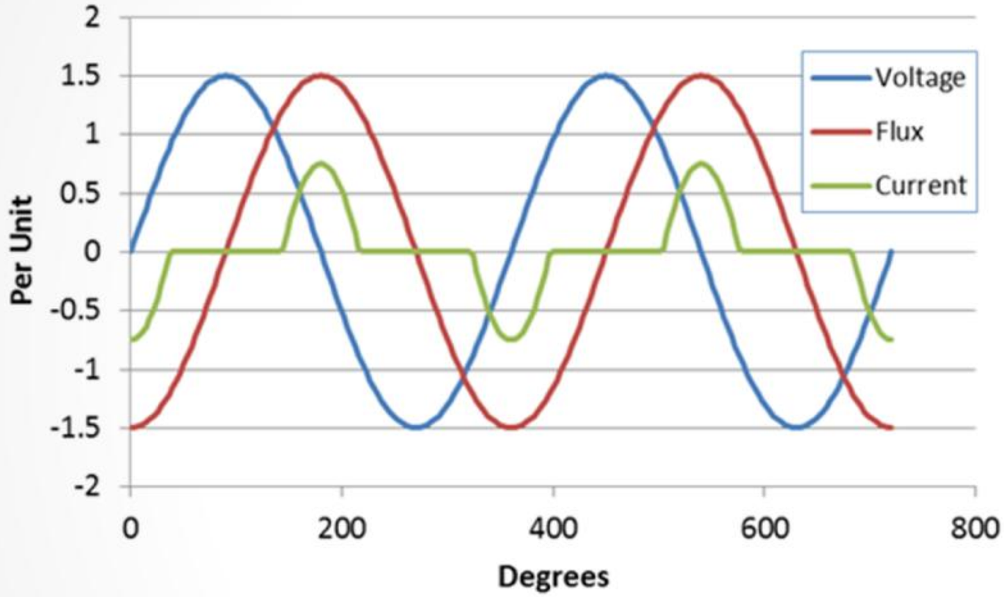
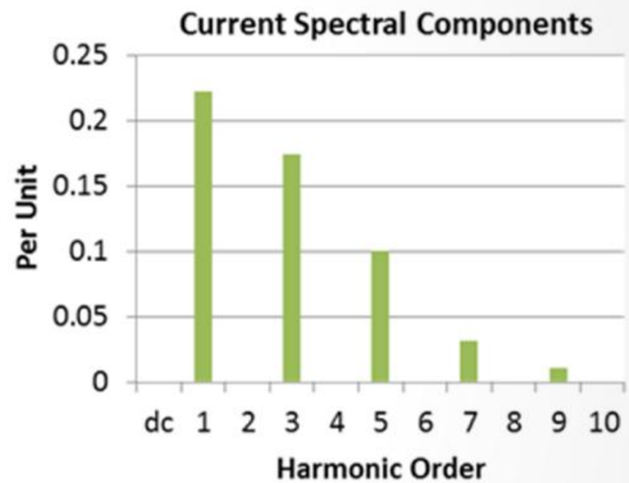
Fundamentals of Offset Saturation

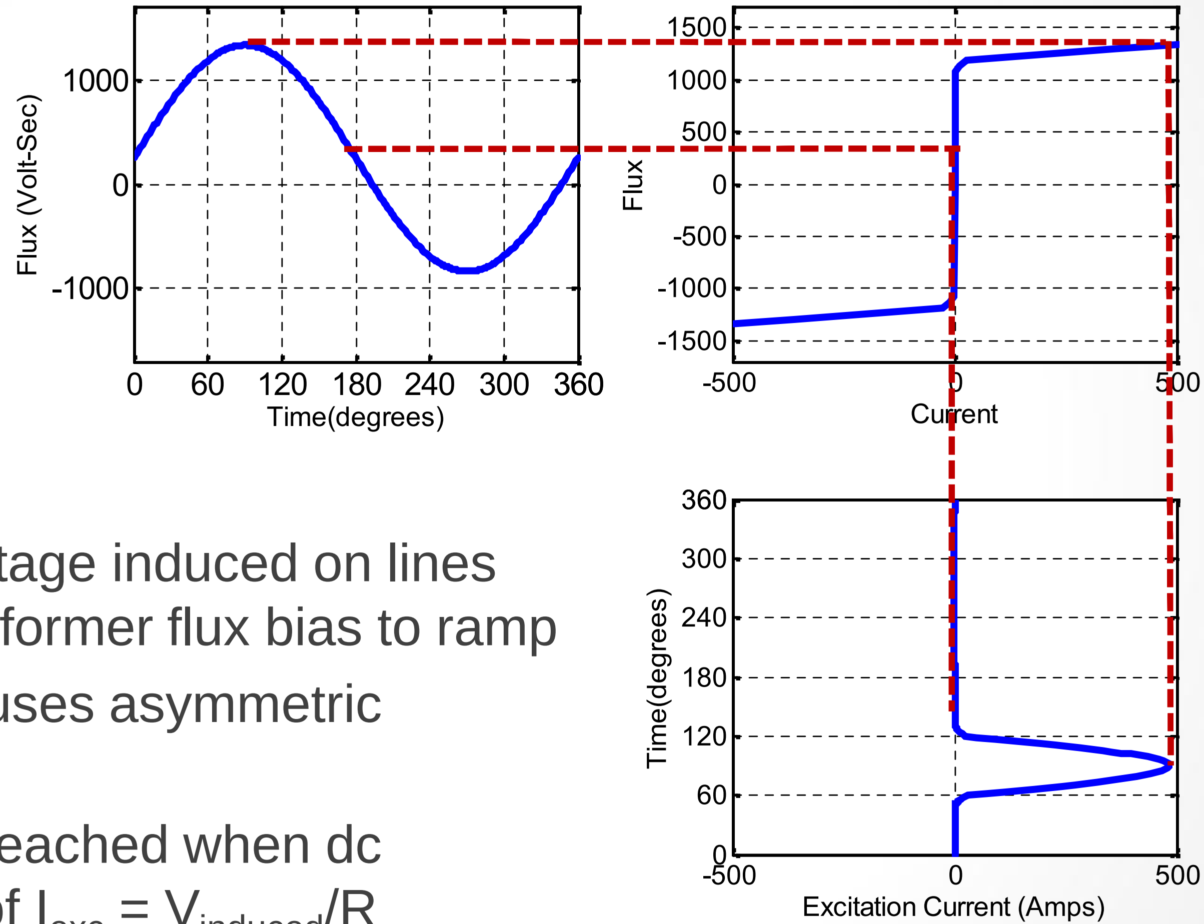
Symmetrical Saturation





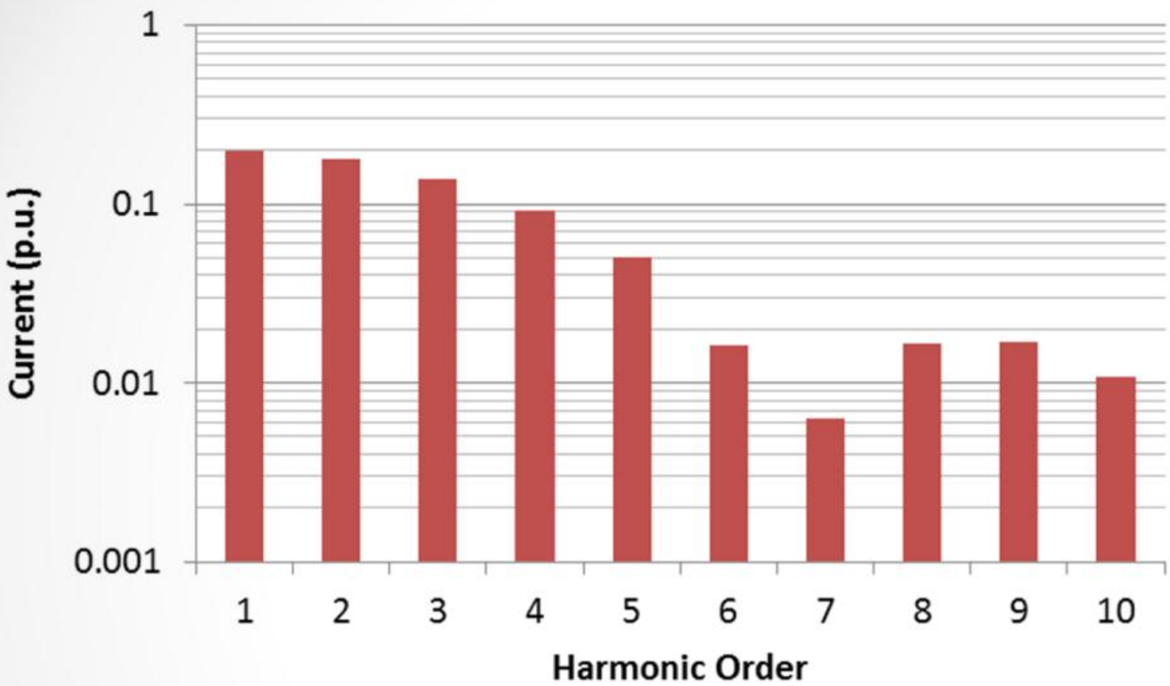
- Symmetric exciting current pulses
- Exclusively odd-order harmonic components

