Helping to keep the lights on,
businesses running
and communities strong®

Power Quality 101

Michael B. Marz, Principal Transmission Planning Engineer

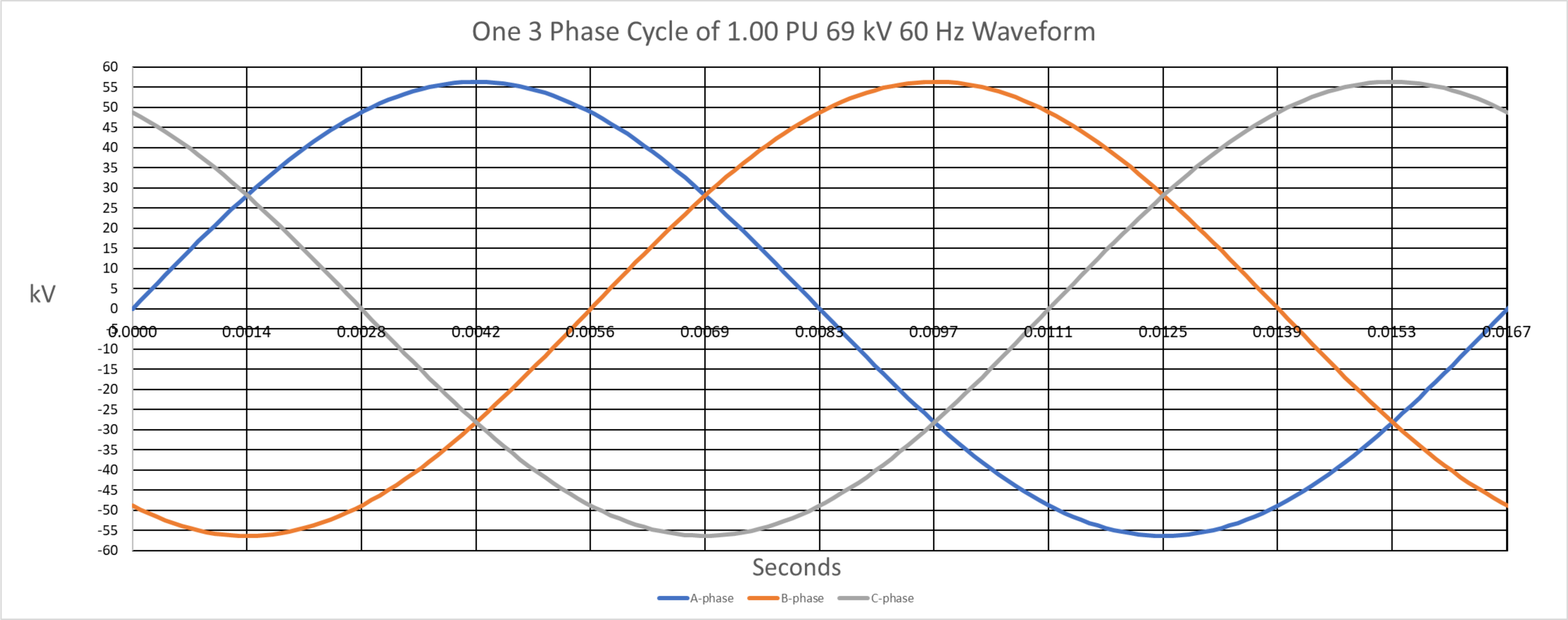
54th Annual Minnesota Power Systems Conference
November 8, 2018
St. Paul, MN

Outline

- **Introduction**
  - What Is, Isn't and Might Be PQ Phenomena?
  - What Should You Know About PQ?
  - Presentation Goals Presentation
- **PQ Phenomena**
  - Sags and Surges
  - Flicker
  - Harmonics
  - Interharmonics
  - Geomagnetic Disturbances
  - Voltage Unbalance
- **Summary/Conclusion/Questions**

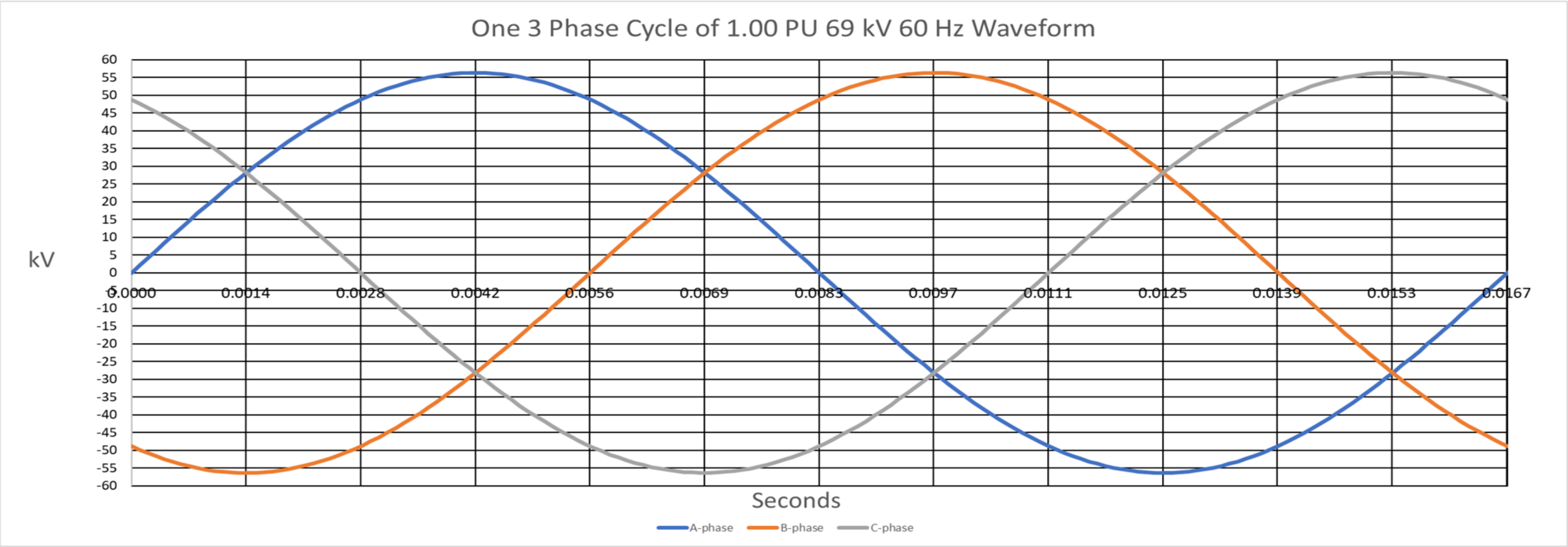
What is a Power Quality Phenomena?

- **“Anything” that Distorts a 60 Hz Waveform**
  - Magnitude Too High or Too Low
  - Frequencies in Addition to 60 Hz (above or Below 60 Hz)
  - Can be Steady State or Transient, Periodic or Non-Periodic



The 60 Hz 1 PU 69 kV Waveform

- **What is the 69 kV? Line-to-Line RMS.**
- **Waveform is 56.3 kV Peak Line-to Ground.**
- **For a Sine Wave:**
  - Peak = RMS * $\sqrt{2}$ and Line-to-Line = Line-to-Ground * $\sqrt{3}$
  - L-G Peak = L-L RMS * $\sqrt{2/3}$



What isn't a Power Quality Phenomena?

- **Complete Interruptions of Power**
  - Must Last Longer than Fault Clearing Time
  - Shorter Interruptions are "Sags"
- **Steady State 60 Hz Voltage Excursions**
  - Voltage Too Low – Voltage Stability, etc.
  - Voltage Too High – Ferranti Effect, etc.
- **Phenomena that Occur off the Grid**
  - Stray Voltage and Other Grounding Issues that Don't Affect Grid Voltage or Current or Frequency
  - Electromagnetic Coupling to Railroad Tracks, Pipelines, etc.

What Are Power Quality Phenomena? (Others May Have Different Answers)

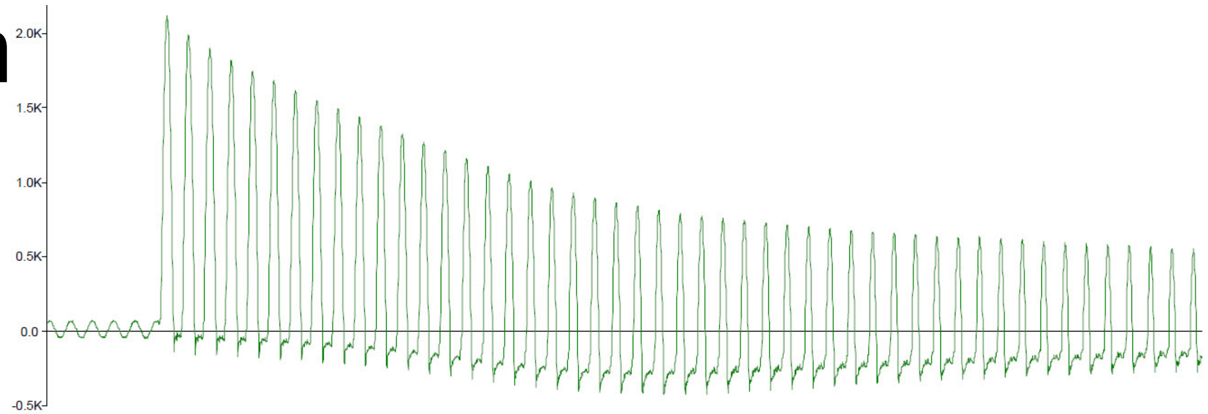
- **Transients: Lightning, Faults, Switching Events**
  - Sources of Short Duration High (or Low) Voltages
  - Outages Caused by Transients are Not PQ Events
- **Ferro-Resonance – High Voltage**
- **Geomagnetic Disturbances (GMD)**
  - Some Aspects Appear Essentially Steady State
  - Other Aspects are at Higher and Lower Frequencies
- **Voltage Unbalance**
  - A Steady State 60 Hz Phenomena
  - Can Affect Motor Heating (Similar to Some PQ Phenomena)

What Should We Know About PQ?

- **Ideally "We" includes Utilities and Customers**
- **Identify what is a PQ Issue**
- **Determine Cause of PQ Issues**
  - What PQ Phenomena is Causing Issue?
  - Why is this an Issue Here and Now?
- **Know How to Measure and Quantify Impact**
  - Determining the Source of the PQ Issues
  - Propagation on the Grid
- **Know Standards, Guidelines and Criteria**
- **Know How to Resolve Issue**
  - Reduce PQ Issue Source
  - Decrease Sensitivity to PQ Issue

Goals of this Presentation

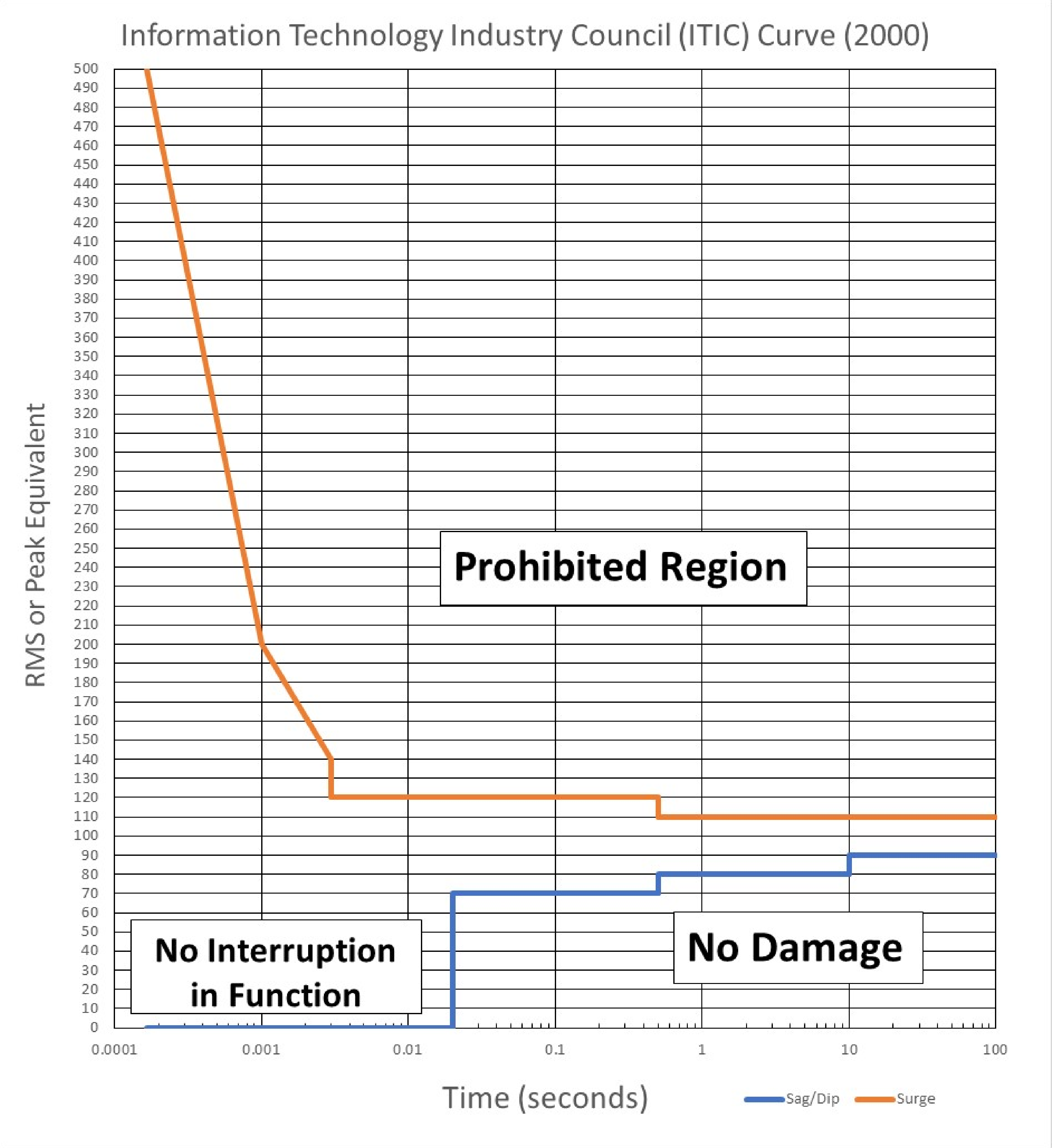
- **Introduce You to Common PQ Phenomena**
  - Sources and Propagation on the Grid
  - How to Measure and Quantify Impact
  - Standards, Guidelines and Criteria
  - Typical Resolution
- **Have an idea of what is Happening**
  - Most PQ Issues are to Some Degree Unique
  - All Issues Discussed Could be there Own Tutorial
  - Know Enough NOT to be Dangerous and Able to Find Additional Inform



Phenomena #1: Dips/Sags and Surges

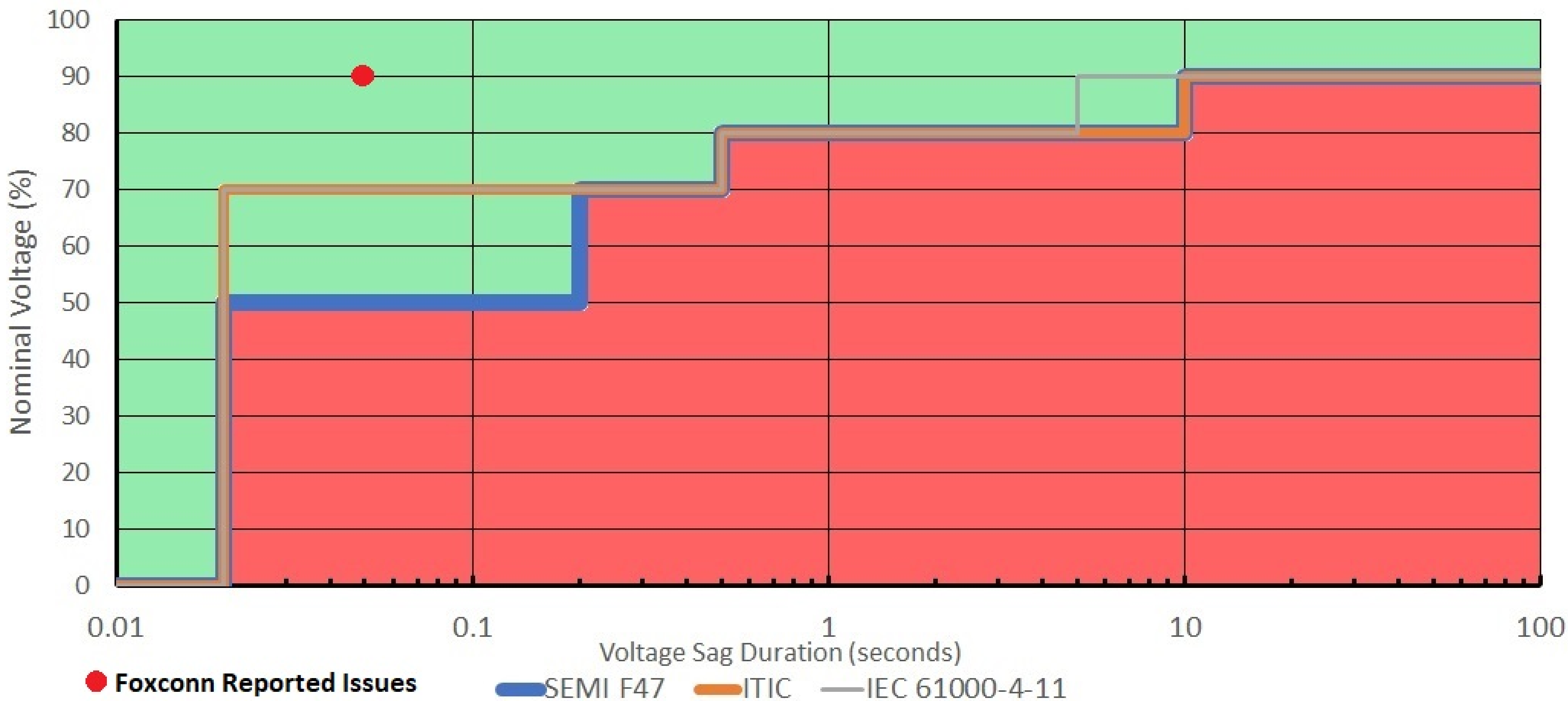
- **Temporary Under or Over Voltage**
  - Magnitude and Duration Vary and Determine Severity
  - Under and Over Voltages Greater Than a Minute Not PQ?
- **Terminology: Dips and Sags not the Same?**
  - Dip - Temporary Reduction in Voltage (IEC Preferred Term)
  - Sag – an RMS Variation in Magnitude between 10% and 90% of nominal between 0.5 cycles and 1 Minute.
  - This presentation will not distinguish between the two.
- **Concerns**
  - Surges: Primarily Equipment Damage, but also Misoperation
  - Sags: Primarily Tripping, but also Misoperation

Definition: ITIC Curve



- Single Phase 120 V Equipment
- Designed for Manufacturers and Users
- Other Curves Exist
- May Not Apply to All Equipment
- 90% - 110% Steady State OK?

SEMI F47 - 0706



- **Applies to Electronics Manufacturers**
- **Balances Equipment Cost and Ride Through**
- **Does Not Consider Product Quality (Red Dot)**

Some Sources of Surges

- Ferroresonance (0.1 Hz to 1 kHz)
- Load Rejection (0.1 Hz to 3 kHz)
- Fault Clearing (50 Hz to 3 kHz)
- Capacitor or Line Switching (50 Hz to 20 kHz)
- Transient Recovery Voltages (50 Hz to 100 kHz)
- Lightning (10 kHz to 3 MHz)
- GIS Disconnector Switching (100 kHz to 50 MHz)

Lightning and Switching Surges

- **High Frequency and Short Duration**
- **External Voltages (Around Equipment) Can Cause Outages – May also Damage Equipment**
- **Internal Voltages (Inside Equipment) can Cause Failure or Shorten Equipment Life**
- **Controlled By Surge Arresters**
  - Arresters can Handle “All” Lightning (short Duration)
  - More Caution when applying arresters for switching surges (energy handling capability of arresters a concern)
  - Long Term Overvoltages, if high enough, can cause arrester failure (Dynamic Overvoltage when switch line and Cap together)

Surge Arrester Application I

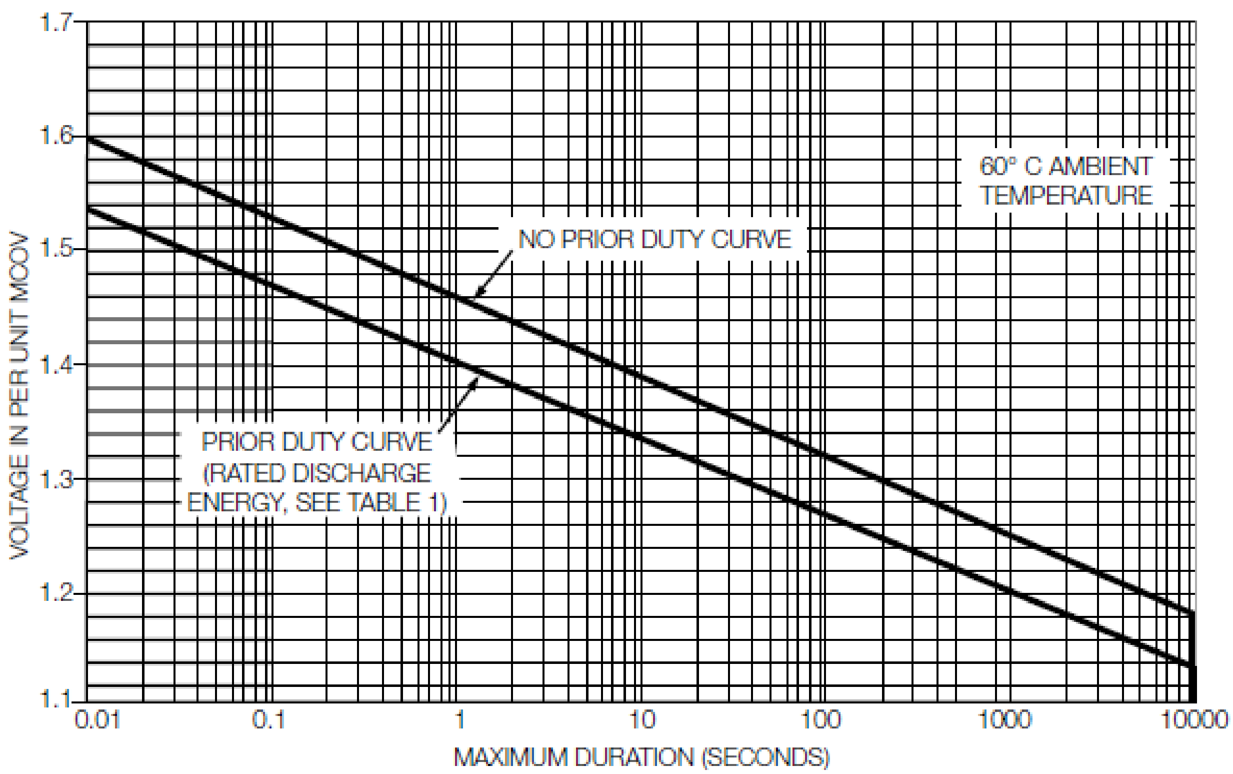
- **Protective Levels Used to Determine Up to Three Protective Margins**

Arrester Rating (kV rms)	Arrester MCOV (kV rms)	TOV* (kV rms) 1 sec	TOV* (kV rms) 10 sec	Front-of-wave Protective Level** (kV Crest)	Maximum Discharge Voltage (kV crest) 8/20 µs Current Wave 1.5 kA	3 kA	5 kA	10 kA	20 kA	40 kA	Switching Surge Protective Level*** (kV crest) 125 A	250 A	500 A	1000 A
3	2.55	3.73	3.56	9.3	7.0	7.4	7.7	8.4	9.4	11.0	6.1	6.3	6.5	6.7
6	5.10	7.47	7.11	18.2	13.9	14.7	15.4	16.7	18.6	21.4	12.2	12.6	13.0	13.5
9	7.65	11.2	10.7	27.2	20.9	22.0	23.1	25.0	27.7	31.7	18.3	18.9	19.5	20.2
10	8.40	12.3	11.7	29.7	23.0	24.2	25.4	27.4	30.4	34.8	20.1	20.7	21.4	22.2
12	10.2	14.9	14.2	36.0	27.9	29.4	30.8	33.3	36.9	42.1	24.4	25.2	26.0	26.9
15	12.7	18.6	17.7	44.7	34.7	36.6	38.3	41.4	45.9	52.2	30.4	31.3	32.4	33.5
18	15.3	22.4	21.3	53.7	41.8	44.0	46.2	49.8	55.2	62.8	36.6	37.7	39.0	40.4
21	17.0	24.9	23.7	59.7	46.4	48.9	51.3	55.4	61.3	69.7	40.7	41.9	43.4	44.9
24	19.5	28.6	27.2	68.4	53.3	56.1	58.8	63.5	70.3	79.9	46.7	48.1	49.8	51.5
27	22.0	32.2	30.7	77.0	60.1	63.3	66.3	71.6	79.3	90.0	52.7	54.3	56.1	58.1
30	24.4	35.7	34.0	85.4	66.6	70.2	73.6	79.4	87.9	99.8	58.4	60.2	62.3	64.4
33	27.5	40.3	38.4	96.2	75.1	79.1	82.9	89.5	99.1	112	65.9	67.8	70.2	72.6
36	29.0	42.5	40.5	101	79.2	83.4	87.4	94.4	105	119	69.5	71.5	74.0	76.6
39	31.5	46.1	43.9	111	86.0	90.6	95.0	103	113	129	75.4	77.7	80.4	83.1

http://www.cooperindustries.com/content/dam/public/powersystems/resources/library/235_SurgeArresters/CA235022EN.pdf

Surge Arrester Application II

- **TOV and Energy Handling**



	Ratings		
Arrester Characteristic	**AZES**	**AZEH**	**AZEX**
System Application Voltages	3-345 kV	3-230 kV	3-138 kV
Arrester Voltage Ratings	3-360 kV	3-240 kV	3-108 kV
Rated Discharge Energy, (kJ/kV of MCOV) Arrester Ratings: 3-108 kV 120-240 kV 259-360 kV	 3.4 5.6 8.9	 5.6 8.9 –	 8.9 – –
System Frequency	50/60 Hz	50-60 Hz	50/60 Hz
Impulse Classifying Current	10 kA	10 kA	10 kA
High Current Withstand	100 kA	100 kA	100 kA
Pressure Relief Rating, kA rms sym Metal-Top Designs Cubicle-Mount Designs	 65 kA 40 kA	 65 kA 40 kA	 65 kA –

http://www.cooperindustries.com/content/dam/public/powersystems/resources/library/235_SurgeArresters/CA235022EN.pdf

Surge Arrester Application III

- Arrester Application Tables
- Why is Grounding Important?
- Unusual Systems May Require Different Application

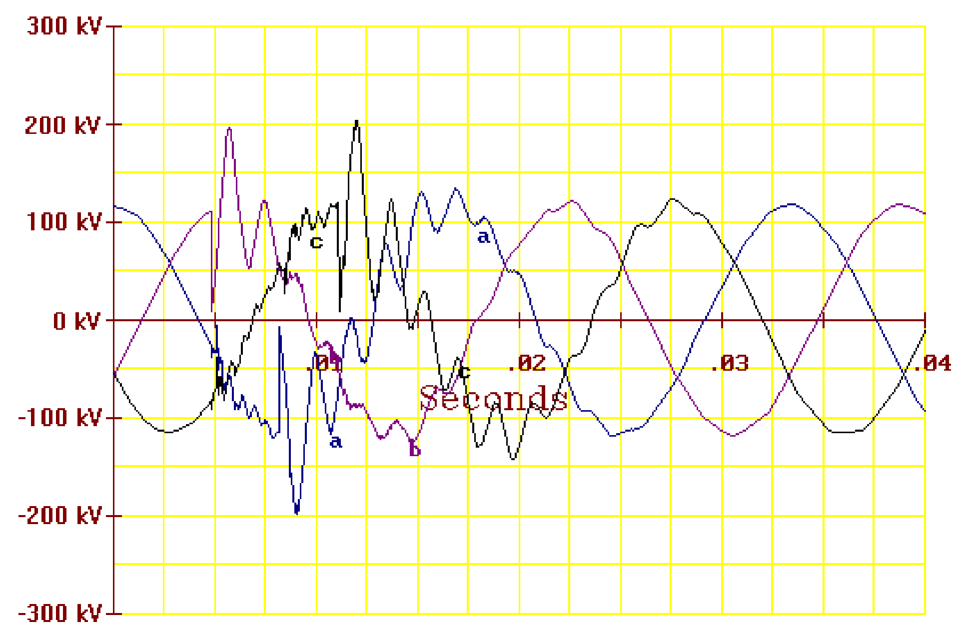
System Voltage (kV rms)		Suggested Arrester Rating (kV rms)	
Nominal	Maximum	Solidly Grounded Neutral Circuits	High Impedance Grounded, Ungrounded, or Temporarily Ungrounded Circuits
2.4	2.52	–	3
4.16	4.37	3	6
4.8	5.04	–	6
6.9	7.24	–	9
12.47	13.2	9-10	–
13.2	14.0	10	15-18
13.8	14.5	10-12	15-18
20.7	21.8	15	–
23.0	24.2	–	24-27
24.9	26.4	18-21	–
27.6	29.0	21-24	27-30
34.5	36.5	27-30	36-39
46.0	48.3	–	48
69.0	72.5	54-60	66-72
115	121	90-96	108-120
138	145	108-120	132-144
161	169	120-144	144-168
230	242	172-192	228-240
345	362	258-312	288-360

http://www.cooperindustries.com/content/dam/public/powersystems/resources/library/235_SurgeArresters/CA235022EN.pdf

