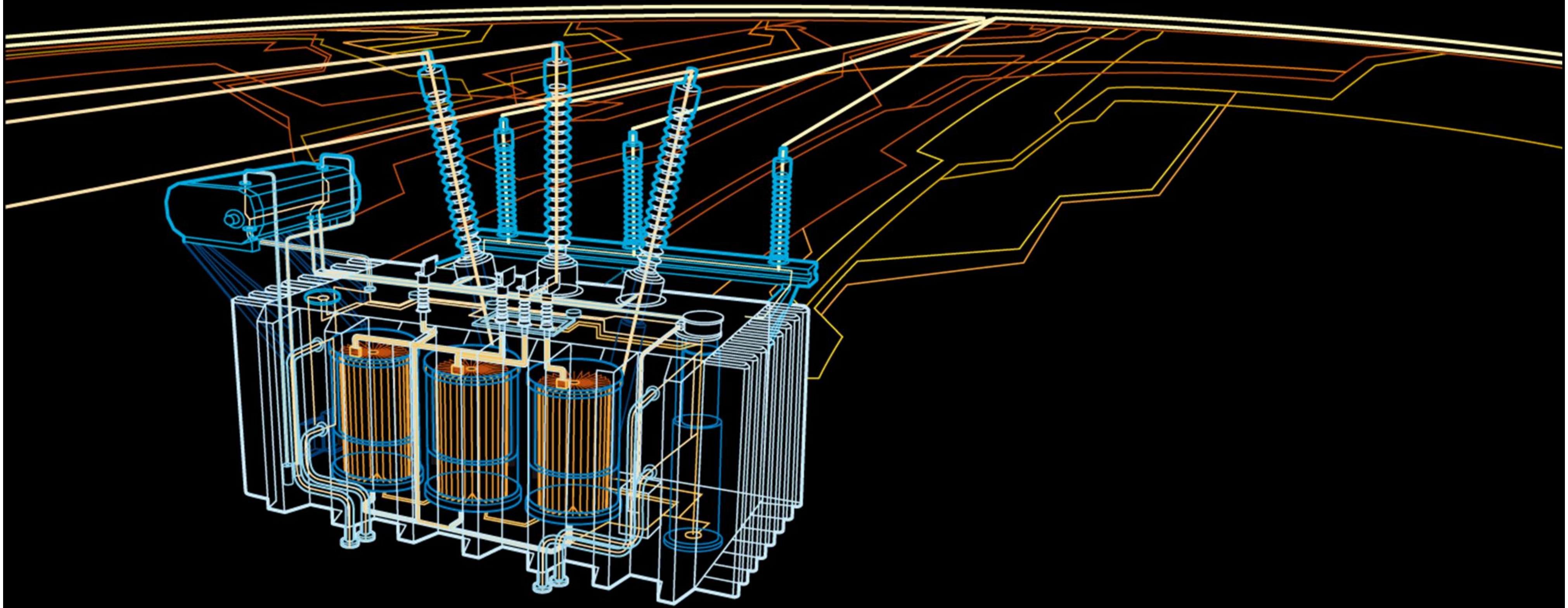

Effect of GIC on Power Transformers & Power Systems

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ABB Power Transformers; St. Louis , MO

PSRC Meeting

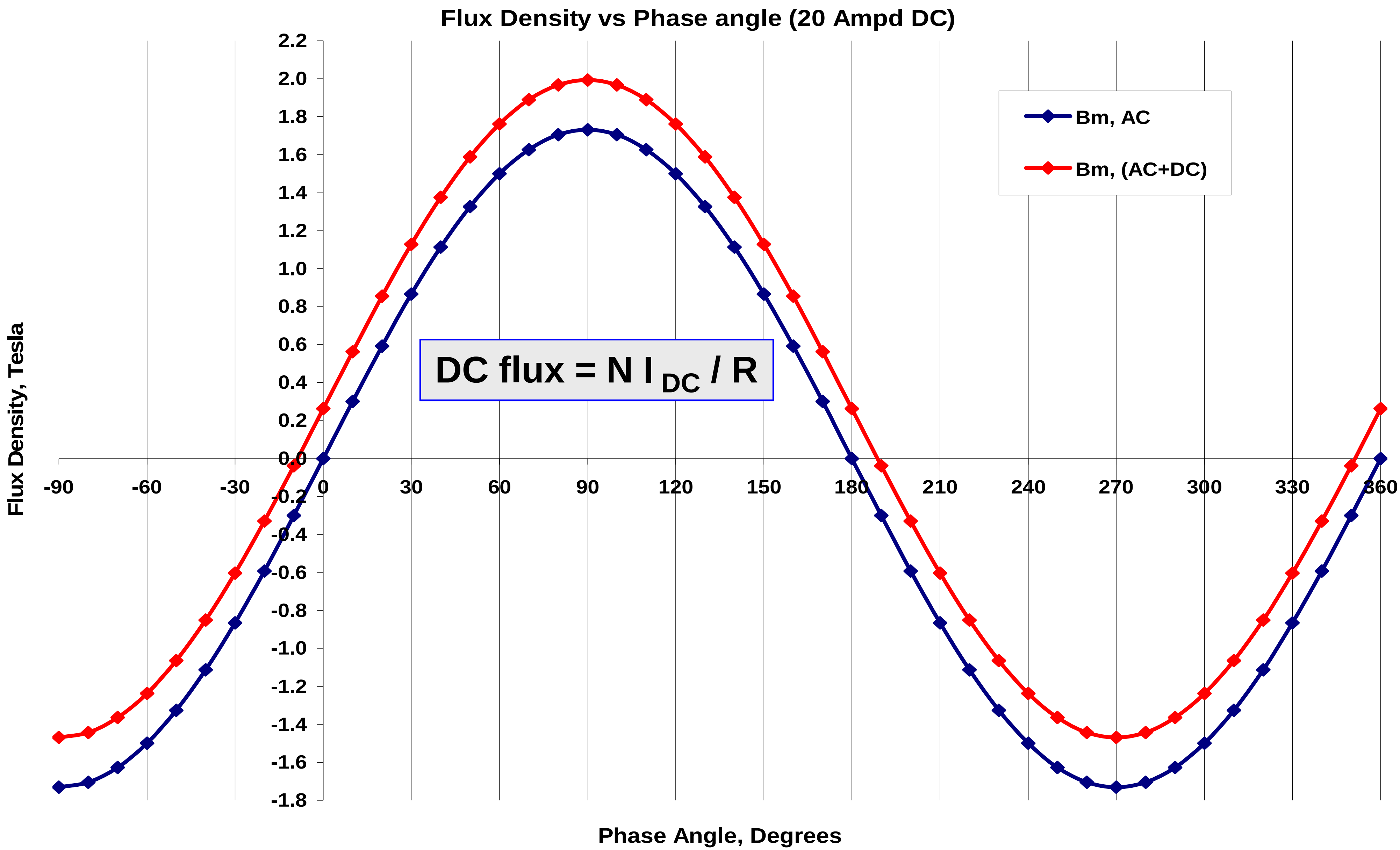
May 14, 2014

Outline of Presentation

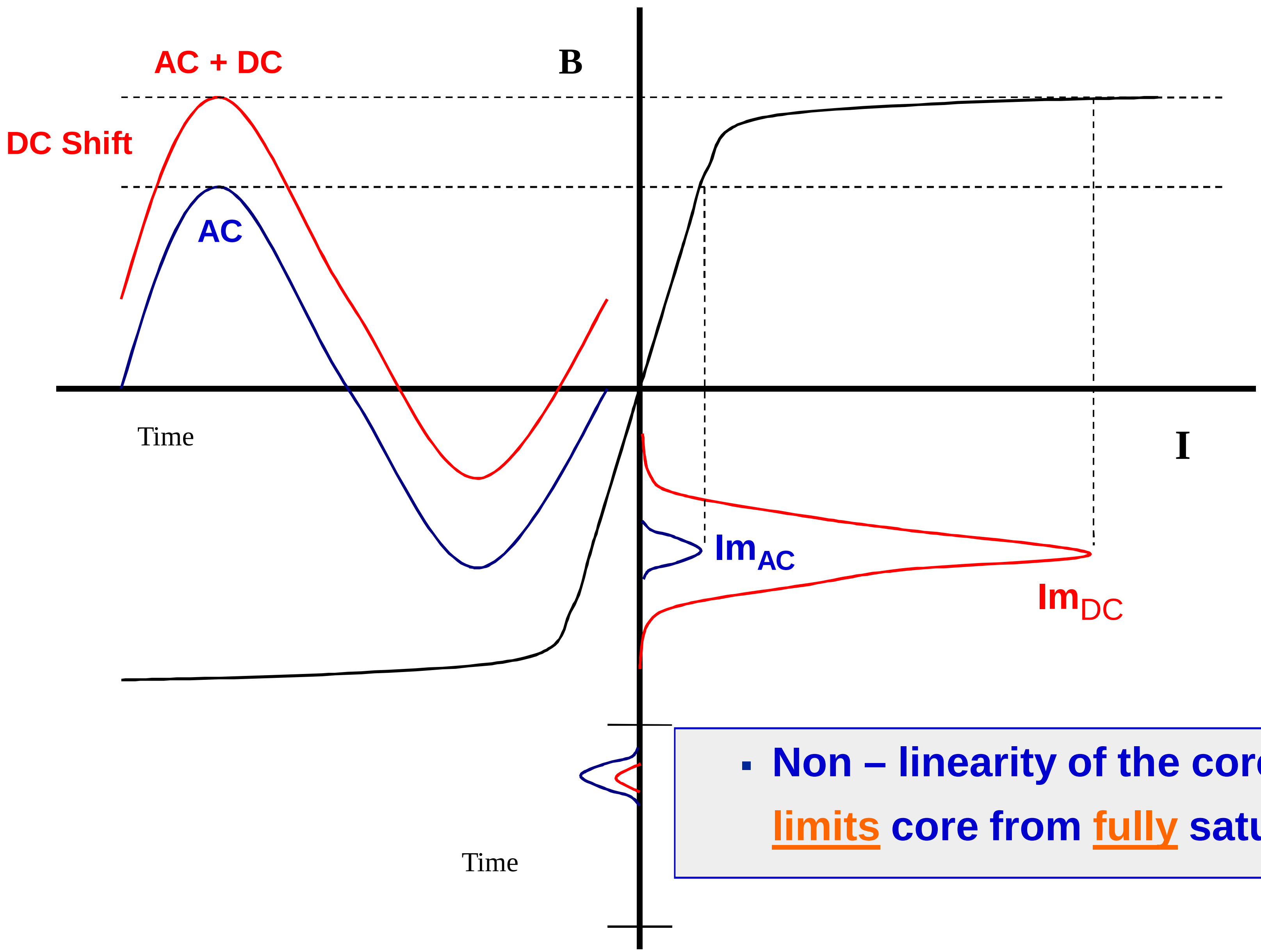
- Effect of DC on Power Transformers
- Effect of GIC on Power Transformers
- History of recent significant GMD events
- Effect of GIC on Power systems
- Mitigation of Effects of GIC
- GIC Fleet Assessment
- Determining the GIC Capability of a Power Transformer
- Summary and Concluding Remarks