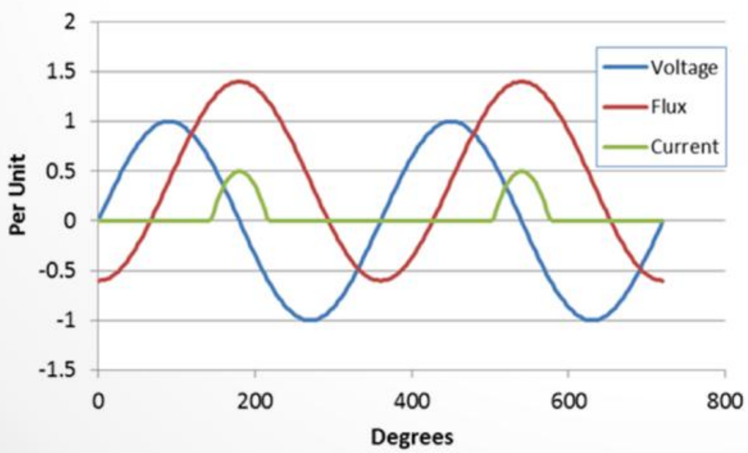
Flux Offset



- Quasi-dc voltage induced on lines causes transformer flux bias to ramp
- Flux bias causes asymmetric saturation
- Equilibrium reached when dc component of $I_{exc} = V_{induced}/R$

Exciting Current Spectral Components

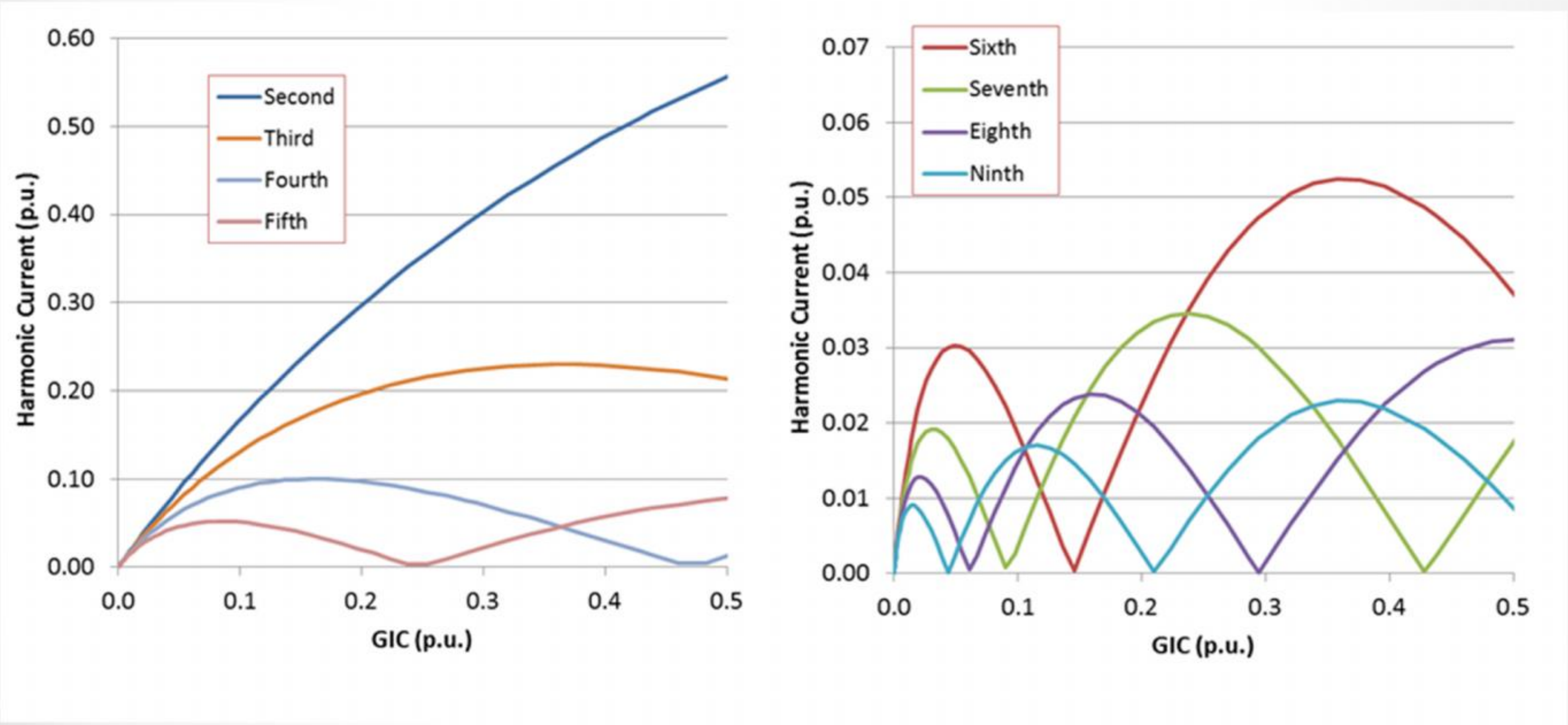




- Exciting current consists of components at all multiples of fundamental frequency
- i.e., odd and even harmonics are produced

Harmonic Components vs. GIC

Bank of Single-Phase Transformers



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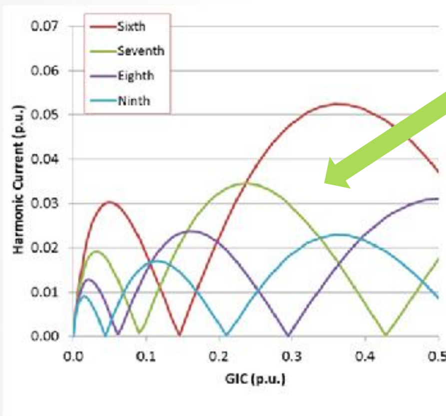
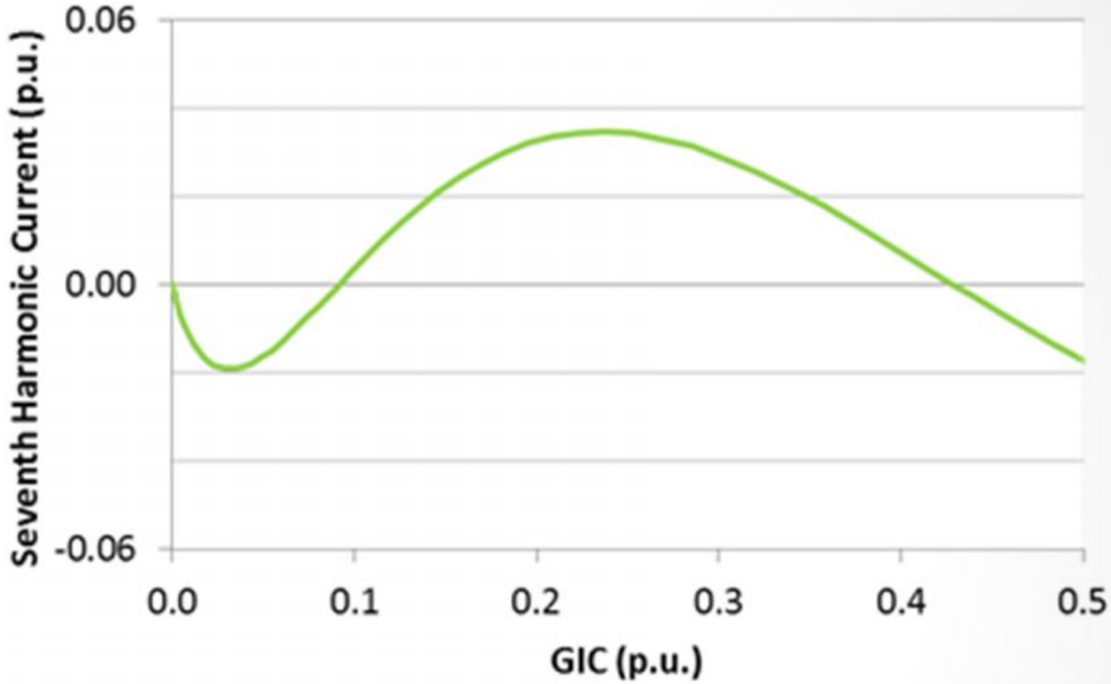
Harmonic Magnitude Reversals





- “Beating” of magnitude is actually magnitude reversals
- Reversals at shorter intervals of GIC with higher harmonics

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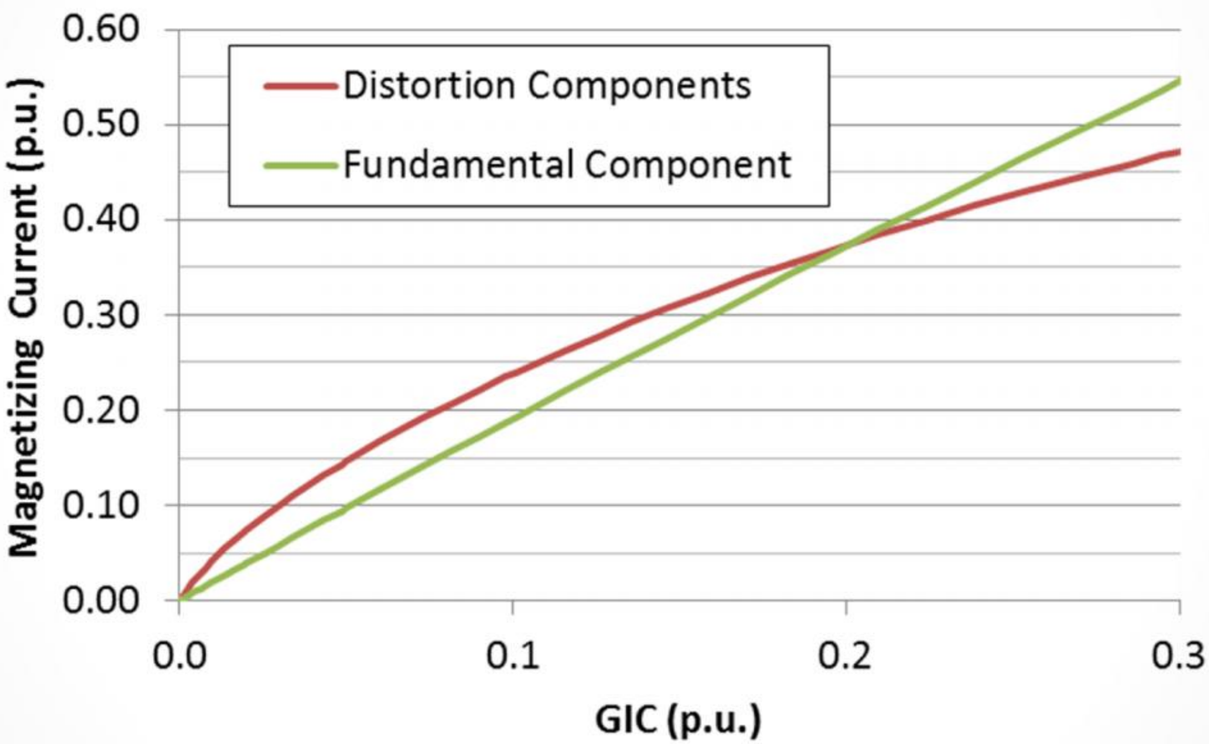
Comparison of Harmonics and Fundamental Components of I_{exc}