Isolated Capacitor Switching Transients

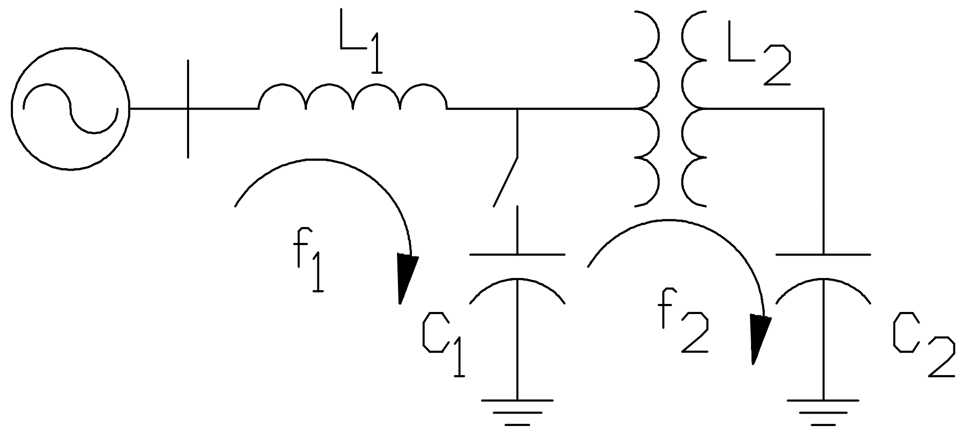
- **Voltage Up to 2 times Preswitch Voltage (Worse with Re-Strike)**
- **Frequency** $f = \dfrac{1}{2\pi\sqrt{L_S C}}$
- **Factors Affecting Magnitude and Duration**
  - System strength relative to capacitor size
  - Transmission lines, loads, nearby capacitances
  - Switching device characteristics, control, R or L
- **Optimum Closing R: System/Cap Surge Z**

$$R_{optimum} = \sqrt{\frac{L_s}{C}}$$



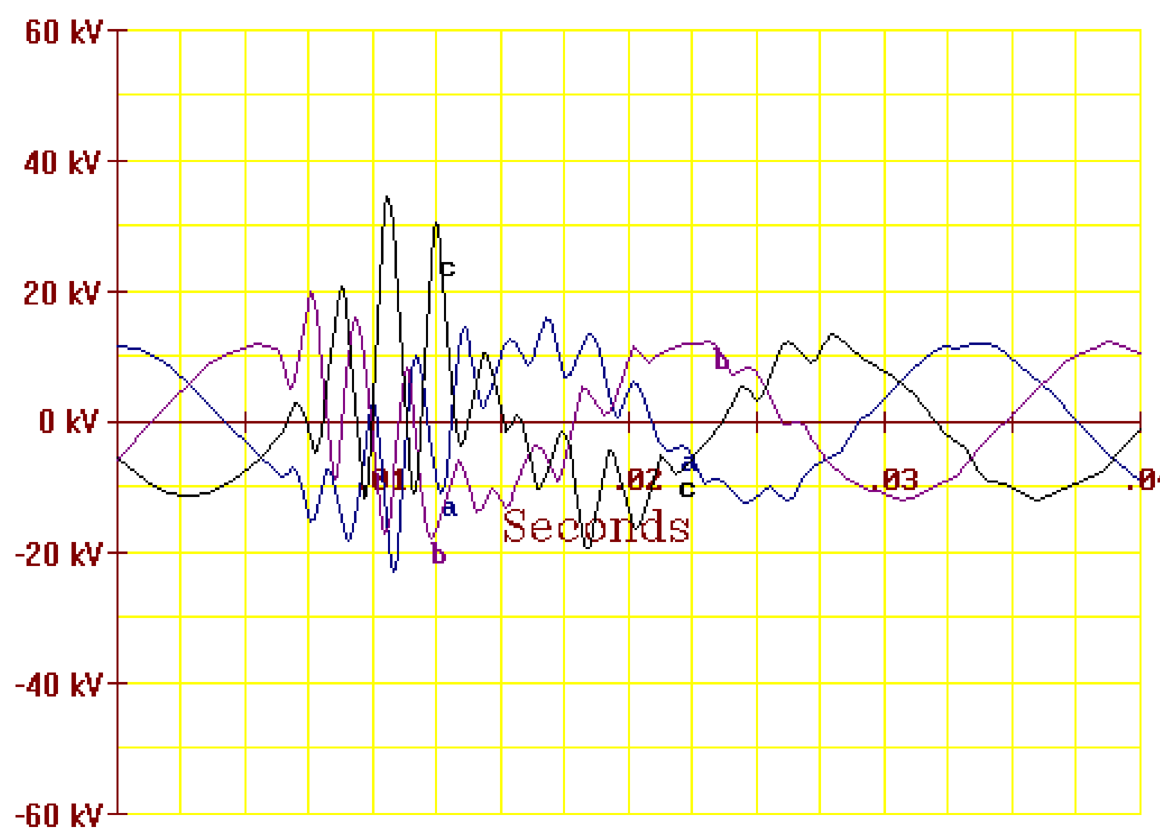
Voltage Magnification

$$f_1 = \frac{1}{2\pi\sqrt{L_1 C_1}}$$



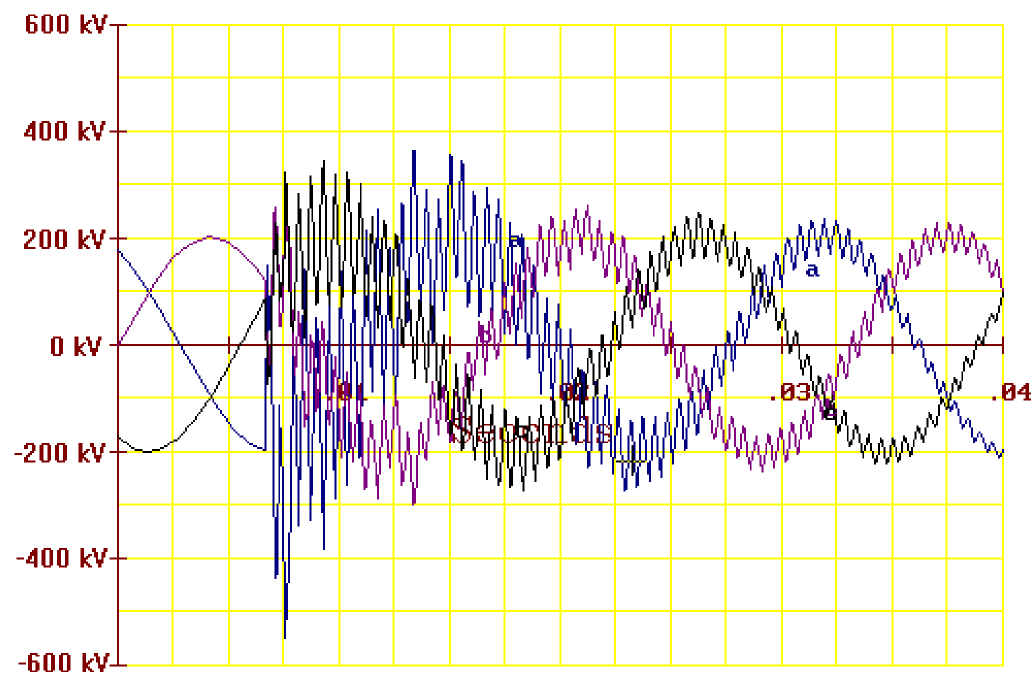
$$f_2 = \frac{1}{2\pi\sqrt{L_2 C_2}}$$

- **If F1=F2, High Voltage Magnitude and Energy Transients at C2**
- **Effected by System Loading and Nearby Caps**
- **Model Xformer Loss Frequency Dependence**



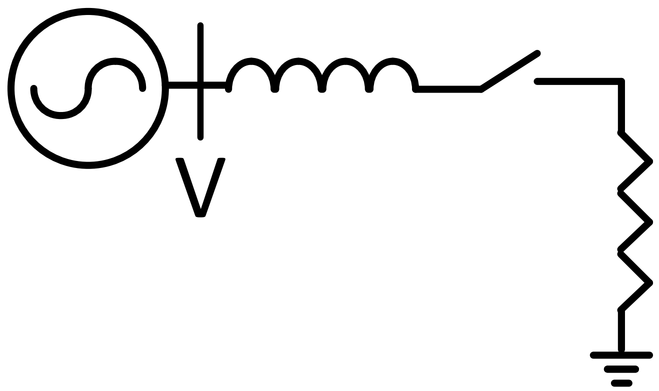
Xformer Termination Ph-Ph Transients

- Cap Energizing Initiates Traveling Wave
- Wave can Double at Transformer Termination
- Arresters Limit Phase Voltages to ~2.0 pu
- Worst Case Phase to Phase Voltage ~ 4.0 pu
- Transformer Ph-Ph Withstand 3.4 pu?
- Can be Worse on Longer Lines



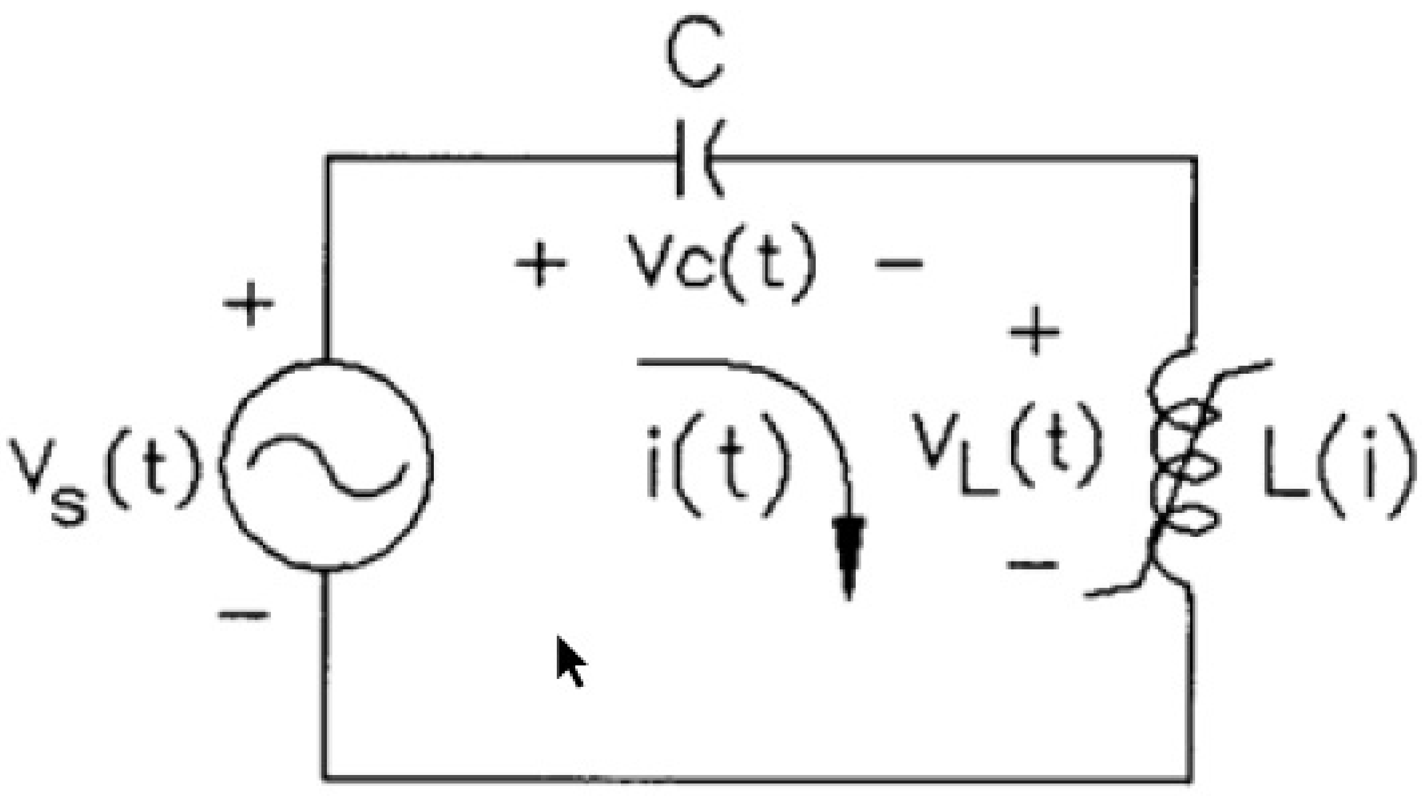
Surges: Fault Clearing and Load Rejection

- **During Fault Reactive Sources Try to Increase Voltage – May Cause to overvoltage following Fault Clearing**
- **When large load lost, voltage drop through system reduced increasing system voltage. May be significant.**
- **Usually these overvoltages not too severe and short enough that they aren’t a problem**
- **Mitigation may be required in some cases**
    - Fast Switching Capacitors (out) or Reactors (In)
    - Desensitize Loads



Ferroresonance

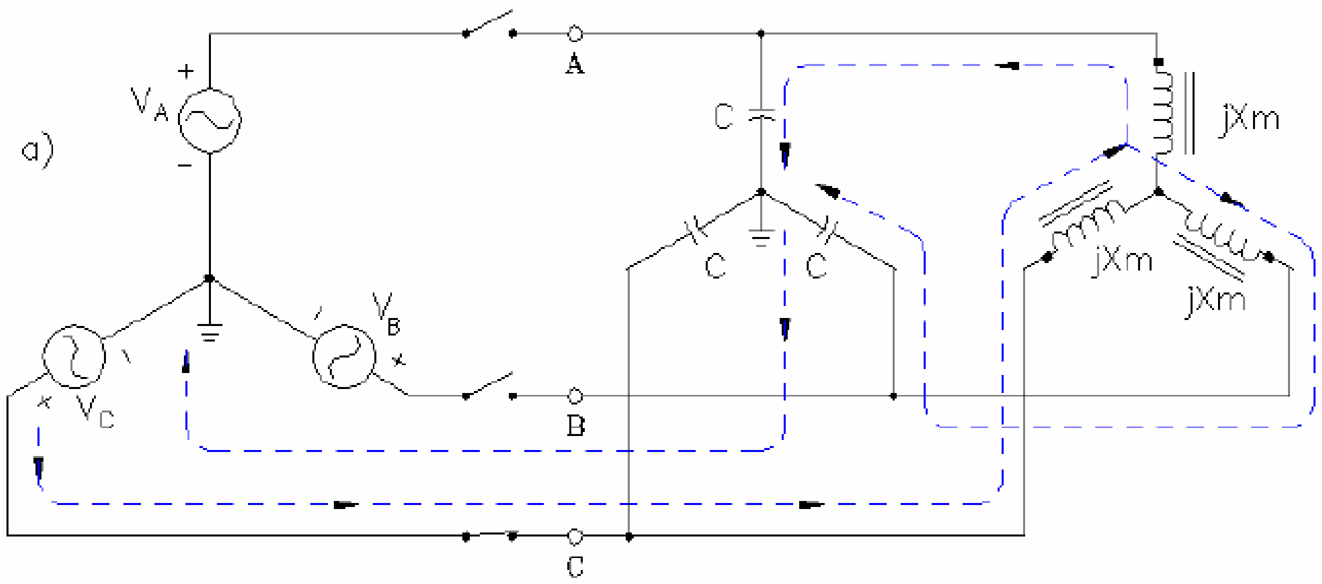
- **Everyone's Favorite Boogieman – 3 to 5 pu Voltages Possible**
- **A Non-Linear Effect that Can't be predicted Using Linear Models**
- **When will it Occur?**
  - Series C
  - Changing Value of L
  - May Change Over Time
- **Series Cap**
- **Lightly Loaded Xformer**
- **Single Pole Switching**
- **Transient May Start It**

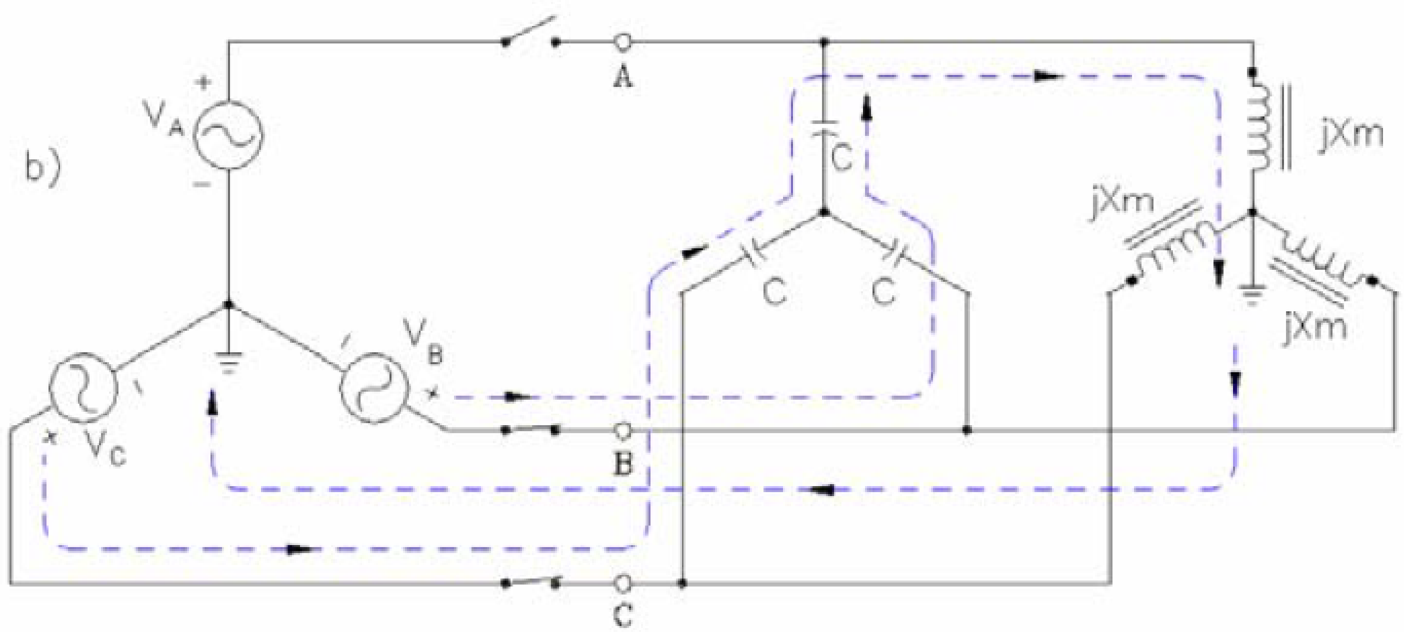


"Understanding and Dealing with Ferroresonance" Bruce Mork of Michigan Tech, MIPSYCON 2006.

Increased Possibility of Ferroresonance

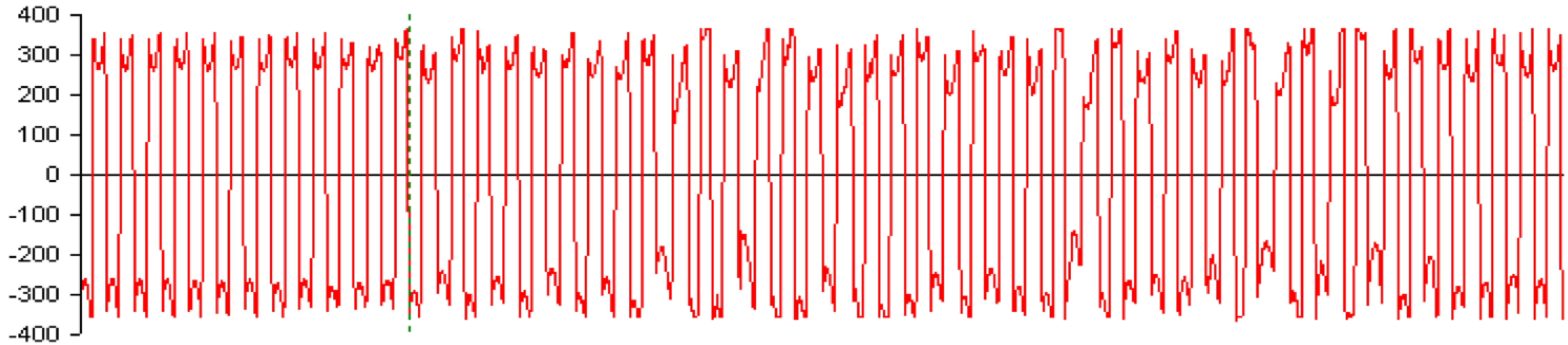
- Possible with any Transformer, but more Common with 3-phase Delta and single phase transformers and VTs Energized through series Cap
- Capacitor can be actual cap, cable, stray cap, surge caps, etc.
- Open Phase can cause parallel cap to become series cap



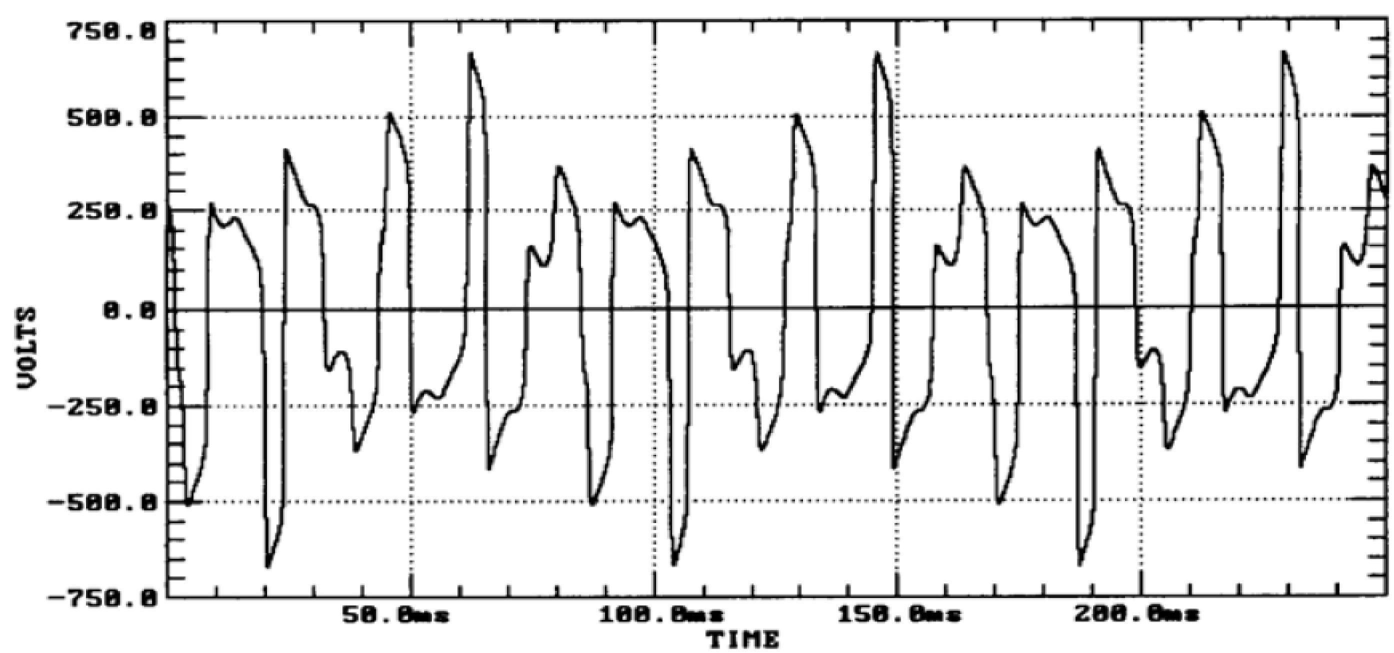


Ferroresonance Waveforms

- **345 kV (281 kV = 1 pu)**
  - "Classic" Square Wave Shape



  - Chaotic Waveshape



Preventing Ferroresonance

- **Ensure the transformer loaded while switched**
  - Load Transformer over 20% (higher better)
- **Don’t Use Single Pole Switching**
- **Avoid Inadvertent Open Phase (Fuse Operation, etc.)**
  - Eliminate fuses. Rely on feeder breaker for fault interruption.
  - Use three-phase switchgear instead of fuses. This is not economical in many cases.
  - Open or close all three cutouts as simultaneously as possible.

Voltage Sags – Sources and Effects

- **Affects Transmission and Distribution Systems**
  - Causes and Effects Similar in Type Not Necessarily Scale
  - Lower Voltage Events More Common, but Effects Less Severe
- **Sources:**
  - Faults
  - Energizing Large Loads (Motors)
  - Transformer Inrush
- **Effects**
  - Lights Blinking, Electronics Resetting
  - Loads Tripping – Paper Mills, etc.
  - Equipment Misoperation – Poor Quality Product

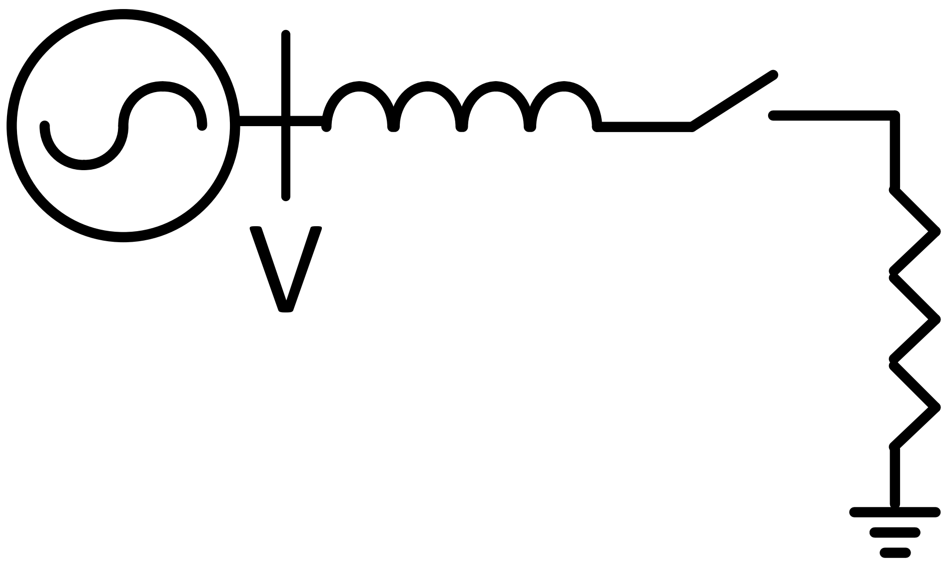
Faults

- **Most Cleared in Primary Time (3-5 cycles)**
- **Magnitude depends on Fault Impedance and Proximity**
- **More Common at Lower Voltages – Lower Insulation Levels make Lightning Protection Less Effective**
- **Four ATC 345 kV Busses: 19 Events – 5 Outside ATC**
- **5 on 345 kV System, 14 on 138 kV (None ≤ 69 kV)**
- **14 in ATC Territory: Lightning: 2 (1-345 kV, 1-138 kV), Equipment: 7 (Insulator, Arrester, Breaker, Guy Wire), Other: 5 (galloping, animals, unknown)**

345 kV	Sub #1		Sub #2		Sub #3		Sub #4	
Voltage	< 95%*	< 90%	< 95%*	< 90%	< 95%*	< 90%	< 95%*	< 90%
One Year	18	7	9	2	9	1	12	6

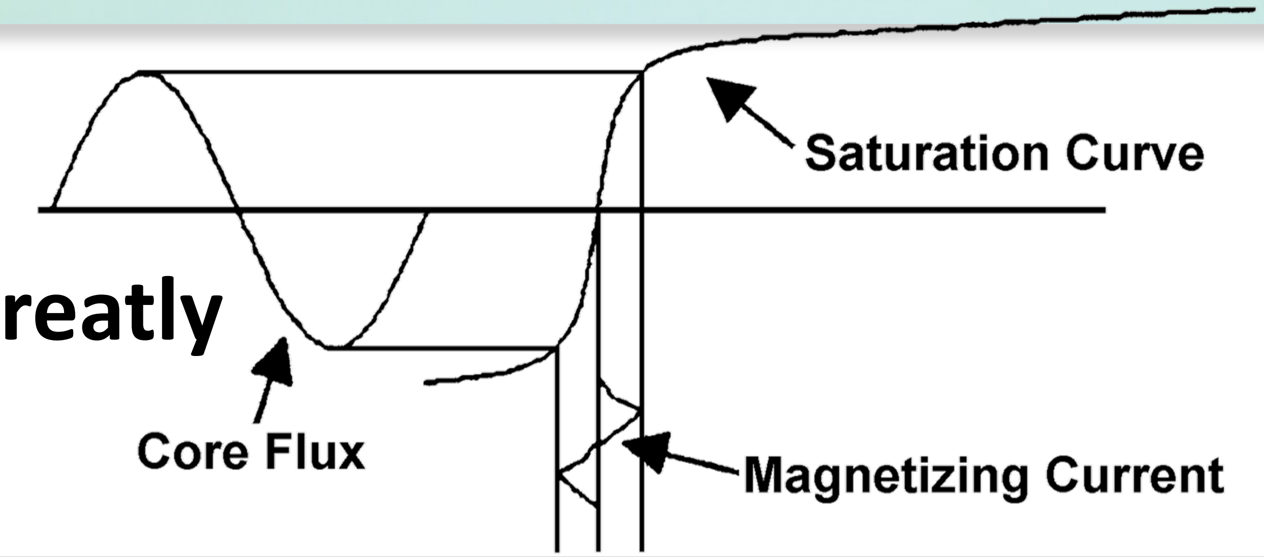
Note: #1 Connects to #2 & #3. #2 Connects to #1 & #4. #3 Connects to #1 & #4. #4 Connects to #2 & #3.

