



FINGRID

FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

ESA-SPACE WEATHER WORKSHOP

The Netherlands

17. November, 2005

by

J. Elovaara

FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

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FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Potential effects of GIC's in the electrical networks:

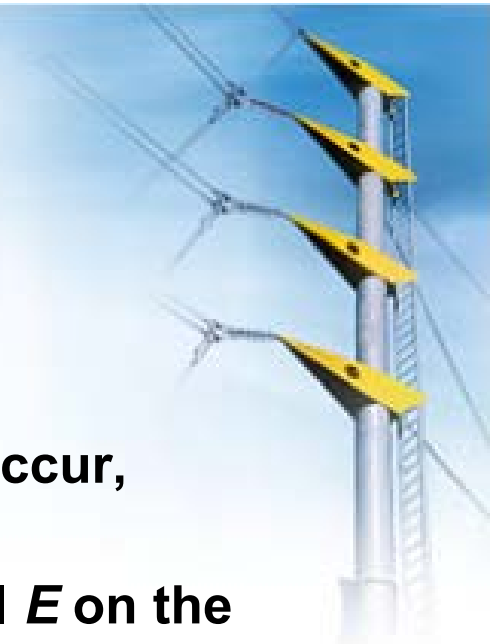
- **DC-half-cycle magnetization of transformers which causes saturation of the transformers and increase of the leakage fluxes in the transformer**
- **Consequences of transformer saturation**
 - increase of the reactive power demand in the system - risk of reactive power unbalance and voltage instability
 - generation of harmonic voltages and currents - protection relays may operate incorrectly => erroneous/unnecessary trippings leading to black-outs
 - impaired quality of supply voltage (non-sinusoidal form)
- **Increased leakage fluxes might cause**
 - hot spots in the metallic parts of the transformer
 - these might deteriorate the organic insulation materials



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Large GI-currents in transmission systems can occur, when:

- the overhead lines are long (high longitudinal E on the surface of the earth along the line)
- the specific resistivity of the ground is high (in Finland the median value of the resistivity of the surface layers is $2300 \Omega\text{m}$ because the solid rock is near the surface of the earth)
- the grid has an electrical connection to the earth
- the country is situated at the high latitudes (auroral zone)



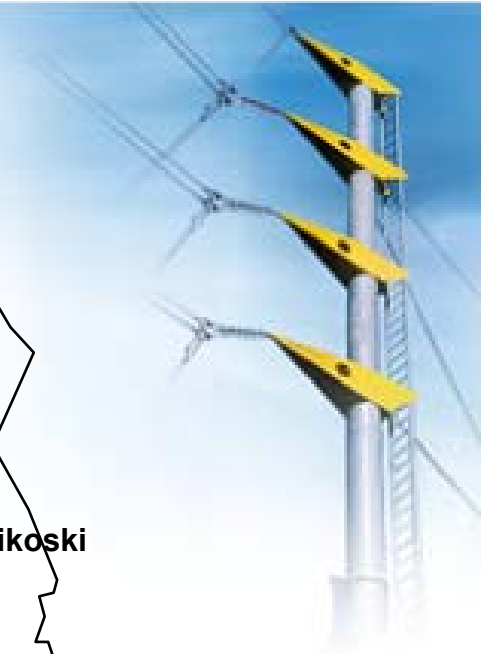
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About the GIC-measurements in the Finnish 400 kV grid

- The Finnish 400 kV (and 220 kV) grid(s) are effectively earthed, i.e. the neutral points of the 400 kV windings of the system transformers (400/400/125 MVA, 417/117/21 kV) are earthed (via fault-current limiting reactors) in most substations
- Consequently, geomagnetically induced currents can occur in the 400 kV overhead line network and they flow especially between transformers which have grounded neutral points
- The occurrence of the GIC's has been monitored since 1976 by measuring pseudo-stationary DC-currents from the 400 kV neutrals of certain system transformers