Effect of DC on Transformer Cores

DC Flux Density Shift in Transformer Cores

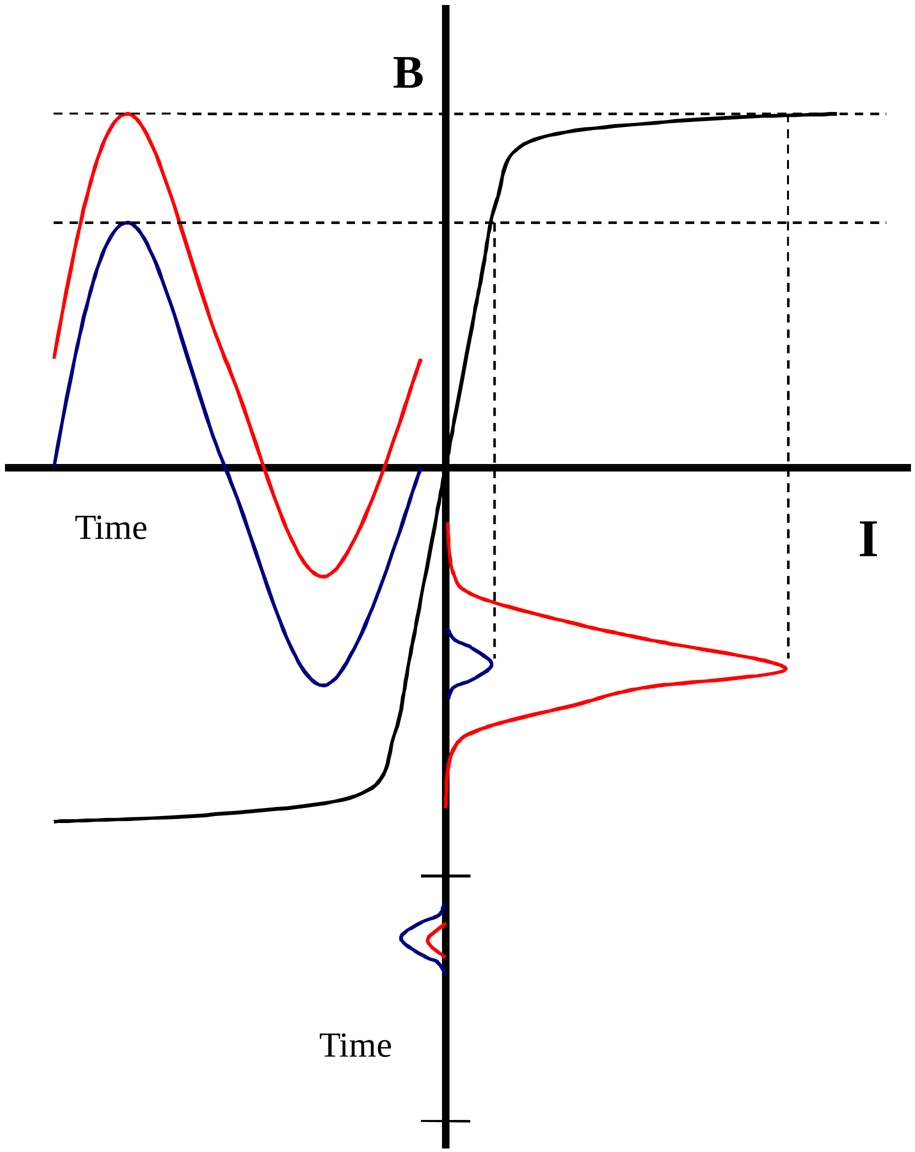


DC causes Part – Cycle, Semi – Saturation of the core



- Non – linearity of the core material <u>limits</u> core from <u>fully</u> saturating

