Dietrich Bonmann, ABB AG Bad Honnef, March 15, 2016

Impact of GIC on transformers and the transmission network

Impact of GIC on transformers and the transmission network : „From GIC to black-out“

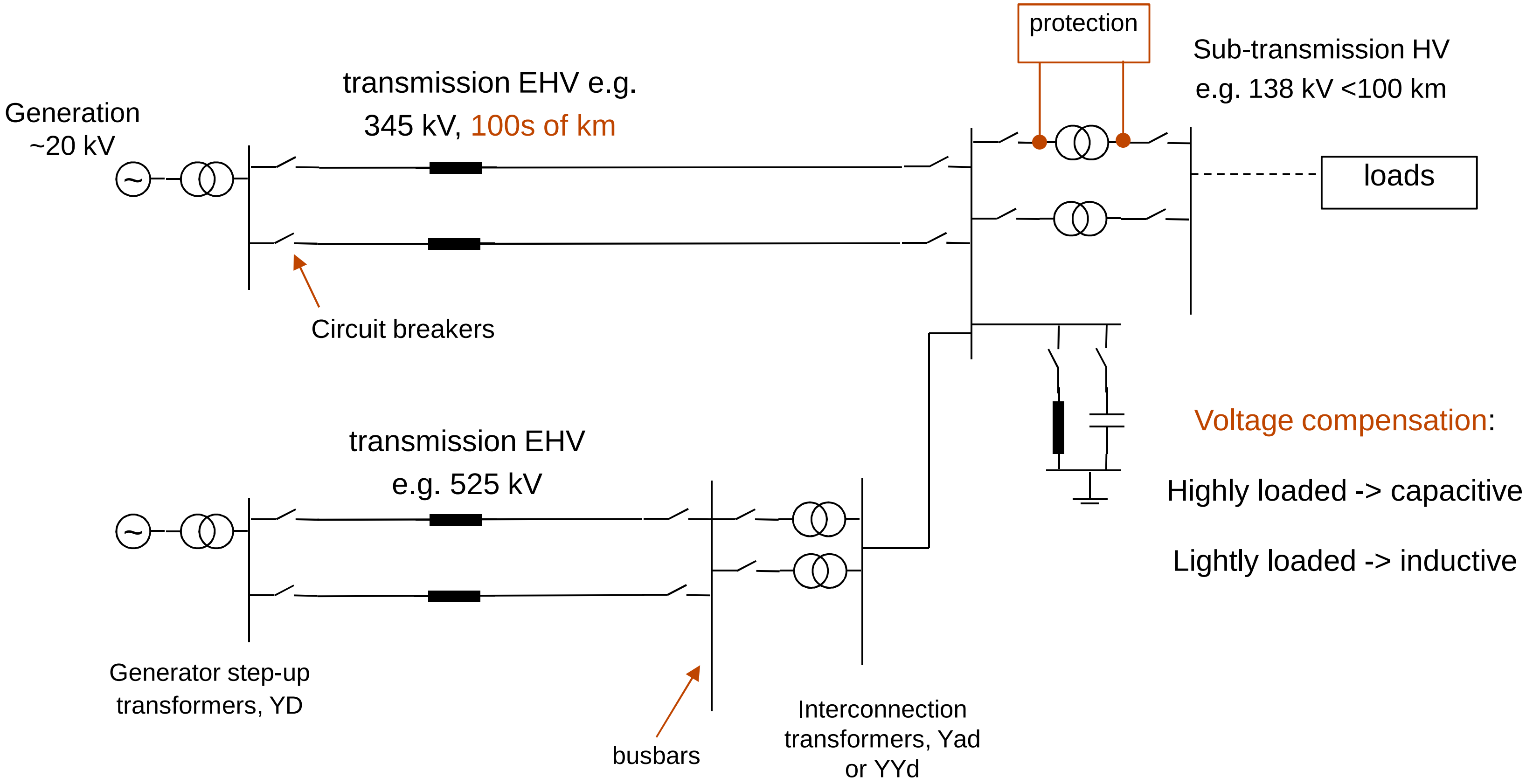
- Main network components
- GIC effects on the network and components, overview
- Transformers: source and subject of harmonics
  - Transformer GIC testing
- Effects on the system and components
  - Protection
  - Capacitors, reactors
- Optional: Regulatory activities in North America
- Optional: Transformer GIC susceptibility screening
- Mitigation measures
- Optional: Failures attributed to GIC in recent years

Impact of GIC on transformers and the transmission network : „From GIC to black-out“

- Under strong GIC transformers become a source of significant current harmonics due to saturation of their magnetic cores
- Three-limb, three-phase transformer cores are much less susceptible to this effect than all other core types.
- Wide area black-outs are more likely caused by systematic malfunction of the protection system and or failure of voltage stabilizing devices than by transformer failures.
- Some transformer may suffer accelerated thermal aging or even a thermal failure, typically this happens with a delay of hours to months, not leading to a black-out.
- The capability to ride through severe GIC events can be improved for new transformers only.
- Harmonics and reactive power consumption can be reduced in some locations only (neutral blocking or compensation).
- The protection system and operating practices need to be enhanced to minimize the consequences of GIC events.

Impact of GIC on transformers and the transmission network

Main network components



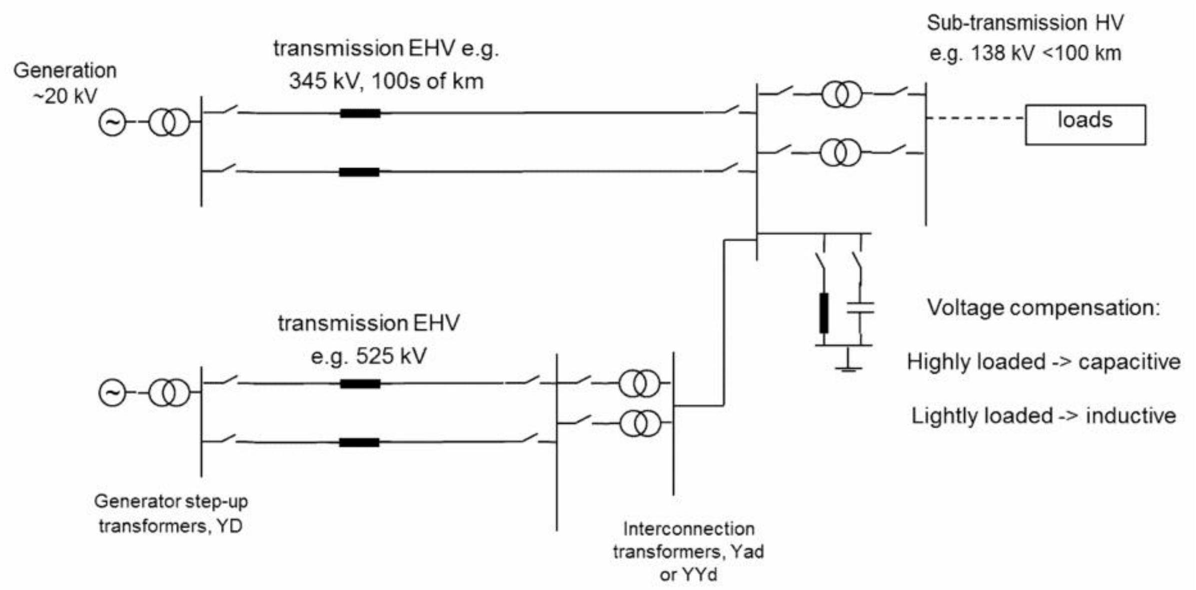
Impact of GIC on transformers and the transmission network
Protection and control system