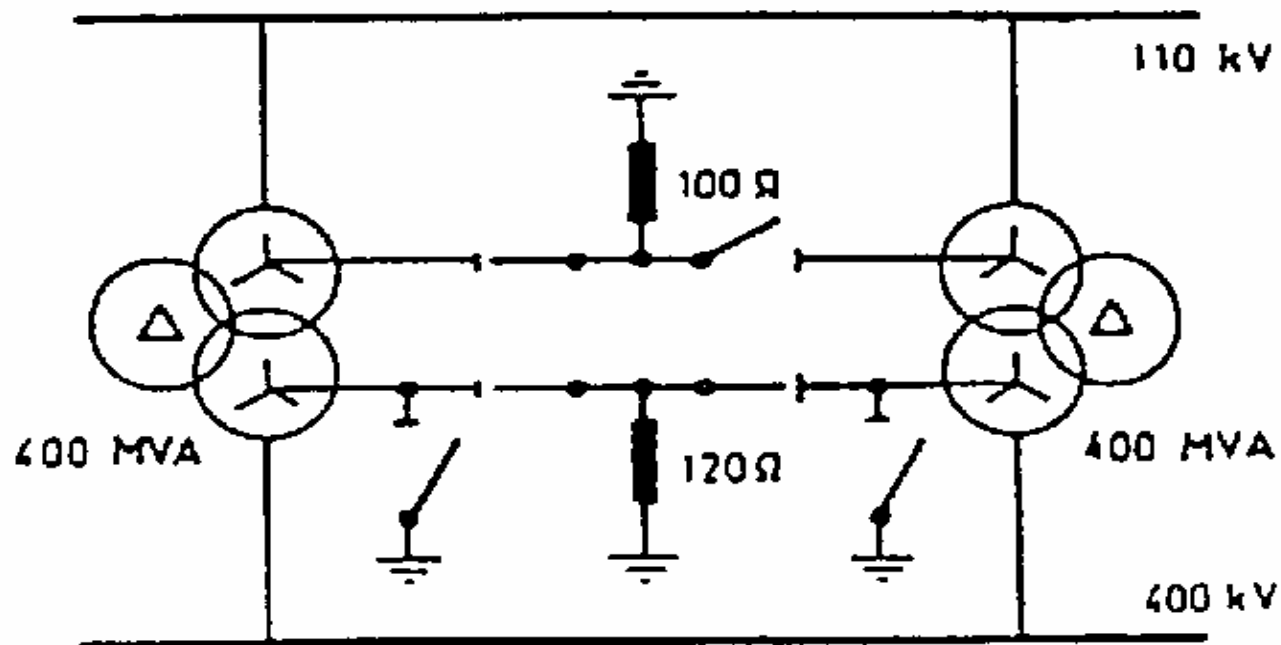
Fingrid's 400 & 220 kV network in 2005

- 400 kV line
- 220 kV line
- |— 400 kV line with series capacitor



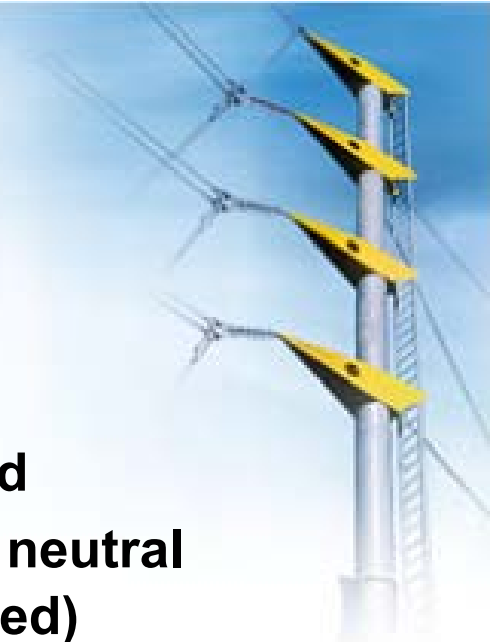
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Example about the use of a current limiting reactor
(the ohm-values indicate the inductive reactance)