Energizing Large Loads



- **Load Draws Current Through System Reducing Voltage**
- **Motor Starting Current Depends on Multiple Parameters, Typically:**
  - Direct on Line from 5 to 9 times motor current.
  - Star Delta 4 times
  - Soft Start from 2 to 4
  - VSD variable speed driver from 0 to I

Transformer Inrush

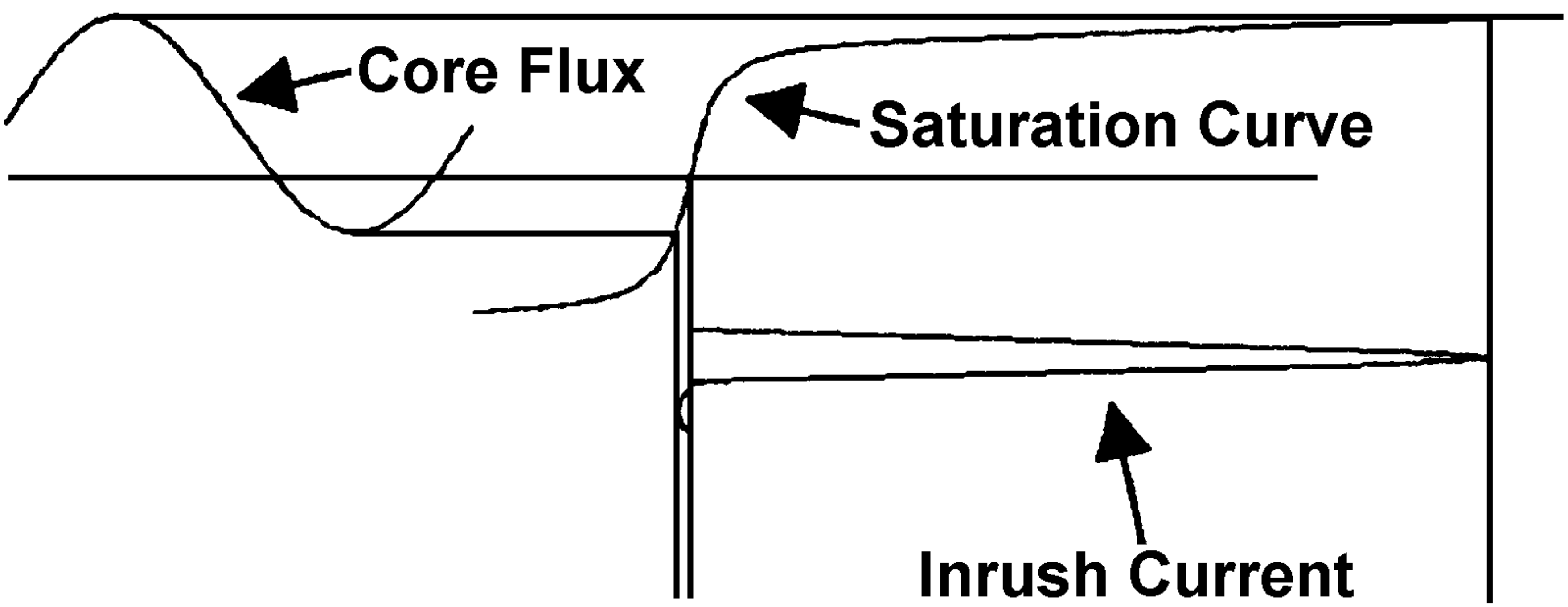


- **Current Magnitude Varies Greatly**
  - Transformer Design
  - System Strength
  - Flux: Residual and Prospective (Point on Wave)
- **Issues/Problems**
  - High Currents Cause Voltage Drop
  - Voltage Distortion, Relay and Fuse Misoperation, etc.
  - Becoming More Common? Transformer Design? Applications? Load Sensitivity?
- **Transformer Saturation Curve Relates Flux and Current (1-Phase Symmetrical Example)**

"Experiences with Voltage Drop During Large Transformer Energization: Arrowhead Phase Shifting Transformer and Beyond," M. Marz, D. Maki, MIPSYCON 2009

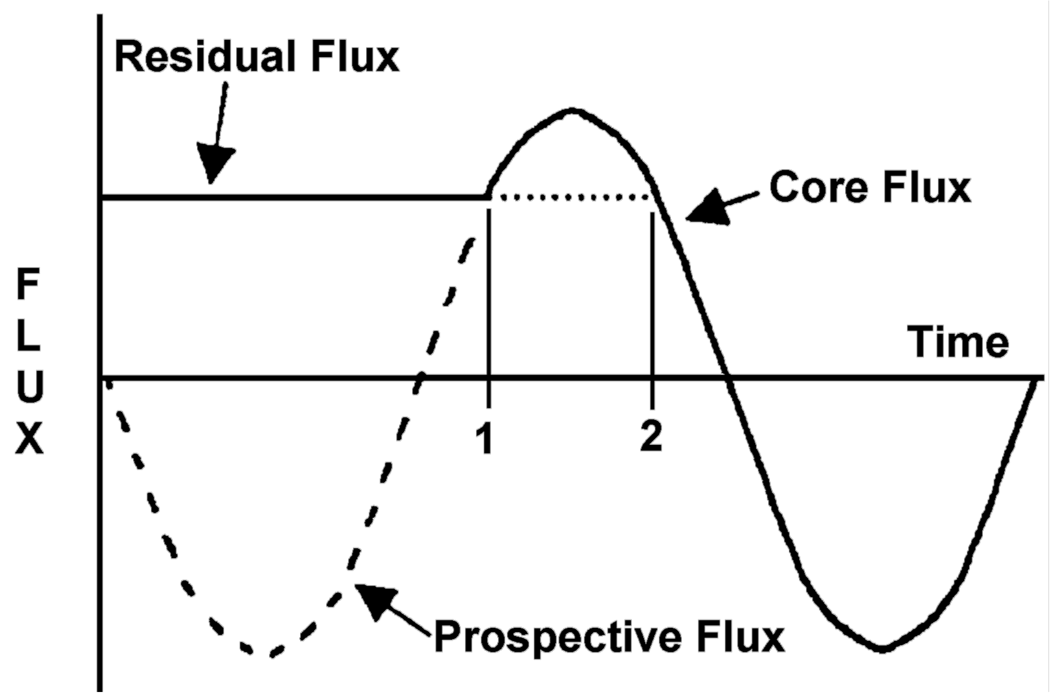
Residual Flux

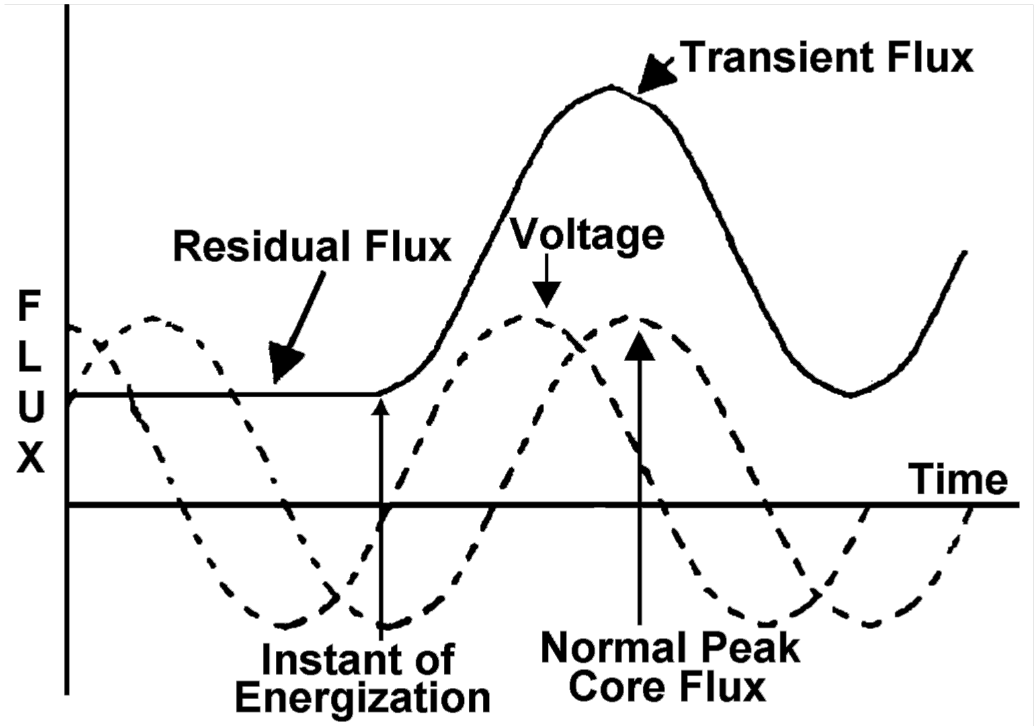
- Transformer De-Energization Leaves Core Magnetized with Up to 85% of Peak Normal Flux (20-70% Typical)
- High Silicon Steels and Cold Rolling Increase Residual Flux and Possible Maximum Peak Inrush Current
- Residual Flux Determined by Core Material, Gap, Capacitances and Current Chopping



Best and Worst Case Scenarios

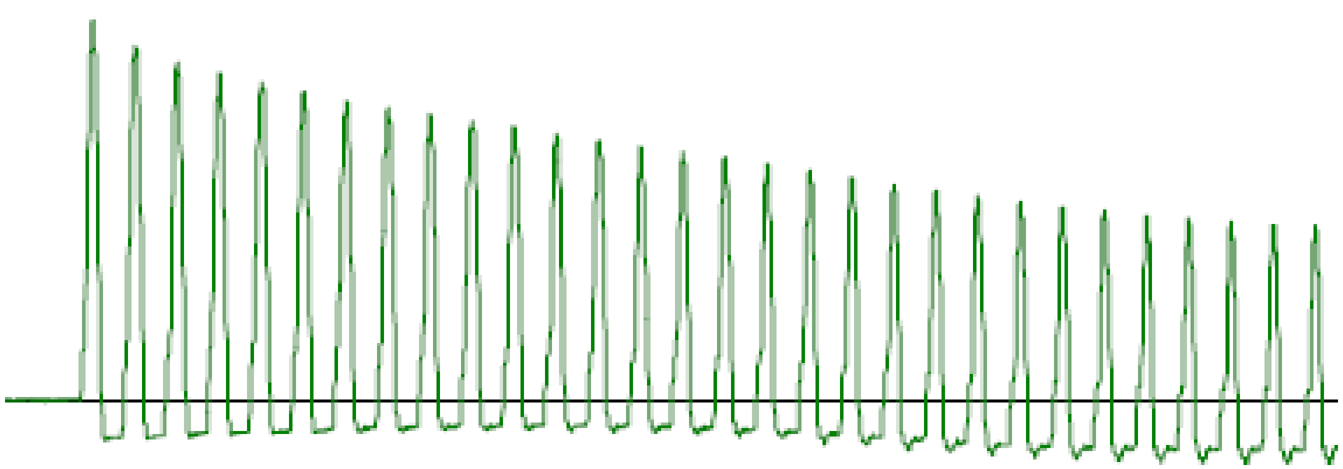
- **Best: Energize when Residual and Prospective Fluxes Equal (Inrush=Magnetizing Current)**
- **Worst: Energize when Residual Flux Max and Prospective Flux Min or Vice Versa**
- **Transient Flux 2.85 times Steady State Peak**

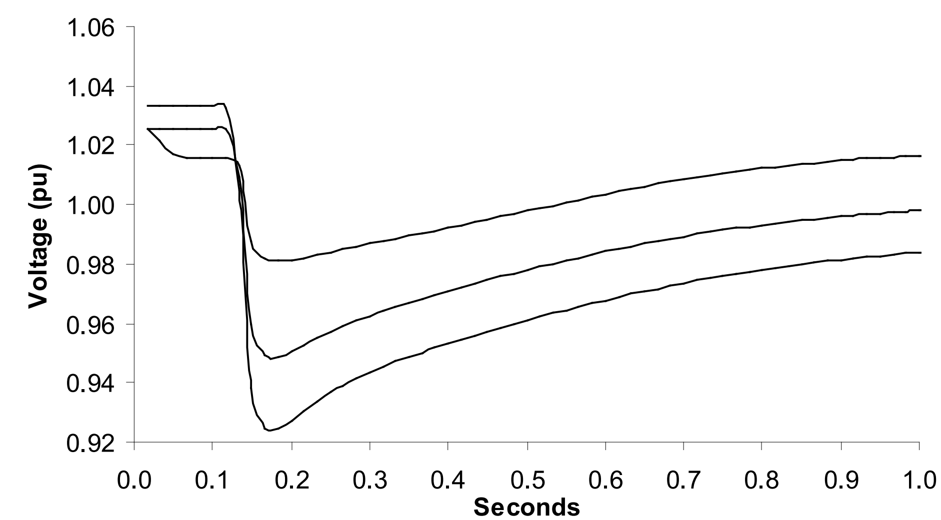




Inrush Currents and Voltage

- **Three Phase Transformer Energization More Complicated due to Coupling, etc.**
- **Sympathetic Inrush: Smaller, Longer Dip and Potential Protection Problems**
- **Inrush Current Magnitude and Duration Determined by: Saturation Curve, Residual Flux, Prospective Flux and Energizing Circuit Impedance (Higher Impedance: Deeper, but Shorter Dip)**
- **Even Harmonics, Steadily Decline**





Conservative Voltage Dip Calculation

- **Maximum Current Reciprocal of Sum of the Source (X), Transformer Primary Leakage (Xp) and Minimum Magnetizing (Xc) Reactances**
- **Assumes Xc + Xp = 2.5*XT (XT is the Sum of Primary and Secondary Leakage Reactances)**
- **How Conservative?**

$$V_{sag} = \frac{X}{(X + 2.5 * X_T)} pu$$

Nagpal, M., T. G. Martinich, A. Moshref, K. Morison, and P. Kundar "Assessing and Limiting Impact of Transformer Inrush Current on Power Quality," IEEE Transactions on Power Deliver, April 2006.

$$V_{\min} = 1 - (\frac{(MVA_{XFMR} / MVA_{SYS})}{(MVA_{XFMR} / MVA_{SYS)}) + 0.025 * X_T)}) pu$$

Minimum Inrush Voltage Table

Ratio of Bus Short Circuit MVA to Transformer MVA	Transformer Percent Impedance									
	6	7	8	9	10	11	12	13	14	15
5	42.9%	46.7%	50.0%	52.9%	55.6%	57.9%	60.0%	61.9%	63.6%	65.2%
10	60.0%	63.6%	66.7%	69.2%	71.4%	73.3%	75.0%	76.5%	77.8%	78.9%
15	69.2%	72.4%	75.0%	77.1%	78.9%	80.5%	81.8%	83.0%	84.0%	84.9%
20	75.0%	77.8%	80.0%	81.8%	83.3%	84.6%	85.7%	86.7%	87.5%	88.2%
25	78.9%	81.4%	83.3%	84.9%	86.2%	87.3%	88.2%	89.0%	89.7%	90.4%
30	81.8%	84.0%	85.7%	87.1%	88.2%	89.2%	90.0%	90.7%	91.3%	91.8%
35	84.0%	86.0%	87.5%	88.7%	89.7%	90.6%	91.3%	91.9%	92.5%	92.9%
40	85.7%	87.5%	88.9%	90.0%	90.9%	91.7%	92.3%	92.9%	93.3%	93.8%

Minimizing Inrush Voltage Dip

- **Method Used Depends on Inrush Severity, Frequency of Energization, Load Sensitivity, Economics, etc.**
- **Minimize Residual or Prospective Flux**
  - Controlled Deenergization
  - Demagnitize Transformer Prior to Energization
- **Put Impedance Between Source and Transformer**
  - Closing Resistor (magnitude and duration important)
  - Remote Energization (can make worse at transformer)
- **Control Switching so Energization Occurs when Residual and Prospective Fluxes Equal**
  - Crude (Slow Disconnect)
  - Sophisticated (3-phase Controlled Closing)

Transformer Inrush Summary

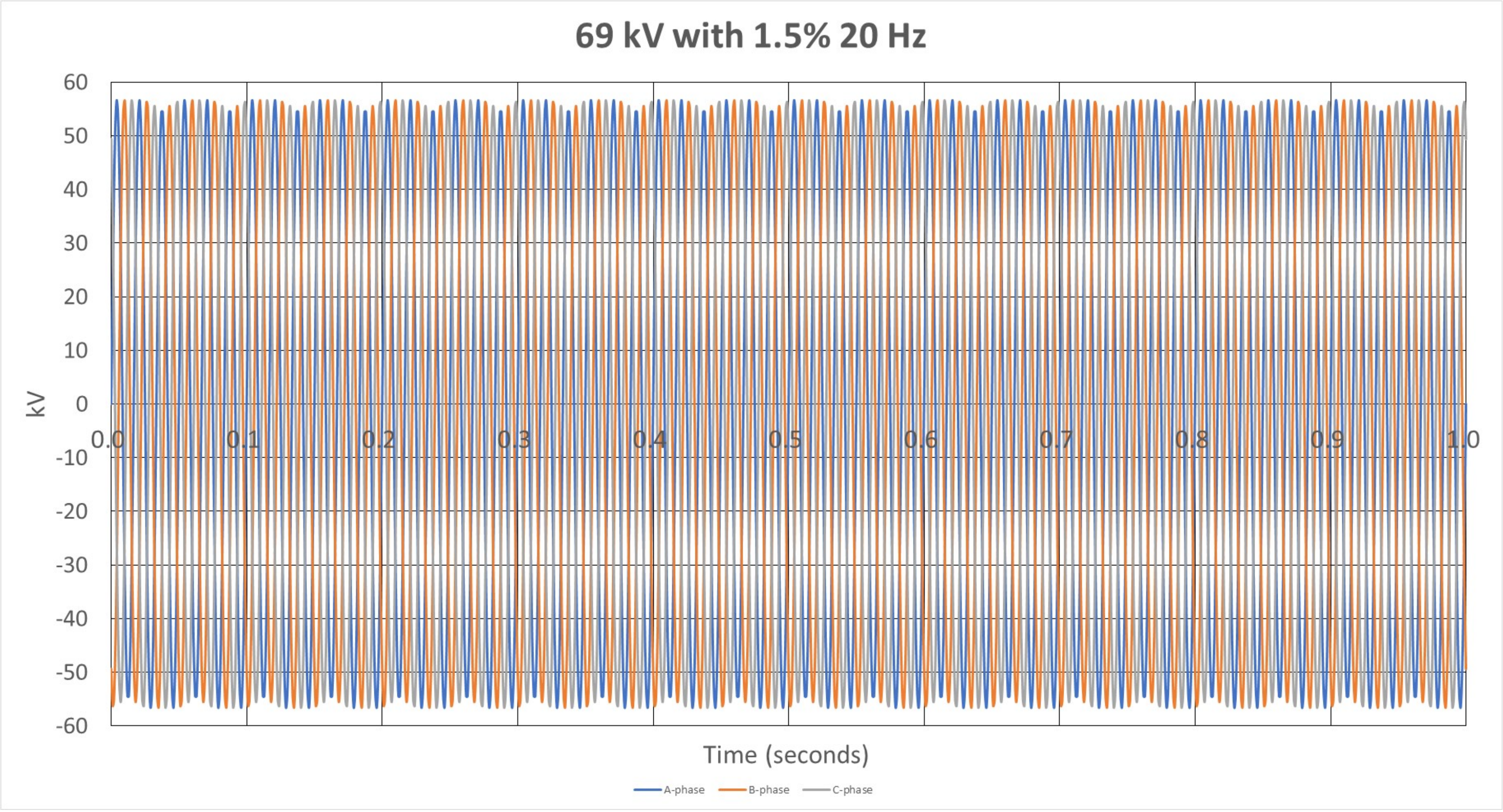
- **Transformer Energization Voltage Dips Becoming More of a Problem?**
- **New Large Transformer Applications Should be Screened to Determine if Detailed Analysis Necessary**
- **Mitigation Effectiveness and Convenience Must be Considered**
- **Controlled Closing - Timing Achievable?**
- **Closing Impedance – Requirements Met?**

Solutions for Voltage Sag Issues

- **Is Tripping Caused by Sag Necessary?**
  - Protection Tripping Load May be set Too Sensitive
  - Surprising how often this is the case
  - Can Less Sensitive Equipment Solve the Problem
- **Solution Should Be Economically Reasonable**
  - Don’t Spend $100 to solve a $10 Problem
  - May Be Better to Desensitize Load than Fix Voltage
- **How can You Fix in Sag?**
  - Fast Switched Capacitors ($)
  - Static Var Compensator ($$)
  - STATCOM ($$$)

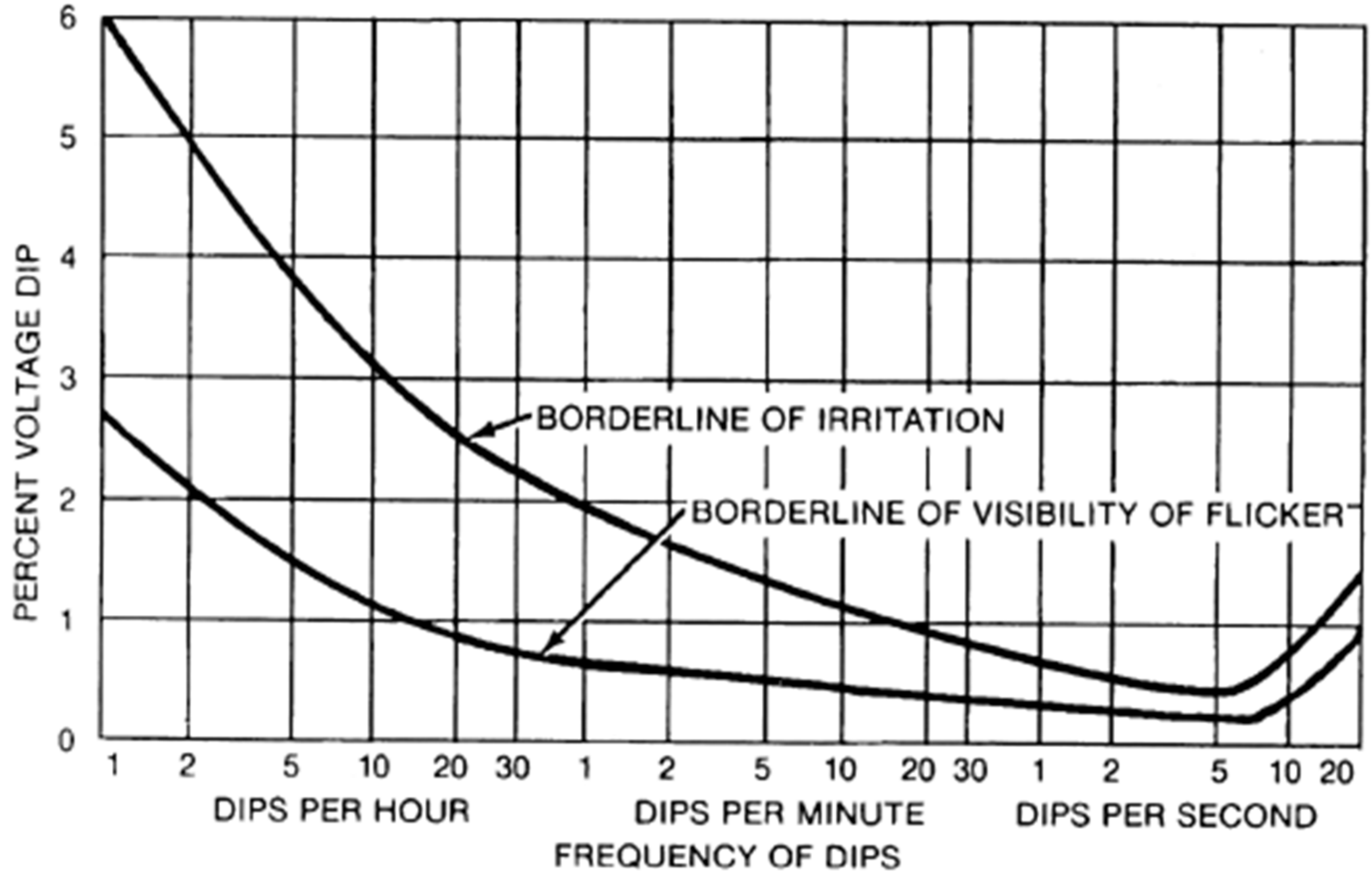
Phenomena #2: Voltage Fluctuation/Light Flicker

- **Voltage Fluctuations**
  - Voltage Changes within Normal Operating Limits
  - Caused by Rapid Changes in Current (Real or Reactive Power Demand)
  - Generally Voltage Varies Less than 6% and below 20 Hz (0.5% at 7 Hz)
  - Single or Multiple Frequencies



GE Flicker Curve

- Based on 120 V Incandescent Lights
- Doesn't Consider Multi-frequency Flicker
- Other Flicker Curves Exist – All Similar



Voltage Fluctuation Causes

- **Equipment with Rapid Current Variations**
- **Large Demand Changes Compared System Strength**
    - Electric Arc Furnaces (AC worse than DC)
    - Static Frequency converters
    - Cycloconverters
    - Rolling Mill Drives
    - Large Motors During Starting
- **Smaller : Welders, Regulators, Cranes, Elevators, etc.**
- **Other: Cap Switching, Xformer Tap Changing, etc.**
- **Intermittent Generators (Wind Turbines)**
- **Low Frequency (<120 Hz) Interharmonics**
- **Loose Connections**

Voltage Fluctuation Effects

- **Flicker – Subjective Human Response to Luminance Changes**
  - Can Cause Fatigue and Loss of Concentration
  - Discomfort and Reduced Work Quality
- **Effects on Equipment – Less Common**
  - Nuisance Tripping due to Relay/Contactor Misoperation
  - Unwanted Triggering of UPS Systems to Battery Mode
  - Problems with some Voltage Sensitive Electronics (Medical Labs, Security Systems, Communications, Test Equipment, Manufacturing Processes, etc.)
  - Increased Losses, Rotor Wear, Changes in Torque & Power and Hunting in Synchronous Motors and Generators
  - Excessive Vibration, Reduced Mechanical Output and Shortened Life for Induction motors
  - Phase-controlled rectifiers with DC-side parameter control: Decreased power factor, generation of non-characteristic harmonics and interharmonics, damage to system components
  - Reduced Efficiency for Electro-Heat Equipment

Voltage and Luminous Flux

$$\varphi = V^X$$

- **Where φ =luminous flux, V = applied Voltage and X =exponent depending on slight source**
- **X is Typically 3.1 to 3.7 for Incandescent Lights**
- **X is Typically around 1.8 for Fluorescent Lights**
- **Incandescent Lights are more sensitive to voltage fluctuations than Fluorescent Lights**

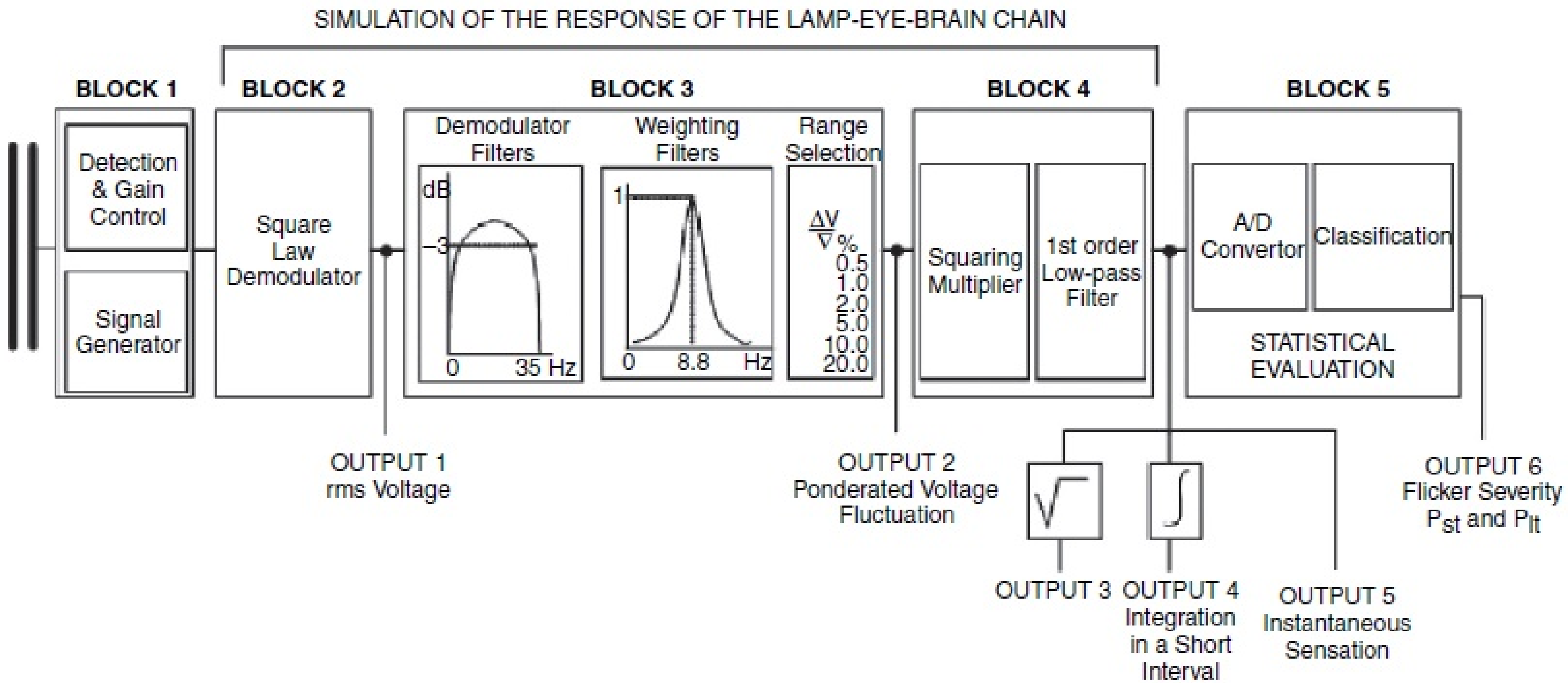
Measurement

- **Used to Evaluate Supply Quality and Type Test Equipment Emission Levels**
- **Based on Effects on Lighting and Influence on Humans**
  - P_{ST} – Short-Term Flicker Severity
  - P_{LT} – Long-Term Flicker Severity
- **IEC Flickermeter Adapted by IEEE with Appropriate modifications for 120 Volt Systems**
- **IEC 61000-4-15 & IEEE 1453**

IEC Flickermeter

- **Simulates Physiological Visual Perception (Lamp-Eye-Brain)**
- **Five Blocks Defined in IEC 61000-4-15 (Testing and Measurement Techniques – Flickermeter – Functional Design and Specification) Accepted by IEEE 1453 with Modifications for 120 V System**
- **Block 1 – Independent Voltage Adaptor: Allows Measurements to be Expressed in Percent**
- **Block 2 – Square Law or Quadratic Demodulator: Separates Fluctuation from Main Signal**

IEC Flickermeter



- **Block 3 - Demodulator and Weighting Filters: Three Filters to Remove Unnecessary Frequencies and Weight Remaining Frequencies to Model eye-brain response**
- **Block 4 – Nonlinear Variance Estimator: Completes Eye-Brain Response Using Additional Filters and Multipliers**
- **Block 5 – Statistical Evaluation: Output Categorized in Classes and a Cumulative Distribution Calculated**

IEEE 1453 Limits

Levels	Compatibility	Planning	
	LV ≤ 1 kV	1 kV < MV ≤ 35 kV	HV-EV > 35 kV
Pst	1.0	0.9	0.8
Plt	0.8	0.7	0.6

Note: LV ≤ 1 kV, 1 kV < MV ≤ 35 kV, 35 kV < HV ≤ 230 kV, EHV > 230 kV

- ***Pst*** **is the weighted average flicker over a 10 minute interval**
- ***Pit*** **represents flicker measured over a two hour interval (cube root of 1/12 of the sum of 12 consecutive** ***Pst*** **values cubed)**
- **Different limits for compatibility (perception) and planning.**
- **Planning limits not to be exceeded >1% of the time (99% probability level) and compatibility limits are not to be exceeded >5% of the time (95% probability level) over a minimum of a week**
- **If the limits met at the point of common coupling (PCC), no other customer's service should be impaired.**

Flicker Rules of Thumb

- **EPRI - Estimate of Flicker without Compensation**
  - $P_{st} = K_{st} * SCVD = K_{st} * Sccf/Sccn$
  - SCVD = Short Circuit Voltage Depression = Sccf/Sccn
  - Sccf = Short circuit capacity of Arc Furnace at Point of Common Coupling
  - Sccn = Short circuit capacity of system at Point of Common Coupling
  - Kst = varies between 50-100 depending on furnace MVA rating and construction
- **EPRI - Estimate of Flicker with Compensation or DC type furnace**
  - $P_{st} = K_{st} * SCVD * \text{Reduction Factors} = K_{st} * Sccf/Sccn * \text{Reduction Factors}$
  - Reduction Factors
    - High Reactance Design 0.8 to 1.0
    - DC Furnace 0.5 to 0.75
    - Conventional SVC 0.5 to 0.75
    - STATCOM (dependant on size and controls) 0.17 to 0.33
- **IEC - If Smax/Ssc ≤ 0.1% no additional analysis required**
  - Smax is maximum load MVA at point of common coupling
  - Ssc is short circuit MVA at point of common coupling
- **Identical furnaces**
  - Two: rating multiplied by the square root of two
  - Multiple: rating multiplied by the cube root of the number of furnaces.