- Normal operation of the network is handled by the dispatch and control centers within the restraints of all network components: Voltage, frequency, real and reactive power. Generation dispatch and topology have to be adjusted to the loading.
- However, there are always some unscheduled disturbances, e.g. lightnings, storms, equipment failure.
- The network has to be designed in such a way that a fault can be detected, localized and isolated without impact to those parts of the network that are not directly affected. (N-1, N-2 security). Contingency planning.
- Damaging excessive stresses on the components (loads, voltages, magnetic flux, temperature…) have to be detected and mitigated, typically by switching off the transmission component at risk or by load shedding.
- Electrical protection devices measure currents, voltages, at the terminals of the pieces of primary equipment. Criteria: simple threshold, current sum, impedance, etc.…rely on accurate measurements. Harmonic filtering and logics are applied to discriminate true faults from transient conditions and to localize internal/external faults for the protected zone.

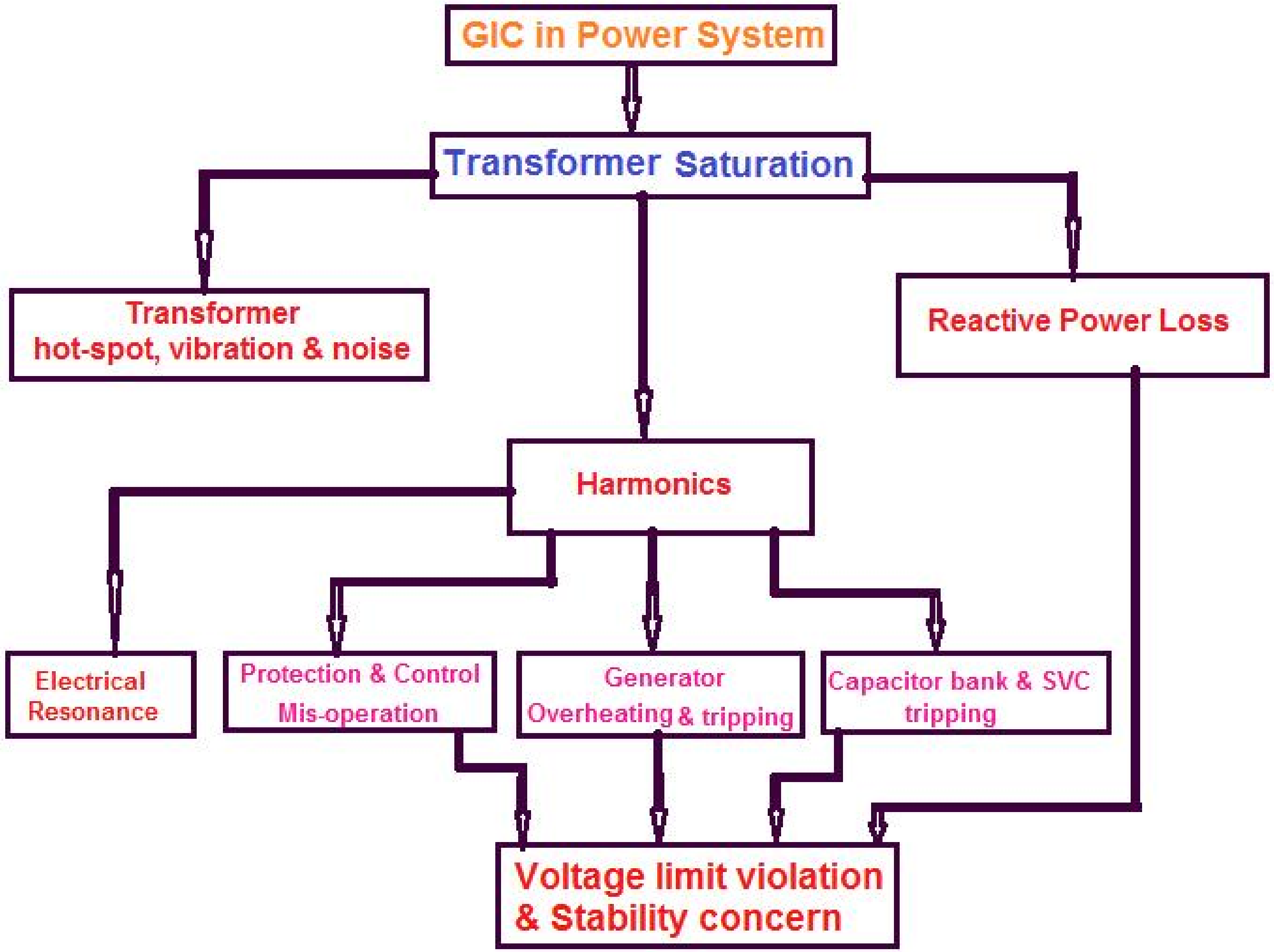
Impact of GIC on transformers and the transmission network

Causes of blackouts

- Single equipment failure (transformer, reactor, transmission line, breaker…) should be covered by N-1 contingency planning,
- Thermal overload of several lines, cascading trips
- Voltage instability