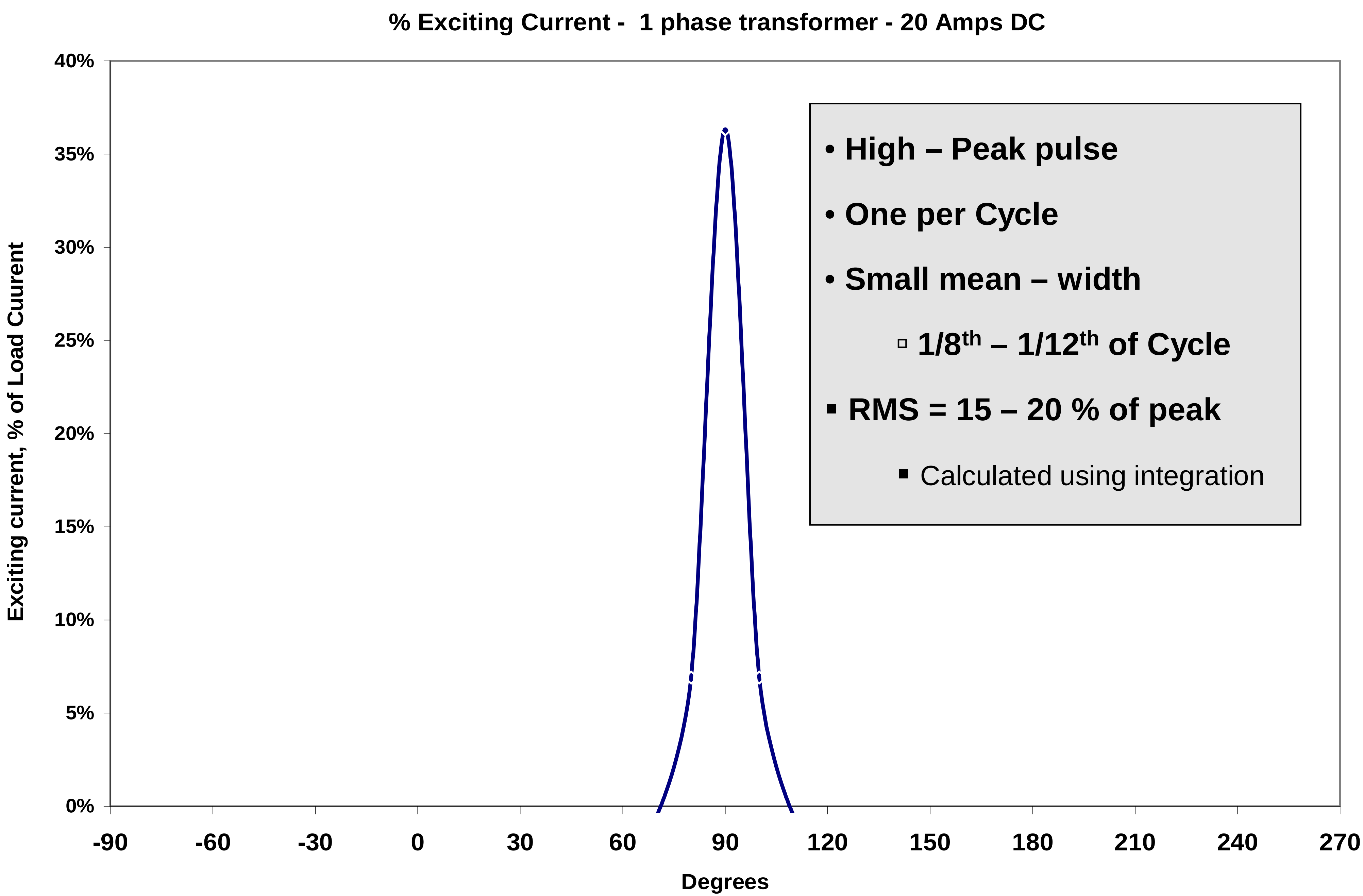
Flux density shift caused by DC



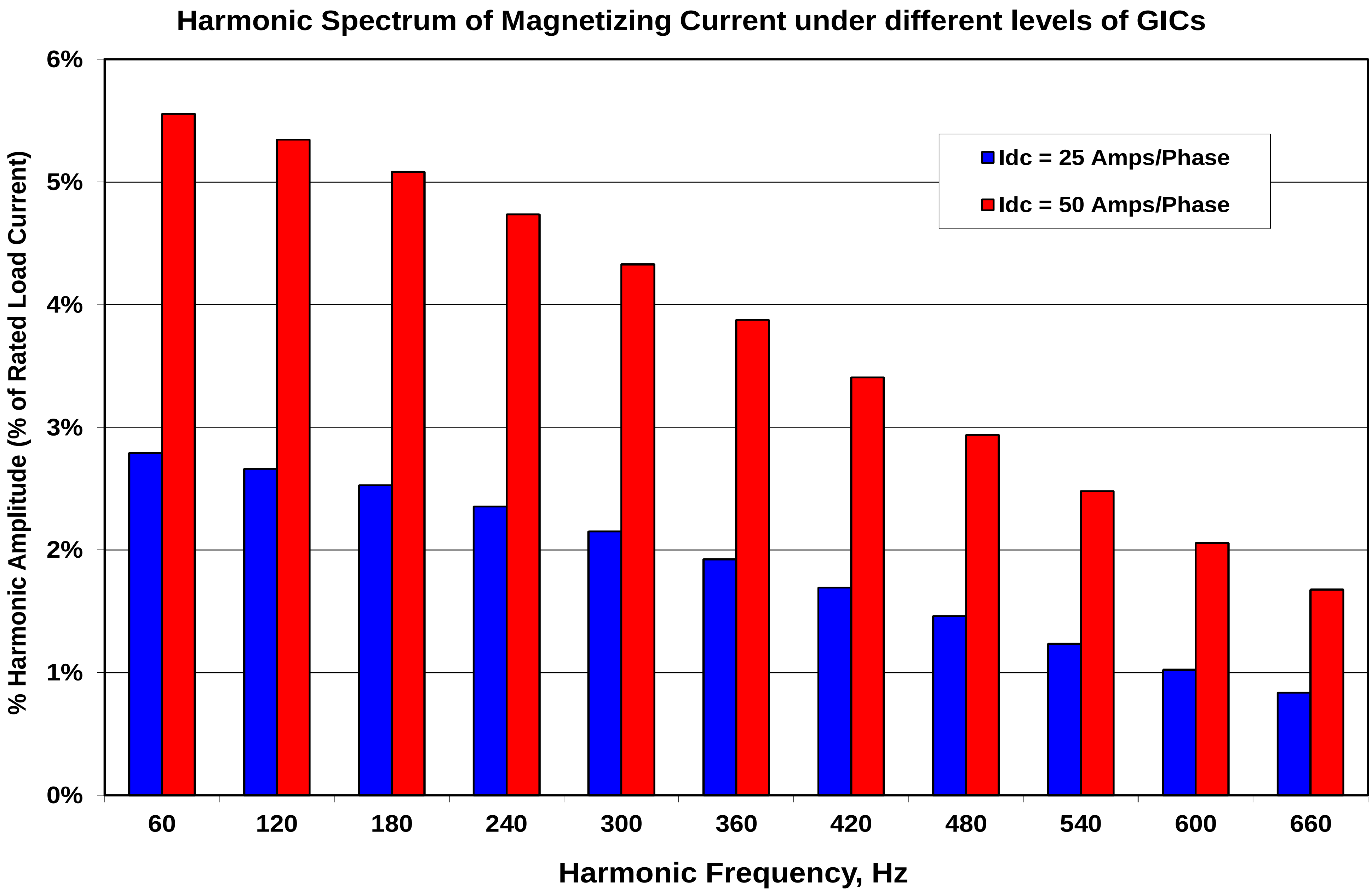
GIC Amps / Phase	ΔB dc, Tesla	B m (dc + ac), Tesla
5	0.417	1.936
10	0.459	1.978
15	0.482	2.001
20	0.499	2.018
25	0.510	2.030

- Non – linearity of the core material <u>limits</u> core from <u>fully</u> saturating

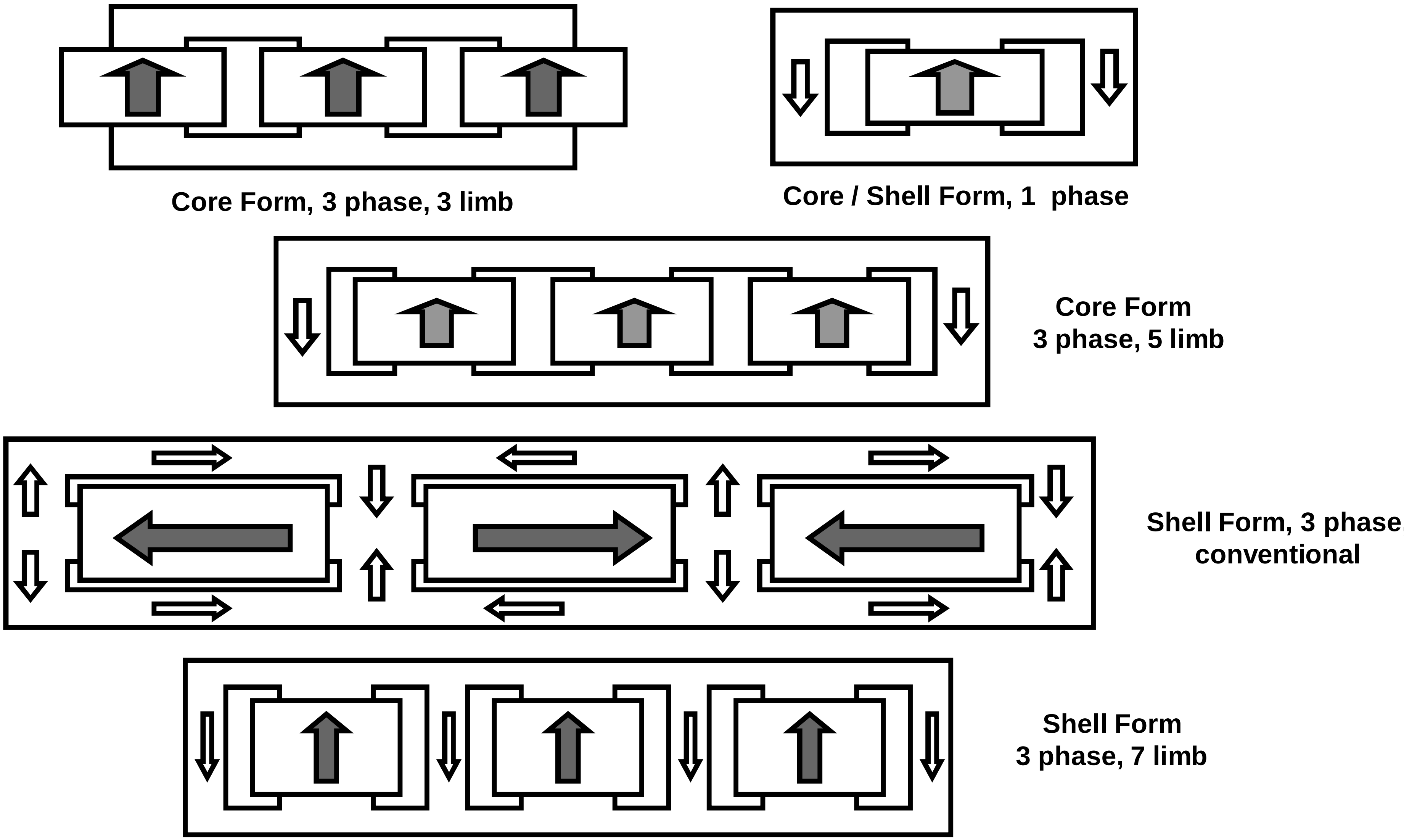
Magnetizing current pulse caused by DC / GIC



Current Harmonics Associated with DC / GIC



DC Flux Path in different Core – Types



- 3 – Phase, 3 – Limb cores require much higher magnitudes of DC to saturate compared to all other core – types
- All other core – types are basically equivalent, other design factors are more relevant