Voltage Fluctuation Solutions

- **Increase System Strength**
  - New Line or Transformer
  - Generation
- **Reduce Load Current Draw**
  - Add Reactor in Series with Load
  - Will Likely Make Process Less Efficient
- **Fast Acting Var Supply – STATCOM**
  - Usually Less Expensive than Strengthening System
  - Used at Some Arc Furnaces

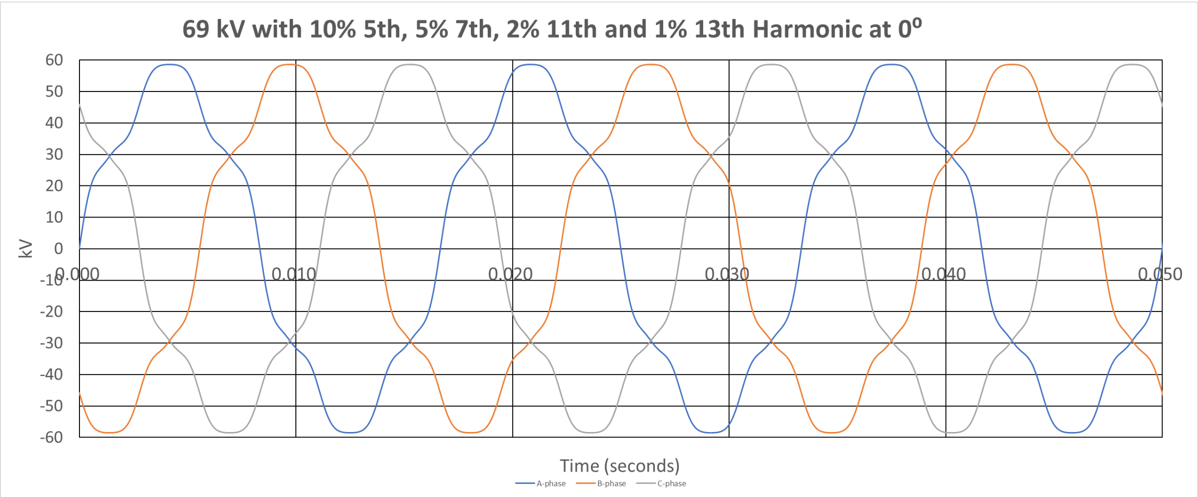
Standards

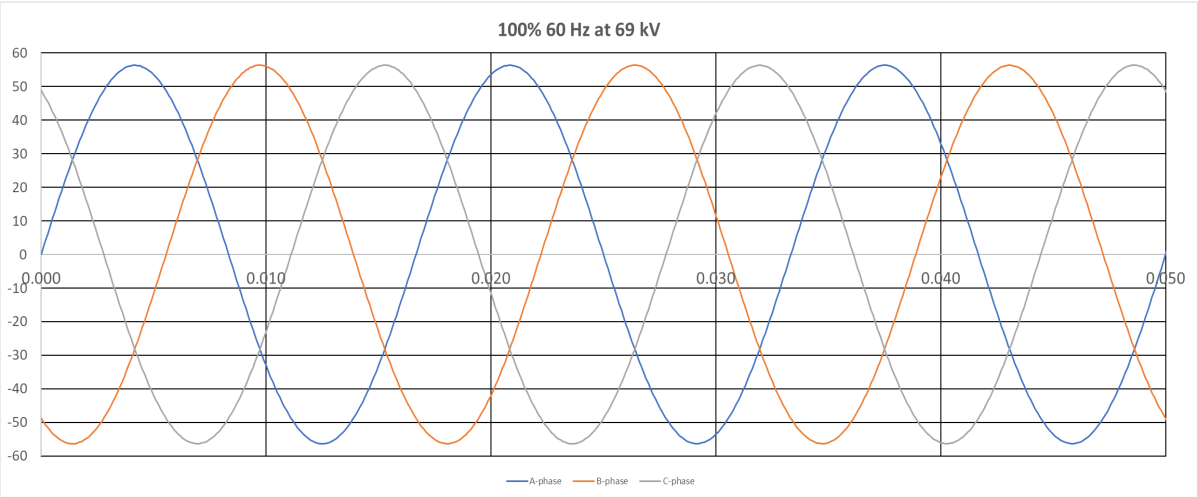
- **Much More information in Standards**
- **IEEE**
  - IEEE 1453-2015 - IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems
  - IEEE 141-1993 - IEEE Recommended Practice for Electric Power Distribution for Industrial Plants
  - IEEE 519-2014 - IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems
- **IEC**
  - IEC TR 61000-3-7:2008 - Electromagnetic compatibility (EMC) - Part 3-7: Limits - Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems
  - IEC 61000-4-15:2010 - Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques - Flickermeter - Functional and design specifications

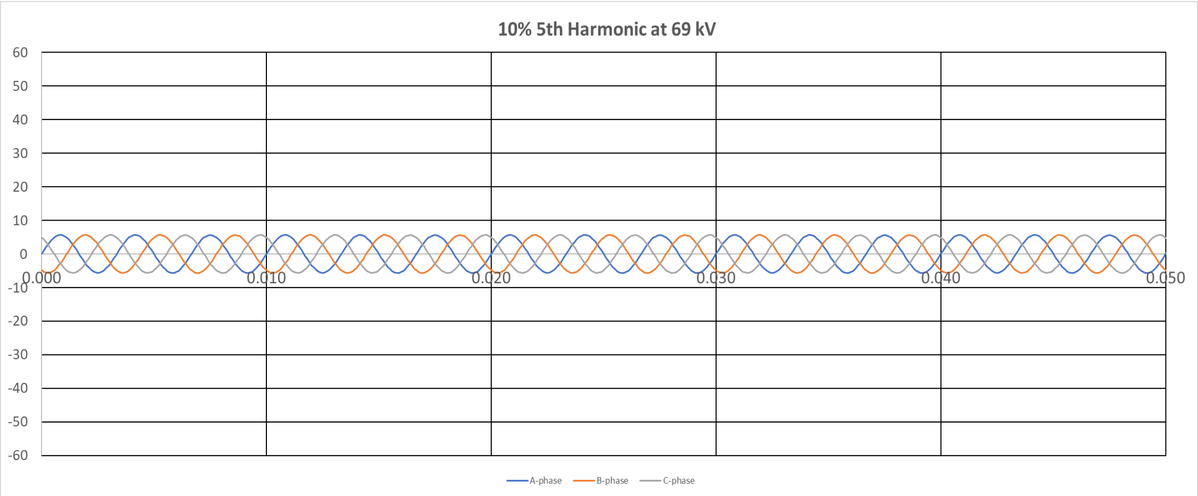
Phenomena #3: Harmonics

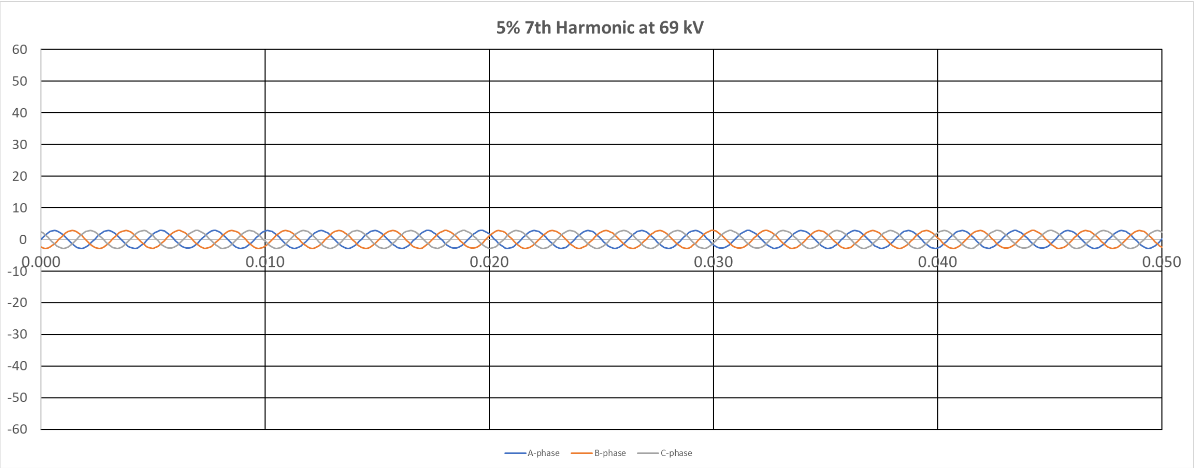
- **What are Power System Harmonics?**
  - Additional Waveform Components Whose Frequency is Multiples of the Fundamental – Additional Heating (Aging)
  - With a 60 Hz Fundamental: 120 Hz is 2nd Harmonic, 180 Hz is 3rd Harmonic, etc.
- **Any Waveform Repetitive at Fundamental Frequency Can be Described by Fundamental & Harmonic Components**
- **If Only Odd Harmonics Present, Waveform will be Symmetrical Across X-Axis**
- **Harmonic Angles Affect Waveshape**
  - Usually Not a Concern
  - Can Affect Peak Value – Higher Peak Can Stress Insulation

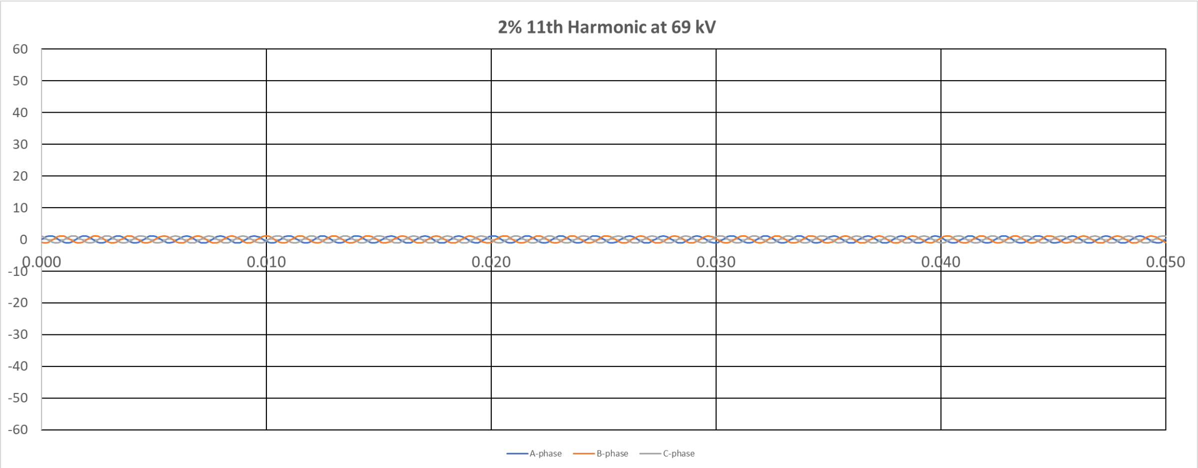
Waveform and Harmonic Components

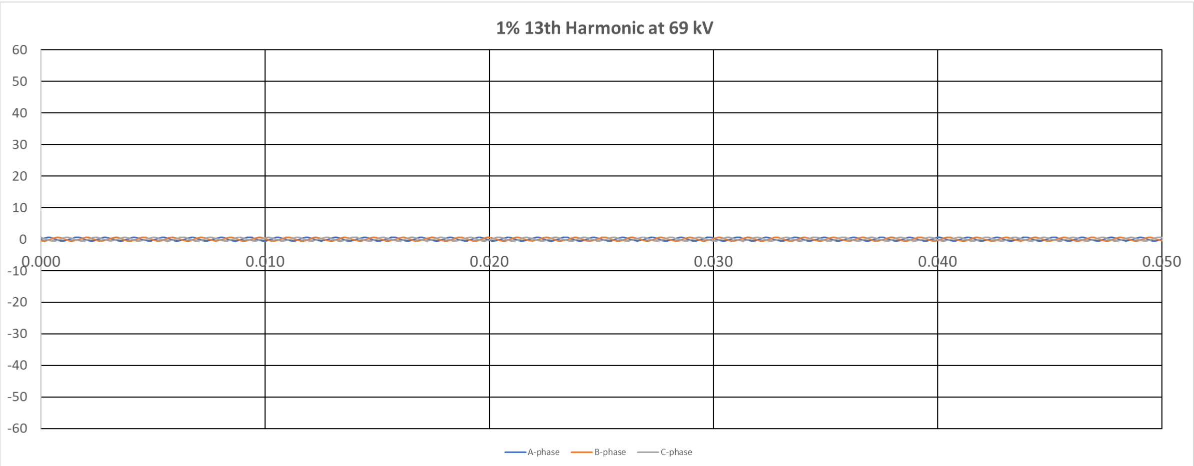




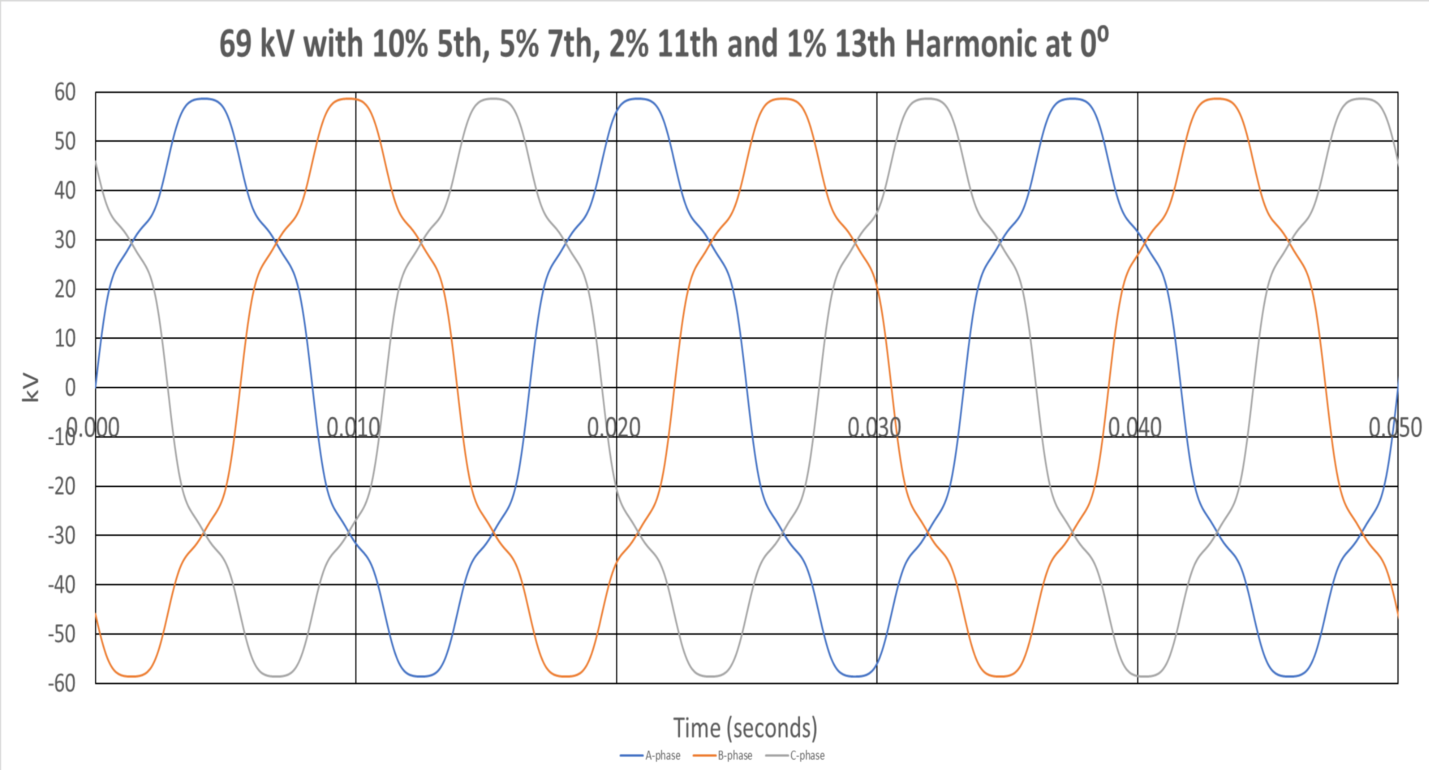


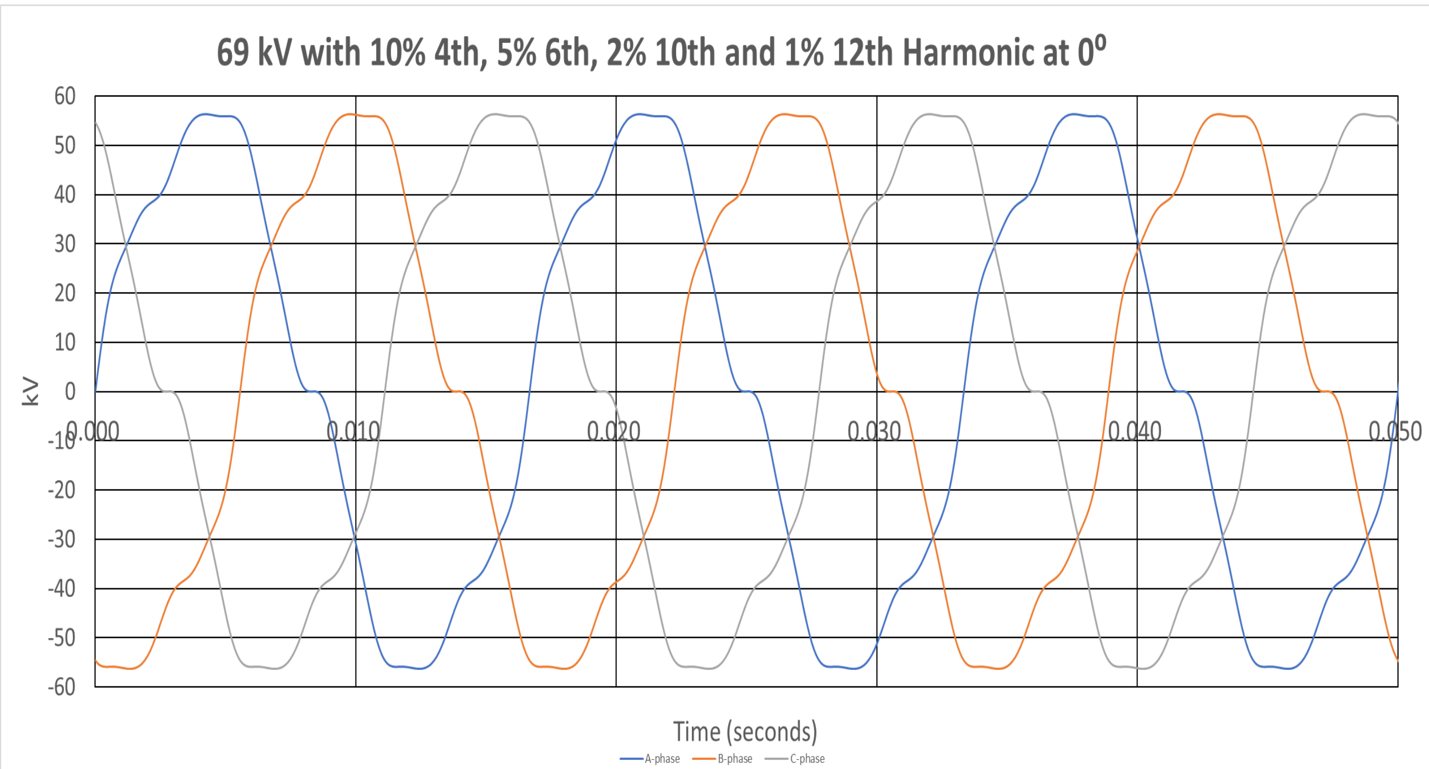






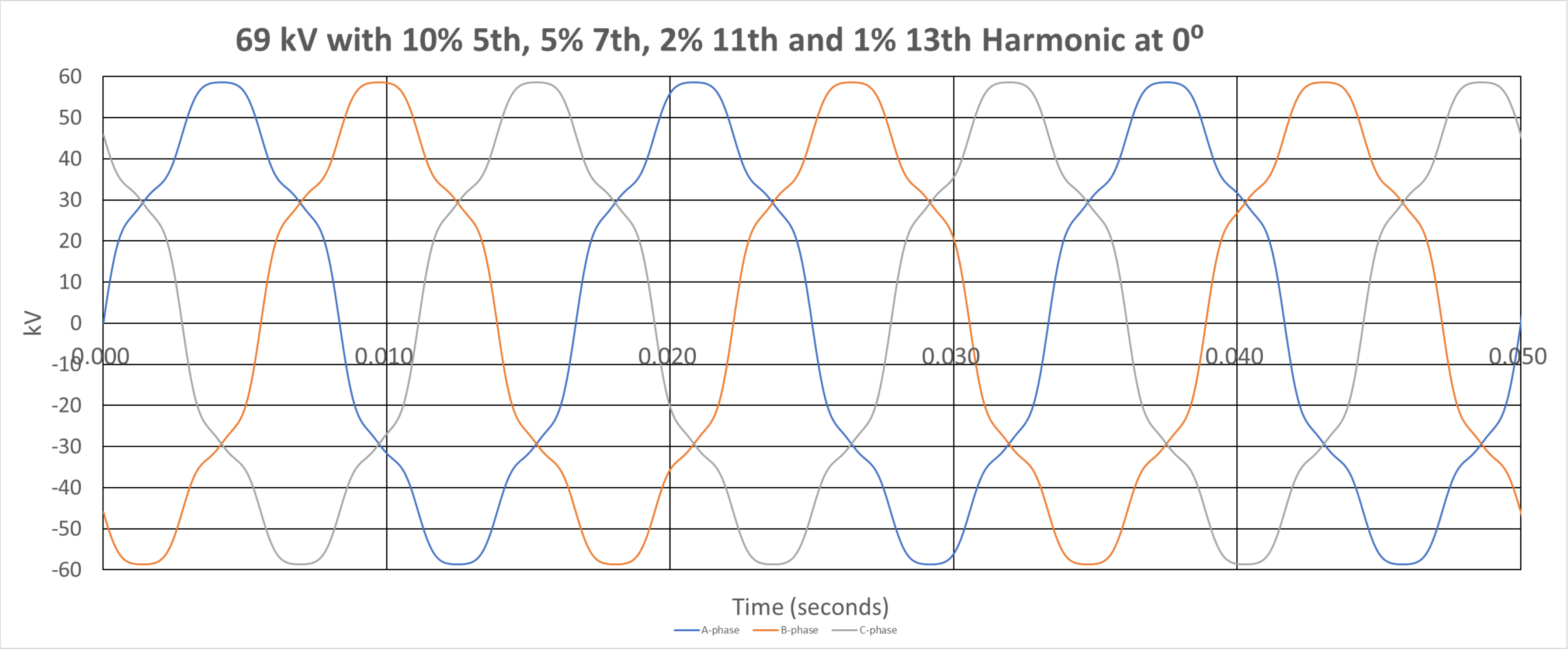
Odd and Even Harmonics

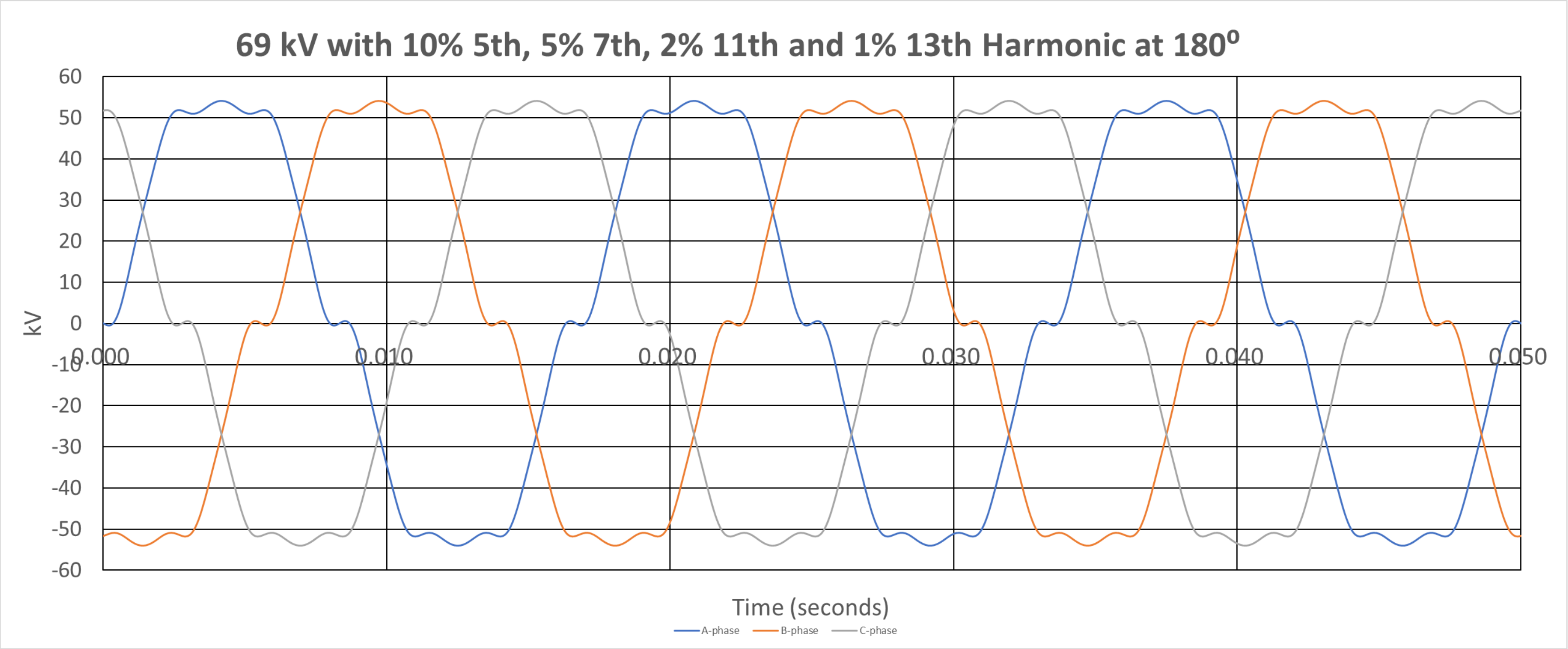




- **Waveform with Only Odd Harmonics is Symmetrical Across X-Axis**
- **Waveform with Even Harmonics is Not**

Different Harmonic Angles





Harmonic Propagation

$$X_C = \frac{1}{j\omega C} \qquad X_L = j\omega L$$

- **As Frequency Increases, Reactor Impedance Goes Up, Capacitor Impedance Goes Down**
- **At Higher Frequencies Shunt Capacitors are Harmonic Sink**
- **Generators also Tend to be Harmonic Sinks**
- **Power Systems are Primarily Inductive - High Frequency Harmonics Don’t Travel Far Before Sinking in Shunt or Stray Capacitance**

Resonant Frequency

$$f = \frac{1}{2\pi\sqrt{LC}}$$

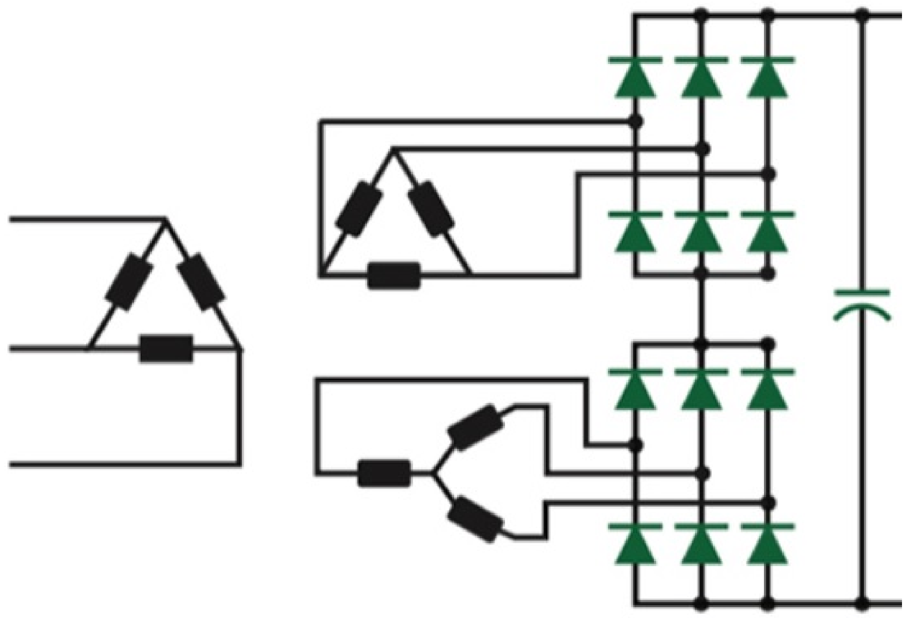
- **Series LC Circuit at Resonance Frequency is a Low Impedance Path (Filter)**
- **Parallel Resonance Increases Impedance at Harmonic Frequencies**
- **Since System is Primarily Inductive, Every Shunt Capacitor has a frequency it Resonates at**
- **Capacitors Near Harmonic Sources have a Parallel Resonance Frequency with the System**