GIC effects



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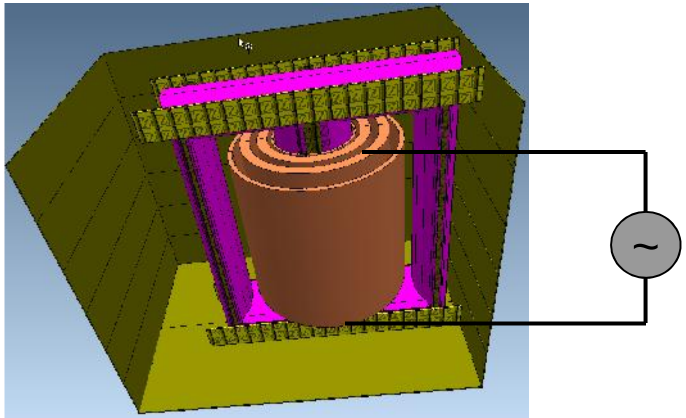
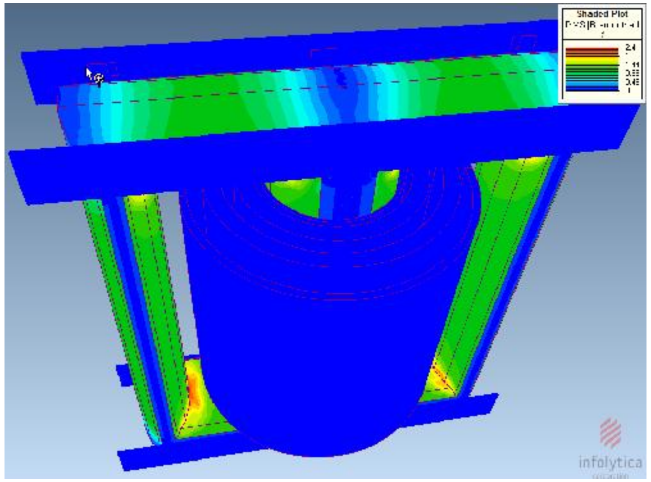
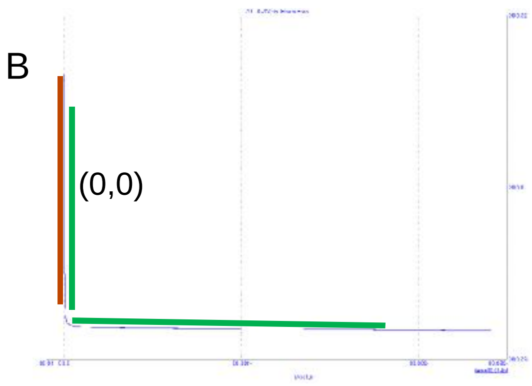
Effects of geomagnetically induced currents and DC
Transformers, physical effects

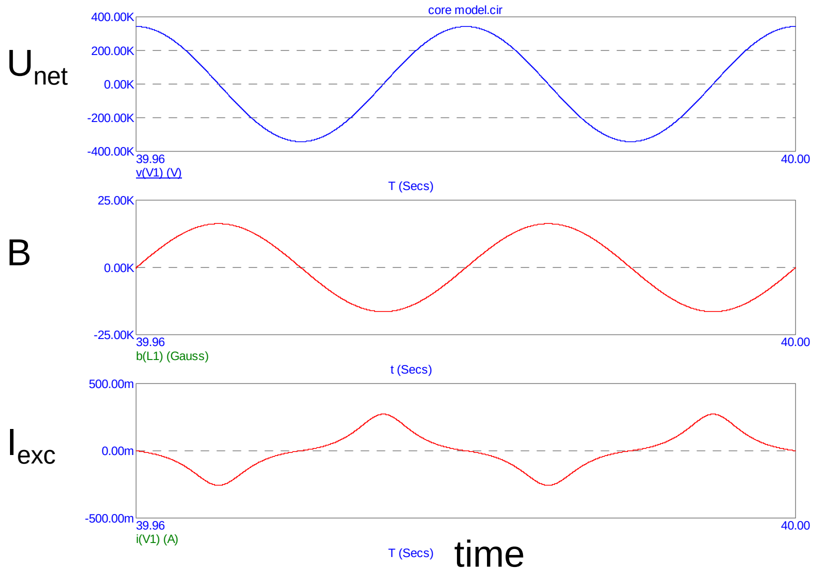


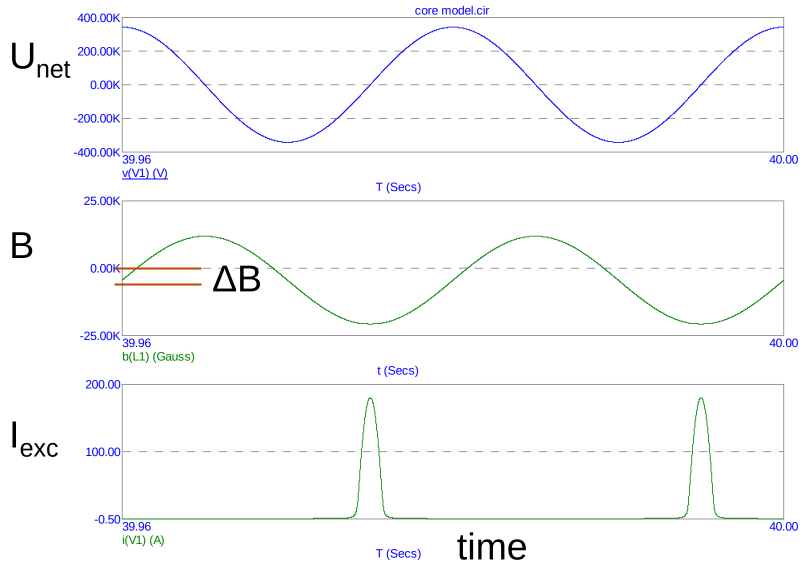


- Transformers use the principle of induction: a voltage is induced in a conductor coil encircling a changing magnetic field. (A magnetic field is produced by a current in a conductor. It can be identical to the coil)
- In power transformers magnetic steel is used inside the windings to concentrate and guide the magnetic field in a smallest possible volume.
- In magnetic steel a very small excitation current produces a high magnetic flux density (of the 10000 times higher than in air or oil) , such that a very small „no-load“ current is required to maintain the desired voltages.
- However this ferromagnetic effect saturates at a certain flux density (~ 2 Tesla)

Effects of geomagnetically induced currents and DC Transformers, physical effects



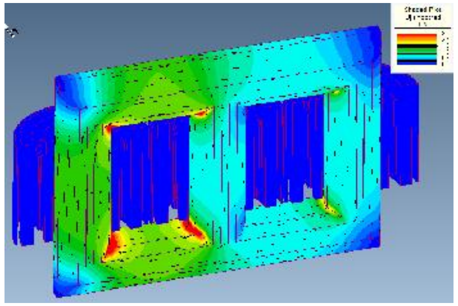




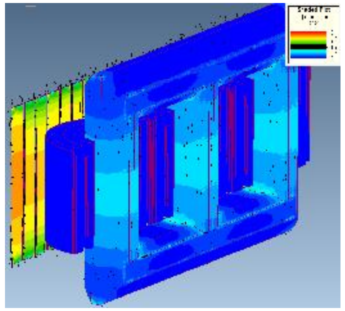
- Without dc (red) the core is very easy to magnetize with a very small excitation current.
- When a DC current pre-magnetizes the core the sinusoidal variation of flux is still the same, but shifted by ΔB towards saturation in one half cycle (green).
- In the fraction of the cycle where the flux density exceeds the saturation value for the core a much higher current is needed to produce the same flux variation inside the winding.