Effect of DC / GIC on Core Losses and Core Noise

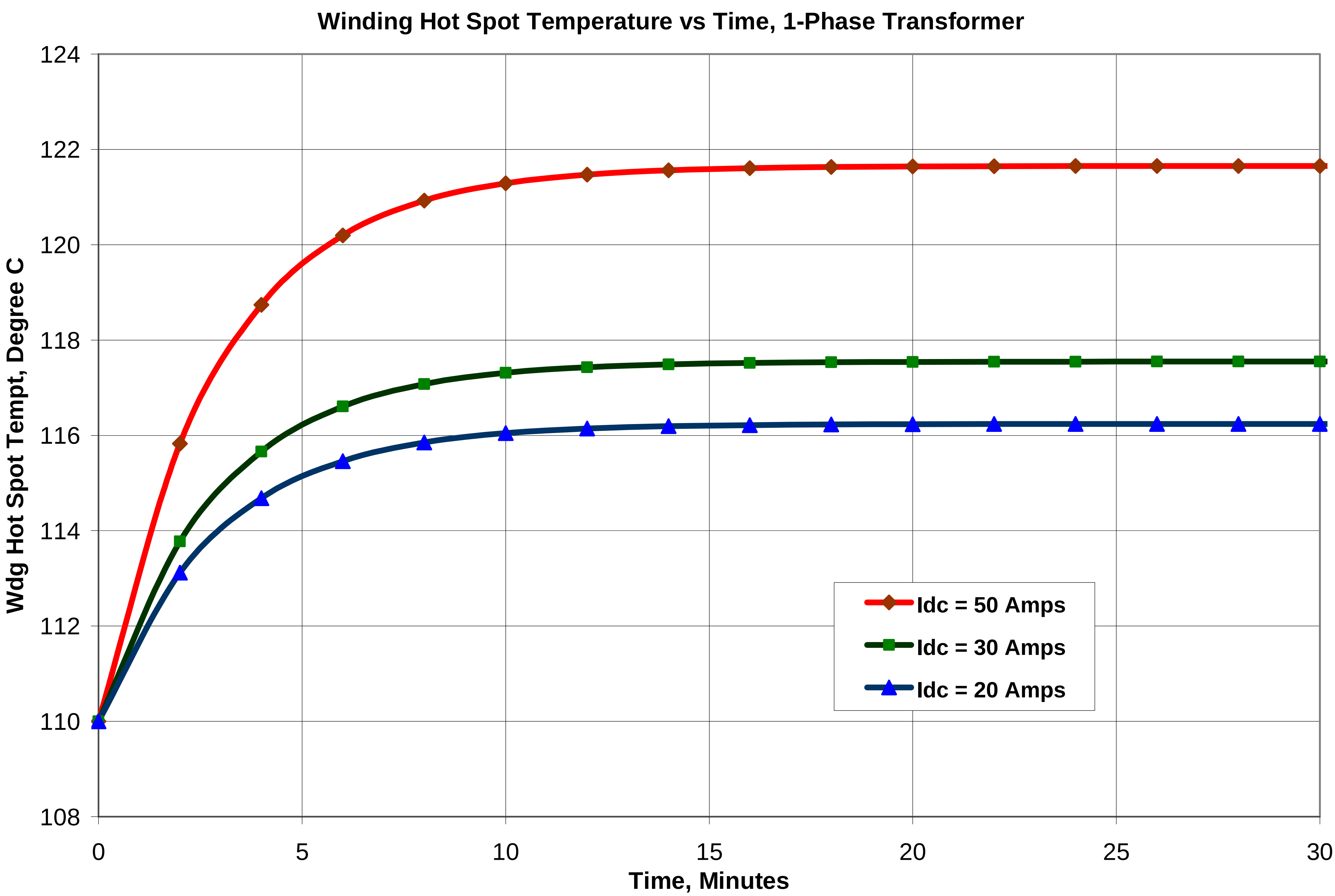
GIC (A/Phase)	Core Loss Increase	Core Noise level Increase (dB)
15	29.0%	29.6
20	31.5%	31.2
30	35.3%	33.7
40	38.1%	35.4
50	40.4%	36.9
100	48.2%	41.6
200	56.9%	46.7

- Increase in core loss / noise level is significant even at low levels of DC
- Noise increases in level and also in frequency content
    - Typically, 120 / 240 / 360 / 480 Hz => Much higher $\geq$ 480 Hz

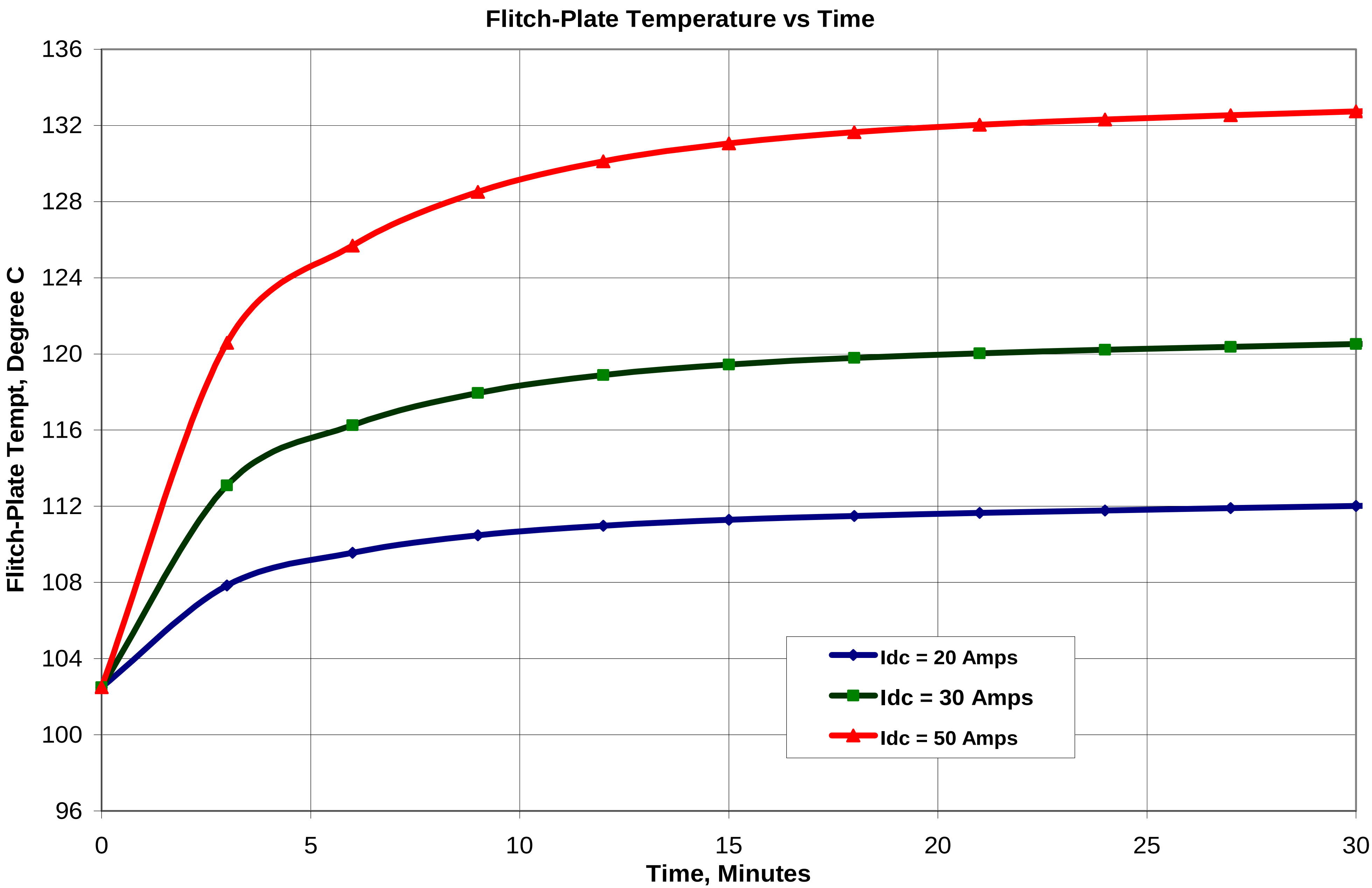
Effect of DC / GIC on Load Losses

- **A high magnitude pulse of magnetizing current**
  - High magnitude of leakage flux, rich in harmonics
  - Higher I^2 R and eddy current losses in windings & structural parts
  - Increase is lower than expected because of low RMS value
- **Some of the core flux flows outside the core**
  - Causing higher windings, tie – plates, and tank losses
- **Core saturation can result in a significant change in the leakage flux pattern**
  - Resulting in high winding circulating currents in <u>some</u> designs