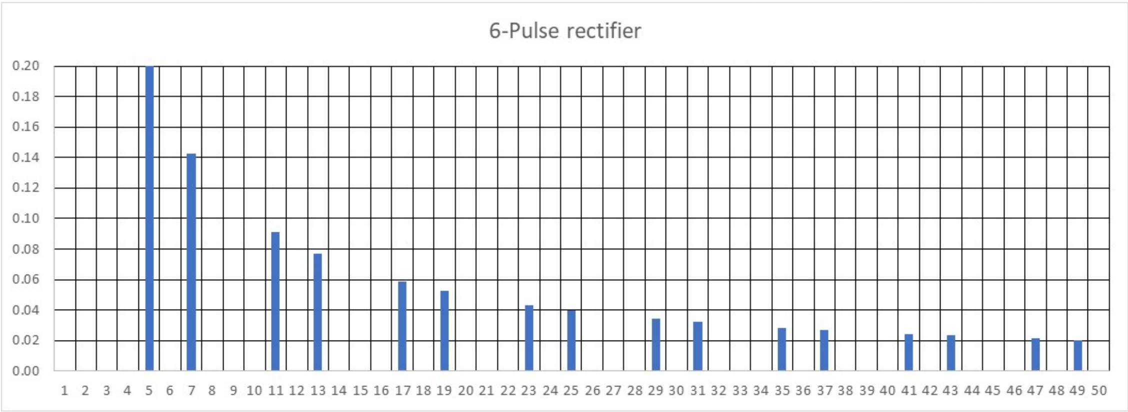
Harmonic Sources

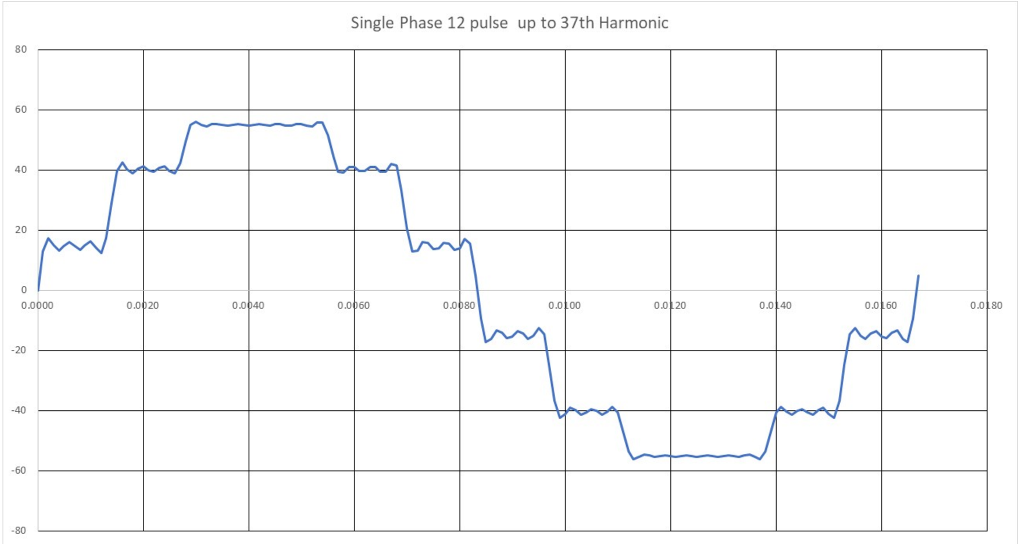
- **Non-linear loads and sources (no kidding!)**
- **AC/DC Rectifiers (loads) and Inverters (sources)**
  - Converters of various design are everywhere!
  - LCC HVDC and SVC that use Thyristors
  - Battery Charges and Computer Power Supplies
  - Power Electronics
- **Arcing Devices (Furnaces, Fluorescent Lighting)**
  - Compact Fluorescent Lights, Dimmer Switches, etc.
  - Welding Machines
- **Saturated Transformers and Motors**
  - Less Metal is Cheaper – Operate in saturation area

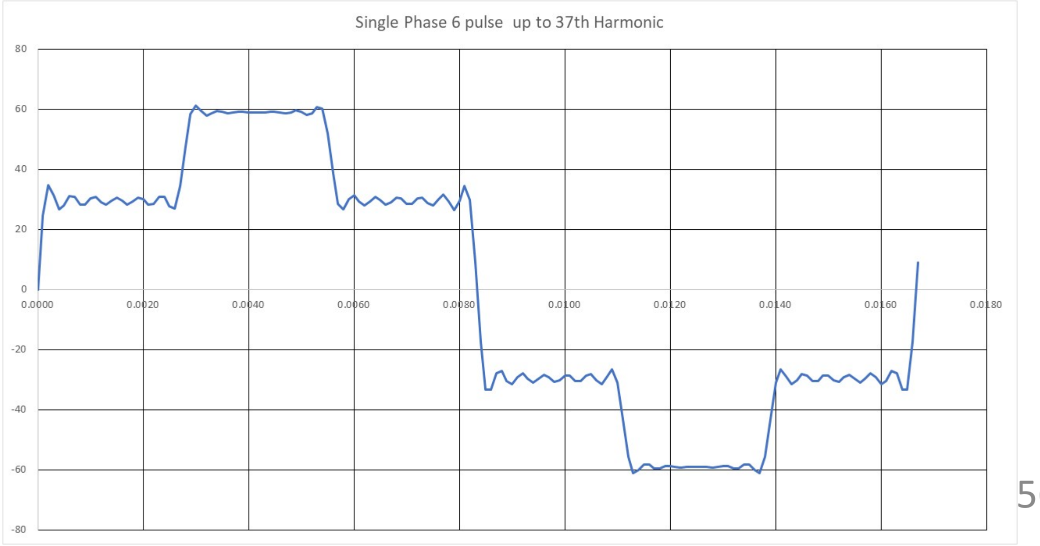
Rectifiers

- **6 and 12 pulse Rectifiers Most Common**
  - 6 pulse produce harmonics with frequencies of 6n±1
  - 12 pulse produce harmonics with frequencies 12n±1
  - 6-pulse cheaper – Largest Harmonic Usually the 5th









Effects of Harmonics

- **Heating – Extra current can overheat equipment, especially transformers, motors , cables, etc.**
- **Neutral overload (relay misoperation)**
- **Communication Interference**
- **Loss of Machine Efficiency**
- **Nuisance tripping of thermal protection**
- **Measurement Errors**
- **Harmonic Higher and Effects Worse if Resonance Present!**

Harmonics and Capacitors

- **Effects on Capacitors**
  - Heating, Dielectric Stress, Increased Losses
  - Capacitors are a Sink for Harmonics
  - Can Reduce Capacitor Life
  - Potential for Resonance – Worsen Harmonic Problems
  - Cap tripping and Fuse Blowing
- **IEEE 18-2002**
  - Caps Designed for up to 135% kvar Rating
  - Continuous RMS Overvoltage 110%, Peak Overvoltage 120% and 180% Overcurrent.

Cap & 20% 5th Harmonic Voltage

- $X_C = \frac{1}{2\pi f C}$, **4160 V, 300 kV Cap**
- **Xc = 57.5 Ω at 60 Hz, Xc = 11.54 Ω at 300 Hz**
- **Currents**
  - $I_{60Hz} = \frac{4160V}{\sqrt{3} * 57.7\Omega} = 41.62\text{ A}$
  - $I_{300Hz} = \frac{0.20 * 4160V}{\sqrt{3} * 11.54\Omega} = 41.62\text{ A}$
  - Total RMS Current = $\sqrt{41.62^2 + 41.62^2}$ = 58.86 A
  - 58.86/41.62=141.4%
  - This is > 110% Continuous and 120% Peak Current Limits!
  - Fuse Should Blow! Or Cap will suffer loss of life.
- **Capacitor Switching can cause transient harmonics that will flow through cap as well.**

Capacitor Resonance

- **Parallel Resonance Causes Current Multiplication**
- **Series Resonance Causes Voltage Magnification**
- **Can damage nearby equipment**
- **Harmonic Resonance should be checked before capacitor application**
  - Convert Short circuit into L calculate resonance frequency!
  - Dugan Rule – Resonance always at 5th harmonic!

Harmonics and Transformers

- **Harmonics Combined with Transformer Non-linear Core Increase losses and Heating in Transformers**
- **This Can Shorten Transformer Life**
- **Transformers Applied Near Harmonic Loads Should be Derated or K-Factor Transformers Applied**
- **K-Factor Transformers Designed for Harmonics**
  - Double Sized Neutral, Heavier Copper and Multiple Conductors or Different Geometry

Harmonics and Equipment

- **Electronics – Usually OK if Below Harmonic Limits**
  - May Both Produce and Be Affected by Harmonics
  - My Be Sensitive to Changes in Zero Crossing Point
  - Inaccuracies Can be a Problem with Meters, Relays, Medical Devices, etc.
- **Cables – at High Levels Derating May be Necessary**
  - I^2*R losses increase and Skin Effect (heating)
  - Both Worse at Higher Frequencies
- **Motors and Generators**
  - Increased Losses
  - Oscillations Due to Negative Sequence Harmonics

Measurement

- **Point of Common Coupling (PCC)** –Where multiple customers may be connected: Metering point, service entrance or facility transformer.
- **Point of Service** - Connection point between customer and utility
- Harmonic Sources usually Modeled as Currents that Distort Voltage
- While Individual Harmonics can be a problem, Total Harmonic Distortion or Total Demand Distortion Normally Relate to Heating
- THD: Total Harmonic Distortion (Voltage or Current):
- $THD = \sqrt{\frac{sum\ of\ squares\ of\ amplitudes\ of\ all\ harmonics}{square\ of\ amplitude\ of\ fundamental}} * 100\%$
- TDD: Total 15 minute Demand Distortion (Used for Current)
- $TDD = \sqrt{\frac{sum\ of\ squares\ of\ amplitudes\ of\ all\ harmonic\ currents}{square\ of\ maximum\ demand\ load\ current}} * 100\%$
- Other: TIF (Telephone Interference Factor), etc.

IEEE 519 – 2014 Voltage Limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Current Limits (120 V to 69 kV)

Voltages Between 120 V to 69 kV and All Generators

Maximum Harmonic Current Distortion for Odd Harmonics (Percent of I_L)

I_{SC} = maximum short circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at PCC
Note 1: Even Harmonics are limited to 25% of the odd harmonic limits listed above.
Note 2: Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed.
Note 3: All power generation equipment is limited to the I_{SC}/I_L<20 limits listed in this table.

I_{SC}/I_L	Individual Harmonic Order					
	< 11	11<=h<17	17<=h<23	23<=h<35	35<=h	TDD
<20	4.0%	2.0%	1.5%	0.6%	0.3%	5.0%
20<50	7.0%	3.5%	2.5%	1.0%	0.5%	8.0%
50<100	10.0%	4.5%	4.0%	1.5%	0.7%	12.0%
100<1000	12.0%	5.5%	5.0%	2.0%	1.0%	15.0%
>1000	15.0%	7.0%	6.0%	2.5%	1.4%	20.0%

Current Limits (>69 to 161 kV)

- **Maximum Harmonic Current Distortion for Odd Harmonics (Percent of I_L)**

I_{SC}/I_L	Individual Harmonic Order					
	< 11	11<=h<17	17<=h<23	23<=h<35	35<=h	TDD
<20	2.0%	1.0%	0.75%	0.3%	0.15%	2.5%
20<50	3.5%	1.75%	1.25%	0.5%	0.25%	4.0%
50<100	5.0%	2.25%	2.0%	0.75%	0.35%	6.0%
100<1000	6.0%	2.75%	2.5%	1.0%	0.5%	7.5%
>1000	7.5%	3.5%	3.0%	1.25%	0.7%	10.0%

I_{SC} = maximum short circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at PCC
Note 1: Even Harmonics are limited to 25% of the odd harmonic limits.
Note 2: Current distortions that result in a dc offset are not allowed.
Note 3: All power generation equipment is limited to the I_{SC}/I_L<20 limits listed.

Current Limits (>161 kV)

- **Maximum Harmonic Current Distortion for Odd Harmonics (Percent of I_L)**

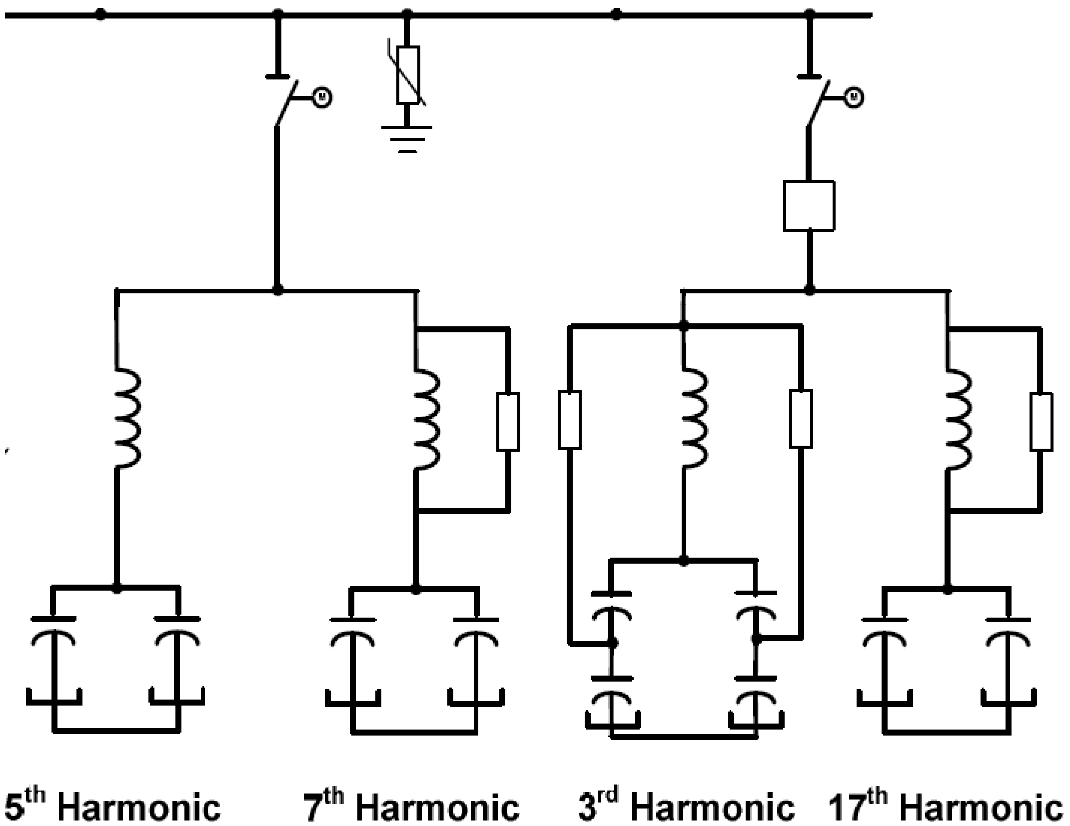
I_{SC}/I_L	Individual Harmonic Order					
	< 11	11<=h<17	17<=h<23	23<=h<35	35<=h	TDD
<50	2.0%	1.0%	0.75%	0.3%	0.15%	2.5%
>50	3.0%	1.5%	1.15%	0.45%	0.22%	3.75%

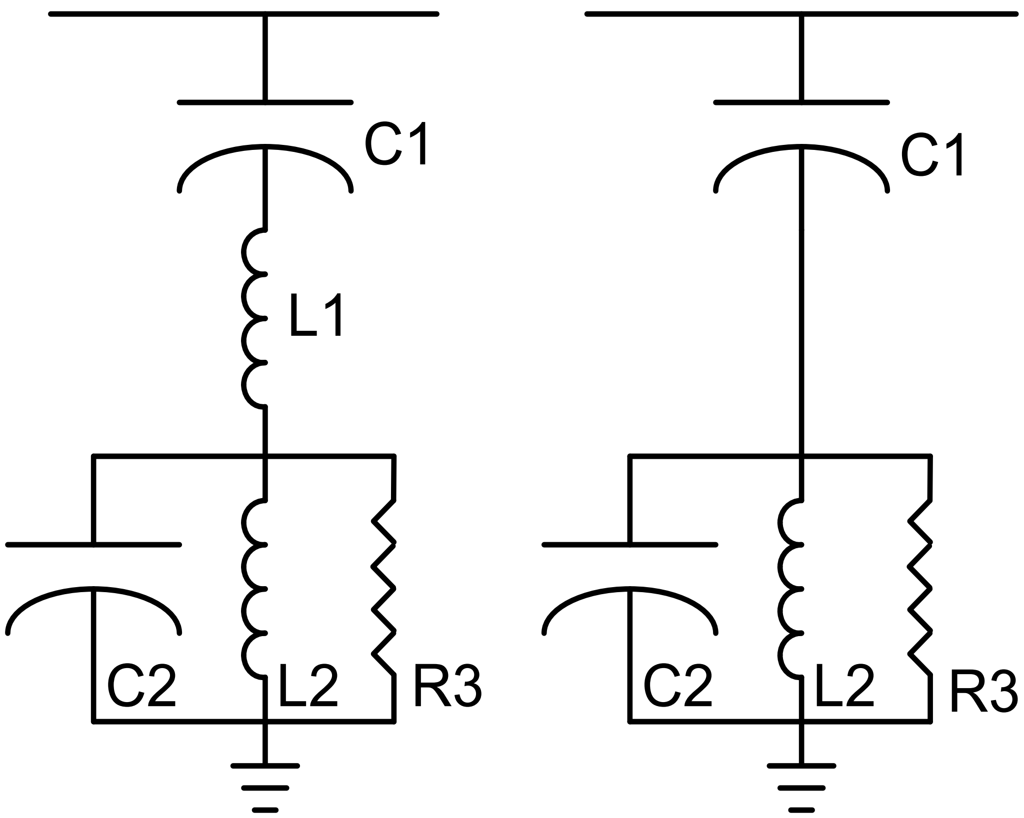
I_{SC} = maximum short circuit current at PCC
I_L = maximum demand load current (fundamental frequency) at PCC
Note 1: Even Harmonics are limited to 25% of the odd harmonic limits.
Note 2: Current distortions that result in a dc offset are not allowed.
Note 3: All power generation equipment is limited to the I_{SC}/I_L<50 limits listed.

Harmonic Solutions

- **Adjusting Harmonic Source Operation: Is Operation (Mis-operation) causing Harmonics Necessary?**
- **Filters**
  - Capacitors Usually Needed so adding a reactor to tune is an obvious solution
  - Filters Can Be for Single or Wide Spectrum
  - High Pass Filters May be Necessary
- **Hardening Equipment to Harmonics**
  - Over-Rated or Equipped with Own Filters

Filter Examples





- Left – Benson Lake SVC Filters
- Right Mackinac HVDC Filter Modification
- Sized for Frequencies and Reactive Requirements
- Simulations Required to Confirm Design

Standards

- IEEE 519-2014 - IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems
  - 1992 Version longer with more discussion
  - 1992 Revision Draft Application Guide Available
- IEC 61000-4-7: General Guide on Harmonics and Interharmonics Measurements and Instrumentation
- IEC 61000-3-2: Limits for harmonic current emissions (equipment input current ≤ 16A per phase)
- IEC 61000-3-4: Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A per phase

Phenomena #4: Interharmonics

- What are Interharmonics? - Definitions
- Where Do They Come From? - Sources
- What Do They Do? – Effects
- How are They Measured? – Metering
- What Levels are Acceptable? – Standards/Guidelines/Limits
- How are they Controlled? - Mitigation

Interharmonic Definition

- **IEEE: “A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating”**
- **IEC: “Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental. They can appear as discrete frequencies or as a wide-band spectrum.”**

What are Interharmonics?

f_1 = fundamental frequency	
If n – Any Positive Integer	If m – Any Positive Non-Integer
nf_1 is the n^{th} Harmonic	mf_1 is the m^{th} Interharmonic
If $n = 0$, nf_1 is DC	If $m < 1$, mf_1 is a Subharmonic

- **Periodic Waveforms: Only Harmonic Components**
- **Interharmonics not Periodic at Fundamental**
  - All Non-Periodic Waveforms Contain Interharmonics
  - Interharmonics are a Measure of Non-Periodicity

Interharmonics Compared to Harmonics

- **Both Add Signal(s) to the Power Frequency**
- **Both Can Be Magnified by Resonance(s)**
- **Usually Harmonics a Limited Number of Stable Frequencies, Interharmonics Varying Frequencies or Wide-Spectrum**
- **Interharmonics Provide More Opportunities for Undesirable Resonance**
- **Intrharmonics Usually Lower in Magnitude**

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Interharmonic Producing Phenomena

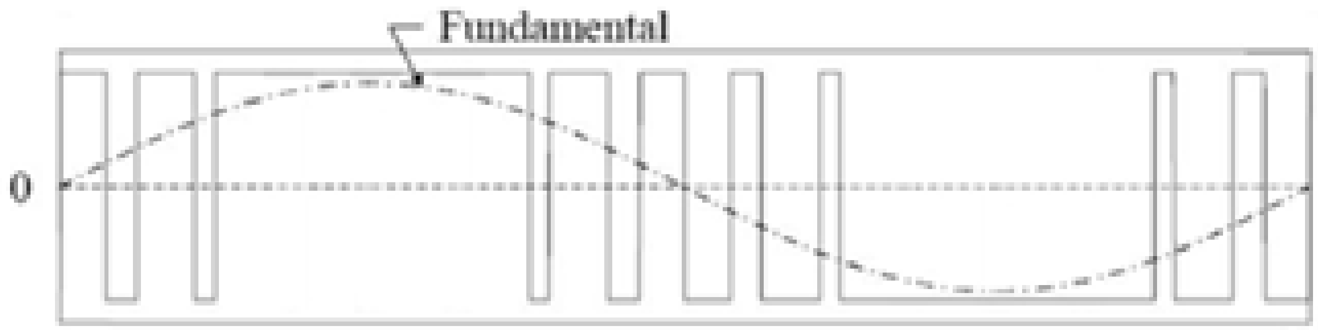
- **Rapid Non-Periodic Load/Current Changes**
  - Loads Operating in a Transient State
  - Voltage or Current Amplitude Modulation
- **Asynchronous Switching Static Converters**
  - Insulated Gate Bipolar Transistors (IGBT), Unlike Thyristors, Can Be Turned Off
  - Voltage Sourced Converters (VSC) Use IGBTs to Regulate Vars, Blackstart, etc.
- **Improve Efficiency, Flexibility and Reliability**
- **Use Increasingly Sophisticated Power Electronics and Communication Systems**
- **The Power Electronics Can Increase Interharmonic Levels and Sensitivity to Interharmonics**

Some Specific Interharmonic Sources

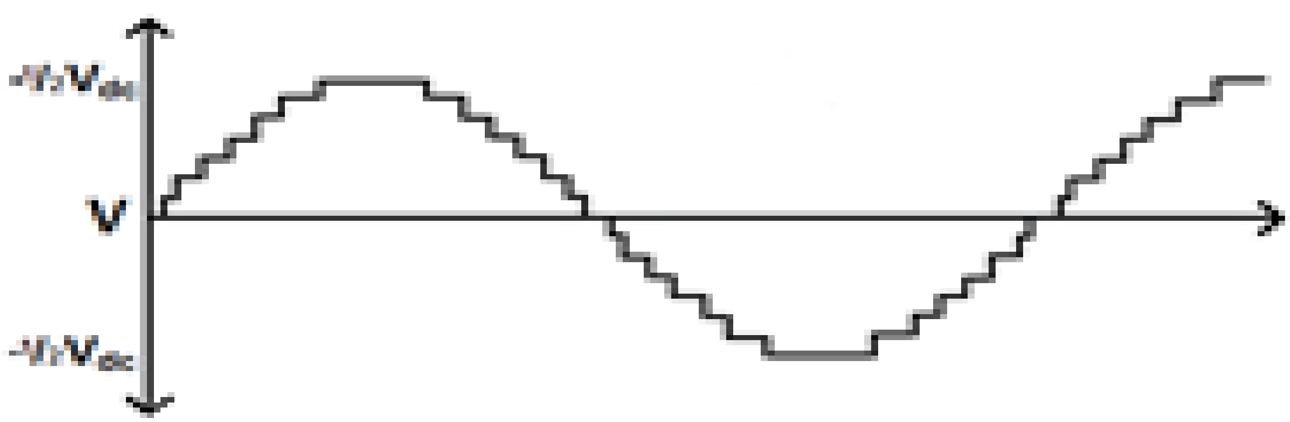
- **Arcing Loads – Arc Furnaces, Welding**
- **Induction Motors – Saturation, Variable Torque, Asymmetry, etc.**
- **Electronic Frequency Converters – Filtering**
- **Traction Power Supplies – Fixed Frequencies**
- **VSCs – Wind Mills, HVDC, etc.**
- **Power Line Communications – Single or Multiple Interharmonic Frequencies**

Voltage Sourced Converters

- **Interharmonics Depend on Design (Pulse Number, Levels, etc.)**
- **Pulse Width Modulation (PWM) More**



- **Modular Multi-Level (MML) and Cascaded Two-Level Designs Generally Less Distortion**



One Way Power Line Communications

- **System Protection Communications**
  - Usually a Limited Number of Frequencies
  - Limited Information to Few Receivers
  - Confined to Small Area by Wave Traps
  - Usually Only Sent During an Event (Rare)
- **Ripple Control of Loads, Capacitors, etc.**
  - Usually a Limited Number of Frequencies
  - Limited Information to Many Receivers
  - Signal Can Be Sent to a Wide Area
  - Signal Usually Sent Infrequently

Two Way Power Line Communications

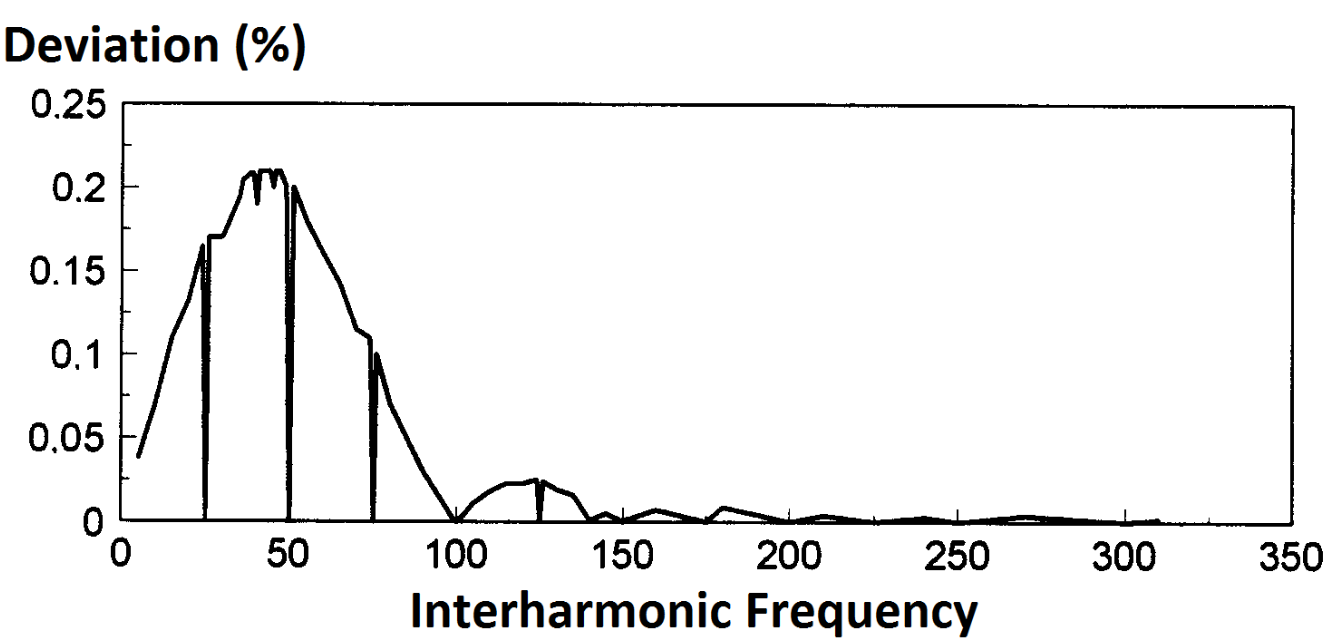
- **Smart Meter Communications**
- **Various Levels of Data Intensity**
  - Minimal – Monthly Usage for Billing
  - High Intensity – Time of Day Billing, Outage Information, etc.
- **Communicates with Hundreds of Meters**
- **Voltage and/or Current Send Digital Bits**
- **Reliable: Multiple Attempts/Error Checking**
- **A Wide Range of Interharmonics**

“Typical” Interharmonic Characteristics

- Generated and Transferred to Any Voltage
- Relatively Little Interharmonic Measurement Data Publicly Available
- “Typical” Transmission Levels Below 0.02%
- Resonance Can Increase Levels to 0.5%
- Typically an Order of Magnitude Below Harmonic Distortion Levels

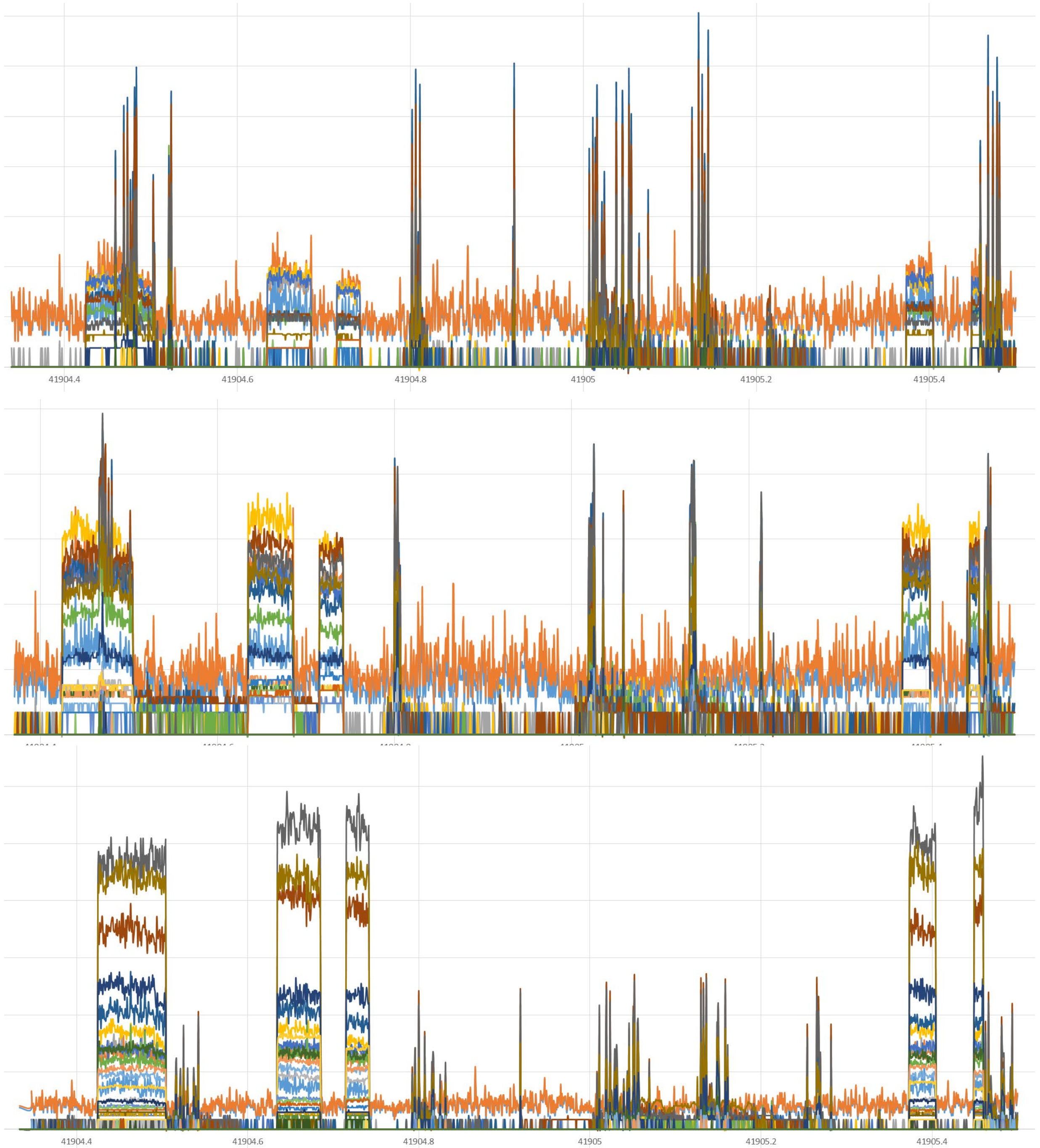
Interharmonic Effects

- **Some Effects Similar to Harmonics**
  - Overloads: Additional Losses, Heating and Saturation
  - Oscillations: Mechanical, Acoustic or Communications
  - Distortion: Affects Zero Crossing or Peak Magnitude
- **Light Flicker – Magnitude & Frequency**
  - RMS Voltage Variation for 0.2% Interharmonic
  - Interharmonics above 2nd Harmonic Not an Issue



Power Line Communication Effects

- Communications are Non-Periodic (Interharmonics)
- A Single Frequency Might be Avoided
- Similar Frequencies Could Interfere
- Increasing Signal Could Cause Flicker



Interharmonic Measurement Requirements

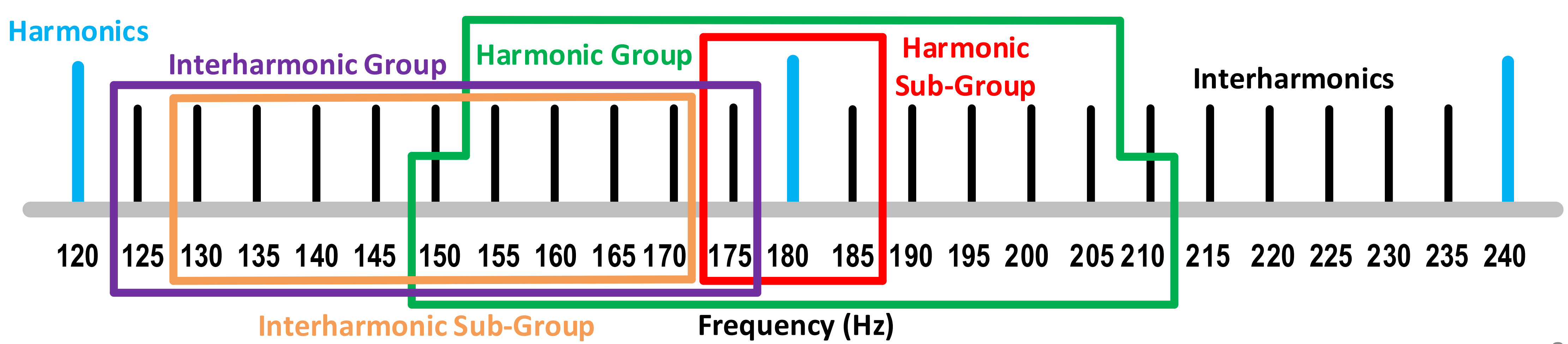
- More Data Intensive than for Harmonics
- Fourier Transform Example: 60 Hz, 50th Harmonic (3000 Hz), and 71.2 Hz Interharmonic
- Harmonic Only: Period = 16.67 msec (one Cycle), Min. Sample Freq. = 4 x 3000 Hz = 12,000 Hz

  Sample Size: 0.0167 Sec * 12,000 Hz = 200
- With Interharmonic: Period = 5 Seconds (0.2 Hz Fundamental Fourier Frequency), Same Minimum Sample Frequency (12,000 Hz)

  Sample Size = 5 Sec* 12,000 Hz = 60,000

Standardized Interharmonic Measurements

- IEC 61000-4-7:2002 General Guide on Harmonic and Interharmonic Measurements and Instrumentation
- For 60 Hz System: 12 Cycle Basis (5 Hz Resolution)
- Based on Concept of Grouping
- Magnitude is Square Root of Sum of Squares of Group Components) Note: Component Angle Information Lost and Waveform Can't be Reconstructed.