Effects of geomagnetically induced currents and DC
Transformers, physical effects

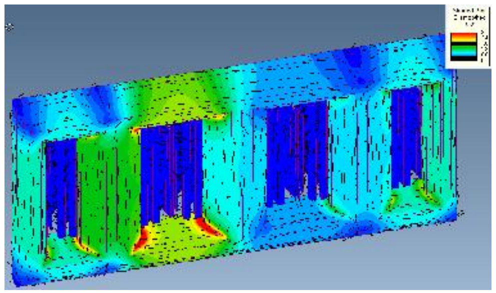
- Three-phase, three-limb transformers are not so easy to magnetize by DC passing through the neutral. → less susceptible to GIC effects.
- Three-phase, AC excitation: return flux of one phase passes through neighbor limbs (example 0.6 A/phase → 1.61 Tesla)
- DC excitation: flux has to find path through oil and tank (example 100 A/phase → 0.54 Tesla shift)
- All other core types are rather easy to magnetize by DC passing through the neutrals (example 1A/phase causes 0.6 Tesla shift in main limbs)



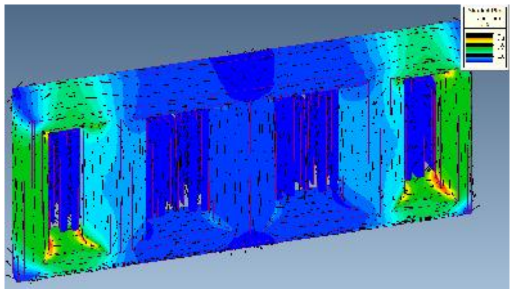
3-pase AC



GIC, without AC



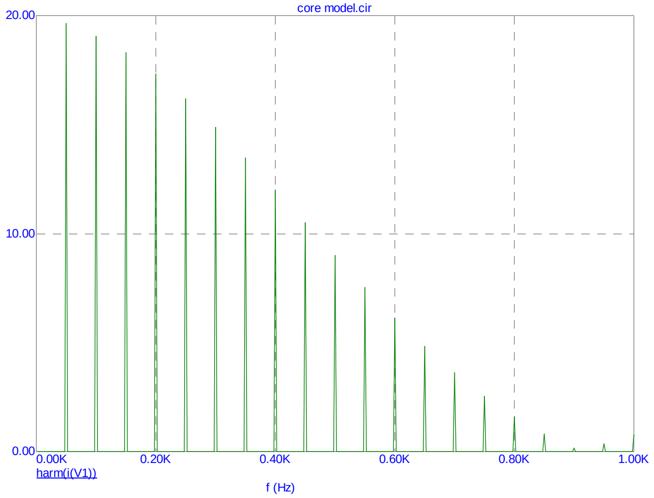
3-pase AC



GIC, without AC

Effects of geomagnetically induced currents and DC
Transformers, physical effects

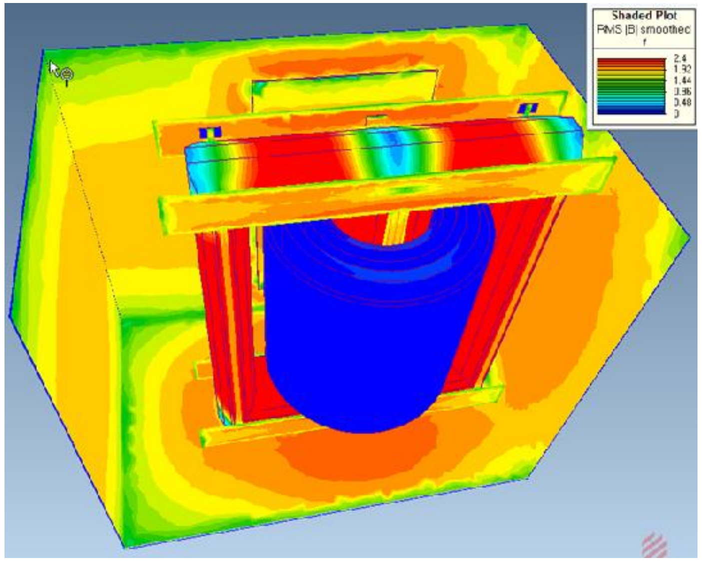
- Core losses increase by up to 50…60%. Due to the transient nature of the GIC this is normally not a problem.
- Winding losses increase due to the extra current and its harmonic content. For high GIC this is a noticeable effect, but typically does not cause more harm than an occasional overload, unless there are also circulating currents induced by an inadvantageous layout of windings or internal connections.
- The asymmetric magnetisation of the core leads to a strong increase in sound level due to magnetostriction.



Frequency spectrum of the excitation current of a single phase transformer subjected to GIC.

Effects of geomagnetically induced currents and DC
Transformers, physical effects

- When the core saturates magnetic flux will use any magnetic components in its surroundings that will shorten the path of flux lines through air or oil.
- Eddy currents will be induced in all metallic parts causing additional losses and heating.
- Most critical components are the axial tie rods inside the windings and the yoke clamping beams.
- They heat up with time constants of the order of 5 …15 minutes, depending on details of their cooling conditions.
- The magnetic stray field may induce circulating currents where winding parts are connected in parallel. Shell type transformers have such arrangements more commonly than core type transformers.