- System impedance generally increases with frequency
- $\therefore V_{THD} > \Delta V_{fundamental}$ in general

Unique Characteristics of GIC Harmonics

- Numerous <u>coherent</u> sources
- High harmonic current magnitudes
- All low orders are injected; even and odd
- Injections are both in the line modes (positive and negative sequences) and ground mode

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Coherent Sources

- Unlike typical transmission harmonic challenges, not a single-source problem
- All GIC-saturated transformers will simultaneously inject harmonic current, at dispersed locations
- Phase angle of injected harmonic current is directly related to fundamental phase voltage
    - Thus, sources are “coherent” with a defined, rather than random phase relationship
- Complex patterns of constructive and destructive superposition of currents and voltages
- Cannot be studied using ordinary tools and approaches

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Phasor Relationships of I_{exc} Components

- Polarity of odd harmonics are independent of GIC polarity
- Polarity of even harmonics reverse when GIC reverses
- Harmonic current phase angles, relative to an absolute reference, are shifted by *h* times the fundamental phase angle
  - Superposition of the multiple harmonic injections is significantly affected by the fundamental-frequency power flow
  - Fundamental voltage magnitude affects harmonic magnitudes
  - Fundamental voltage phase angle affects harmonic phase angles with increased sensitivity at increasing harmonic order
- Harmonic analysis needs to be coupled to loadflow

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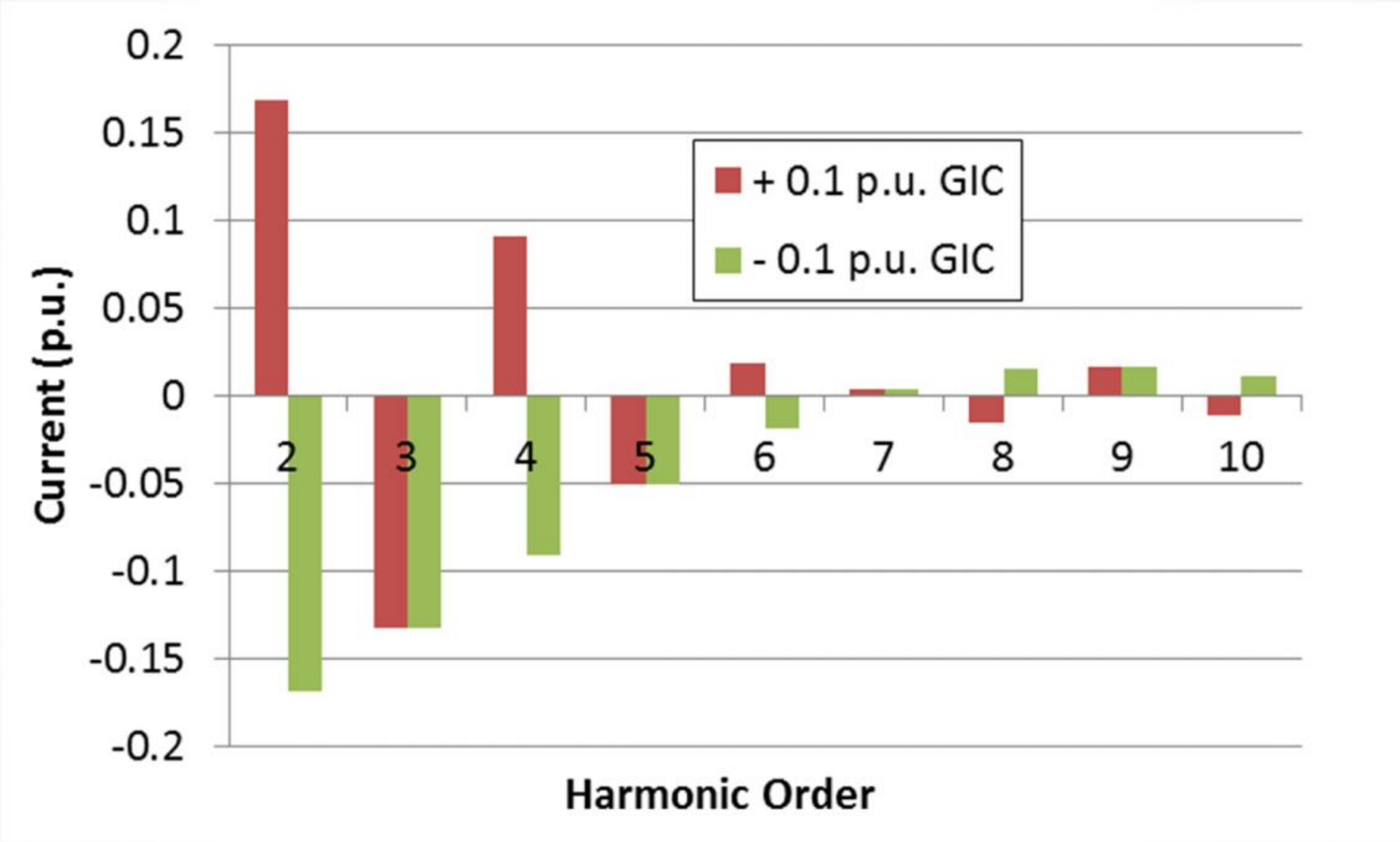
GIC Flow Direction Sensitivity



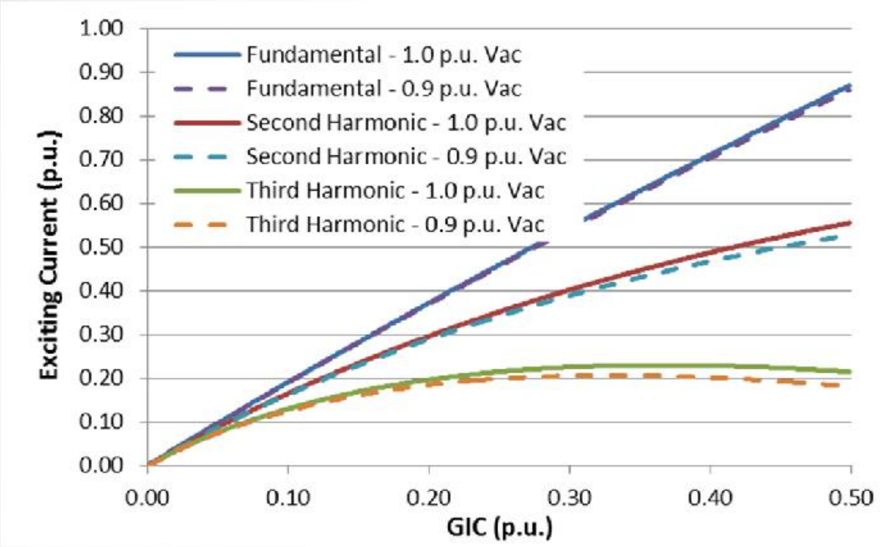
- Odd orders are invariant with GIC flow direction
- Even orders reverse with GIC flow reversal