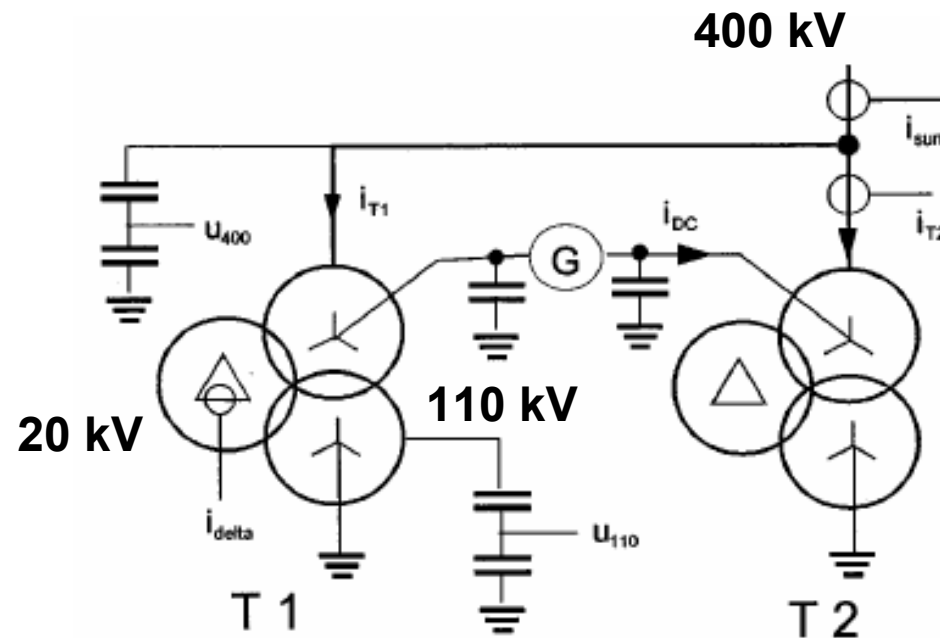
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- The GIC's through transformers are measured (continuously) with a help of a resistor in the neutral point (now also other technologies can be used)
- Measurement points have been selected on the basis of probabilities how GIC's occur in the Finnish system and the measurement points have changed during the years
 - examples of measurement places are Huutokoski, Rauma, Yllikkälä, Pirttikoski, perhaps in future also Alajärvi and Kristiina/Ventusneva (criteria e.g. the latitude of the substation, is the substation a corner point in the system, better coverage in 220 kV grid...)
 - once even the GIC of a line (Nurmijärvi-Loviisa) was measured with a help of a magnetometer



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- Also behaviour of Finnish transformers under half-cycle DC-magnetization has been checked/tested



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The largest GIC's measured so far are:

- Huutokoski 165 A/10 s -value (Jan 4, 1979)
- Rauma 200 A/1 min and Pirttikoski 53 A/1 min (March 24, 1991)
- Rauma 190 A/1 min and Pirttikoski 38 A/1 min (March 25, 1991)