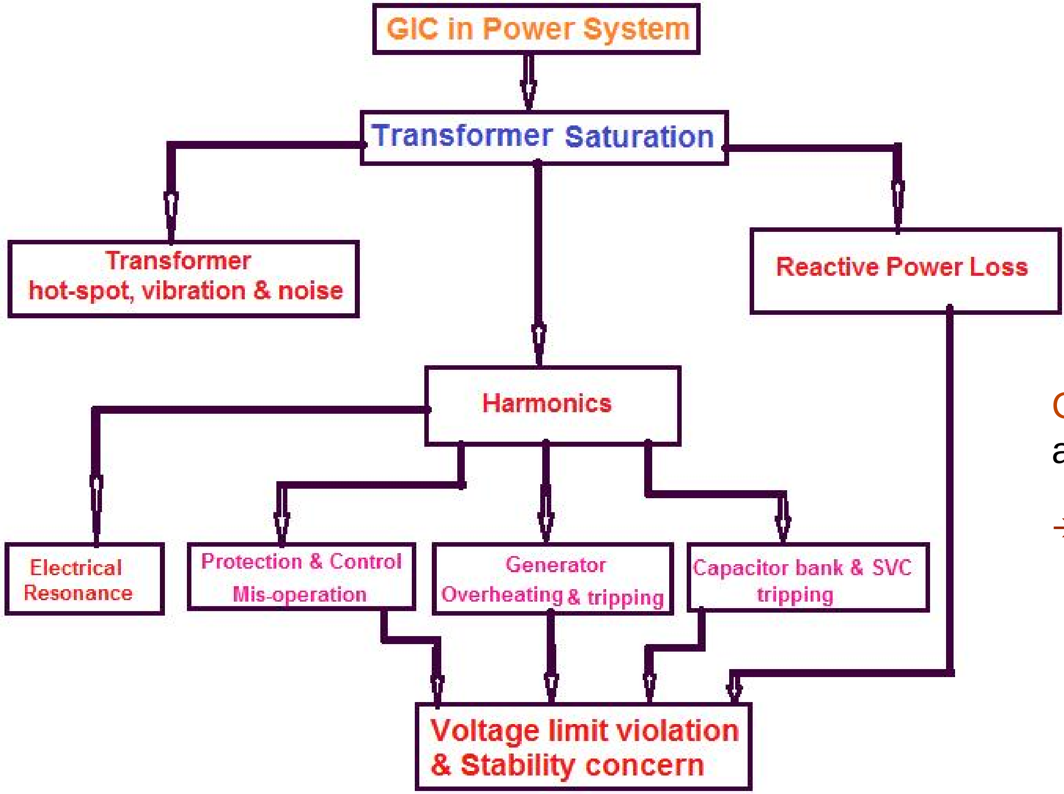


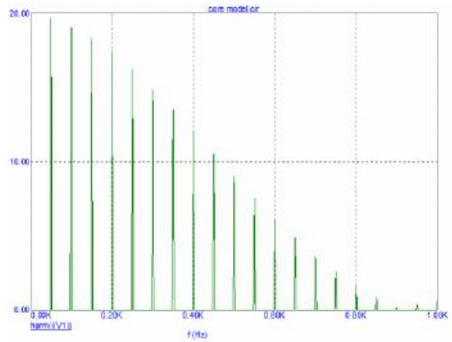
- Actual damage reported:
  - Overheating of internal connection due to circulating current, failure.
  - Gassing due to decomposition of oil at hot structure. Some units de-commissioned.
  - Paint discolorations on tank.

Effects of geomagnetically induced currents and DC Transformers, verification and test

- So far there are no direct measurements of magnetic and thermal effects inside transformers during real GIC events
- Very few experiments with transformers connected to the grid (stiff voltage source) have been conducted. Most had little instrumentation inside the tank, so only harmonics, losses and sound levels are reported.
- FinGrid made a back-to-back experiment on two 400 kV transformers in the network. One of the units had numerous internal temperature sensors.
- A few experiments in the test room of manufacturers with DC of a few Ampéres to 30 A have been reported. Typically in a back to back arrangement of two transformers. The limitation is the power supply that has to withstand high harmonics and has to provide a lot of reactive power. Most likely the voltage will be non-sinusoidal.
- Routine testing with DC is not feasible.
- Simulations will give sufficient insight but should be verified by a few well documented experiments.

GIC effects





Capacitors draw more current when there are harmonics in the voltage

→ Overload or unintentional trip by protection system

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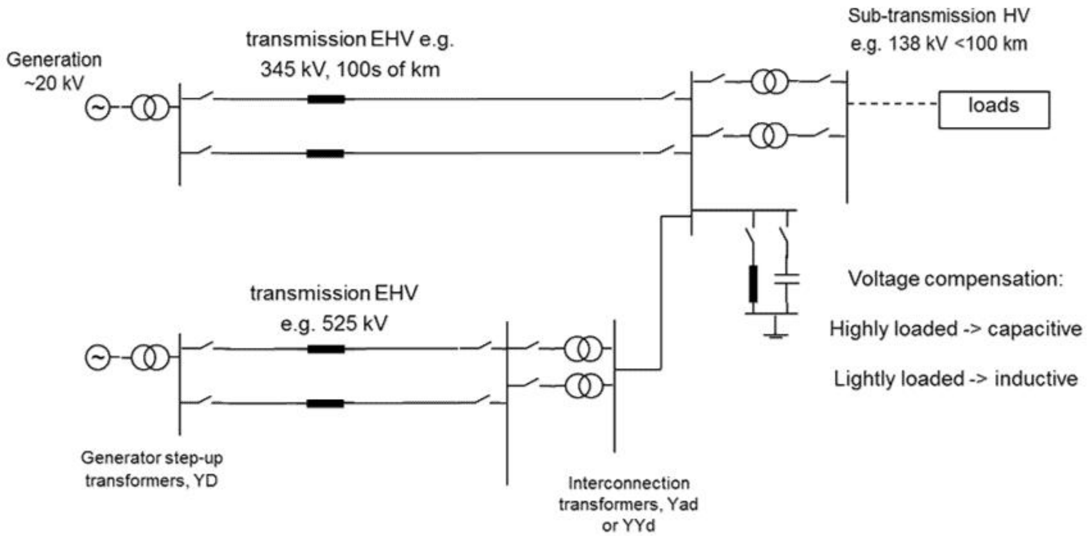
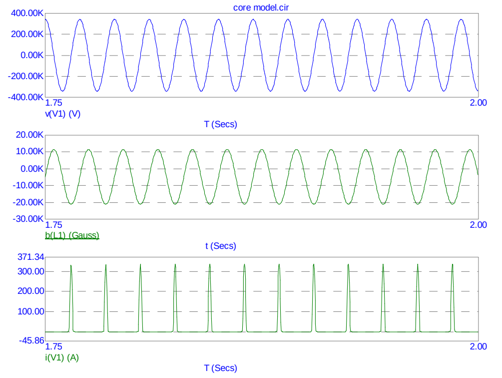
Effects of geomagnetically induced currents and DC
Network effects

- The exciting current exhibits spikes with high harmonic content, reaching amplitudes of the same order of magnitude as the load current.
- Increase in reactive power drawn by the transformer leads to voltage drop → Loads will draw higher current → further voltage drop → either shed some load or switch on shunt capacitors.
- If shunt capacitors are switched off by a „deceived“ protection system when needed most this may lead to **system instability and blackout.**

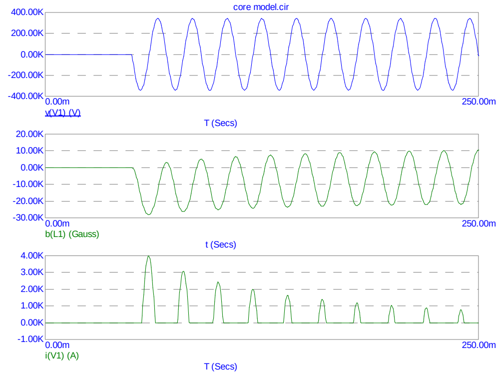


Possible Effects of current harmonics on power systems

- Interfere with protective relays;
  - Capacitor bank and SVC tripping may occur.
  - The 2nd order harmonic could cause transformer differential relay mis-operation.
  - The 3rd order harmonic may cause some line differential relay mis-operation.
  - Generator overheating and tripping may occur.
- Interference with metering devices, control and communication circuits, and with sensitive electronic equipment.
- Possible amplification of harmonic levels resulting from series or parallel resonances. Might damage equipment.
- Increase equipment losses and thus the thermal stress.
- Increase in equipment noise and vibration.