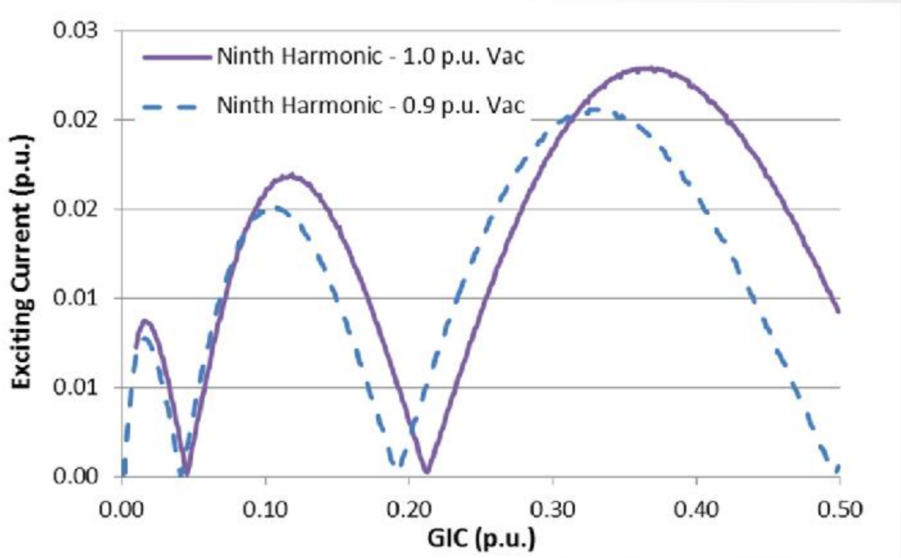
Fundamental Phase Angle Relationship

Order	$\lvert I_{exc} \rvert$	I_{exc} Component Phase Angles					
		$\angle V_{fund} = 0°$		$\angle V_{fund}=+10°$		$\angle V_{fund}=-10$	
		$I_{GIC}=+0.1$	$I_{GIC}=-0.1$	$I_{GIC}=+0.1$	$I_{GIC}=-0.1$	$I_{GIC}=+0.1$	$I_{GIC}=-0.1$
1	0.191	-90°	-90°	-80°	-80°	-100°	-100°
2	0.167	90°	-90°	110°	-70°	70°	-110°
3	0.131	-90°	-90°	-60°	-60°	-120°	-120°
4	0.09	90°	-90°	130°	-50°	50°	-130°
5	0.051	-90°	-90°	-40°	-40°	-140°	-140°
6	0.019	90°	-90°	150°	-30°	30°	-150°
7	0.004	90°	90°	160°	160°	20°	20°
8	0.015	-90°	90°	-10°	170°	-170°	10°
9	0.016	90°	90°	180°	180°	0°	0°
10	0.012	-90°	90°	10°	-170°	170°	-10°

Phase angle of harmonic component is shifted by $n \cdot \phi$ relative to an absolute reference

Fundamental Voltage Sensitivity





- Single-phase bank I_{exc} components are normalizable

$$I_n(I_{gic},V_{ac}) = V_{ac} \times I_n(I_{gic}/V_{ac},1.0)$$

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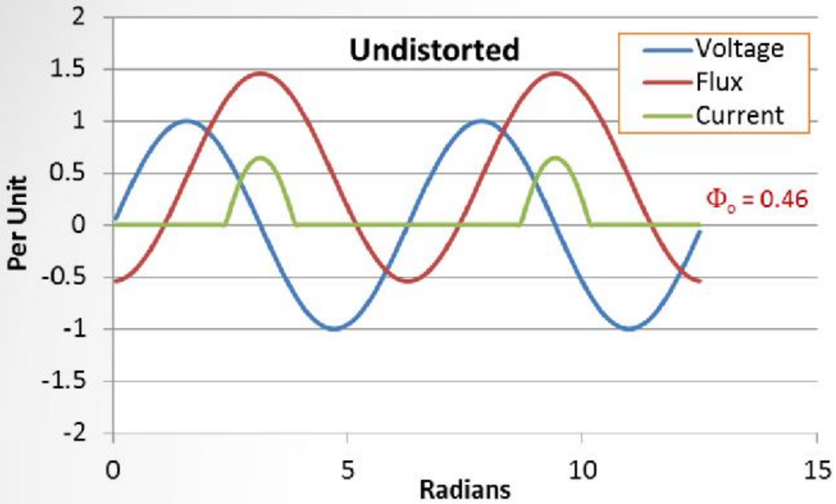
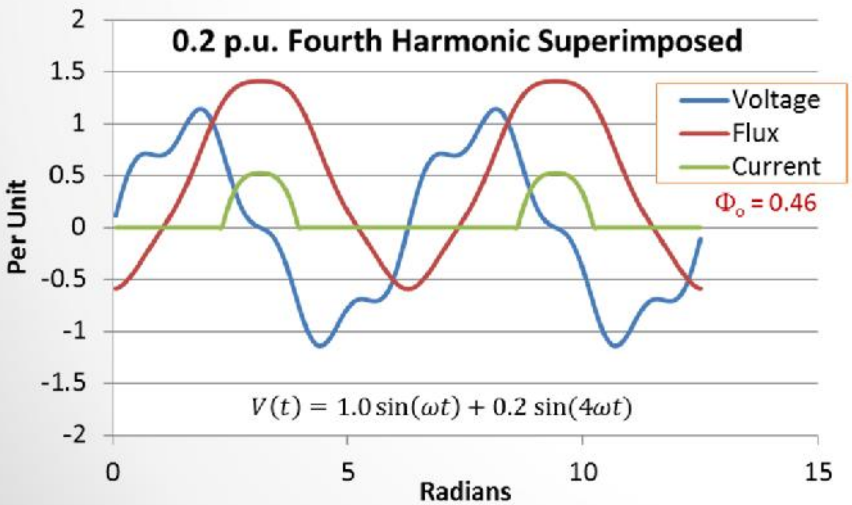
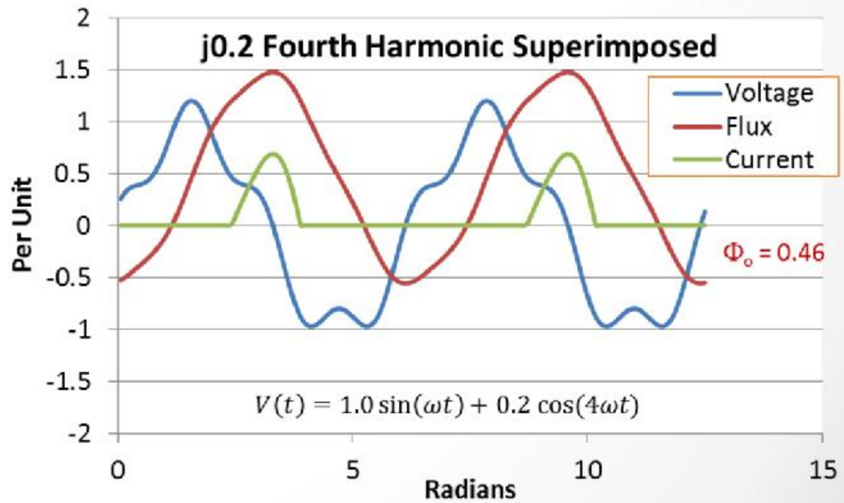
Impact of Voltage Distortion on I_{exc}



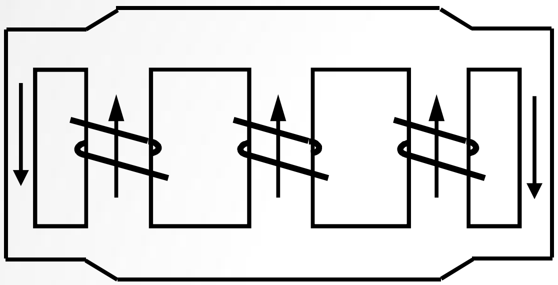
- Voltage distortion changes the shape and magnitude of the exciting current
- Relative phase angle of the distortion can substantially affect the character of the exciting current