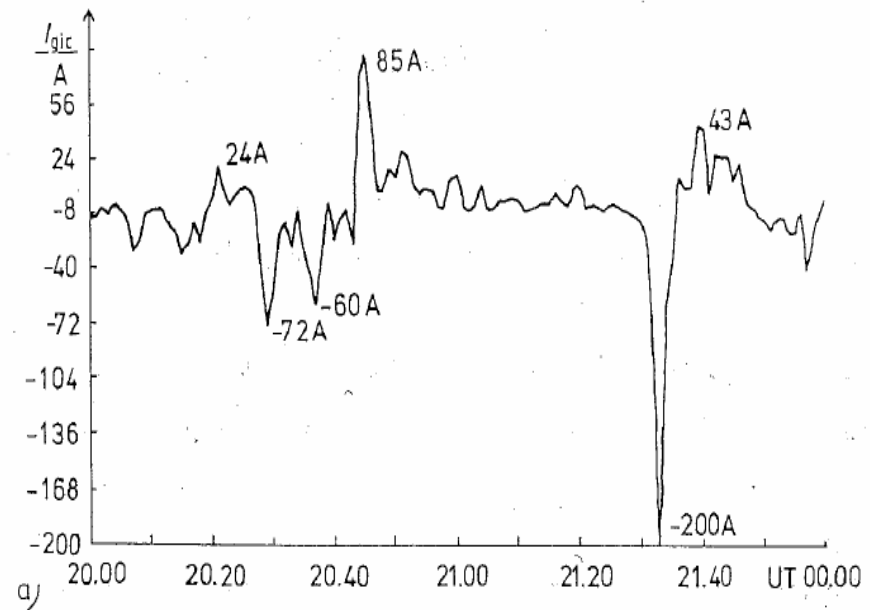
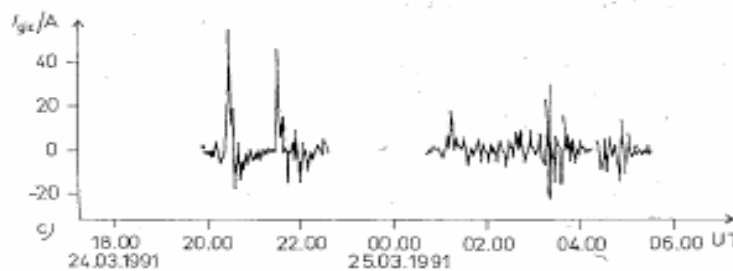
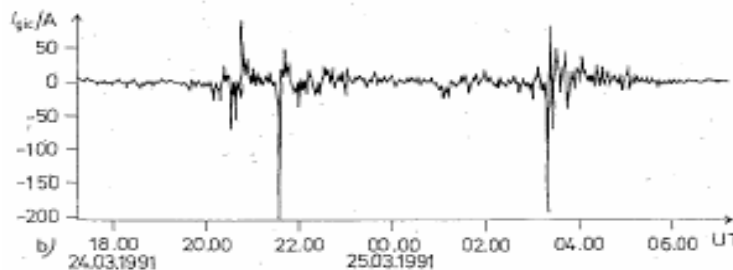
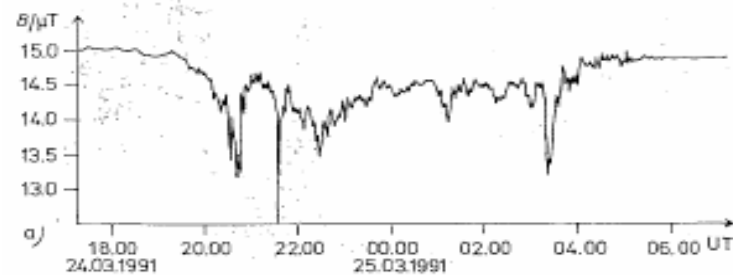
Since then essential changes in the grid has been made (e.g. series capacitors taken into operation) and at present the neutral currents are smaller

Examples of the time trends of the currents in transformer neutrals are given in the following