Voltage, core flux density and excitation current under GIC



Voltage, core flux density and excitation current after energizing (Inrush)

Impact of geomagnetically induced currents and DC
Regulatory and standards activities

- 2012: In the USA the Federal Energy Regulatory Commission (FERC) issued a final ruling to the North American Electric Reliability Council (NERC) to develop reliability standards that address the impact of geomagnetic disturbances (GMD) to ensure continued reliable operation of the nation's Bulk-Power System
- Those standards will require owners and operators to conduct initial and continuing assessments of the potential effects of specified "benchmark GMD events" on equipment, especially EHV transformers, as well as the Bulk-Power System as a whole
- Recently published: IEEE C57.163-2015 Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances
  - Focus is more on „transformer as a victim" to DC
  - Other equipment and protection not covered

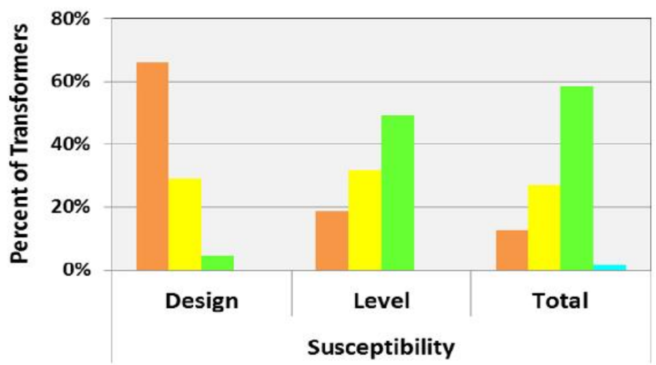
Effects of geomagnetically induced currents and DC
Transformers, susceptibility screening

- North American Electric Reliability Council NERC: transformers with a wye-connected winding greater than 200 kV should be evaluated for GIC susceptibility
- Design-based susceptibility
  - Winding design
  - Core type
- GIC level based susceptibility
  - High/medium/low DC calculated for a benchmark magnetic storm at the specific transformer locations
- Total GIC susceptibility
  - Suggests four scopes of further design evaluations

Table 2—Transformer total susceptibility to the effect of GIC

	GIC exposure level (amperes per phase)		
Classification of transformer design–based susceptibility	Low exposure (≤ 15 A)	Medium exposure (> 15 A to < 75 A)	High exposure (≥ 75 A)
Not susceptible (A)	I	I	I
Least susceptible (B)	I	II	III
Susceptible (C)	II	III	III
Highly susceptible (D)	II	IV	IV

Table 2 from IEEE C57.163-2015



Result of a study of a fleet of transformers > 500 kV in NA, (ref 4)

Effects of geomagnetically induced currents and DC Transformers, specification of „GIC capability"

- Since several years an increasing number of utilities include GIC capability clauses in their transformer specifications.
- I_{peak} in the range 100…400 A and I_{base} in the range 10…50 A encountered.
- Peak durations are 2…5 minutes.
- Level of know-how varies significantly among different utilities.

- The hot spot criteria for the base and peak periods are suggested in analogy to the IEC and IEEE loading guides for long term and short term emergency loading.

IEEE Std C57.163-2015
IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances

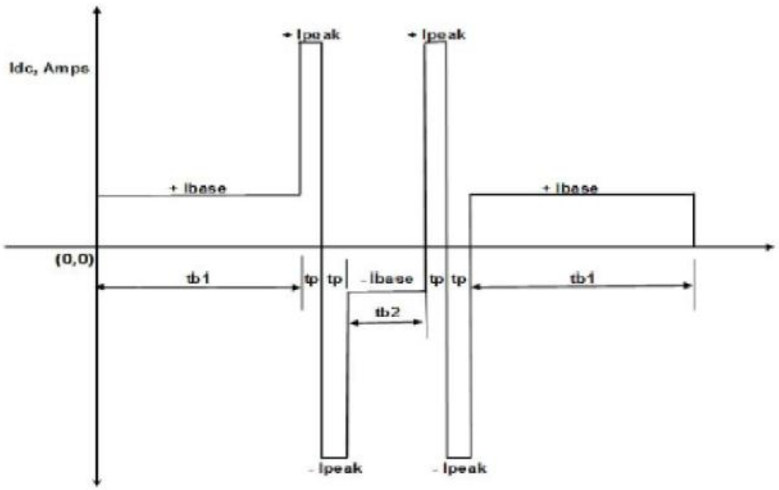
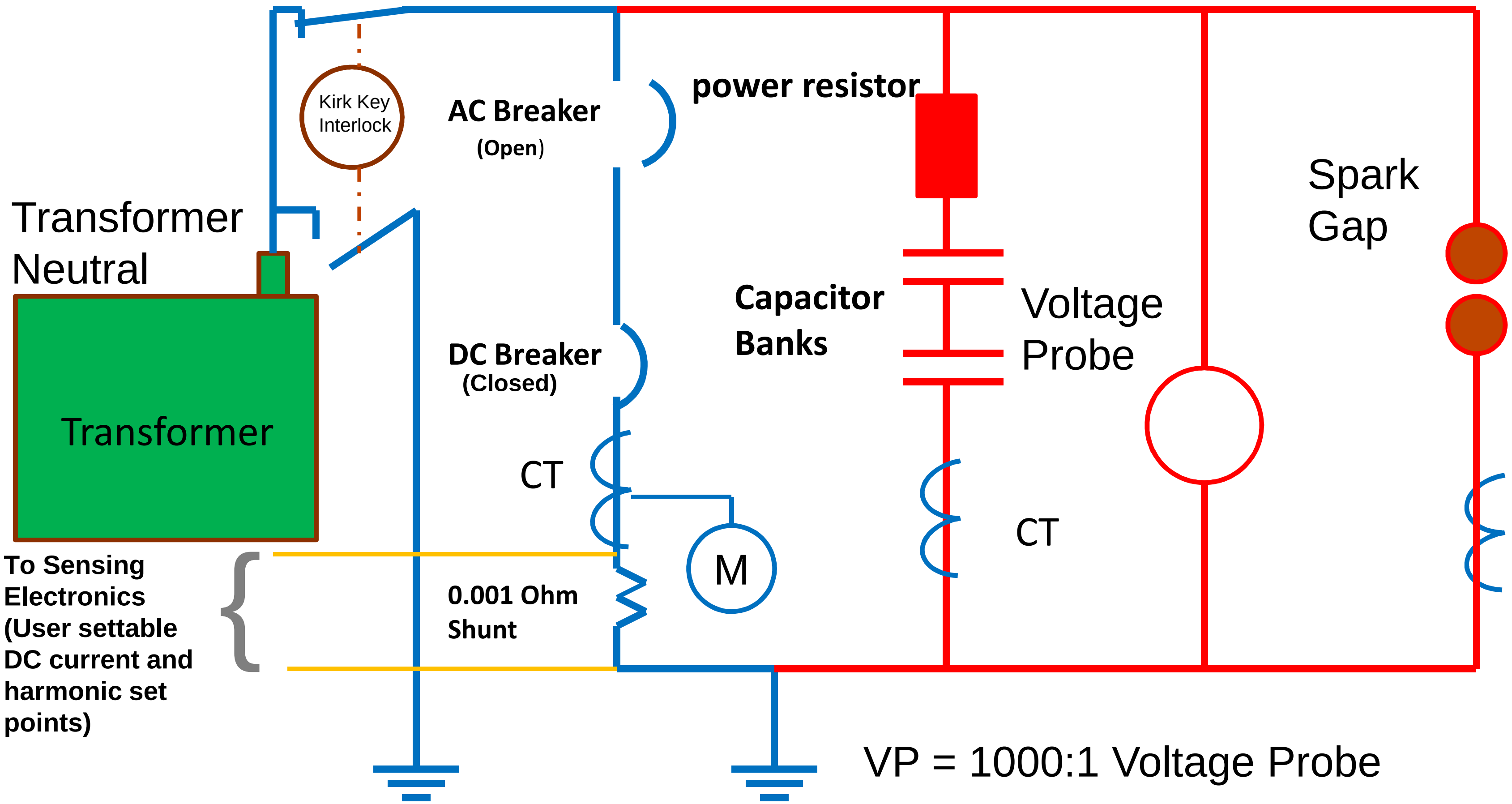