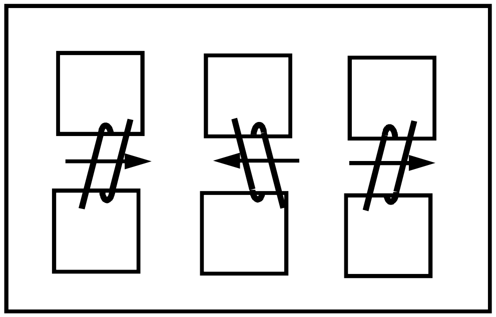


GIC Saturation of Three-Phase Transformers

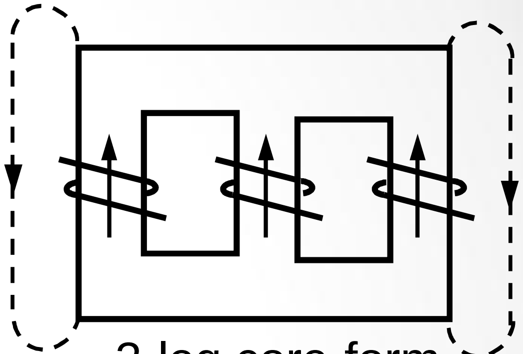
Three Phase Transformer Types



5-leg core-form



conventional shell form

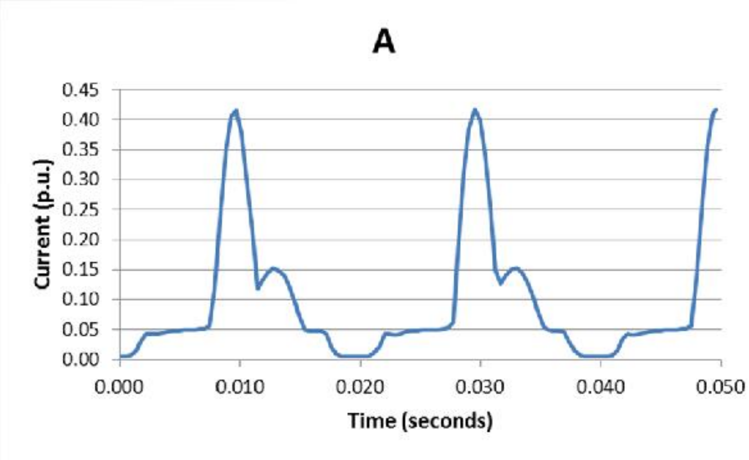


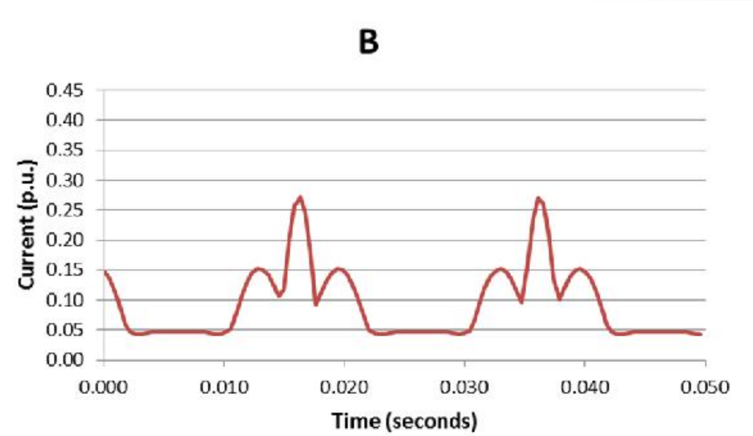
3-leg core-form

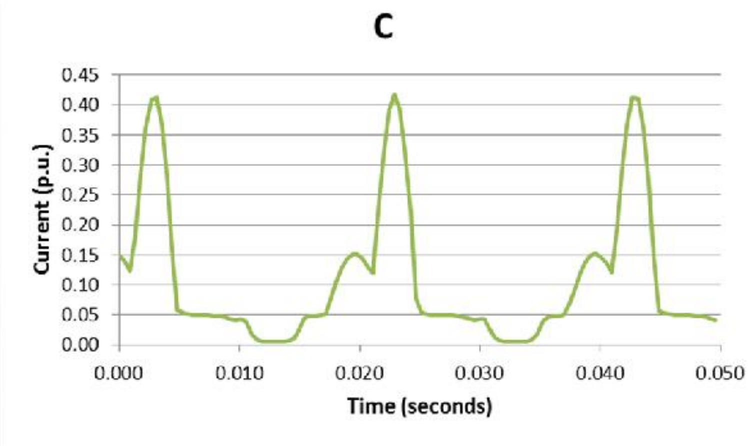
- Three-phase transformers have core limbs that are in the flux paths of multiple phases
- Non-linear phase coupling complicates GIC saturation behavior
- GIC results in different flux offsets and different I_{exc} waveshapes in the outer and inner phases

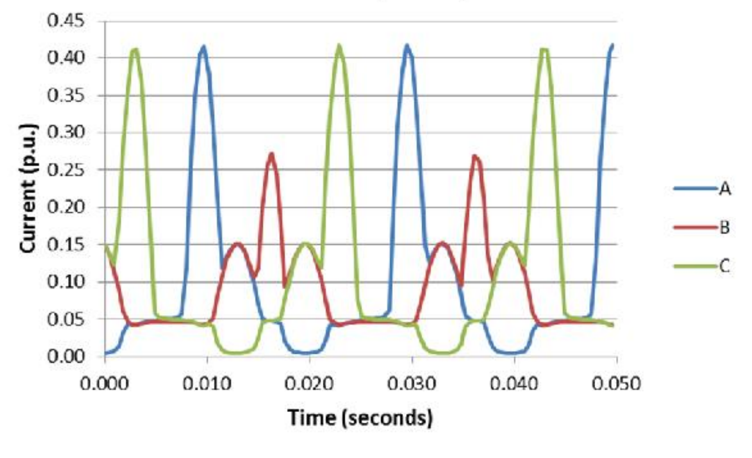
I_{exc} Waveforms for 5-Leg Core Form

At 0.1 p.u. GIC



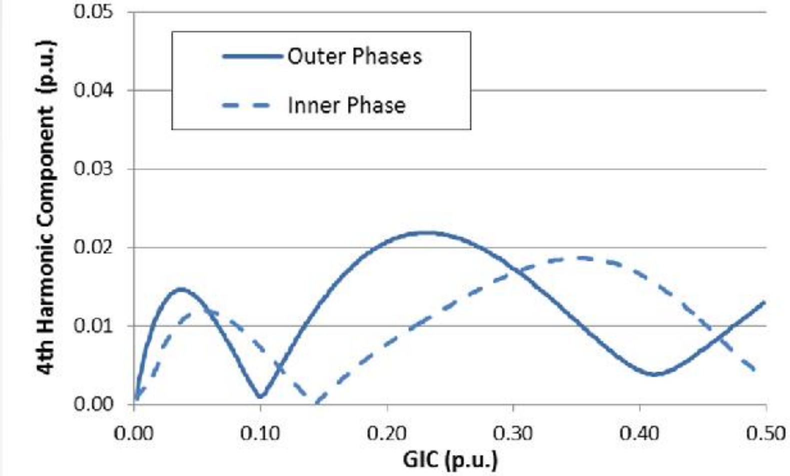




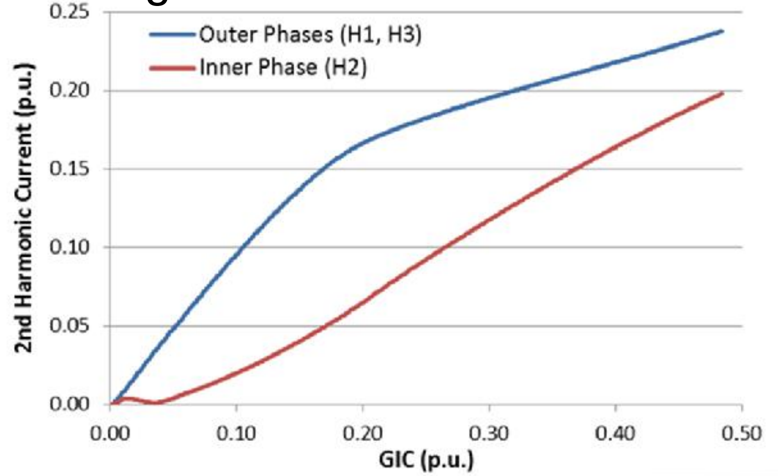


Unbalanced I_{exc} Harmonic Components

Shell Form – 4th Harmonic



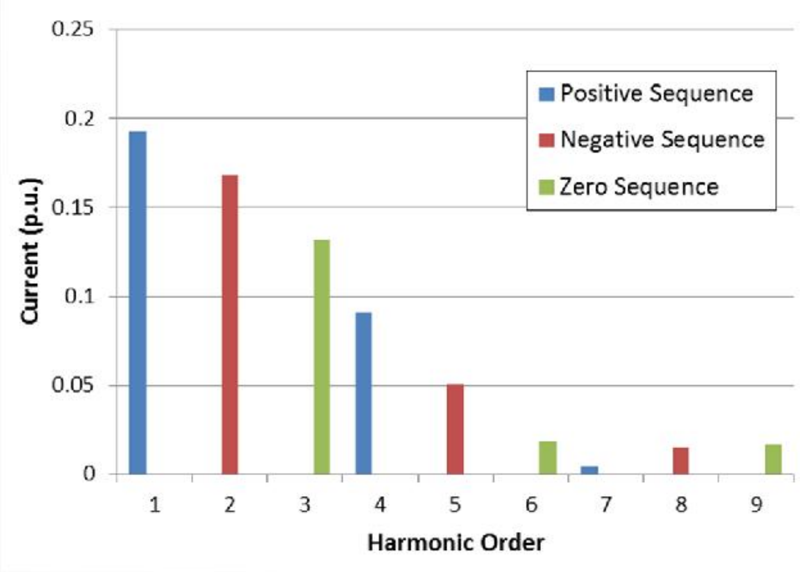
5-Leg Core Form – 2nd Harmonic



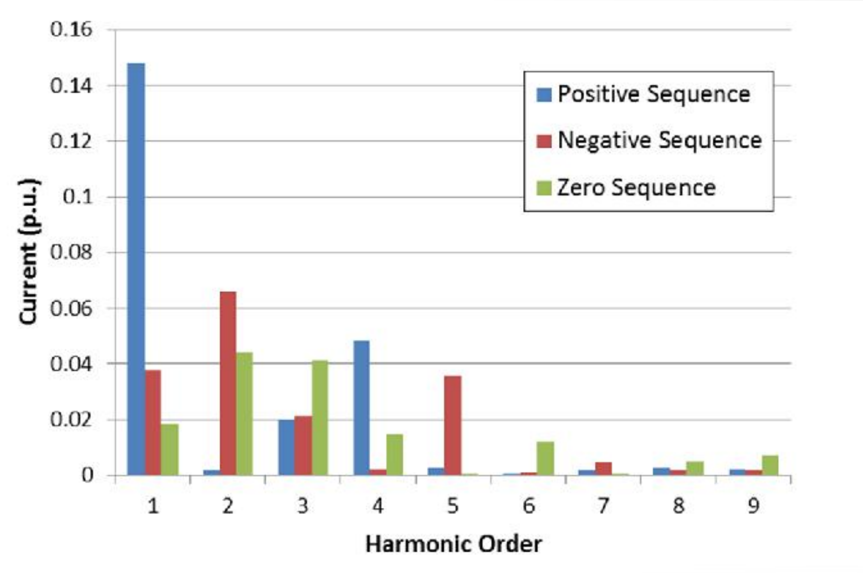
- Imbalance causes harmonic sequence components to not follow “textbook” pattern