Effect of DC on Winding Hot – Spot Temperature

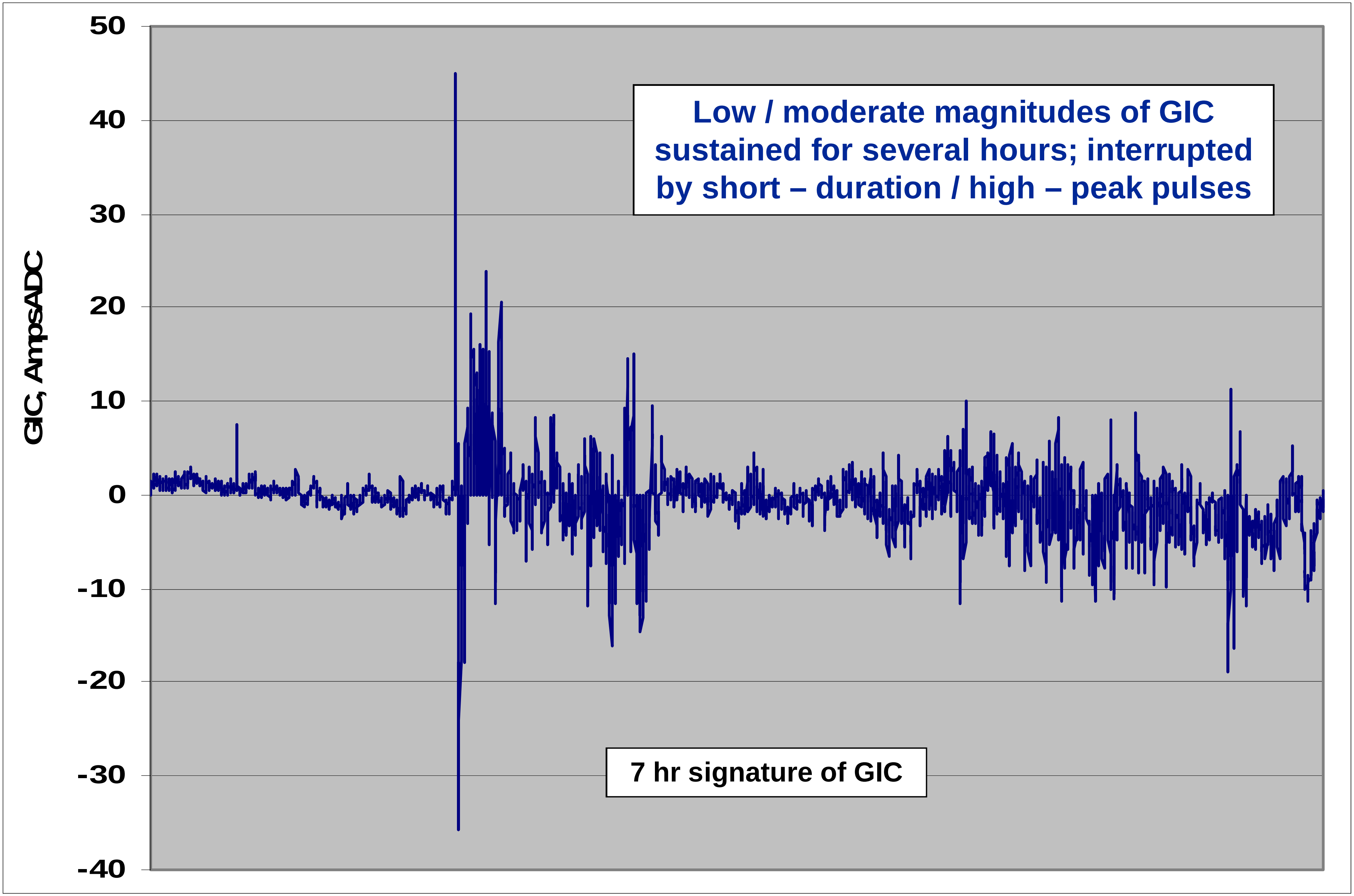


Effect of DC on Hot – Spot temperature of Core Tie – plates

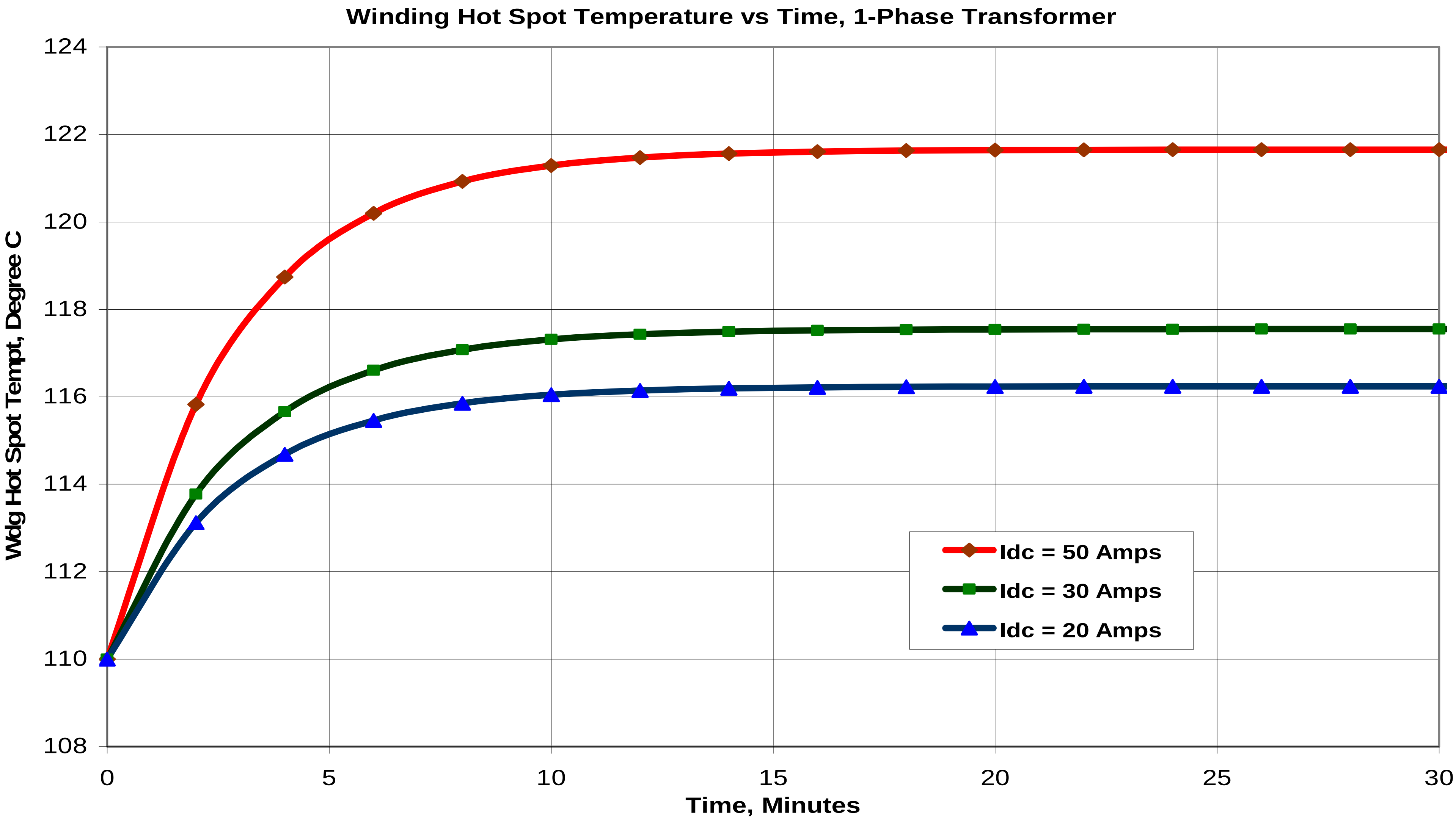


Effect of GIC on Power Transformers

Signature / Profile of GIC



Effect of GIC on Winding Hot Spot Temperature



- Actual temperature rise is much lower for the short duration of high GIC peaks
- For a 2 – minute duration: Rise is 3, 4, and 6 C for GIC of 20, 30, and 50 Amps

Effect of GIC on Core and Oil temperatures

- **Effect of GIC on Core Hot Spot Temperature**
  - At operating conditions
    - Core Hot Spot Temperature rise is 25 – 40 C, and total is $\leq$130 C
  - Increase in core losses due to GIC
    - A fraction of core losses at normal operation
  - Core thermal Time constant is 1 – 2 hrs

    $\Rightarrow$**Insignificant increase in core temperatures**
- **Effect of GIC on Oil Temperature**
  - Increase in total load loss is a fraction of Load losses at full load
  - Time Constant of transformer oil is 8 – 10 hrs
    - => **Insignificant increase in oil temperature**

History of Recent significant GMD Events

History of Recent Significant GMD Events

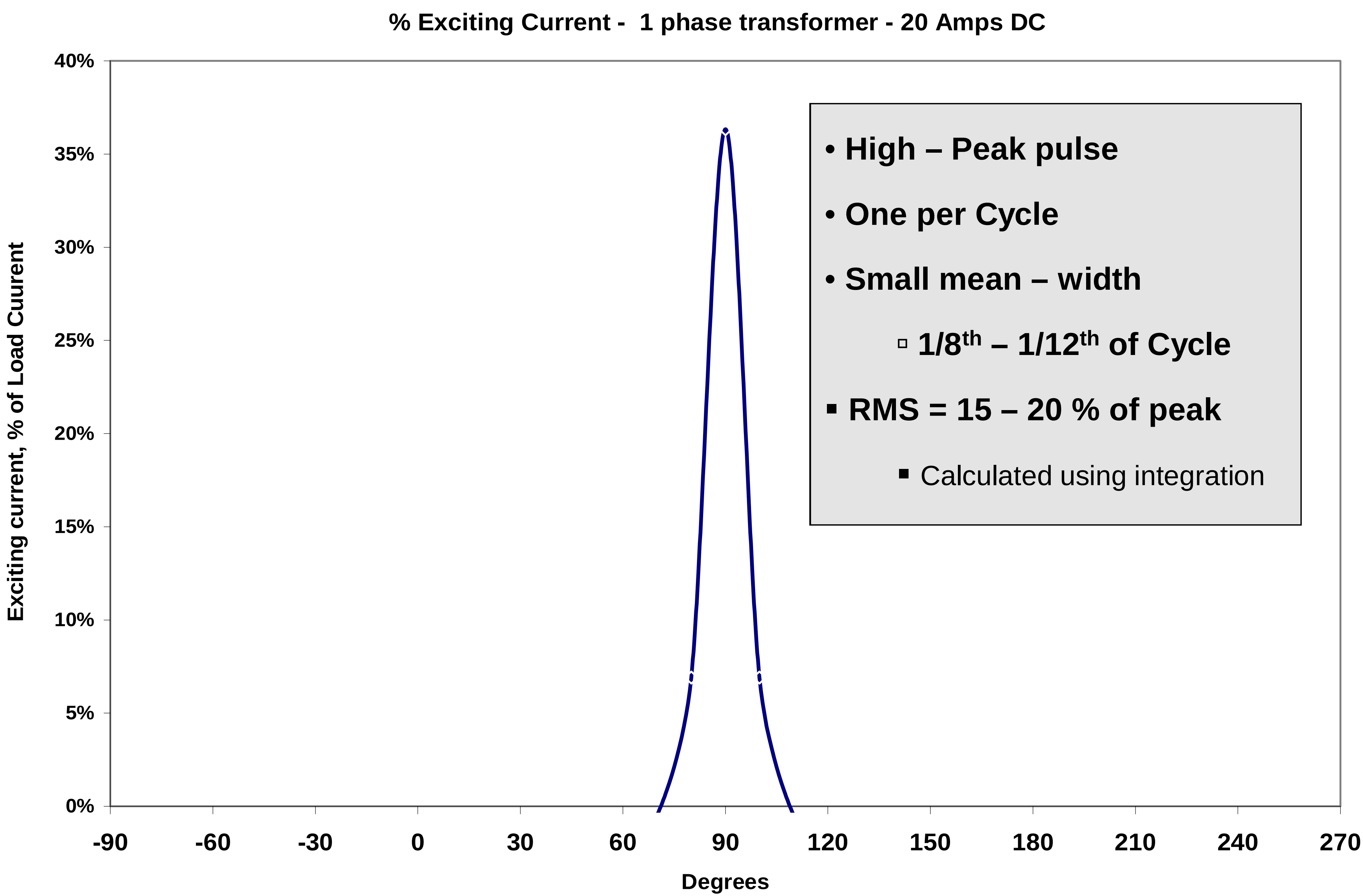
- **March 13, 1989**
  - Base GIC of 20 Amps / phase interrupted by short duration pulses of 80 – 100 Amps / phase in GSU (s) at PSE&G's Salem and Hope Creek Generating stations
    - Significant overheating of series connection in LV of an old shell – form transformer caused by high circulating currents
    - Transformer was taken out of service a week later because of significant gassing
    - Similar but less overheating of others of same design transformers in the area
      - Continued operation
  - Some gassing / tank paint discoloration of a # of transformers in NE of USA
  - An 8 hr. blackout of the HQ system
    - Due to tripping of Capacitor banks / SVC (s); causing system instability
    - Report of dielectric failures of 2 transformers; caused by system Instability

Recent History of Significant GMD events, Cont.