Figure 24—Recommended simplified GIC signature

Effects of geomagnetically induced currents and DC
Mitigation measures

- Monitor solar storms and/or DC in transformer neutrals
- Rescheduling of power flows, adjust topology to minimize DC, even interrupt?
- Ensure availability of reactive power support.
- Switch in neutral DC blocking devices (Transformer neutral insulation has to be designed for that. Resonances? protection issues?)
- Series compensation of long transmission lines (Expensive, resonances?)
- Active compensation (not proven for high amplitudes of DC, needs a dedicated winding in the transformer)
- Design transformers to withstand GIC (only possible for new transformers)

SolidGround™
Ground induced current protection mode



American Transmission Company installation plan
Installed on a 362 kV system in Northern Wisconsin

- ATC plans to gain on-line experience of neutral GIC blocking during a future GMD events.
- Reports will be shared with NERC, EPRI and the Power Industry.

GIC: Literature

1. IEEE C57.163, 2015, IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances
2. GIC Occurrences and GIC Test for 400 kV System Transformer, Matti Lahtinen, Jarmo Elovaara, IEEE Trans. On Power Delivery, Vol. 17, No.2, April 2002
3. Risk evaluation for power transformers during solar storms, J. Raith, B. Wagner, S. Ausserhofer, CIGRE SC A2 & C4 Joint Colloquium 2013, Pref Subj 1, paper 37, Zurich, 2013
4. A Process for Evaluating the Degree of Susceptibility of a fleet of Power Transformers to Effects of GIC, R. Girgis, K. Vedante, G. Burden, IEEE T & D Conf., Chicago, USA, April 16, 2014
5. ABB PowerED Power Education Webinar Series: POWERful insights for the evolving grid, Nov 18, 2014
6. The Effects of GIC on Protective Relaying, B. Bozoki et al., IEEE Trans. On Power Delivery, Vol. 11, No. 2, April 1996
7. Effect of GIC and GIC Capability of EHV Power Transformers – A Case Study on an AEP 765 kV Power Transformer Design, Qun Qiu, David R Ball, Jeffrey A Fleeman, Ramsis Girgis, Kiran Vedante, CIGRE US National Committee 2013 Grid of the Future Symposium.
8. Seyed Ali Mousavi, Electromagnetic Modelling of Power Transformers for Study and Mitigation of Effects of GICs, PhD thesis KTH Stockholm, March 2015, ISBN 978-91-7595-411-0
9. ABB PowerED Power Education Webinar Series: POWERful insights for the evolving grid, Nov 18, 2014

Power and productivity
for a better world™

Impact of geomagnetically induced currents and DC
Failures attributed to GIC in recent years

- Rather few transformer failures could be clearly correlated to GIC events.
- All the additional stresses due to GIC do not require immediate action, 10s of minutes are available to take decisions.
- Typically some gassing due to oil/insulation decomposition is detected.
- 1 shunt reactor failure in South Africa
- Several ~ 5 generator step-up transformers failed days to weeks after a „magnetic superstorm“
- Tank paint discoloration on a number of transformers in North America
- Failure of old shell type generator transformer in North America, internal connection overheated, taken out of service
- A few more transformers of the same design continued operation with some signs of gassing.
- **8 hour black-out at HydroQuebec due to tripping of capacitor bank / SVC**

Impact of geomagnetically induced currents and DC
Failures attributed to GIC

- Sweden / Oct. 31, 2003
  - Report of very strong GMD storm; 3 phase / 5 limb / 400 KV transformers were subjected to 330 Amps GIC in the neutral
  - **20 min. black out / system instability caused by false tripping of 130 KV line due to 3rd harmonics**
  - Low level gassing in the transformers; indicating minor overheating
- 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
- The risk of blackout due to system instability by imbalanced reactive power or by false tripping is higher than that of immediate or permanent transformer failures

Voltage instability
Examples

NERC - Minutes Board of Trustees
(February 23, 2012)

I.9 Conclusions

"The most likely worst-case system impacts resulting from a low probability GMD event and corresponding GIC flow in the bulk power system is voltage instability caused by a significant loss of reactive power support simultaneous to a dramatic increase in reactive power demand.

The lack of sufficient reactive power support was a primary contributor of the 1989 Hydro Québec GMD induced blackout.