Harmonic Sequence Components

Bank of Single Phase Xfmrs



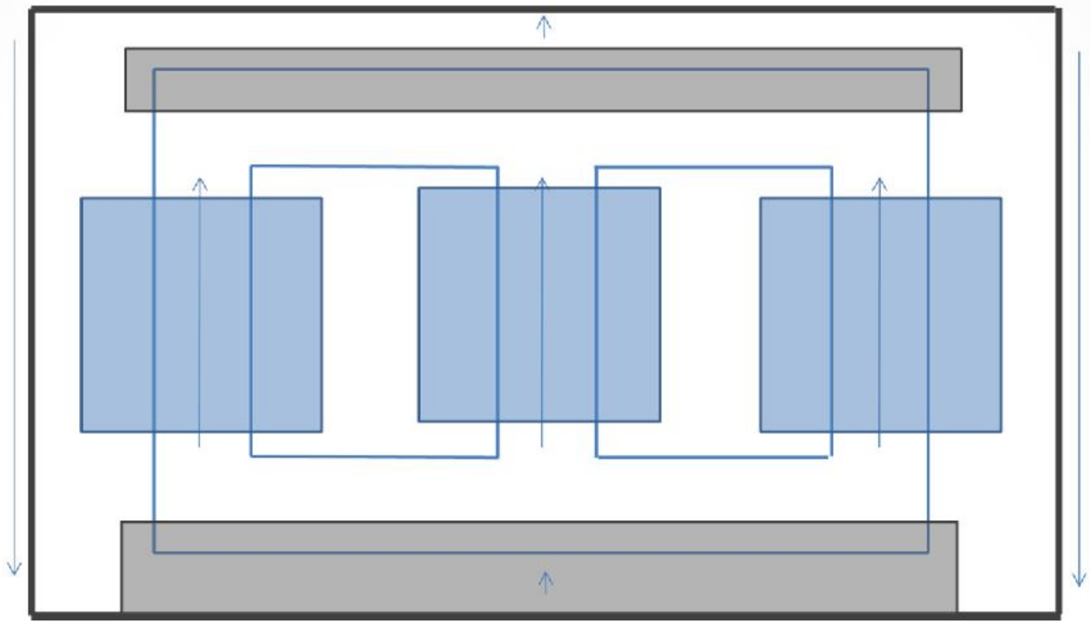
3-Phase 5-Leg Core-Form



"Textbook" Sequence Pattern

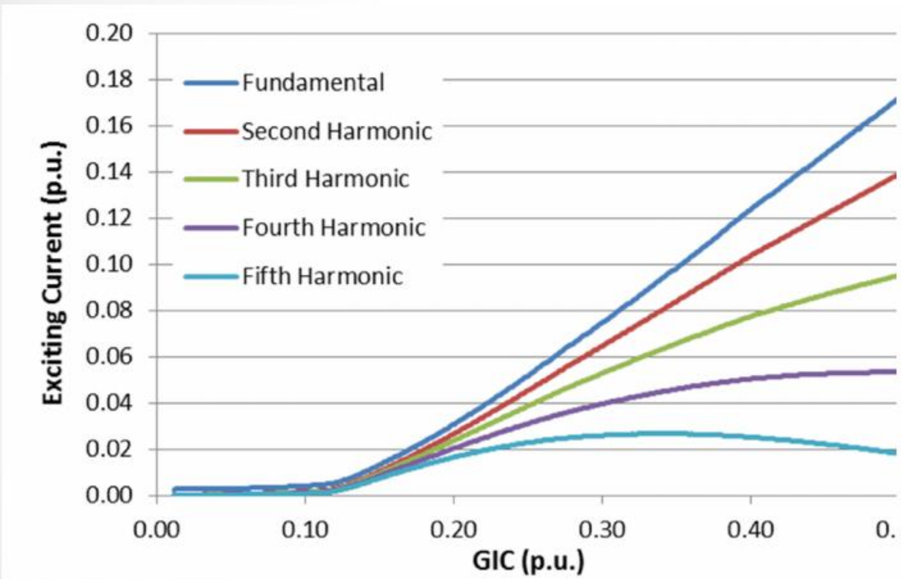
Sequence Component	Harmonic Order
Positive	1, 4, 7, 10, 13, 16…
Negative	2, 5, 8, 11, 14, 17…
Zero	3, 6, 9, 12, 15, 18…

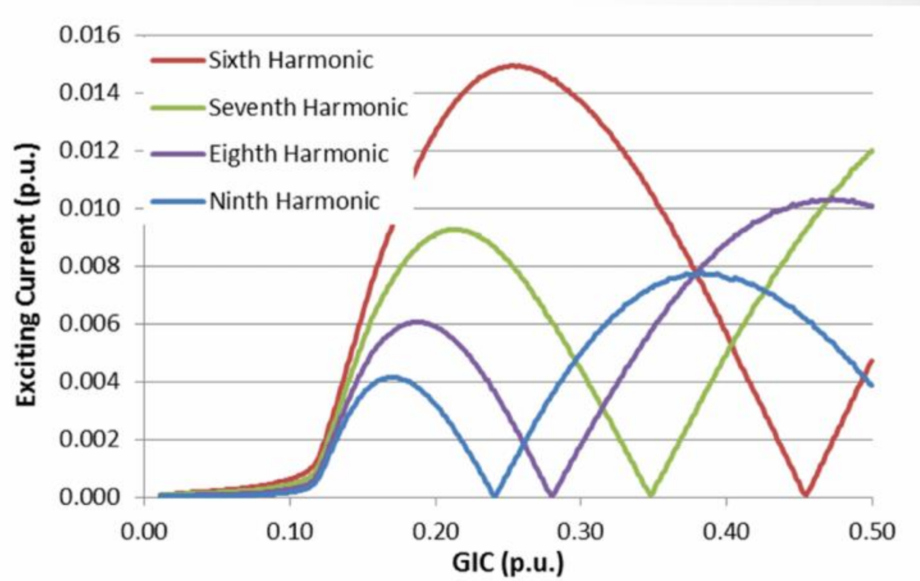
Three-Leg Core-Form
Zero-Sequence DC Flux Paths



- Zero-sequence flux returns outside core
  - Jumps gap through oil to tank
  - Flows through structural members and tank
- Return path is relatively high reluctance
  - Significant GIC must flow to push enough zero sequence flux to bias main legs so that flux peaks reach saturation

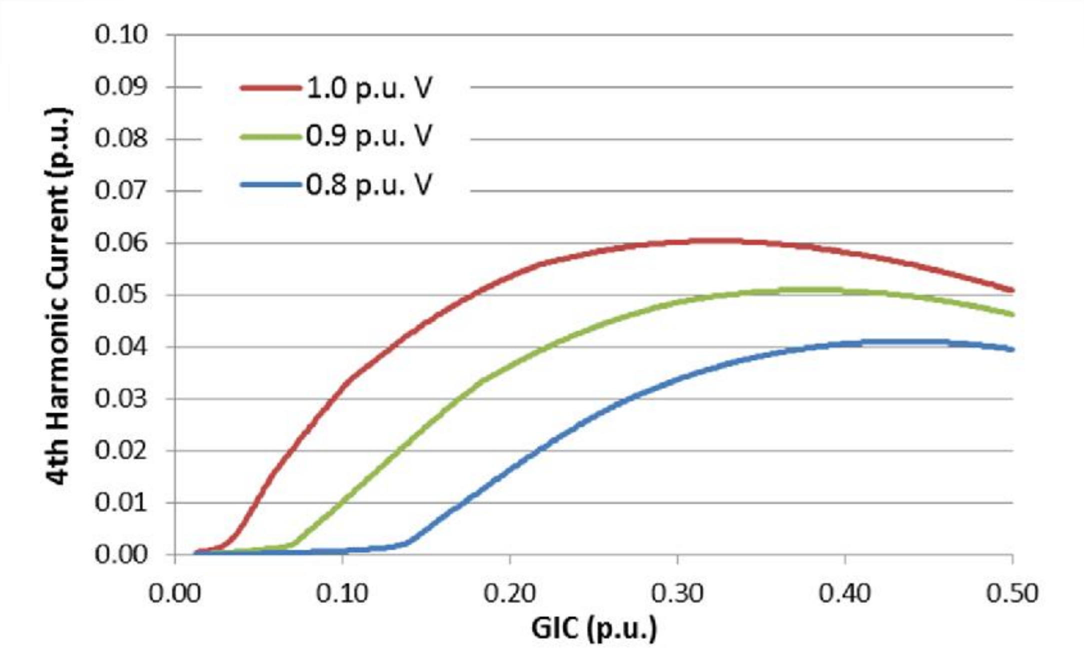
I_{exc} Components for 3-Leg Core





- “Dead region” is very sensitive to the core-to-tank gap reluctance

Voltage Sensitivity – 3 Leg Core Form

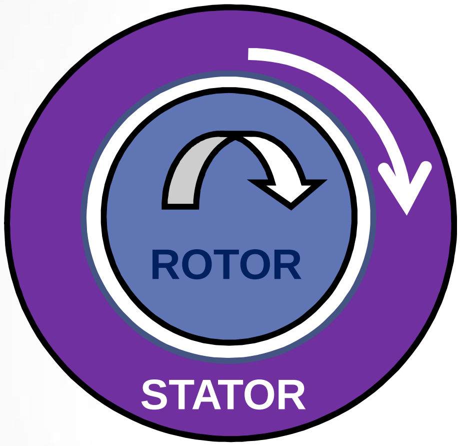


- (Note: smaller core-to-tank gap in this transformer)
- Variation in “dead region” makes wide variation in harmonics with fundamental voltage

Harmonic Current Impact on Generators

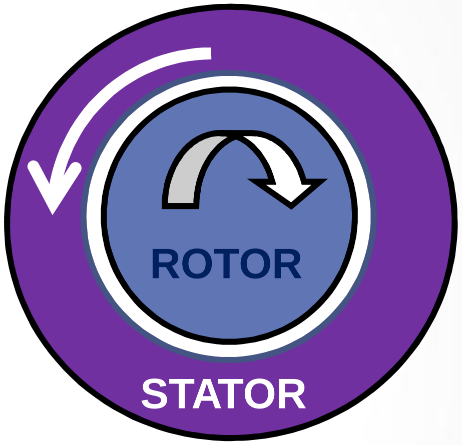
Rotor Heating – Normal Circumstances

Positive Sequence Fundamental Current



- Positive-sequence fundamental creates a magnetic field that rotates at synchronous speed in same direction as rotor
- No dΦ/dt, therefore no induction heating of rotor