- **S. Africa: Nov.'03 – June '04, a few transformers had significant winding damage**
  - Moderate levels of GIC
  - Coincided with winding failures caused by Copper Sulphide
- **Sweden: Oct. 31, 2003: Report of very strong GMD storm; 3 phase / 5 limb / 400 KV transformers were subjected to as much as 330 Amps GIC in the neutral**
  - 20 – 50 minute black out due to system instability caused by tripping of 130 KV line
  - Minor heating / low level gassing in the transformers
- **Reports of one sudden transformer failure in New Zealand and two in Britain**
  - No details given and could not be confirmed to be caused by GIC heating

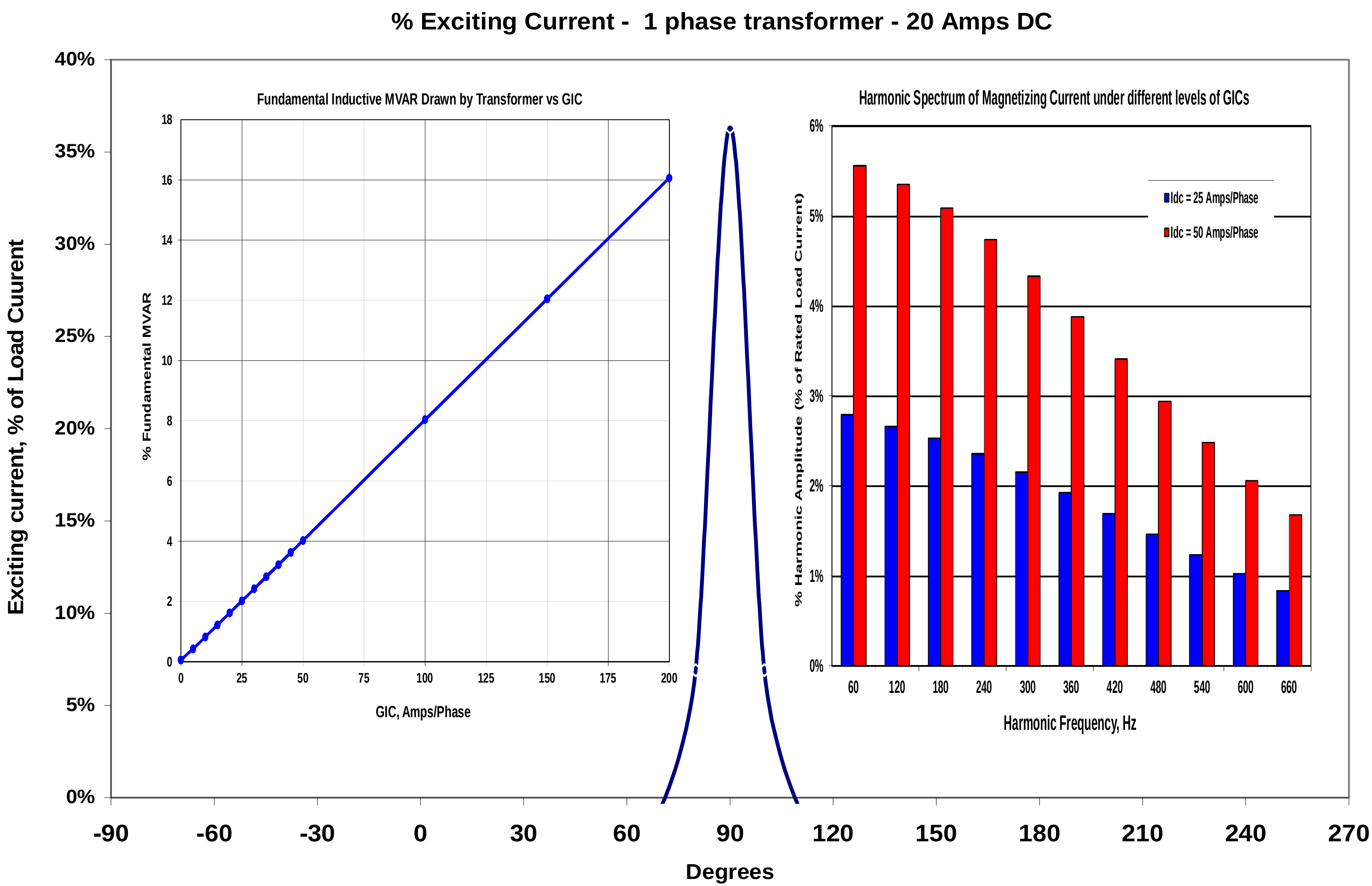
Effect of GIC on power systems

Magnetizing current pulse caused by DC / GIC



- High – Peak pulse
- One per Cycle
- Small mean – width
  - 1/8th – 1/12th of Cycle
- RMS = 15 – 20 % of peak
  - Calculated using integration

Magnetizing current pulse caused by DC / GIC, *cont.*



Effect of GIC on power systems

- **Causes a high magnitude current pulse of ~ 2 msec. duration to flow in the system (once / cycle)**
- **This pulse causes the capacitive components on the system, such as static compensators, etc. to increase their currents and may become overloaded and trip, causing grid instability**
- **The current pulse is associated with high order harmonics:**
  - Electrical resonance may occur and stability of the grid may be compromised.
  - Other harmonics can cause relay miss – operation
  - Low % of 2nd order harmonic could send the wrong message of fault current to the differential relays

Mitigation of Effects of GIC

Available Means of Mitigating the effect of GIC

- **Alerting**
- **Monitoring / Measurements**
- **Simulations and evaluation of risk**
- **Increasing robustness of network**
- **Providing network protection**
- **Proper operating procedures during a storm**
  - Line load – sharing, desensitization of susceptible equipment, and minimizing voltage regulations
- **Installation of appropriate GIC blocking devices if feasible / needed**
- **Taking advice of utilities who have experience (HQ)**

Evaluation of susceptibility of a fleet of Power Transformers to effects of GIC

Back Ground

- **Misconception in the electric power industry**
  - GIC has caused, and would cause, significant damaging overheating to a large majority of power transformers (> 70 %)
- **Overreaction => Calling for:**
  - Conservative operating procedures (Unnecessarily reducing load at low levels of GIC)
  - Installation of expensive GIC Blocking devices
  - Paying more attention to thermal effects in transformers and not to the true issue of increased VAR Demand and effect of harmonics on power system components
- **A recent study confirmed that because of the nature of the GIC currents**:
  - Only a finite number of power transformers with certain design features could experience damaging overheating
  - A larger # of transformers would be susceptible to core saturation & some overheating
  - The rest of the transformers would not be susceptible to either core saturation or damaging overheating

Purpose of Fleet Assessment

- **To Determine which Transformers**:
  - Would be susceptible to damaging overheating
  - Would be susceptible to only core saturation & moderate overheating
  - Would have a low level of susceptibility to either effects of GIC
  - Would not be susceptible to effects of GIC

Evaluation of Total Susceptibility of transformers to effects of GIC

- **Total susceptibility to effects of GIC is determined by:**
  - Transformer Design – Based Susceptibility
  - GIC Level – Based Susceptibility
- **Process was applied to a fleet of over 1600 $\geq$ 500 KV Large power transformers on the US Power Grid, as a Case Study**

Design – Based Susceptibility

- Category – I:
  - Transformers not susceptible to effects of GIC
- Category – II
  - Transformers least susceptible to core saturation
- Category – III
  - Transformers susceptible to core saturation and some windings & structural parts overheating
- Category – IV
  - Transformers susceptible to both core saturation as well as possible damaging windings and / or Structural parts overheating

Parameters Used for Evaluating Design – Based Susceptibility

- Voltage Ratings
- Type of transformer (GSU vs. Auto transformers)
- Shell-form vs. Core Form
- Single-phase vs. three-phase and Core-type
- Winding Connections

GIC Level – Based Susceptibility

- **Level of GIC is determined by:**
  - Geographical region where the transformer is located
  - Location of transformer in the power system
  - Closeness to a large body of water (Ocean / Sea / Lake)
  - Resistance of the soil in that location
  - KV of HV side of Transformer
  - Direction of HV transmission lines
- **GIC – Level susceptibility divides transformers into 3 categories:**
  - High, Medium, and Low
- **These categories are determined using either of the following data:**
  - Calculated relative levels of GIC that transformers in a certain location would be subjected to for a predetermined reference GMD storm
  - Using published information on relative levels of GMD that different geographical regions would be exposed to.