During the geomagnetic disturbance, seven static SVC's tripped off-line within 59 seconds of each other, leading to voltage collapse of the system 25 seconds later."

Effects of geomagnetically induced currents and DC
Capacitors and shunt reactors

- Total harmonic distortion in currents reaches > 30%...**60%**?? (in normal operation….)
- Total harmonic distortion in voltage reaches <10% (in normal operation < 2.5%)

- Harmonics in voltage may cause increased losses in capacitor banks which are installed in some networks for stabilizing the normal AC voltage or for filtering a specific range of harmonics (SVC).
- Harmonics in voltage or current may cause unwanted resonances between capacitances and inductances in the network, producing increased voltage stresses or losses at the capacitors.

Effects of geomagnetically induced currents and DC
Capacitors and shunt reactors

- Shunt reactors are used to keep the voltage in the system within the limits allowed by the grid code.
- Air core reactors are not directly affected by DC currents. For high powers the gapped core design reactor is a common solution. The magnetic circuit is similar to single phase or 5-limb 3-phase transformers, i.e. the magnetic return path around the windings designed to capture magnetic stray flux will saturate.
- When the outer core frame saturates the stray flux will use any other magnetic material like axial tie rods or the tank as return path, which may cause excessive heating and some oil gassing outside the windings. Not a cause for catastrophic failure of the reactor.
- All types of reactors and the capacitors banks might see increased voltages if harmonics hit a resonance of a given reactor with capacitances in the network.
- Modern capacitors have overvoltage withstand >150% of rated voltage.
-
- No damage to capcitors attributed to GIC by 1996

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Effects of geomagnetically induced currents and DC Protection system

- Normal operation of the network is handled by the dispatch and control centers within the restraints of all network components.
- However, there are always some unscheduled disturbances, e.g. atmospheric, storms, equipment failure..
- The network has to be designed in such a way that a local disturbance can be detected and isolated without impact to those parts of the network that are not directly affected. (N-1, N-2 security). Contingency planning.
- Damaging excessive stresses on the components (loads, voltages, magnetic flux, temperature…) have to be detected and mitigated, typically by switching off the transmission component at risk or by load shedding.
- Typically switching off a component increases the load on the remaining ones. Thermal stress and voltage drops increase. If the limits of contingency planning are exceeded cascading thermal trips or voltage instability can cause a black-out.

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Effects of geomagnetically induced currents and DC
Protection system

- The protection (fault management) system has to allow the system to ride through common „intentional disturbances“ like energization or de-enerization of components, transient line faults.
- The protection system has to detect a disturbance (transient flashover on a transmission line, permanent fault in a piece of equipment…) as fast as possible to minimize the damage at the fault location.
- The fault has to be localized in order to allow remedial action.
- The protection devices have to discriminate between signals from internal faults in a component and signals from external faults.
- False trips have to be avoided.
- „Common mode“ false trips could affect multiple pieces of equipment (N-x), a situation for which the system is not designed.

Effects of geomagnetically induced currents and DC
Protection system: current transformers

- In many protection schemes current going into a component (e.g. a busbar, a transformer, breaker) is compared to the current out of the component. A differential current above a certain threshold is indicating an internal fault of the component and causes the breakers to de-energize the component.
- The protection system depends a lot on the exact measurement of currents up to high fault currents.
- This is normally done by „current transformers“ (CT), in principle small transformers transforming rated 100s or 1000s of Ampéres in a single primary conductor to 1 or 5 A in the protection circuit.
- When subjected to DC for ~ 10s of seconds such CTs can saturate and may output deformed signals. Rated currents (the AC portion) are typically transformed with sufficiently small errors for protection purposes even when approaching saturation. Fault currents are transformed with initially noticably reduced amplitude recovering to almost correct amplitude after just one cycle for low ratio CTs or after 10s of cycles for higher ratio CTs.
- Deformed CT signals may cause false trips and interruption of power flow.

Effects of geomagnetically induced currents and DC
Protection system: transformer

- One common „intentional disturbance“ is the transient inrush current that is drawn by transformers for a few seconds after enerization or after clearing a line fault:
- The system shall not switch off the transformer during enerization:
- False trip is avoided by e.g. delay of action, blocking of action as long as the typical inrush harmonics are detected in the current…
- Problem: very similar signature to harmonics due to GIC.
- Real transformer faults happening during a GIC event may be detected later than without GIC.

Effects of geomagnetically induced currents and DC
Protection system: capacitor

- CTs with rather small rated currents are often measuring the unbalance current through the neutral of capacitor banks.
- Harmonics due to transformer saturation will allow higher currents through the neutral of the capacitor bank, causing an „unbalance trip“ and possibly causing a CT overload and failure.
- Overvoltage relays have to apply adequate filtering to avoid false trips.
- GIC induced harmonics may hit capacitor/reactor resonances in filter / SVC installations giving rise to overvoltages. The filter design should avoid this situation. The protection system should not be set too sensitive.

- False tripping of capacitors (that are in operation to keep the voltage within desired limits) will increase voltage problems and risk of system instability.

Effects of geomagnetically induced currents and DC
Result of a susceptibility study in the USA

- Study performed on >500 kV transformers in the USA

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 %

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 %

Table 2—Transformer total susceptibility to the effect of GIC

Classification of transformer design–based susceptibility	GIC exposure level (amperes per phase)		
	Low exposure (≤ 15 A)	Medium exposure (> 15 A to < 75 A)	High exposure (≥ 75 A)
Not susceptible (A)	I	I	I
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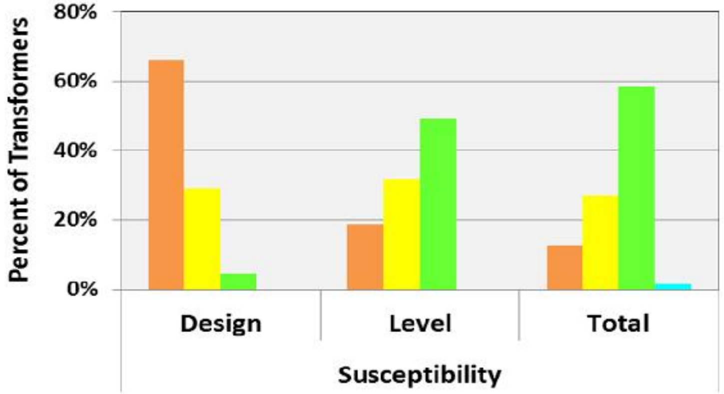
Highly susceptible (D)	II	IV	IV

Table 2 from IEEE C57.163-2015



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

Case Study

- 1593 large power Transformers in service
- ≥ 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.

ABB