Interharmonic Measurement Definitions

- Same Harmonic/Interharmonic Group/Sub-Group Definitions Used for Voltage and Current
- Interharmonic Group Below Fundamental (Sub-Harmonic) is Interharmonic Zero (Usually)
- Interharmonic Group: All 5 Hz “Bins” Between Harmonics

$$IG_N = \sqrt{\sum_{k=1}^{11} Y^2_{(60Hz*N+5Hz*k)}}$$

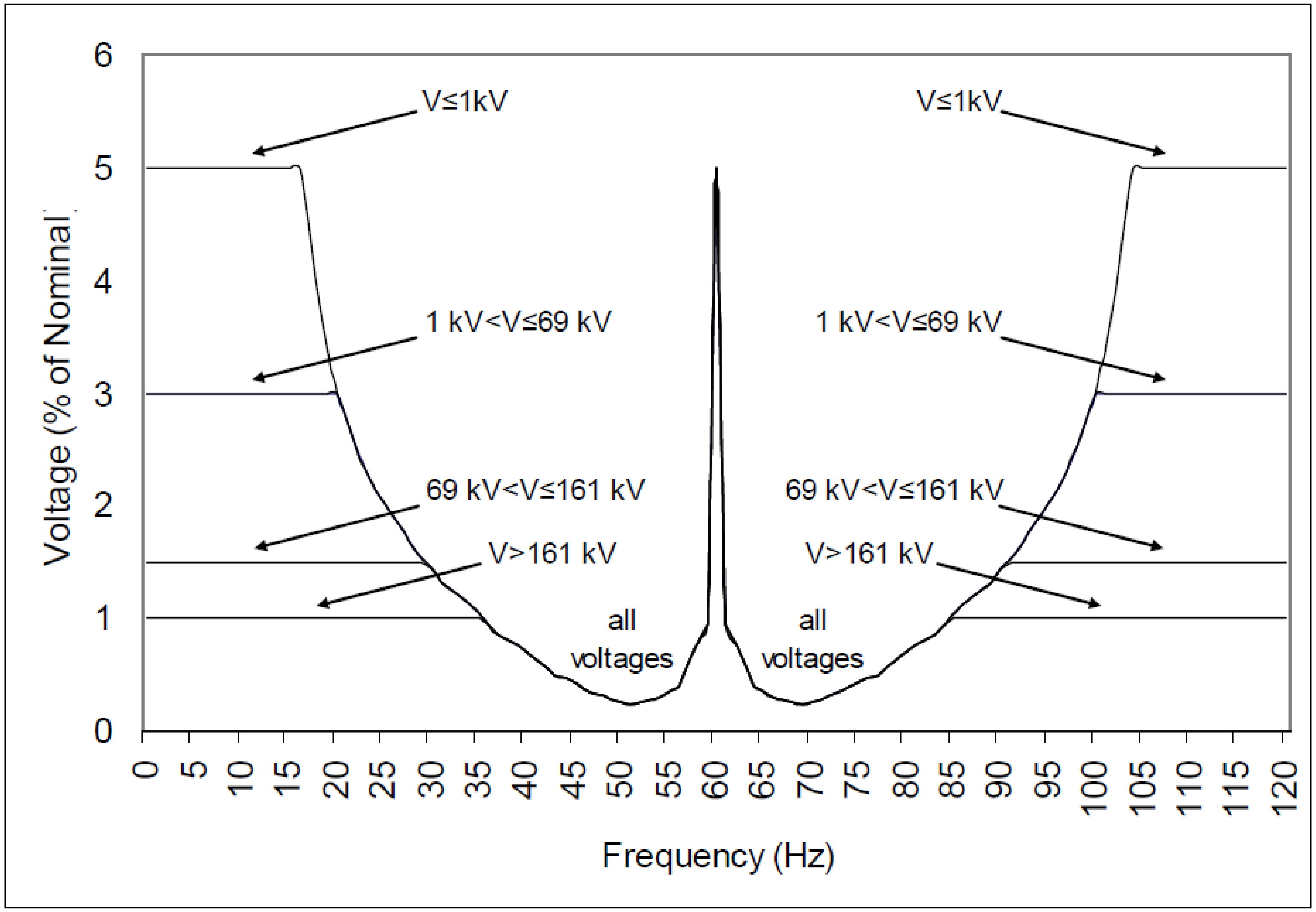
- ATC Combines (RSS) Interharmonic Groups to Give Total Interharmonic Distortion Magnitude

Interharmonic Standards, Guides & Limits

- **Acceptable Level Depends on Concern: Flicker, Effects Similar to Harmonics or Communications**
- **IEEE 519-2014 - Informative Flicker Limits**
  - Otherwise interharmonic effects should be given “due consideration” and “appropriate interharmonic current limits should be developed on a case-by-case basis.”
- **IEC 6100-2-2-2 – Very Similar Flicker Limits**
  - Not enough knowledge of interharmonics for agreement on compatibility limits beyond those for flicker. Includes some discussion on what additional limits might look like.

IEEE Interharmonic Informative Flicker Limits

- From 0.23% to 5% based on Frequency and Voltage Level.
- No Limits Above the 2nd Harmonic.



IEC – What Additional Limits Might be Like

- **For Harmonic Like Issues Interharmonic Voltage**
  - Equal to Next Higher Even Harmonic Limit
  - IEC Limits 2nd – 2%, 4th – 1%, 6th to 8th – 0.5%. 10th to 50th – (0.25*(10/h) + 0.25)%
  - IEEE Harmonic Voltage Limits: ≤ 69 kV - 3% Individual, 5% Total, 69.001 to 161 kV -1.5% Individual, 2.5% Total, >161 kV - 1% Individual, 1.5% Total
- **Ripple Control Receivers (Limited Frequencies)**
  - Voltage Limit to 0.2% Near Control Frequency

Interharmonic "Limits" Beyond Flicker

- **For Wide Spectrum Communications**
- **IEC Suggested "Reference" Level**
  - 0.2% for Each Interharmonic Group Below 50^{th}
  - 0.3% (200 Hz Bandwidth) from 50^{th} to 9 kHz
- **IEEE 519-2014**
  - Effect on Communicates Recognized: Due Consideration Should be Given and Limits Developed Case by Case

Status of Interharmonic Limits

- **No Enforceable Limits**
- **No Consensus on what they should be**
- **Would Be Significantly Lower than Harmonic Limits**
- **Would Be Different for Different Phenomena**
  - Much Lower for Power Line Communications
  - Do Communications Belong on Power Lines?
- **Status Quo: Case By Case Best for Now?**
- **Difficult to Design Equipment that Produces or is Sensitive to Interharmonics**

Interharmonic Mitigation

- **Generally More Difficult than Harmonic Mitigation**
- **Reduce Emission Levels**
  - Could Reduce Equipment Benefits
  - Converter Mvar Control, Arc Furnace Efficiency, etc.
- **Reduce Load Sensitivity**
  - Increase Equipment Ratings (Similar to Harmonics)
  - Timing Other than Power Frequency Synchronization
  - Remove Communication Signals from Power Lines
- **Reduce Coupling Between Sources and Loads**
  - May be Impractical for Multiple Interharmonics (Filters May Increase Other Frequencies)
  - Low Levels of Distortion May be Difficult to Achieve

Interharmonic Summary

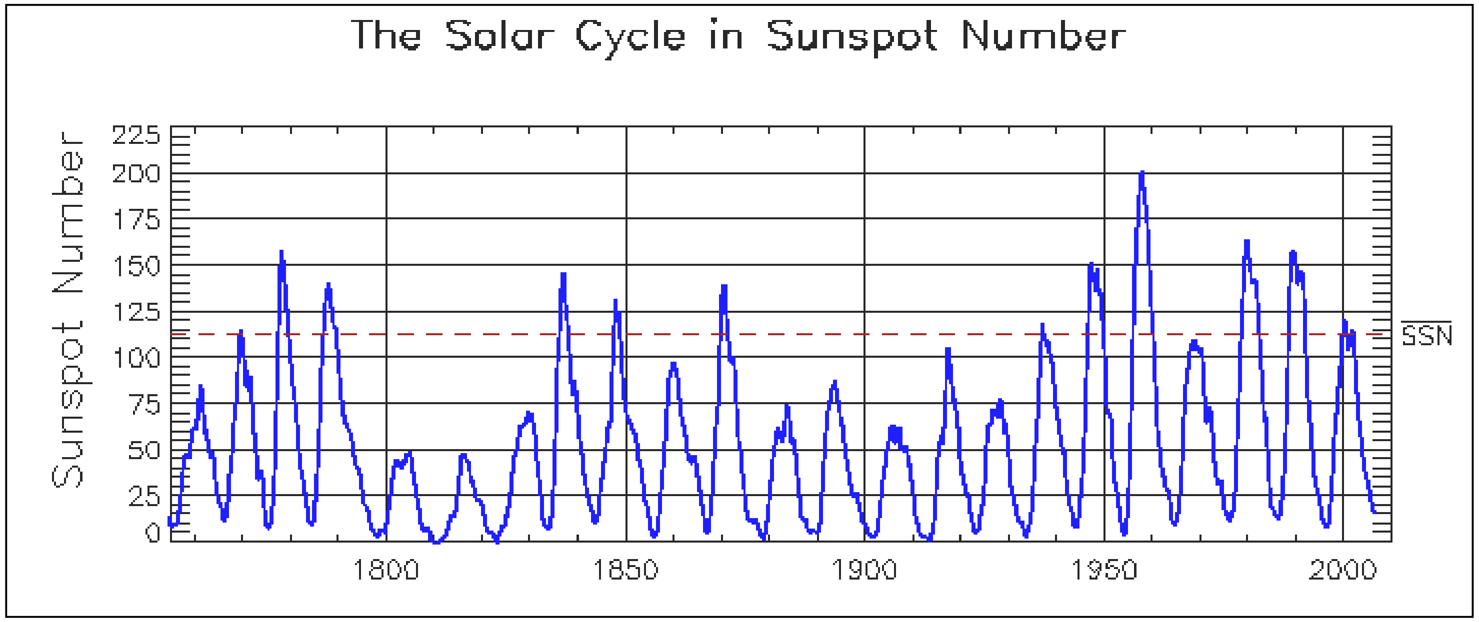
- **Presently Few Large Interharmonic Sources**
  - Use of IGBTs is Increasing
- **Standards for Measurement, But No Limits**
- **Interharmonic Distortion Usually Lower than Harmonic**
  - Newer SVC Designs Produce Lower Interharmonic
  - Will this Continue to be True?
- **Power Line Communications Require Interharmonic Limits Much Lower than Existing Harmonic Limits**
  - Should Power Lines be a Communication Medium?
- **Continue Resolving Issues Case-by-Case?**
  - No Guide for Equipment (or System) Designs

Phenomena #5: Geomagnetic Disturbances

- **GMD is not Usually thought of as a PQ Issue, But…**
  - It is a natural phenomena…like lightning that causes PQ issues
  - It is an "extra" current on the system that can cause equipment heating
  - It can cause equipment to trip or misoperate
  - It can cause voltage collapse
  - It can put harmonics on the system
- **Timely Topic as TPL-007 (Transmission System Planned Performance for Geomagnetic Disturbance) is being Implemented**

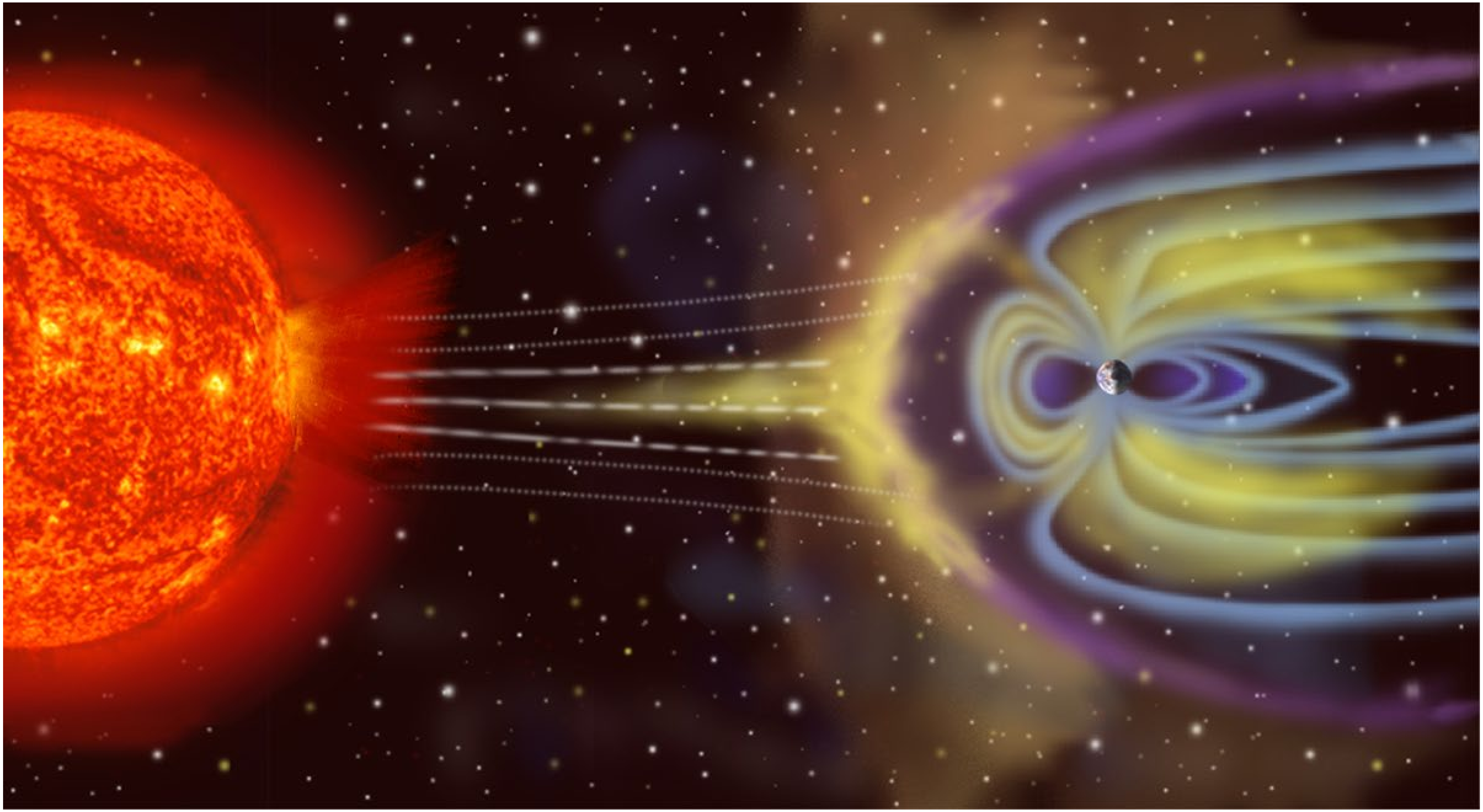
Short Summary of GMD Phenomena

- Flares: Radio & X-Ray Waves. Travel at Light Speed. Affect Communications, Not Power Grid.
- Radiation Storms: Particles (Protons). Reach Earth 30 Minutes after Flare. Affect Satellites, Not Grid.
- Geomagnetic Storms – Mass Ejection (Material & Magnetic Fields). Reach Earth in 1-4 Days. Disrupts Magnetic Field, Induces Potential Earth's Surface. Affects Grid.



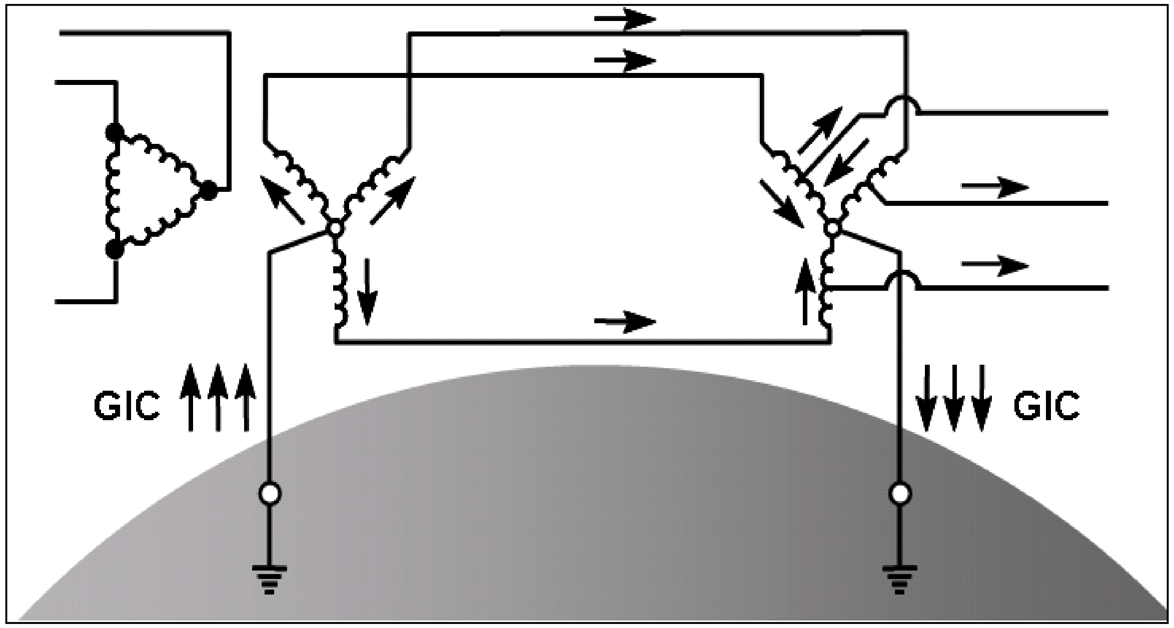
- Approximately 11 year cycle
- Severe Storms Can Happen Any Time

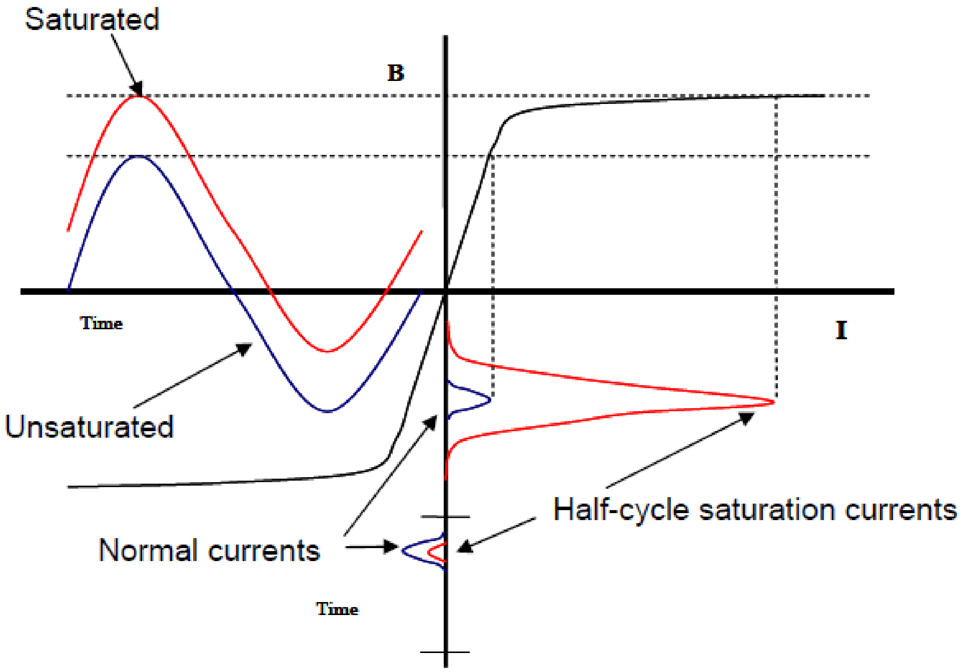
Coronal Mass Ejection



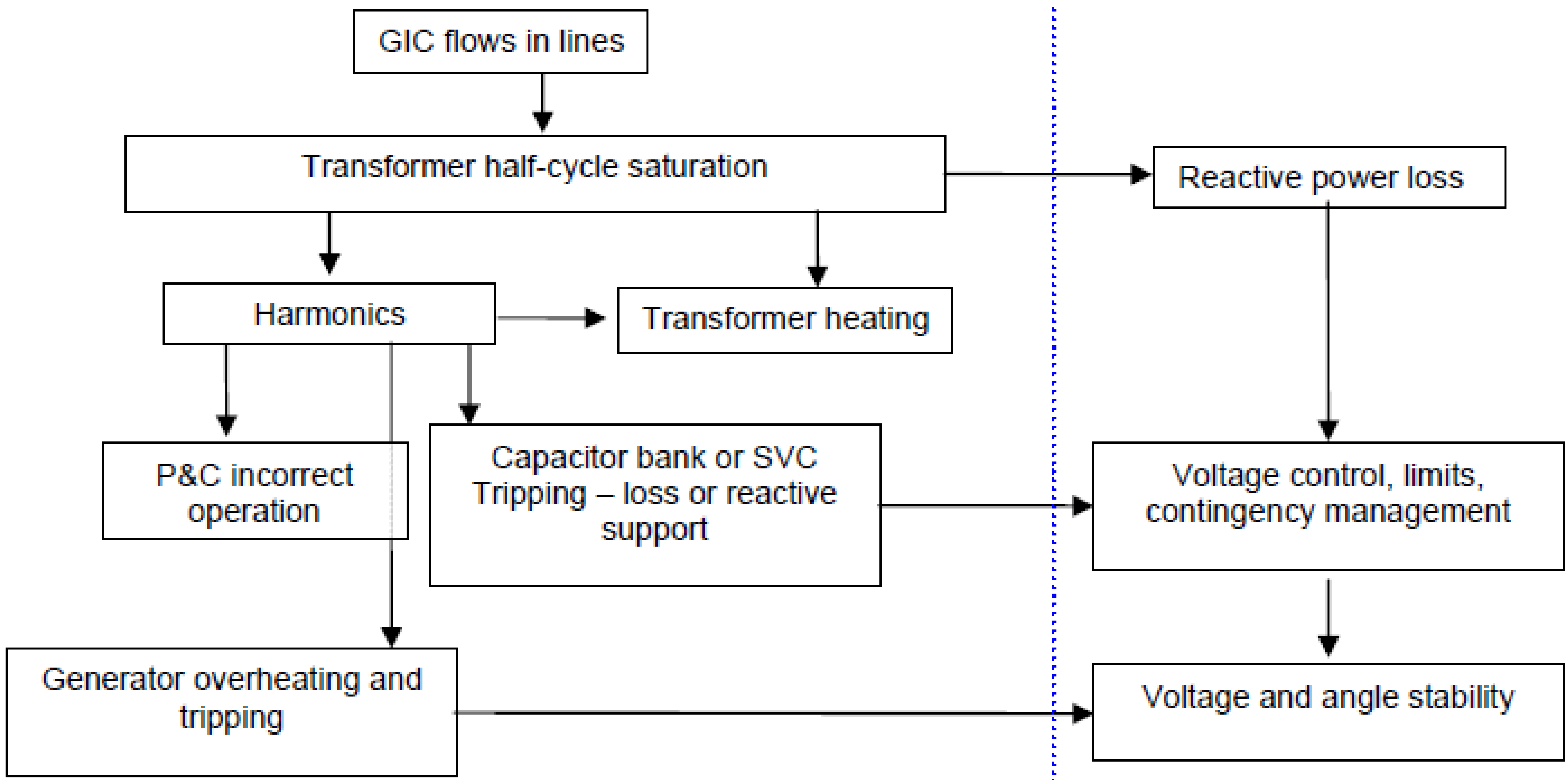
Grid Impacts

- "DC" Geomagnetically Induced Current (GIC) induced in Transmission Line Neutrals
- Transformers Saturate: Increase Reactive Power Requirements, Heating, Harmonics
- Capacitors, SVCs, etc. Tripped by Protection
- Potential for Voltage Collapse



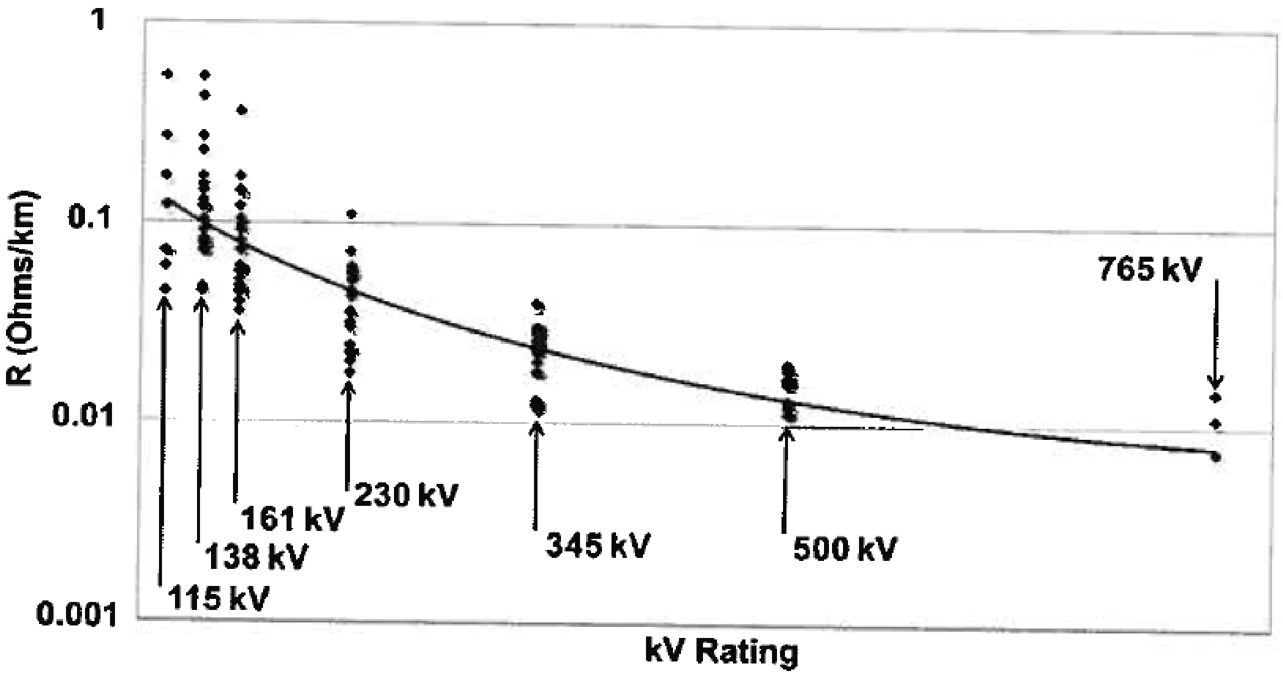


Effects of GIC on Transmission Grid



What Determines Susceptibility to GMD?