Negative Sequence Fundamental Current



- Negative sequence caused by fundamental imbalance causes apparent rotation in reverse
- dΦ/dt induces second harmonic current in rotor face and damper bars
- Heating results

Fundamental Imbalance Limits

- IEEE C50.13 sets limits on generator negative sequence (fundamental frequency; i.e., 60 Hz)
  - Cylindrical rotor generators limited to 5 – 10%
  - An 800 MVA generator is limited to 13% for ten minutes
- Generator I_2 protection typically coordinated with this standard
- IEEE C50.13-2005 now also sets harmonic current limits
  - Based on an I_2-equivalent for harmonic currents
  - I_{2eq} creates rotor heating of an equivalent amount of I_2 (fundamental)

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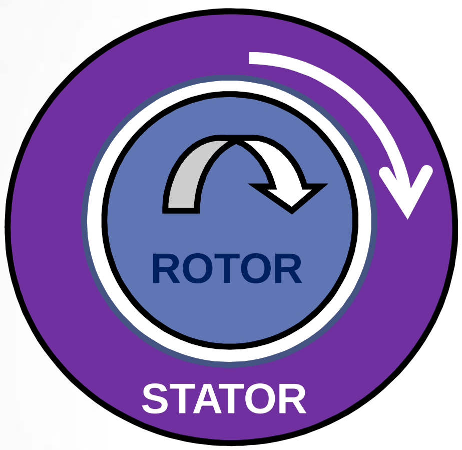
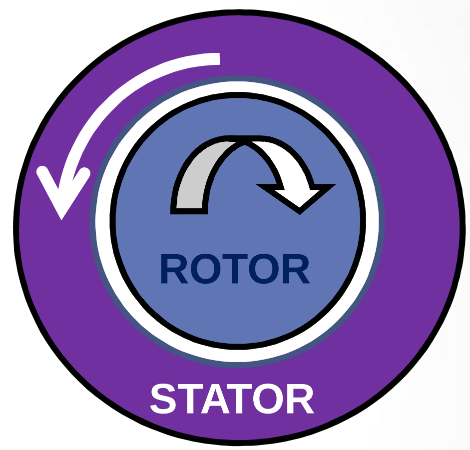
Harmonic Currents in Rotor Ref. Frame

Positive Sequence Harmonic Current



- Positive-sequence harmonic creates a magnetic field that rotates at n $\times$ synchronous speed in same direction as rotor
- dΦ/dt is at a frequency of n-1

Negative Sequence Harmonic Current



- Negative sequence harmonic causes apparent rotation in reverse direction at n x synch speed
- dΦ/dt is at a frequency of n+1

Harmonic Impacts

Heating

- Oscillating flux component seen by rotor
  - o Induces currents in rotor face and in damper windings
  - o Heating of the rotor results
- Potential concentration of heating at rotor bar wedge/slot interface could cause melting and crack initiation
  - o Yielding of rotor bar wedges can cause “eventful” machine failure

Torsional Vibration

- Turbogenerators are complex, with many high-frequency oscillation modes
- Oscillating flux can stimulate modes near these frequencies
  - o Generator designer design for fundamental I_2 (120 Hz on rotor)
  - o GIC-caused harmonics can stimulate frequencies not normally having significant current

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Rotor Heating Due to Harmonic Stator Currents

- In simple form, or a given amount of stator harmonic current:
  - Skin depth on rotor face and damper bars decreases by $1/\sqrt{f_{rotor}}$
  - Therefore, rotor circuit resistance increases by $\sqrt{f_{rotor}}$
  - Power of induced rotor currents increases by $\sqrt{f_{rotor}}$
- "Normal" I_2 results in 2nd harmonic on rotor
  - Positive sequence harmonics at n-1 harmonic
  - Negative sequence harmonics at n+1 harmonic
- Weighting factors to derive I_2-equivalent:

$$\sqrt{\frac{n^{+ve}-1}{2}} \qquad \sqrt{\frac{n^{-ve}+1}{2}}$$

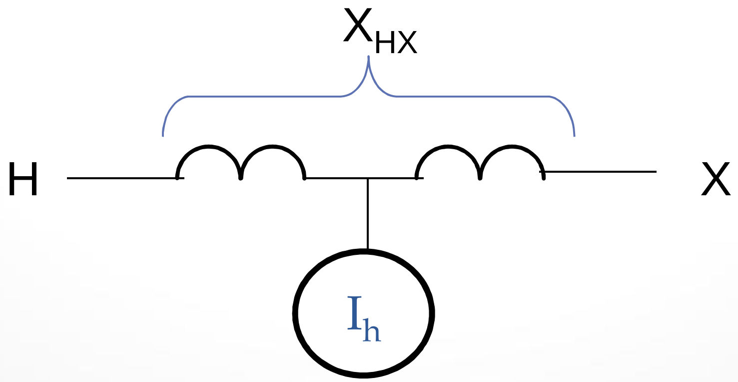
$$I_{2eq} = \sqrt{I_2^{\,2} + \sum_n \sqrt{\frac{n+i}{2}} I_n^{\,2}}$$

Where i=+1 for negative sequence harmonics

i=-1 for positive sequence harmonics

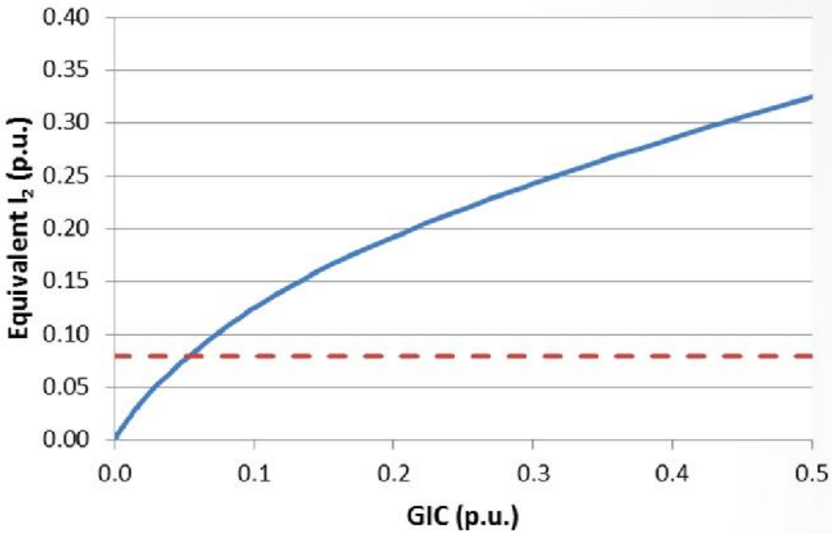
Harmonics in Generator from GSU

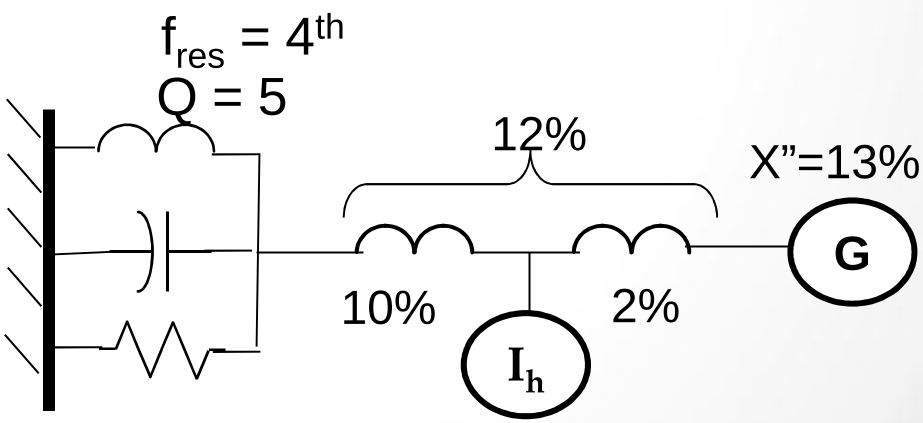
- Exciting current harmonic components created in the GSU divide between generator and grid
  - o Generator is inductive, with Z increasing nearly linearly with frequency
  - o Grids typically have resonances, worse case is when a resonance coincides with a non-zero sequence harmonic
- Reasonable approximation of transformer is a harmonic current source in the midst of the transformer leakage
  - o Division of impedance depends on the primary and secondary air-core impedances
  - o Most of the impedance is on the grid side for core-form transformers



Example: Grid Resonant at 4th Harmonic

- For 350 MVA generator, IEEE C50.13 limits I_{2eq} to 8% (larger generators are even less)
- For a bank of single-phase GSU transformers, 0.055 p.u. GIC results in I_{2eq} at the 8% limit
- 0.055 p.u. GIC for 350 MVA 500 kV transformer = 31.4 A/ph
- 10-minute transient I_2 limit reached at 0.11 p.u. GIC = 63 A/ph