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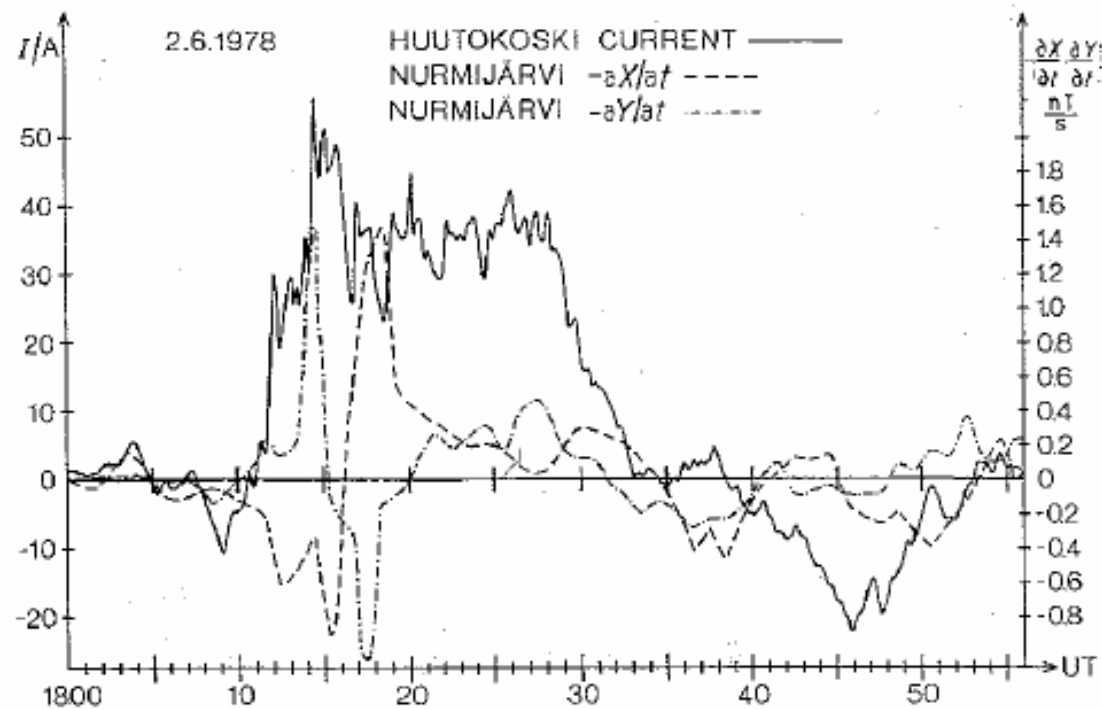
Typical GIC-event, March 1999

Geomagnetic field at Nurmijärvi and GIC in Rauma & Pirttikoski



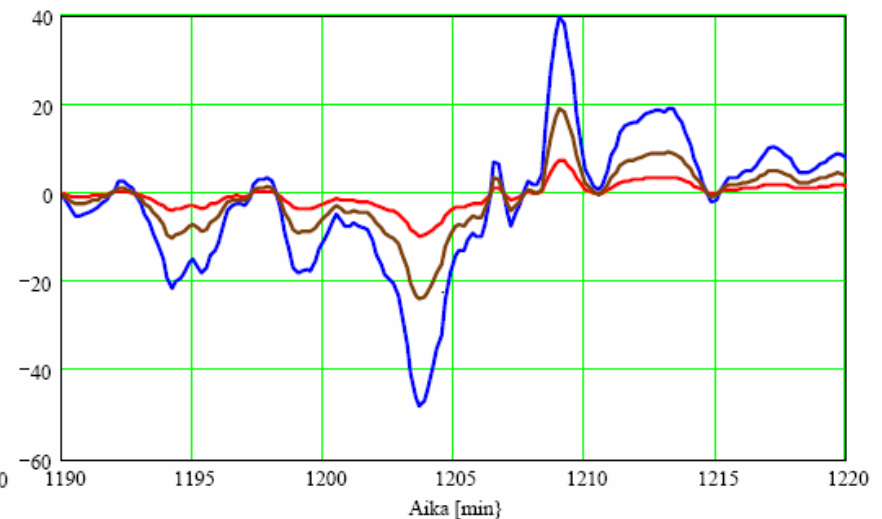
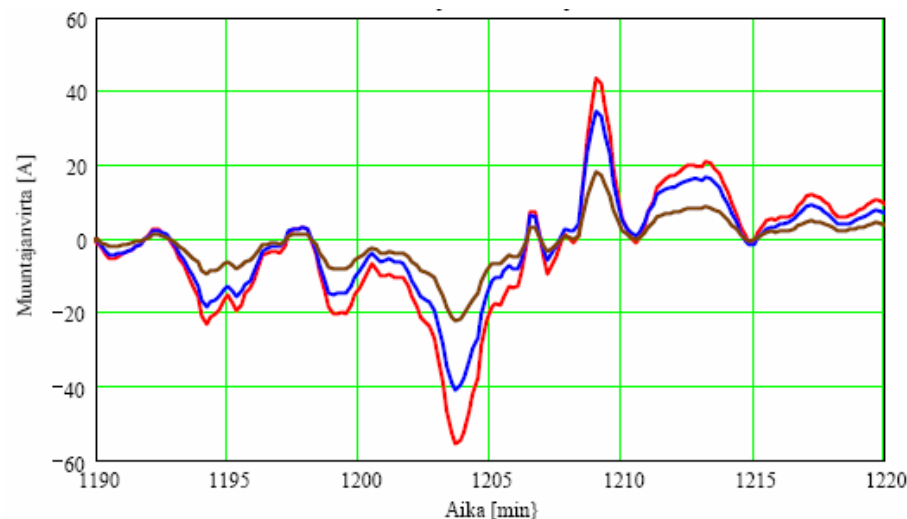
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GIC measured in the neutral lead of the Huutokoski transformer in 1978