Case Study

- 1593 large power Transformers in service
- $\geq$ 500 kV part of the US Electric Power grid
- 1300+ single – phase transformers & 200+ three – phase transformers
- 600+ different designs
- 700+ shell-form transformers and 800+ core-form transformers.
- 200 different shell-form designs and 400 different core-form designs.
- 1400+ transformers are 500 kV transformers and the rest are 765 kV
- 100 MVA – 1000 MVA Power Ratings
- 900+ Autotransformers / 450 Generator Step-Up transformers / 200 other Multi-winding transformers.

Results of Case Study

Number of transformers	Categories of Design-Based Susceptibility				
	Total	IV	III	II	I
Actual Count	1593	1056	464	73	0
% of Total	100 %	66 %	29 %	5 %	0 %

Summary of results of Design – Based assessment of GIC susceptibility

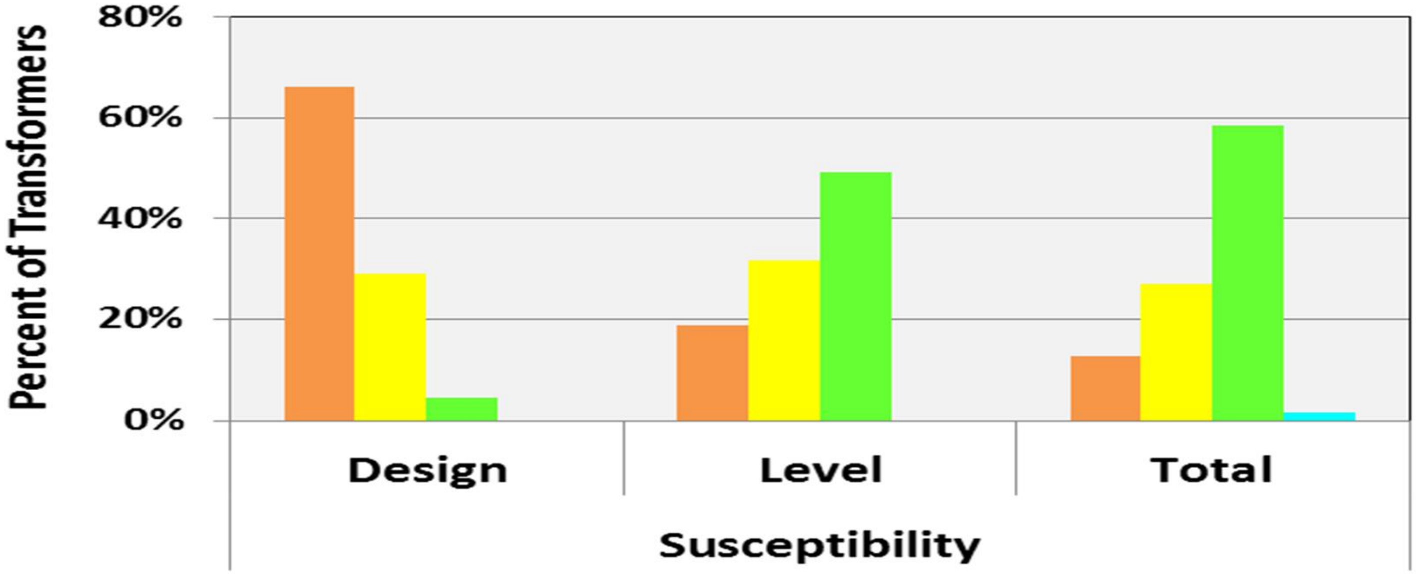
Number of transformers	Susceptibility to Level of GIC Categories			
	Total	High	Medium	Low
Actual Count	1538	290	490	758
% of Total	100 %	19 %	32 %	49 %

Summary of # of transformers susceptible to different levels of GIC

Number of transformers	Total Susceptibility Categories				
	Total	Red	Yellow	Green	Blue
Actual Count	1538	198	415	899	26
% of Totals	100 %	13 %	27 %	58 %	2 %

Summary of results of Total GIC susceptibility of transformers

Final Results of Case Study

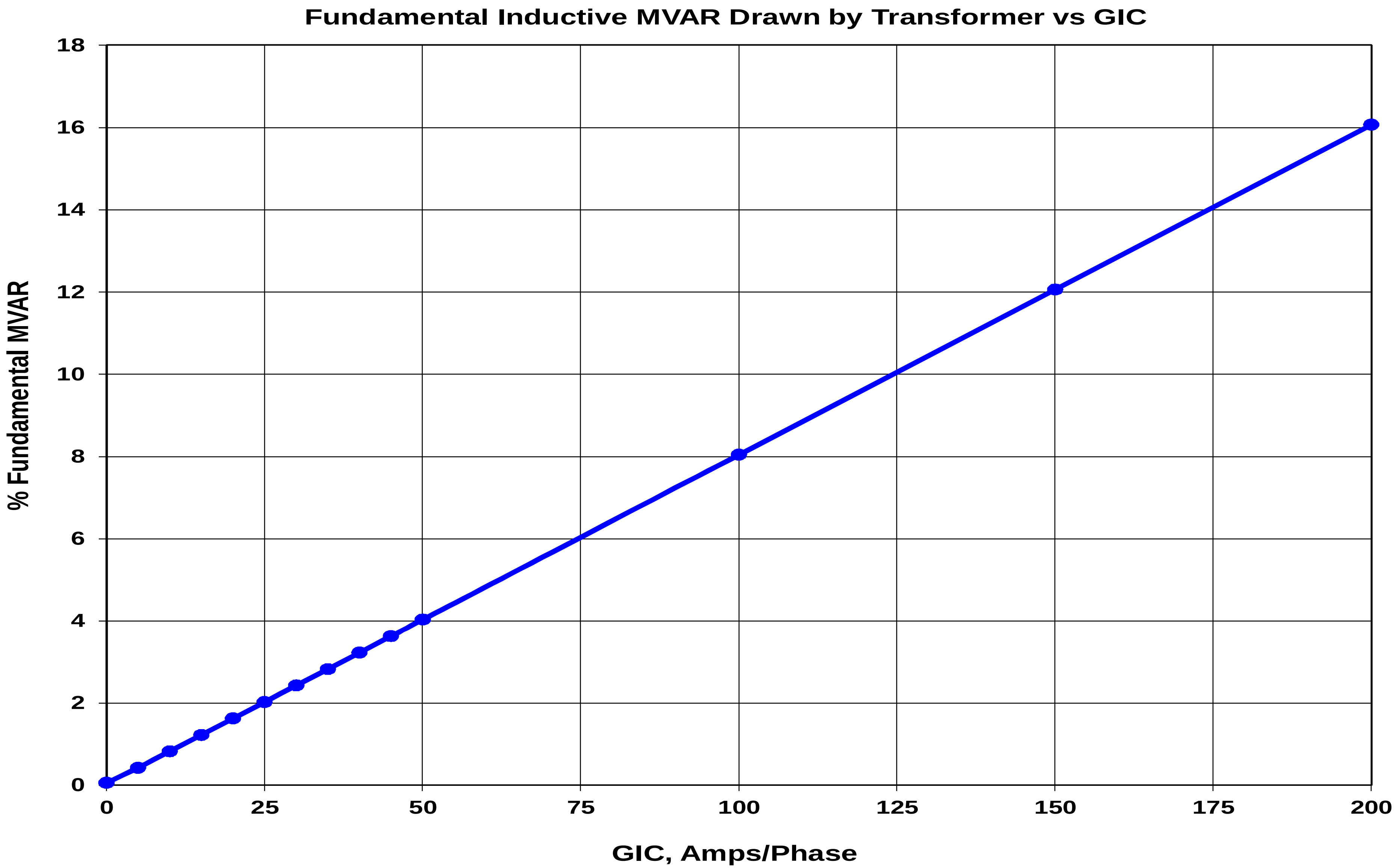


- 2/3rd of transformers were determined, based on their designs, to have a high level of susceptibility to possible damaging overheating, this group drops to about 1 in 8 when considering the locations of these transformers
- Number of transformers that have a medium level of Total susceptibility is only a little lower than that determined to have that level of susceptibility based on the design alone
- The group of transformers determined to have low Total susceptibility to effects of GIC increased from being 1 in 20, when considering the design alone, to about 60 % of all transformers in this study when considering the GIC exposure of these transformers to GIC