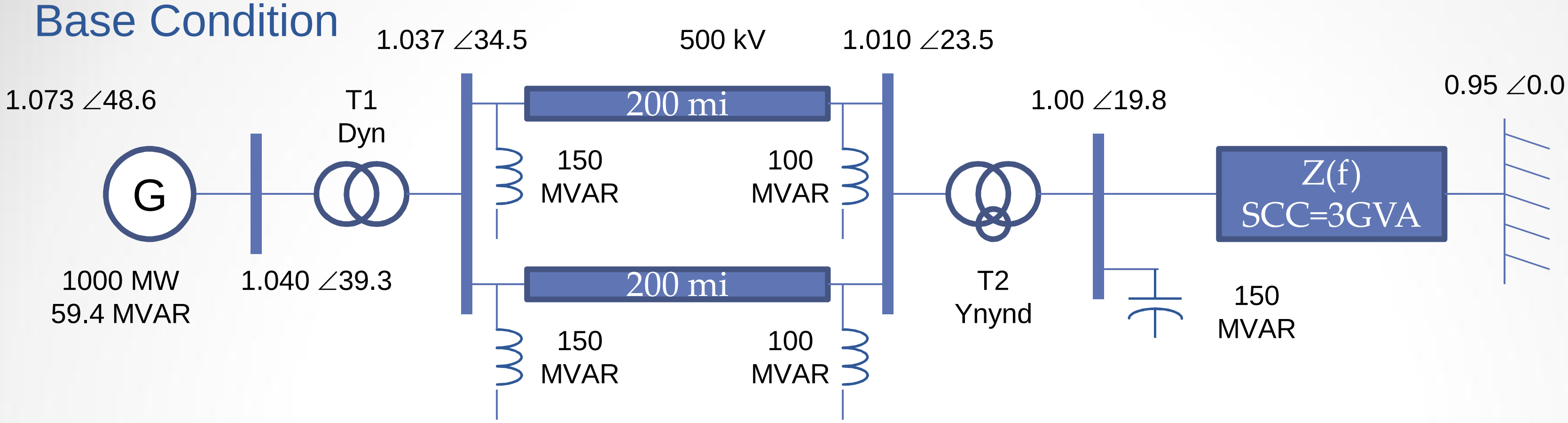


However, not all harmonics in generator are from its GSU

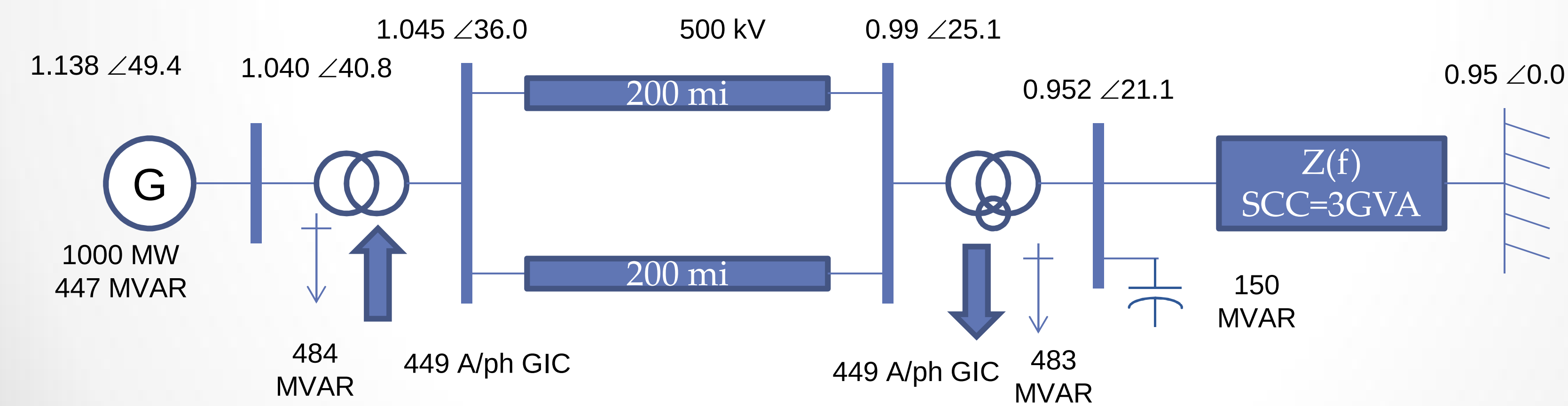
A Severe Hypothetical Example

Simple Case Study

Base Condition



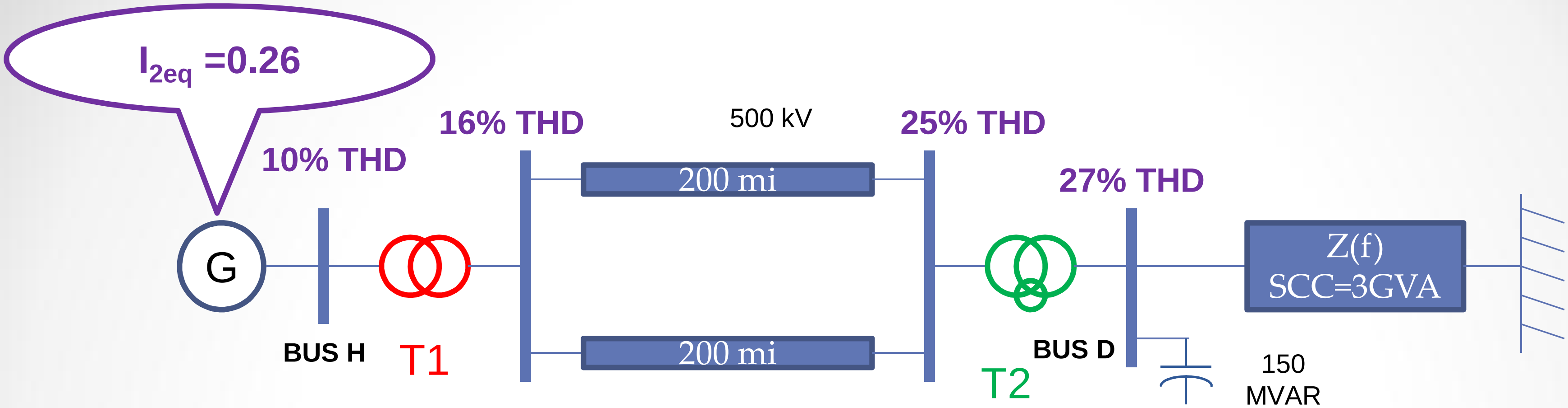
Severe GMD; E-field = 10 V/mi



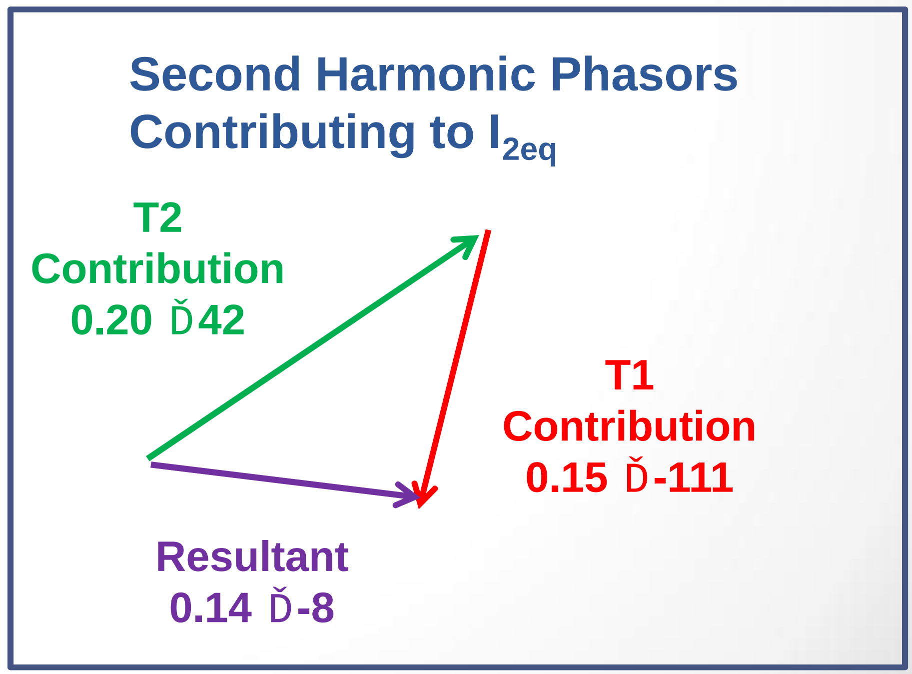
Assumptions:

- Single phase transformers
- Exciting current at the lowest voltage terminals
- ∴ No triplens

Example Case With Iterative Solution



- Dominant contributor to generator I_{2eq} is a transformer 200 miles away!
- Results would have been 65% more severe if non-iterative harmonic analysis used



Common Misconceptions

- Wye-delta GSU blocks GIC from the generator, so there is no problem
  - **WRONG** – extraordinary harmonics are produced which do affect the generator
- Only negative sequence harmonics affect the generator
  - **WRONG**– all non-zero sequence harmonics create oscillating flux
- All the harmonics to which a generator during GIC is from the generator's GSU
  - **WRONG**– Harmonics are being produced throughout the system, and transformers that are remote can contribute to I_{2eq}
- Triplen (3rd, 6th, 9th, etc.) harmonics don't get into the generator
  - **WRONG**– Three-phase transformers create triplen harmonics that are not zero sequence; even single-phase transformer banks will do this if the fundamental voltage is imbalanced

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Conclusions

- For a GMD event strong enough to significantly affect transformers or grid voltage stability, generators may be exposed to damaging harmonic effects
- Most generator protection does not include harmonic contributions to the equivalent I_2
  - Risk of damage to generators
  - Modification of protection would be prudent
- With protection, tripping of generators (and capacitors) could drive the system to voltage collapse at GMD severities less severe than predicted by the GIC-flow studies that don't include harmonic impacts

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