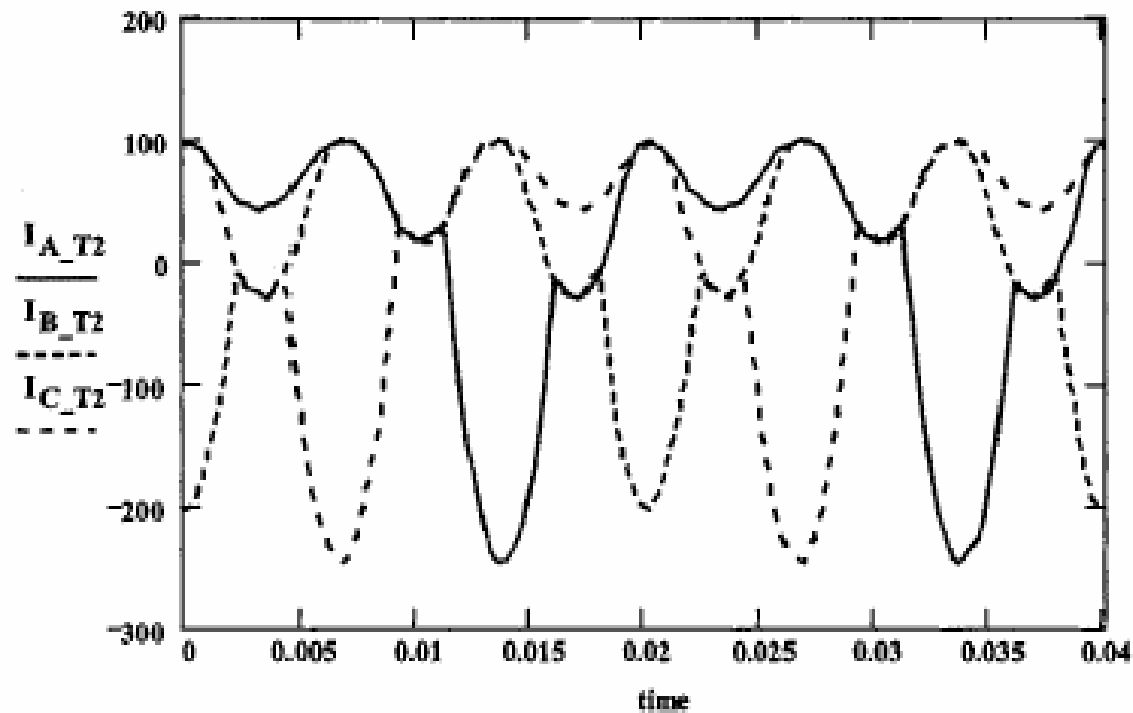
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**Expected GIC's in two adjacent substations in future conditions with different neutral point resistor values
(left/neutral point resistance 2,4 Ω ; right/one neutral point resistance 10 Ω)**