- **Impact Greater Nearer to Poles where Magnetic Field Lines Closer**
- **Line Orientation, in Relation to Storms, Determines GIC Magnitude**
- **Long High Voltage Lines More Susceptible**
  - Potential Difference a Function of Distance
  - Higher Voltage, Lower DC Resistance/km



Planning for GMD

- **How Severe Will “worst case” GMD be On Grid?**
  - Need to Define “worst case” and Study
  - Measure, Model, Mitigate
- **Carrington Event - September 1-2, 1859**
  - Largest GMD Event Ever Recorded
  - About 20 Times Stronger than 1989 Storm
- **“Great Storm” – May 13-15, 1921**
  - About 10 Times Stronger than 1989 Storm
  - Northern Lights Seen in Puerto Rico
  - 100 year Storm?
- **Later Storm Power System Effects**
  - Voltages Go From Low to High in about 10 Minute Cycles

March 13, 1989, GMD Event

- **Hydro Quebec Transmission System Collapsed in 92 Seconds**
  - All Seven SVCs tripped in first few seconds while Reactive Demand Increased 1600 Mvars
  - Generation far from Loads: Long HV lines
  - Six Million Without Service for 9 hours or more
- **Several Transformers Across World Failed**
  - Nuclear Plant GSU in USA (Due to GIC?)
  - Two Large Network Transformers in the UK
  - Two Additional Failures Due to Load Rejection
- **NERC: Over 200 Significant Anomalies including Caps Tripping Due to Harmonics, Low Voltages, etc.**

TPL-007-1: Transmission System Planned Performance for Geomagnetic Disturbance Events

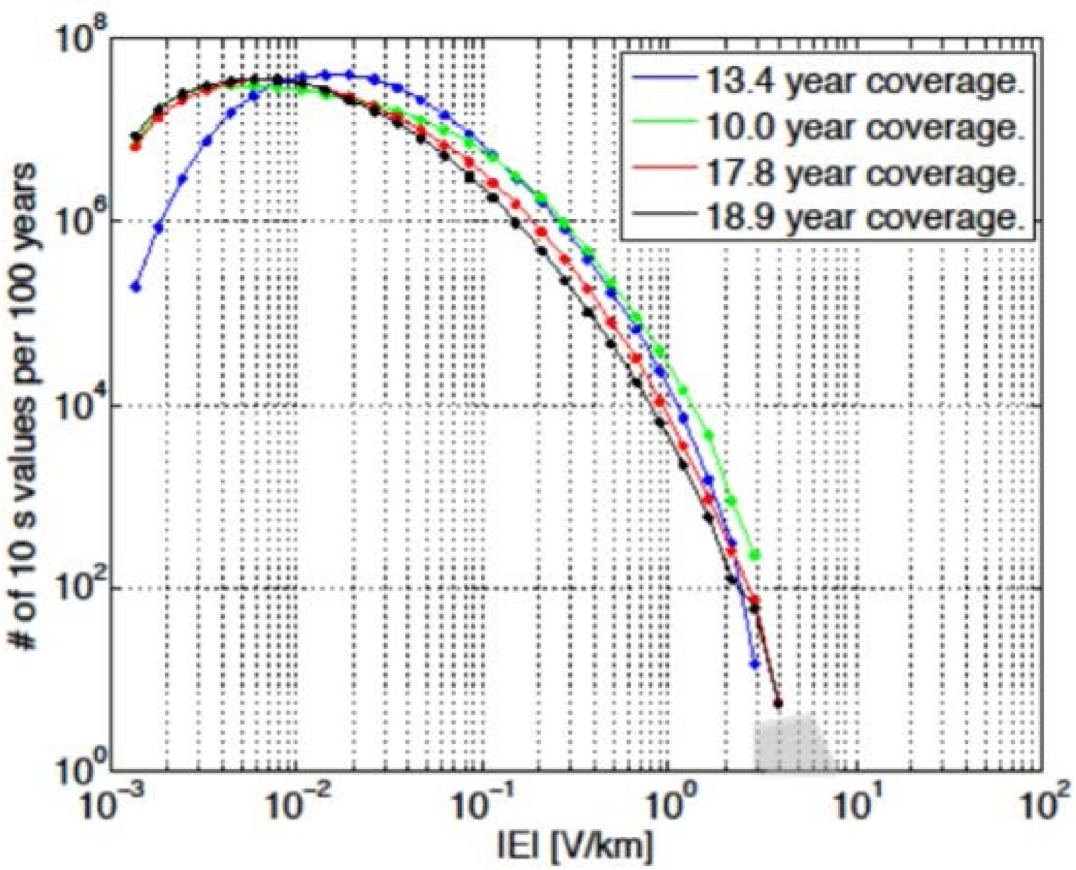
- **FERC Order 830 Approved Sept. 22, 2016**
- **Requires GMD vulnerability assessments of a 1-in-100 year benchmark GMD event.**
- **Requires revisions within 18 months**
  - Revise the benchmark event so not based solely on spatially-averaged data.
  - Require GIC and magnetometer data (if collected) released to public.
  - Include deadlines for the completion of corrective action plans and mitigation actions

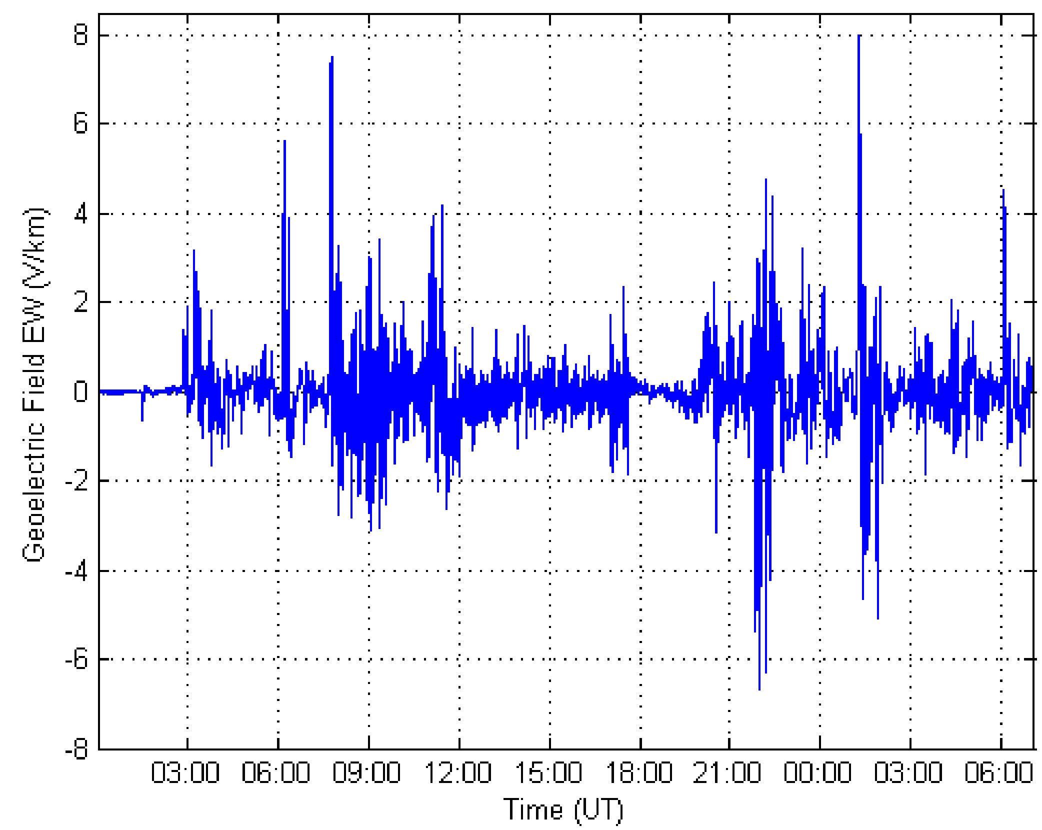
TPL-007-1 Requirements (Summary)

- **R1** - Identify Planning Coordinator and Transmission Planner Responsibilities
- **R2** – Maintain GMD Vulnerability Assessment Models
- **R3** – Establish acceptable steady state voltage criteria during benchmark event (No Cascading or Uncontrolled Islanding)
- **R4** - Complete and document steady state GMD Vulnerability Assessment every 60 months
- **R5** - Provide GIC flow information to transformer owners
- **R6** - If maximum transformer effective GIC 75 A per phase or greater, conduct thermal impact assessment (Y-G, >200 kV)
- **R7** – If performance requirements not meet, develop Corrective Action Plan.

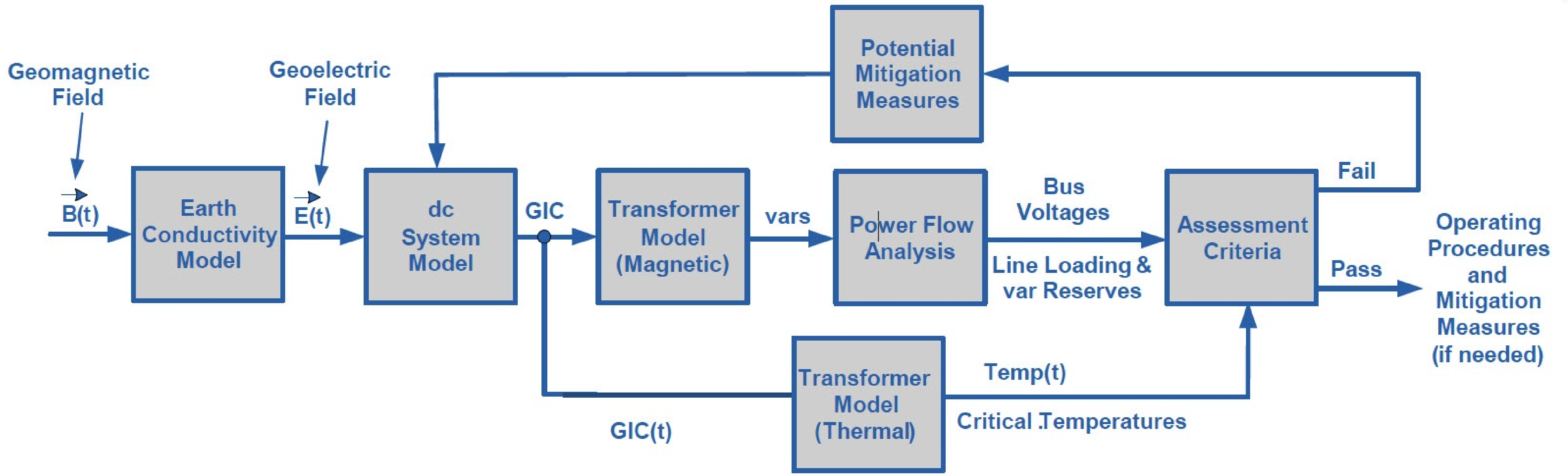
Benchmark GMD Event

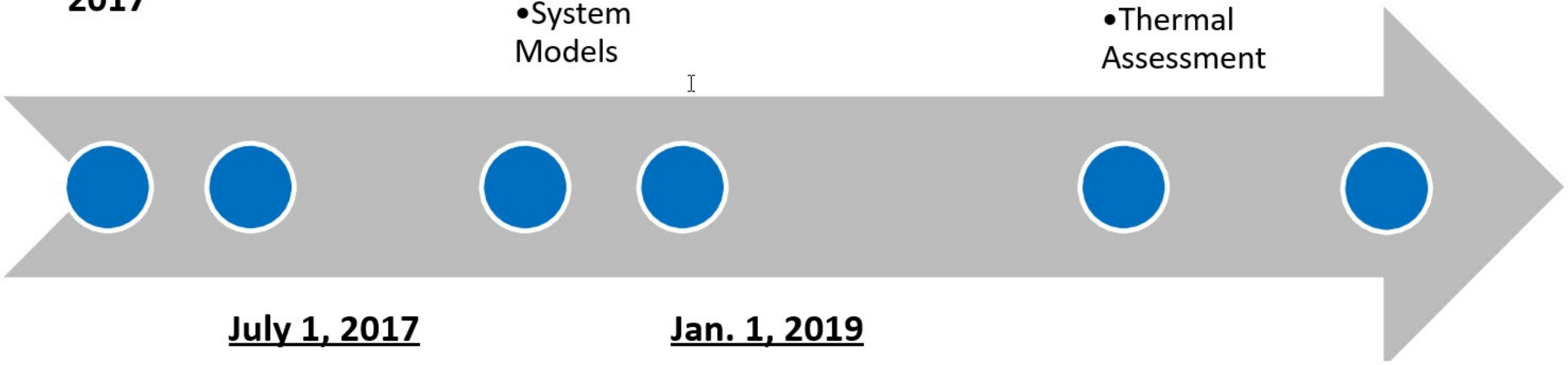
- **Amplitude (8 V/km), Scaled for Latitude and Earth Conductivity**
- **Waveshape from Previous Event March 13, 1989)**





Process not Linear, Schedule Is





Jan. 1, 2017

July 1, 2017
- R1
- Identify Responsibilities

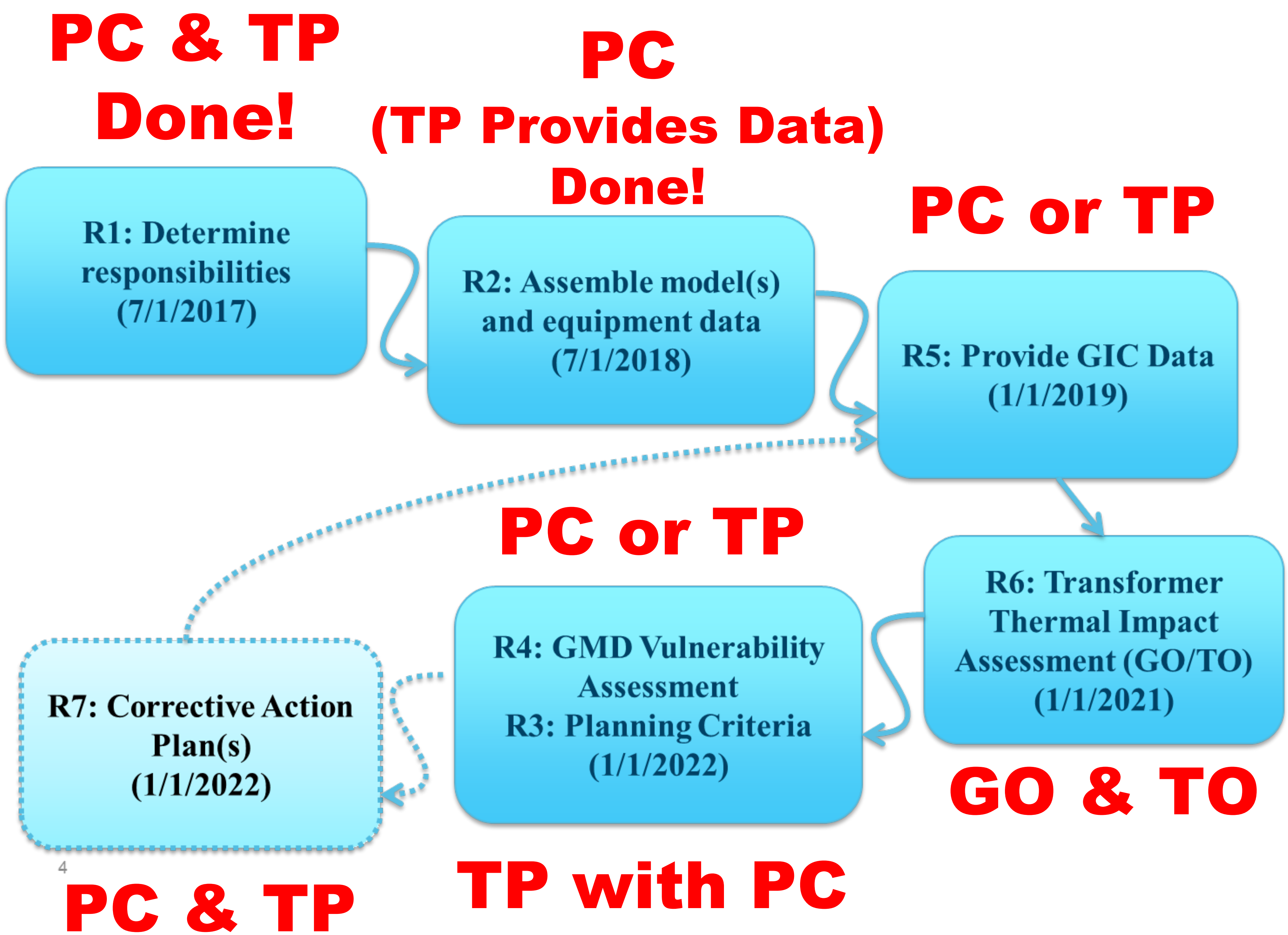
July 1, 2018
- R2
- System Models

Jan. 1, 2019
- R5
- GIC Flow Information

Jan. 1, 2021
- R6
- Thermal Assessment

Jan. 1, 2022
- R3, R4, and R7
- Perf. Criteria
- GMD Assessment
- Corrective Action Plan

Who (PC or TP) Does What? When?



http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx

R2 – GMD Model Assembly (PC)

- Internal/External Info from TOs, GOs, etc. (MOD-032)
  - Data Provided to MISO 12/1/2017, Model Completed 7/1/2018
- GMD Models Require Data Not Used in Other Studies
  - Earth Model, Substation Latitude and Longitude
  - Grounding Resistance (Substation Has One Ground Grid)
  - Transformer Core Design (Available?), Vector Group
  - DC Resistance Information (Lines, Transformers, Shunts, etc.)
  - GIC Blocking Devices, etc.
- Whatever Significantly Affects GIC Included
  - Transformers with High Side Y-Grounded Winding > 200 kV
  - System > 200 kV and Short Ties Between 200 kV Busses
  - Shunt Reactors on Delta Tertiaries Not Included
- Collecting Data & Assembling Model Required Effort

R5 – Provide GIC Data (PC or TP)

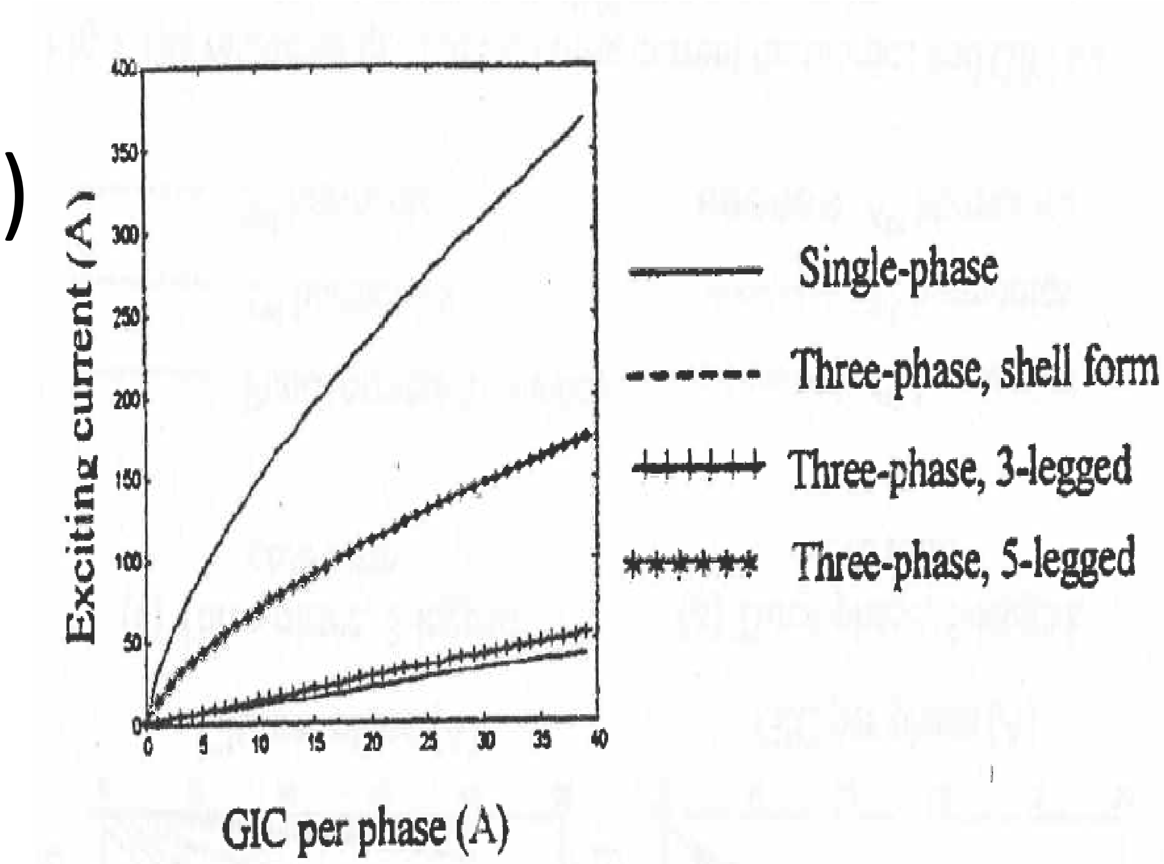
- Preliminary GIC Flow Data from Completed GMD Simulations Provided to BES Transformer Owners
- Most Utilities Agreed to Give PC Responsibility
  - Concentrate Efforts on One Study
  - Eliminate Conflicting Results (In and Out of Service Territory)
  - Time: Must Be Completed by 1/1/2019

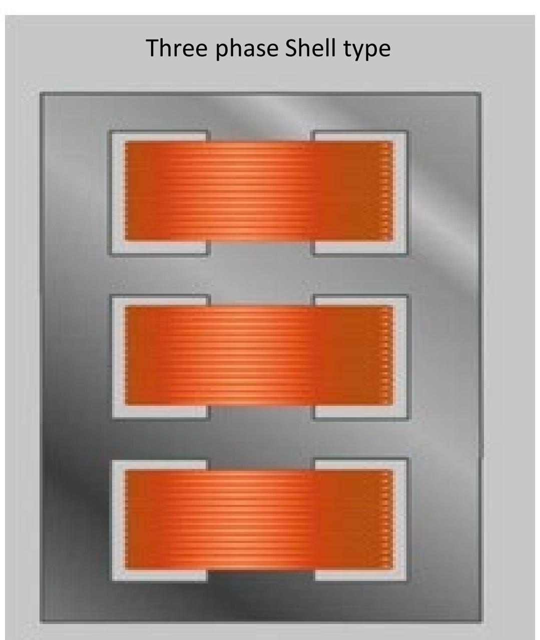
R6 – Xformer Thermal Assessment (GO/TO)

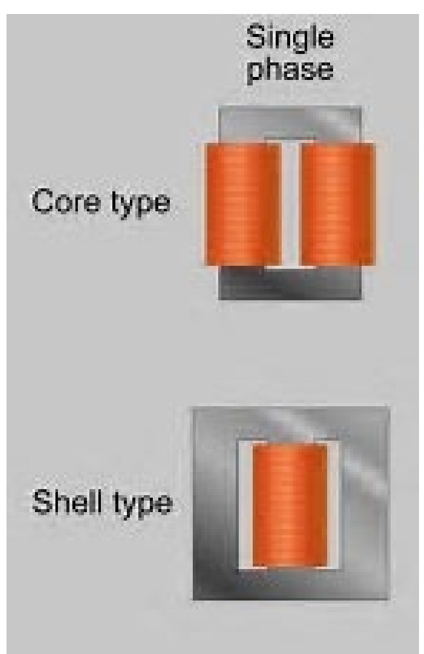
- Transformer Owners Done by 1/1/2021
- If Benchmark Event GIC ≥ 75 A/phase
- Base on GIC Flow Provided (R5)
- Document Analysis Assumptions
- Document Suggested Actions and Analysis to Mitigate GIC Impact (If Any)
- Provide Responsible Entities Results (R1)

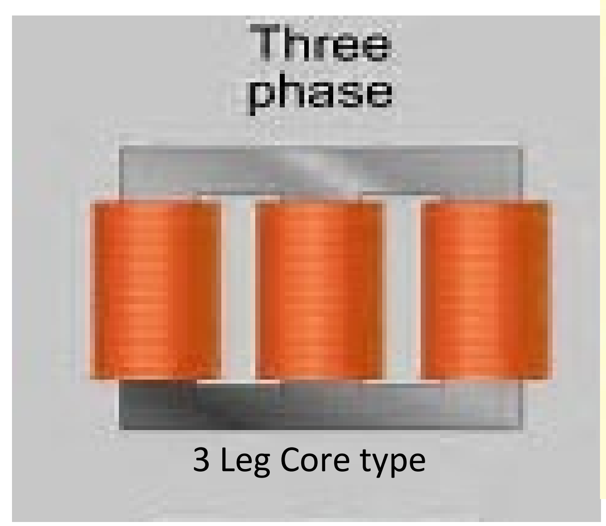
Susceptibility Varies by Design

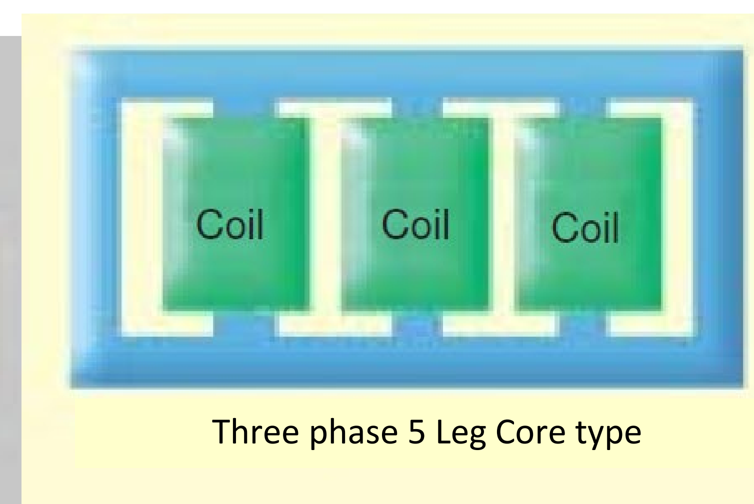
- **Strongly Susceptible**
  - Single Phase (Shell & Core)
  - 3-Phase Shell Form
  - 3-Phase 5 Legged Core
- **Weakly Susceptible**
  - 3-Phase 3 Legged Core











Transformer GIC Thermal Analysis

- **GIC Analysis Requirements**
  - Ambient Temperature
  - Preload Condition
  - DC Current: Amplitude and Duration
  - Temperature Limits: Oil, Windings, Steel Structure
- **ATC to have Manufacturers Perform Analysis**
  - Transformer Design Information Proprietary
  - Have Tools, Models and Expertise
  - Archives of Old Designs
  - Design Records of Defunct Manufacturers
  - Schedule and Budget for this Analysis!

R3 - Planning Criteria (TP with PC)

- **Must Develop Acceptable Steady State Voltage Performance Criteria During Benchmark Event**
  - By 1/1/2022 (In Reality Much Sooner)
  - Probably Not the Same Throughout MISO
  - In Addition to Table 1 Requirements
- **TPL-007 Table 1 Steady State Requirements**
  - No Collapse, Cascading and Uncontrolled Islanding
  - Generation Loss is Acceptable
  - System Adjustments, Transmission Configuration Changes and Generation Dispatch Allowed if Executable in Applicable Facility Rating Time Limits
- **Firm Transmission Interruption and Load Loss Allowed but Must be Minimized**

R4 – Vulnerability Assessment (TP or PC)

- ATC Agreed to Give PC the Responsibility (R1)
- Required Every 60 Months (First 1/1/2022)
- Benchmark Event Using R2 Models
- On and Off Peak Load Models for at Least One Year in Near Term Planning Horizon
- Table 1 Performance Requirements
- Provide Results to (1) Reliability Coordinator, and Adjacent PCs and TPs within 90 Days of Completion and (2) Any Functional Entity that Submits a Written Request and has a Reliability Related Need

R7 – CAP (PC and TP) by 1/1/2022

- **Required if Performance Requirements Not Met**
- **List Deficiencies and Actions Required to Fix**
  - Transmission or Generation Facility Installation, Modification or Removal
  - Protection/RAS Installation, Modification or Removal
  - Operating Procedures (Must Specify How Long Needed)
  - Demand Side Management, New Technologies, etc.
- **Provide to RC, Adjacent PCs and TPs, Functional Entities Referenced in CAP and Any Entity Submitting a Written Request within Required Time Limits**

But Wait! There's More: TPL-007-2

The final ballot for **TPL-007-2 – Transmission System Planned Performance for Geomagnetic Disturbance Events** concluded at **8 p.m. Eastern, Monday, October 30, 2017.**

Voting statistics are listed below, and the Ballot Results page provides the detailed results.

Quorum / Approval
88.74% / 73.35%

Next Steps

The standard will be submitted to the Board of Trustees for adoption and then filed with the appropriate regulatory authorities.