Benefits of Fleet GIC Susceptibility Evaluation

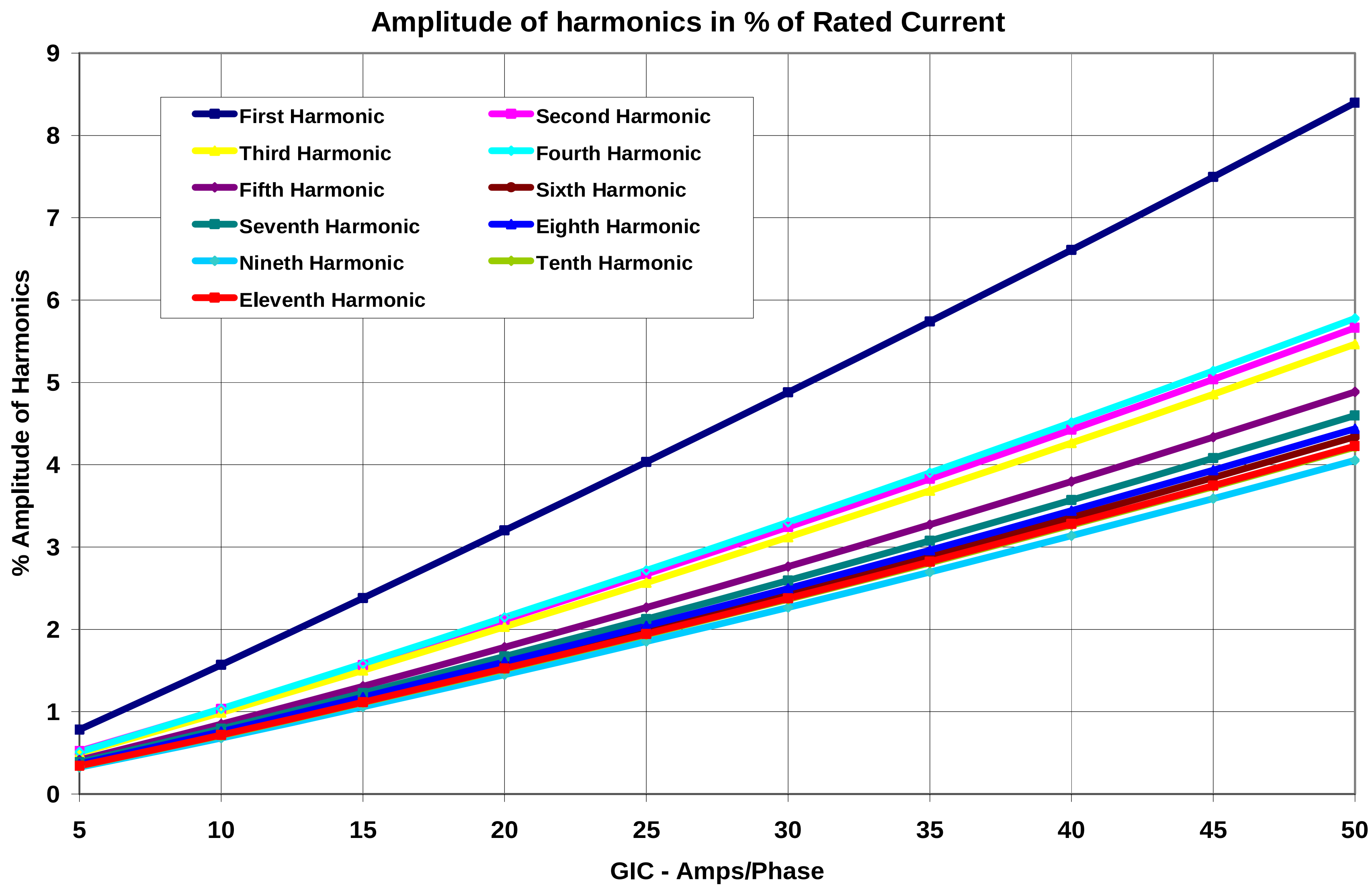
- **Allows Utilities to focus their mitigation / studies effort**
  - Utilities could request manufacturers of transformers, identified to be susceptible to core saturation, to provide data on the additional VAR consumption and current harmonics as a function of the level of GIC the transformer would be exposed to

VAR consumption vs. Magnitude of GIC



Utilities use this data to plan their VAR resources during GMD events

Current Harmonics vs. Magnitude of GIC



Utilities use this data to study effect on their power system equipment

Benefits of Fleet GIC Susceptibility Evaluation, *cont.*

- **Power system analysts would use such data, to perform system simulations for evaluating the response of the power system and its components during a GMD storm. As a result of these studies:**
  - Proper contingencies can be built into the Power System for such magnitudes of VAR, so Voltage Collapse and possible grid black-outs can be avoided
  - Increasing robustness of the network; including providing additional network protection and adjusting settings of relays and other susceptible equipment
  - Developing special / proper operating procedures during a GMD storm
  - Installation of appropriate GIC blocking devices, if needed
- **System blackouts and possible damages to some transformers can be avoided in future GMD events**

Evaluation of GIC Capability of Power Transformer Designs

Benefits of Fleet GIC Susceptibility Evaluation – 2

- Utilities can request manufacturers of transformers, identified as being highly susceptible to damaging windings, and / or structural parts overheating, to perform more detailed thermal analysis to determine the GIC Capability of these transformers; hence avoiding possible damaging overheating

Approach / Definition

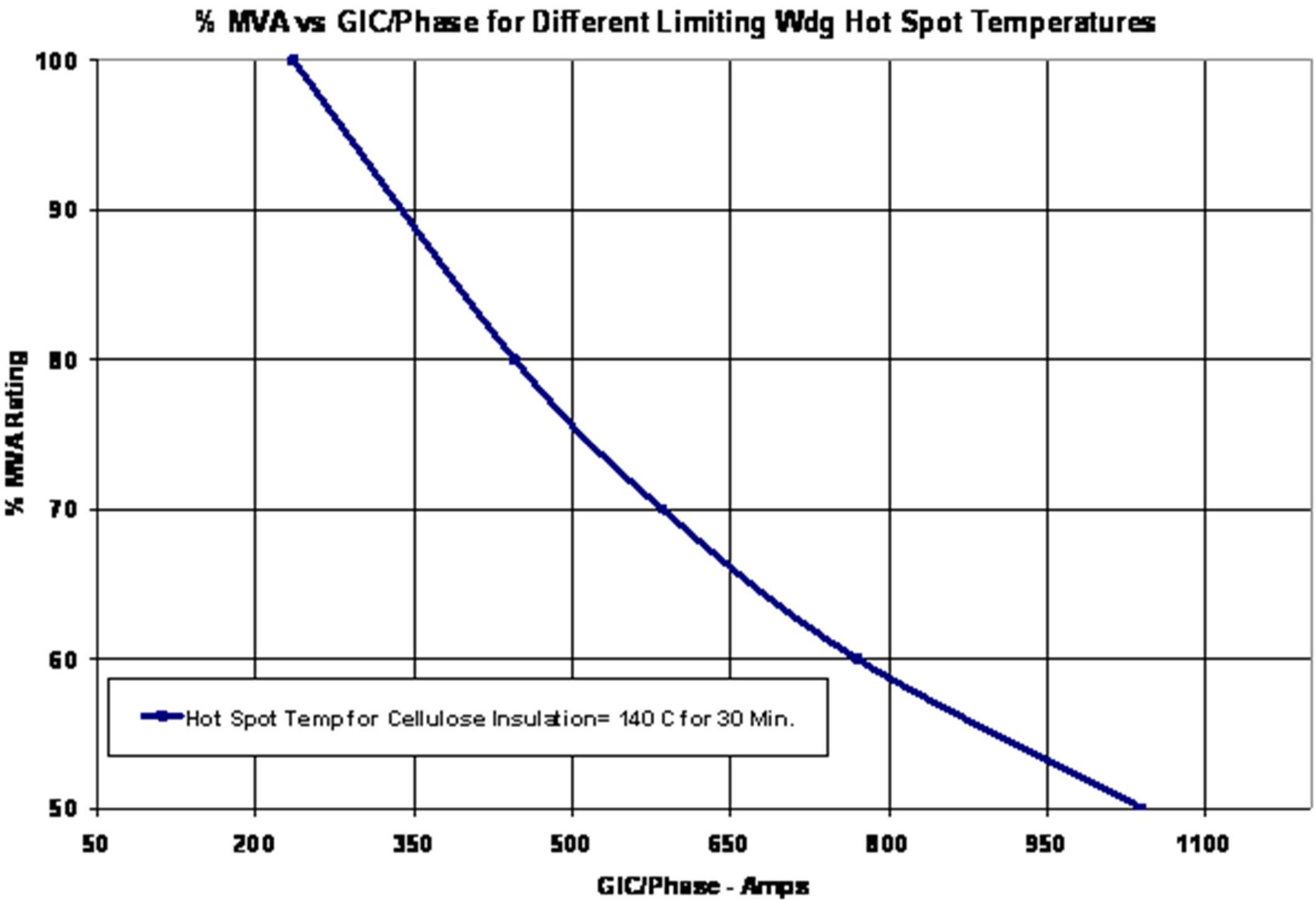
- Combinations of load current and GIC current for which the hot spot temperatures of neither the Windings nor structural parts would exceed certain temperature limits
  - **To limit loss of life of solid insulation**
  - **Avoid formation of gas bubbles**

Approach / Temperature limits

- For low / moderate level **Base GIC**, the hot – spot temperature limits recommended by IEEE / IEC loading Guides to be used for long duration overloading of transformers, are used
  - **Windings: 140 ºC** **Structural parts: 160 ºC** **(IEC & IEEE)**

- For **high – peak, short – duration GIC pulses**, the hot – spot temperature limits recommended by IEEE / IEC Loading Guides to be used for short – duration Emergency overloading of transformers (< 30 minutes), are used
  - **Windings: 160 ºC** **Structural parts: 180 ºC** **(IEC)**
  - **Windings: 180 ºC** **Structural parts: 200 ºC** **(IEEE)**

GIC Capability of a Large 1 – phase Transformer



Summary and Concluding Remarks

- Because of the nature of GIC signature, the majority of large power transformers would not fail thermally even under high magnitudes of GIC
  - Therefore, months / years of blackouts, as claimed, is not real
- The effect of the increased VAR consumption & current harmonics on the power system, and its components, is the real significant consequence of GIC. This is even more true for high levels of GIC. It is important to evaluate this effect

Summary and Concluding Remarks, cont.

- Transformer designs susceptible to damaging windings overheating are those where core saturation changes the leakage flux pattern => Very high levels of winding circulating currents
  - The Salem Transformer was **the** example of these designs
- GIC fleet assessment studies help utilities identify transformers that require magnetic & thermal evaluations; reducing risk of blackouts and possible thermal issues in some old design transformers
- For many technical reasons, DC testing of power transformers in the factory is of little benefit and little relevance to actual operating conditions and is also unnecessary. Also, DC testing of transformers on the power Grid for partial verification of some calculations may be ok but the cost is very high and the test would be performed at no load

Thank you