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Effect of DC-magnetization (200 A) on the phase currents of a 400 MVA 3-winding 5-leg transformer (YNyn0d11)



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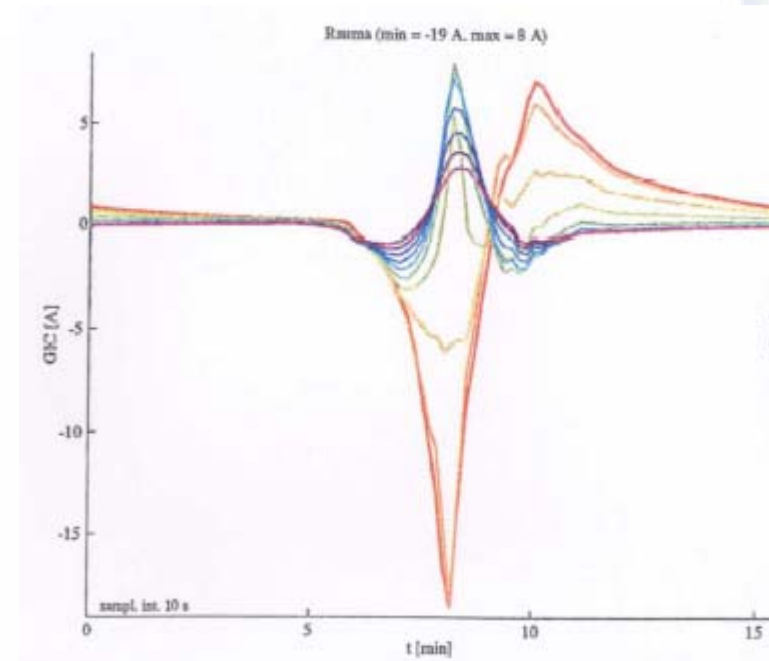
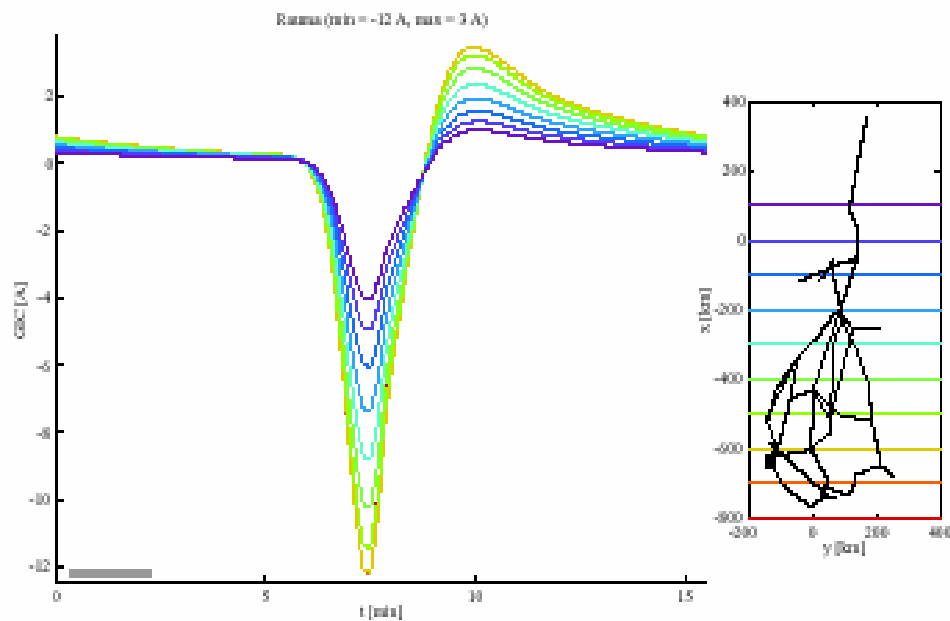
Research co-operation with Finnish Meteorological Institute