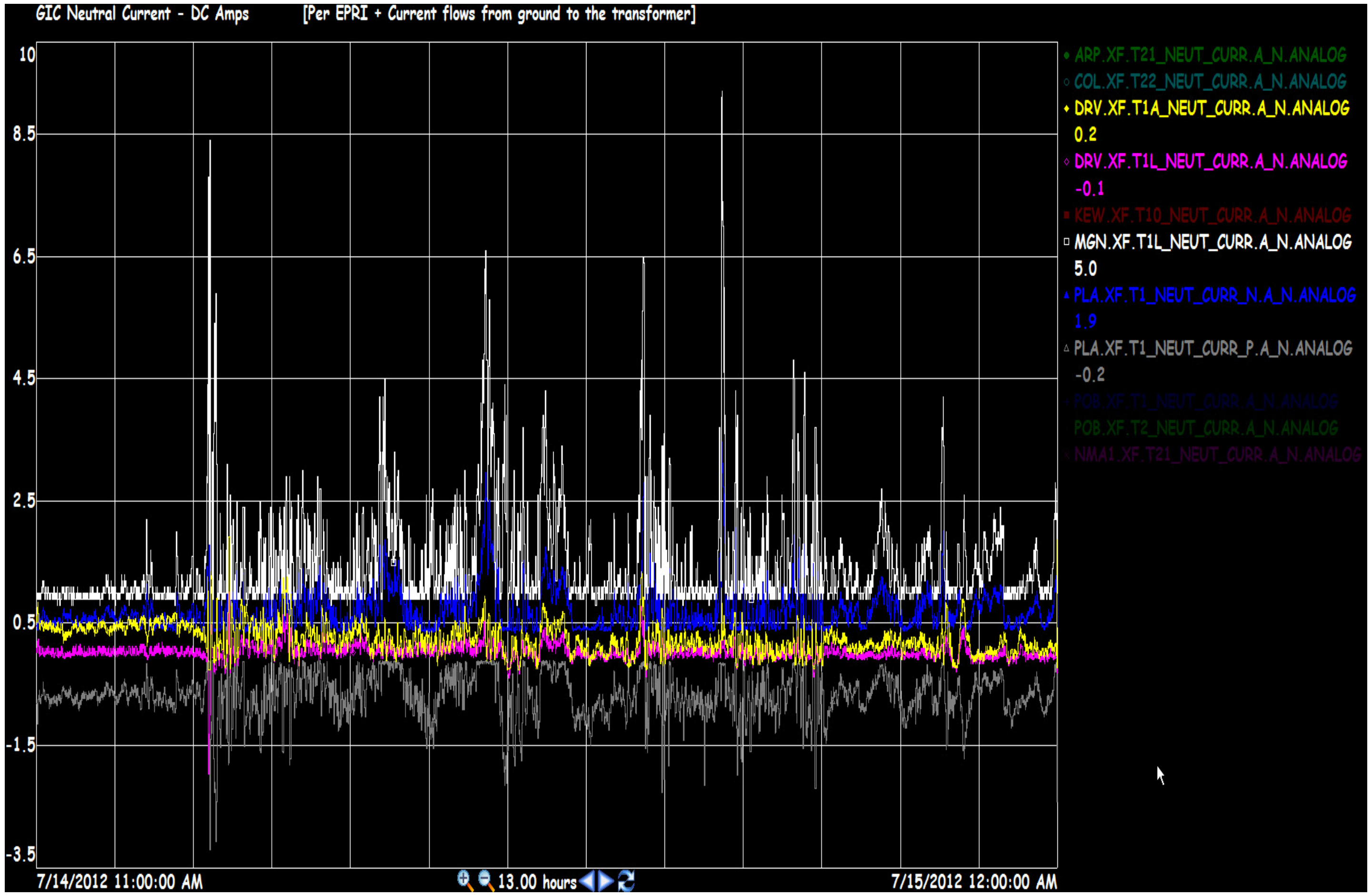
- **R8 – Supplemental Vulnerability Assessment**
- **R9 – Supplemental GIC Flow to Transformers**
- **R10 – Supplemental Thermal Assessment**
- **R11/12 – Measure GIC & Geomagnetic Data**
- **CAP Timelines – 2 yr Procedure, 4 yr Hardware**
- **Future: GMD Harmonic Analysis (EPRI)**

EPRI GMD Harmonic Analysis

- **GMD Caused Transformer Saturation Creates Harmonics**
- **2016 Report: Assessment Guide: GMD Harmonic Impacts and Asset Withstand Capabilities**
- **GMD harmonics can adversely impact bulk power system equipment and systems, including protection systems.**
- **TPL-007 Requires that devices that would trip during GMD Event Should be Taken Out of Analysis**
- **Understand GMD Related harmonic issues of equipment including 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.**

EMS Monitoring and Alarm

- 46 of 62 transformers will have harmonics measurements
- 2nd ("Even")Harmonics to indicate partial saturation
- Excitation current to indicate full saturation
- Estimate MVAR consumed in the transformer
- 20 minute history for trending, Monitor Bus voltage

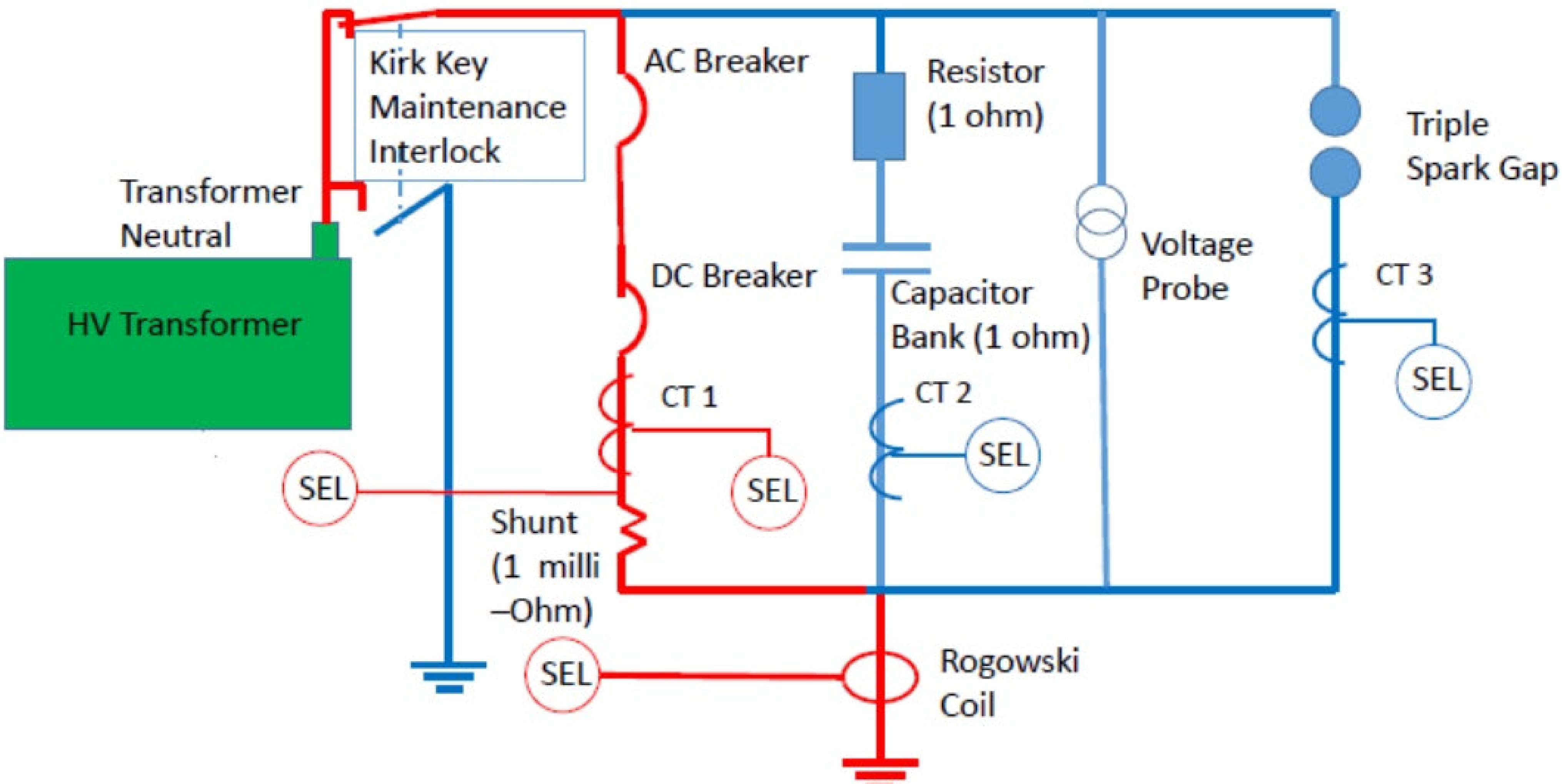


ATC Operational Procedure (Real-time)

- Preemptive measures
- Add Caps at substation where 2nd harmonics present or Transformer MVAR Load Increases
- Monitor voltage to determine capacitance to add
- Switch out reactors in the area
- Unload saturated transformers that exhibit “Even” harmonics and/or MVAR load increases
- Notify Maintenance if transformer saturates for next day follow-up testing

Blocking Device

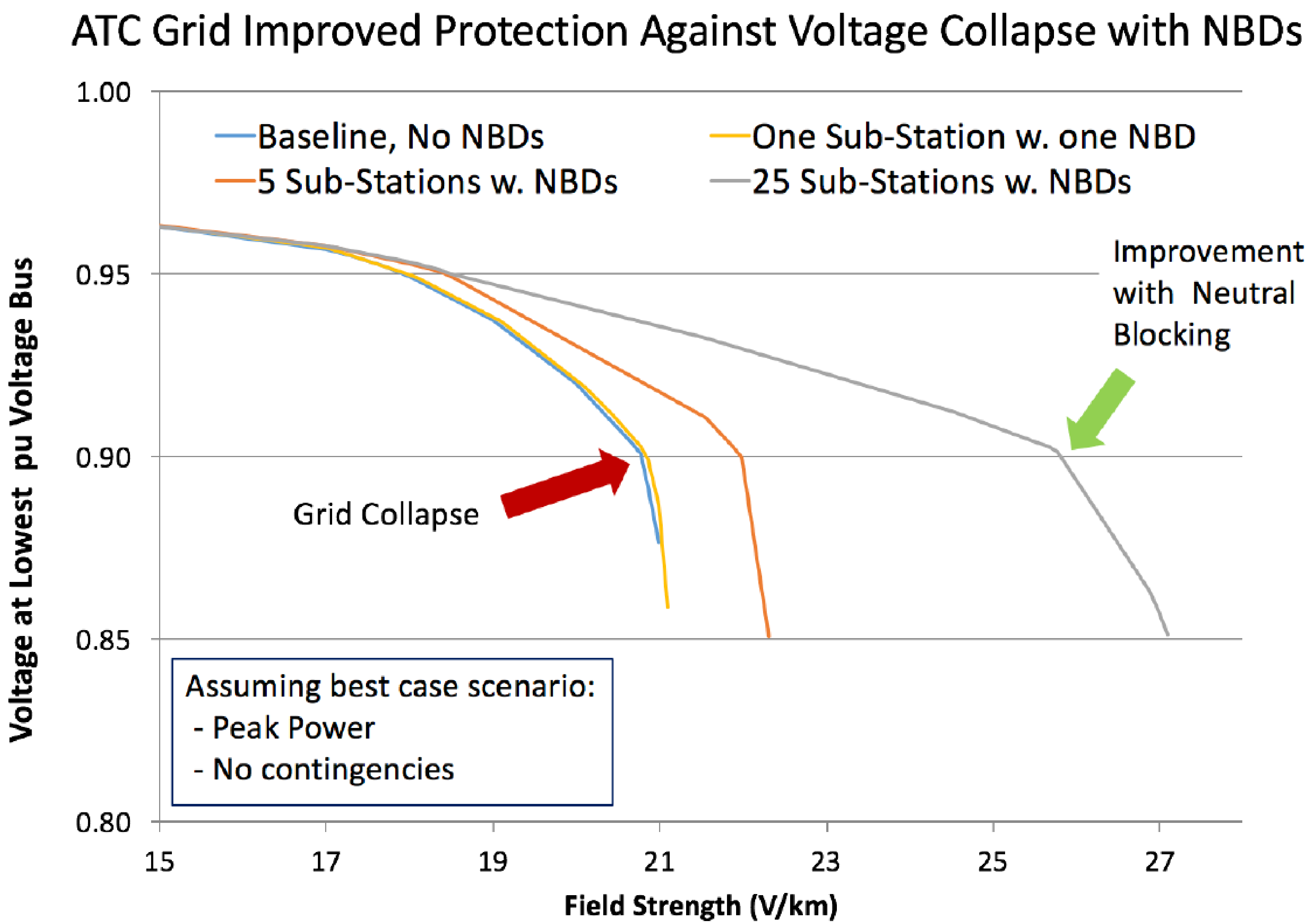
- **Put in Transformer neutral**



“HV Power Transformer Neutral Blocking Device (NBD) Operating Experience in Wisconsin” – M. Marz, et. al. – MIPSYCON 2017

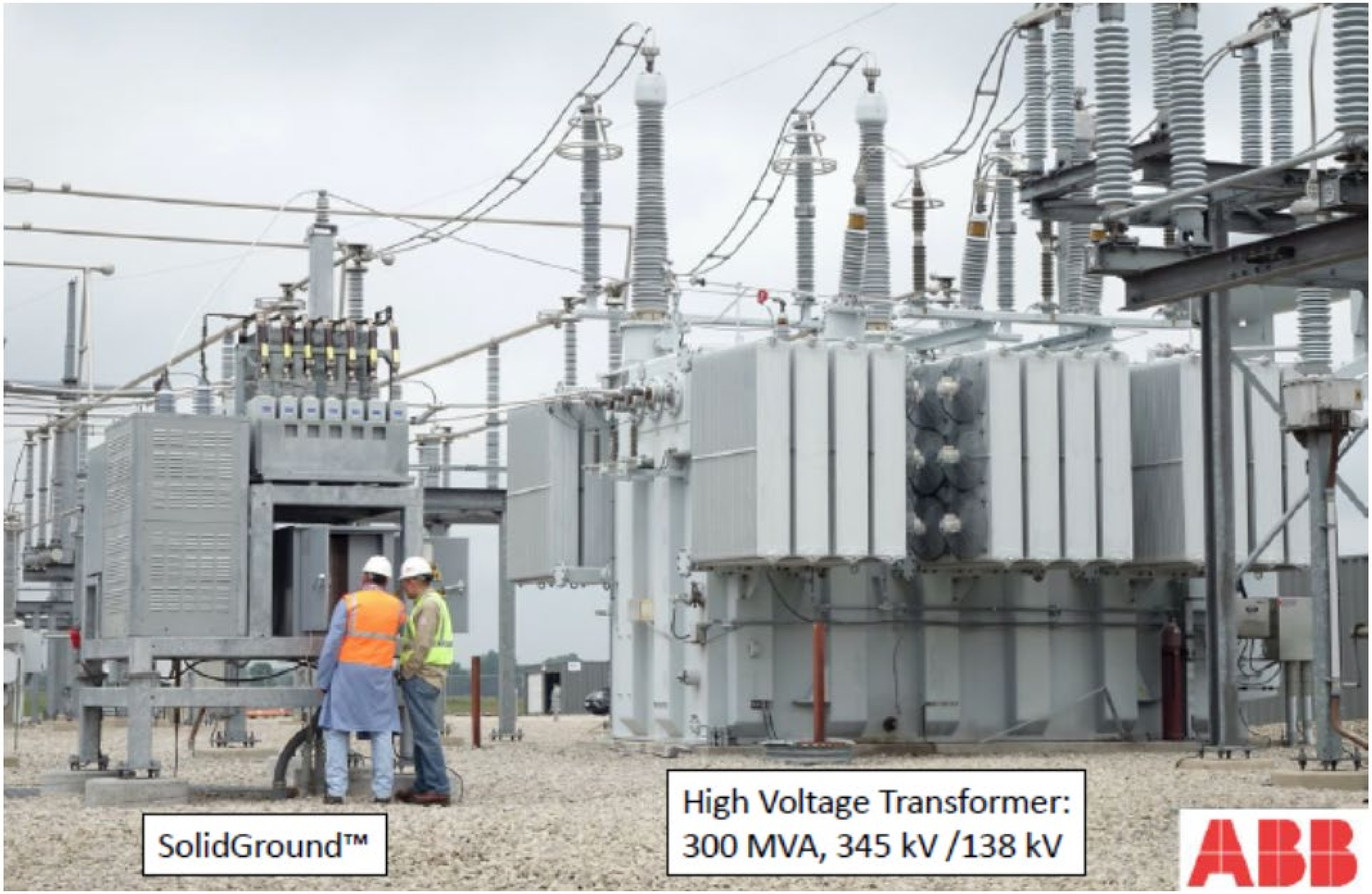
How Many Devices Needed?

- **Devices Must be Placed Strategically**



ATC's Blocking Device

- **Installed February 2015 – Operating as Designed**

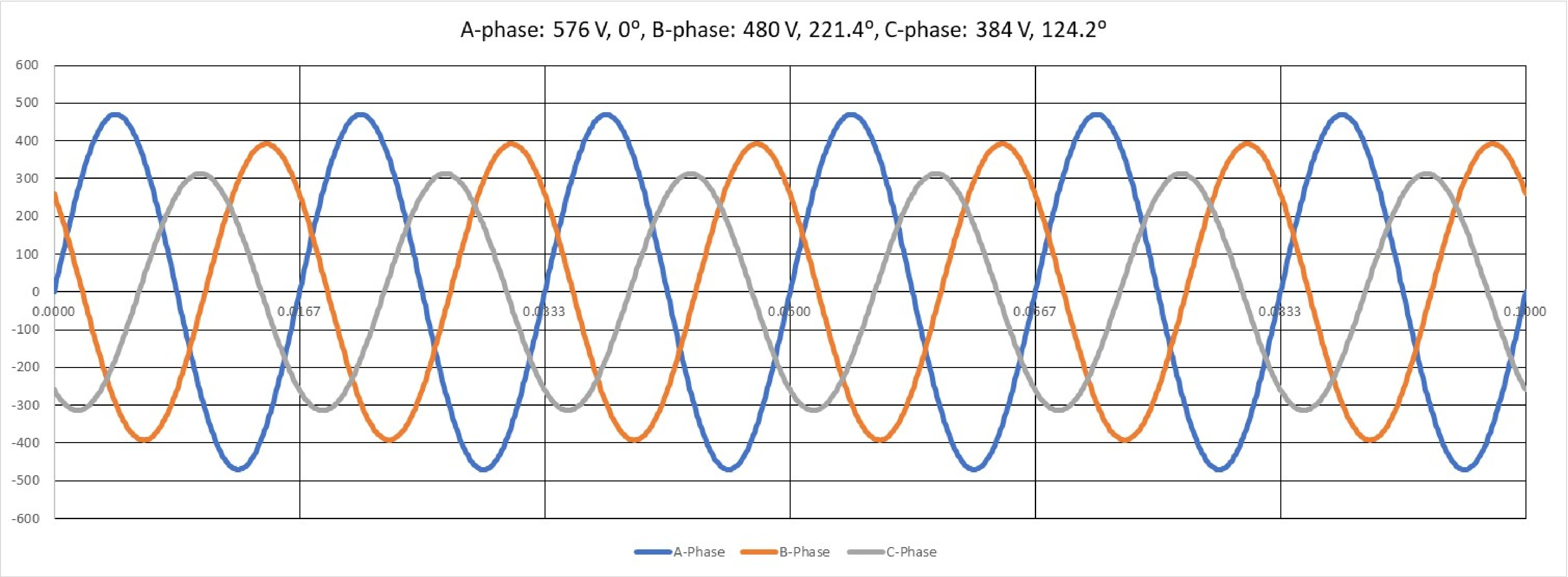


GMD Mitigation/Summary

- **Transformer Heating**
  - Blocking Device
  - Future Transformers Designed for Expected GMD
- **System Voltage Collapse**
  - System Operating Procedures
  - Multiple Blocking Devices Strategically Placed
  - Series Capacitors on Long Lines Contributing Most to GMD
- **TPL-007 Geared to Keeping the Grid Operating**
  - What if Choice Between Blackout and Transformer Damage?

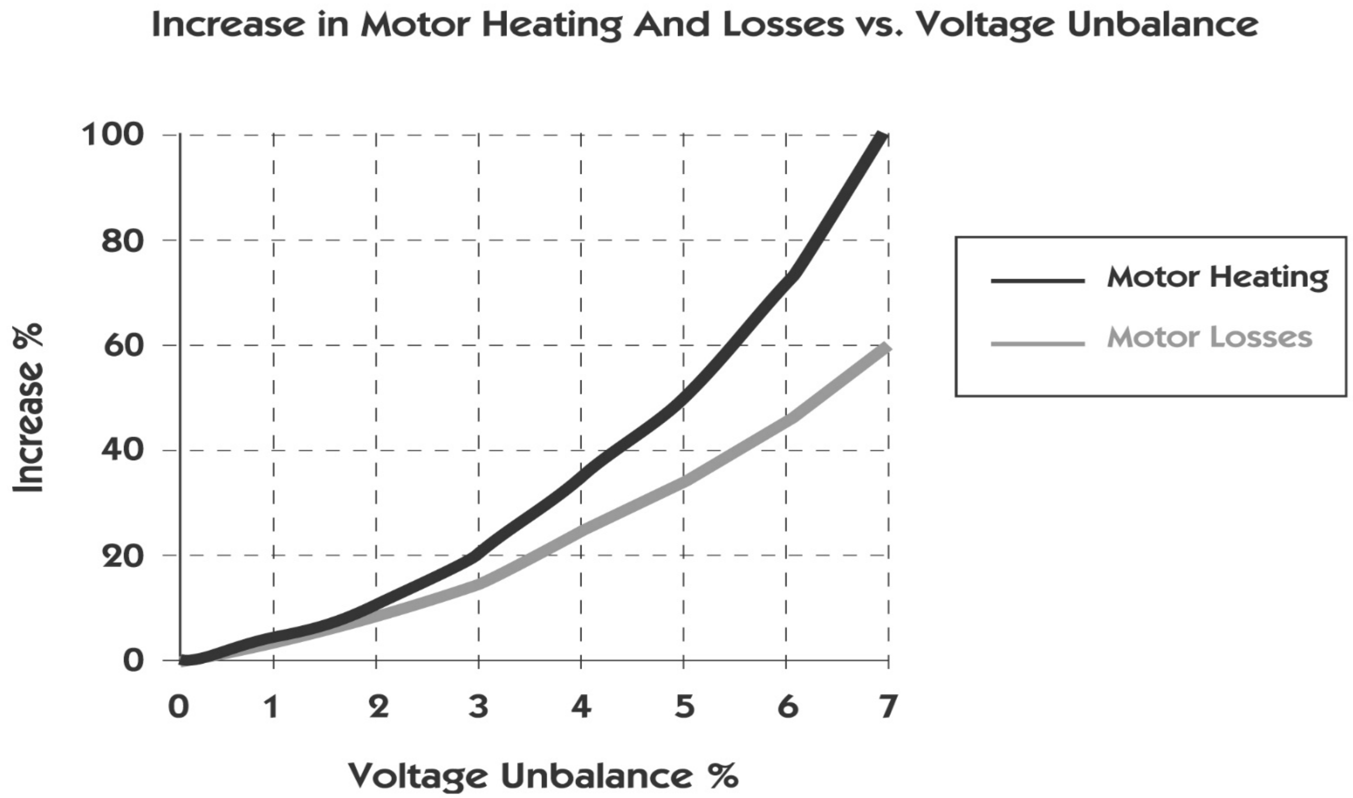
Phenomena #6: Voltage Unbalance/Imbalance

- Three Phase Voltage RMS Values Not Equal
- Angles Between Phases are Not Equal



Causes & Effects

- **Causes:**
  - Unequal Distribution Impedance (Used to Fix Previous Unbalance)
  - Unequal Distribution of Single Phase Loads
  - Mismatched Xformer Taps
  - Blown Capacitor Fuses
  - Unbalanced Loads
  - Open Phase



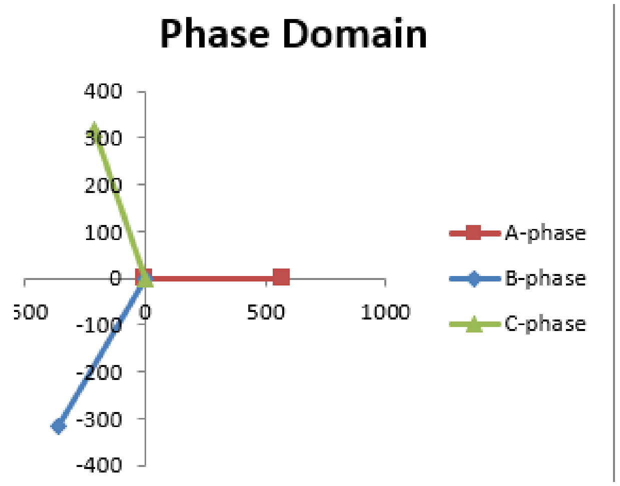
- **Effects**
  - Control Misoperation
  - Increased Heating and Reduced Life of Induction Motors/Relays
  - Reduced Life of Variable Frequency Drive Front End Diodes
  - Reduced life of capacitors, etc. Due to increased Current
  - Increased Loses due to Increased Current

Voltage Unbalance Calculation

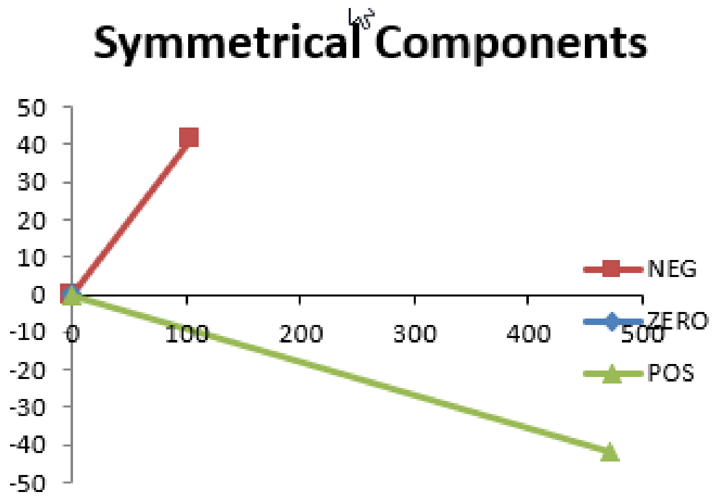
- **National Equipment Manufacturer's Association (NEMA)**
  - Line Voltage Unbalance Rate (LVUR) = (Max Voltage Deviation from Average Line Voltage)/(Average Line Voltage)
- **IEEE - Phase Voltage Unbalance Rate (PVUR)**
  - Same as LVUR, but uses Phase Rather than Line Voltage
- **"More Precise" – Uses Average of Three Phase Voltages**
  - Total Imbalance = Sum Difference Each Phase and Average
  - % Imbalance = (Total Imbalance/2)/Average Voltage
- **True Definition – Voltage Unbalance Factor (VUF)**
  - %VUF =((Negative Sequence/Positive Sequence)) * 100
  - Approximation = $(82 * \sqrt{(\Delta a^2 + \Delta b^{2+} \Delta c^2)})/V$ avg
- **(Highest Phase-Lowest Phase)/Lowest Phase**
- **Results Usually Similar at Low Levels of Unbalance (<5%)**

Measurement Example

- V_{ab}=576V 0^o, V_{bc}=480V 221.4^o, V_{ca}=384V 124.2^o
- **IEEE Definition – %PVUR**
  - Average = (576 V+480 V+384 V)/3 = 480 V
  - Maximum Deviation from Average = 96 V
  - %PVUR = (96/480) = 20%

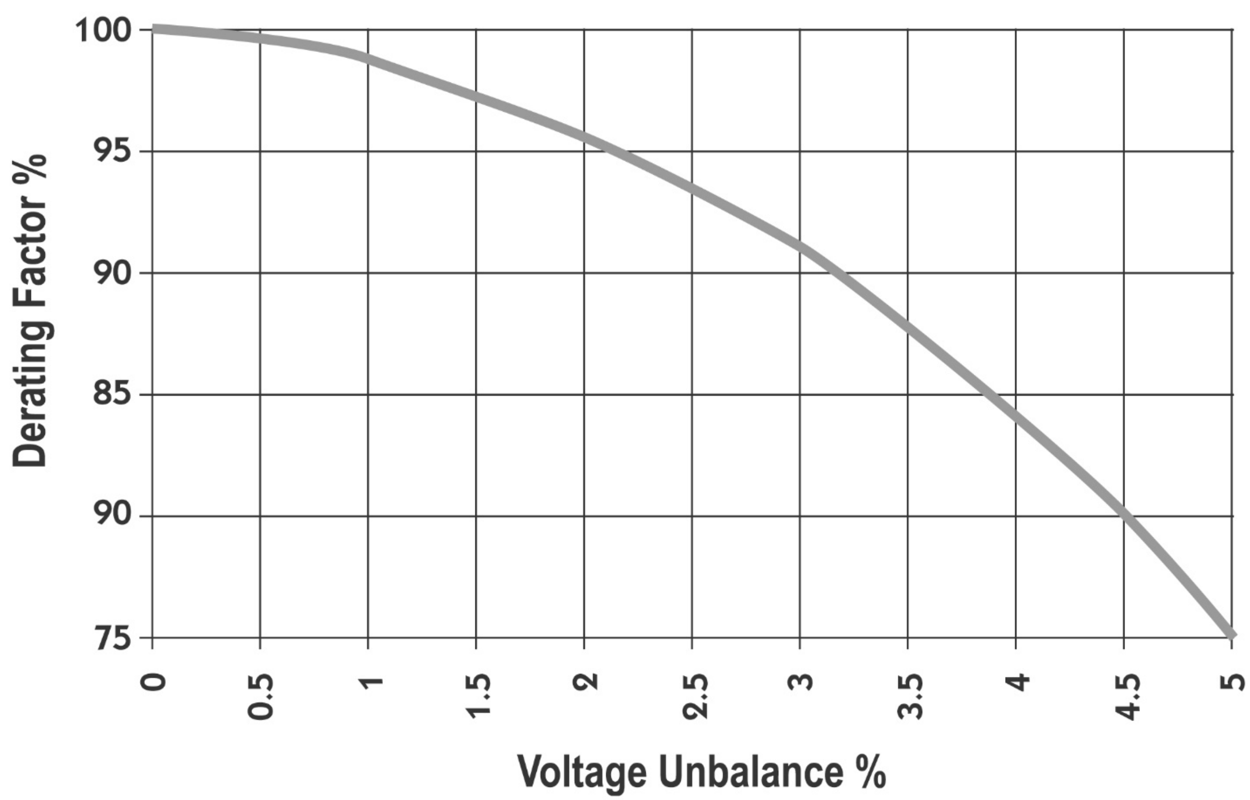


- **"More Precise" – Average 3 Phase Voltages = 480 V**
  - Total Imbalance = 96 V + 0 V +96 V = 192 V
  - % Imbalance = (192 V/ 2)/480 V = 20%
- **VUF – Symmetrical Components**
  - Positive: 473.1 V -5 ^{o}, Negative: 112.6 V 22 ^{o}
  - %VUF = (112.6/473.1) = 23.8%
  - Approximation: (82*135.8)/480 = 23.2%



Limits

- ANSI C84.1 – Electric Power Systems and Equipment – Voltage Ranges: 3% at meter under no-load conditions
- Most Utilities: 2.5% Maximum Deviation from Average
- Some Motor Manufacturers: CURRENT Unbalance < 5% (1% VOLTAGE Unbalance ~ 6-10% CURRENT Unbalance)
- NEMA: Motors Give Rated Output at 1% Unbalance
- (Highest-Lowest) /Lowest Limit <4%



Mitigation

- **Eliminate Causes:**
  - Equalize Distribution System Impedances
  - Equally Distribute Single Phase Loads
  - Check Transformer Taps Not Mismatched
  - Replace Blown Capacitor Fuses
  - Avoid Unbalanced 3-Phase Loads
  - Fix Open Phases
  - Transpose Lines
- **Apply Three Phase Voltage Regulators**
- **Phase Balance Relay Protection**

Voltage Unbalance Summary

- No Widely Used Agreement on Calculation Method or Limits
- Utilities, Manufacturers and End Users Need to Agree on Criteria and Guidelines and Assessment Methodology for Each Application
- Usually Not an Issue, But Could Go Unnoticed Except for Reduced Equipment Life

Questions?
Discussion