- Three different co-operation projects have been going on with following aims
 - calculation of GIC-distribution in the Finnish transmission grid on the bases of time-variations in the magnetic field of the ground
 - statistical estimation of the currents flowing in the neutrals of the 400 kV windings of the system transformers
 - effects of different space current distributions on GI-current distribution in the "earthed grids"
- At present Fingrid has available quite representative data giving the induced **electric field strengths** at the surface of the earth => Fingrid is able to estimate the effect of grid extensions on the magnitudes of GIC's in the grid

FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

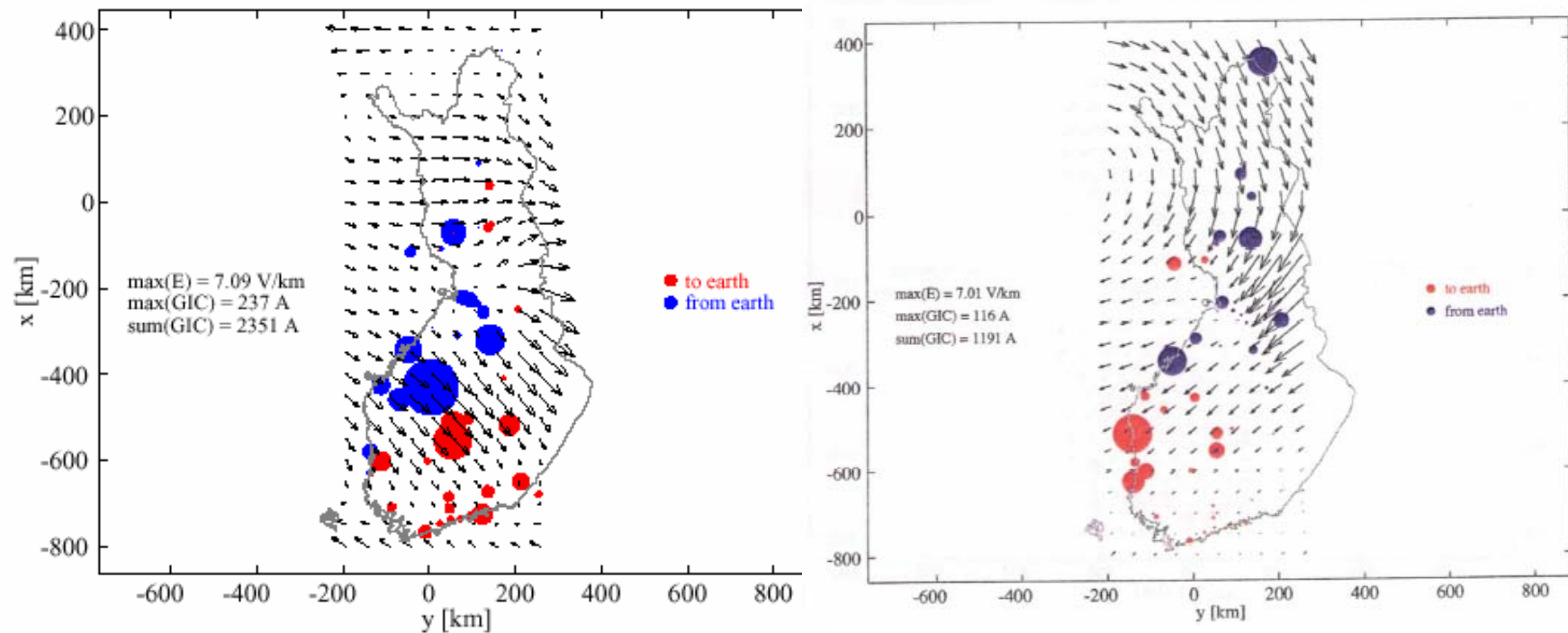
Effects of a horizontal line
current (E-W) in space (110
km) in Rauma

Effect of a westward travell-
ing surge (WTS, 10 km/s) in
GIC in Rauma



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Geoelectric field (arrows) and GIC (circles) distribution in events on 1995-04-07-16:47UT and 1998-05-04-05:32 UT



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

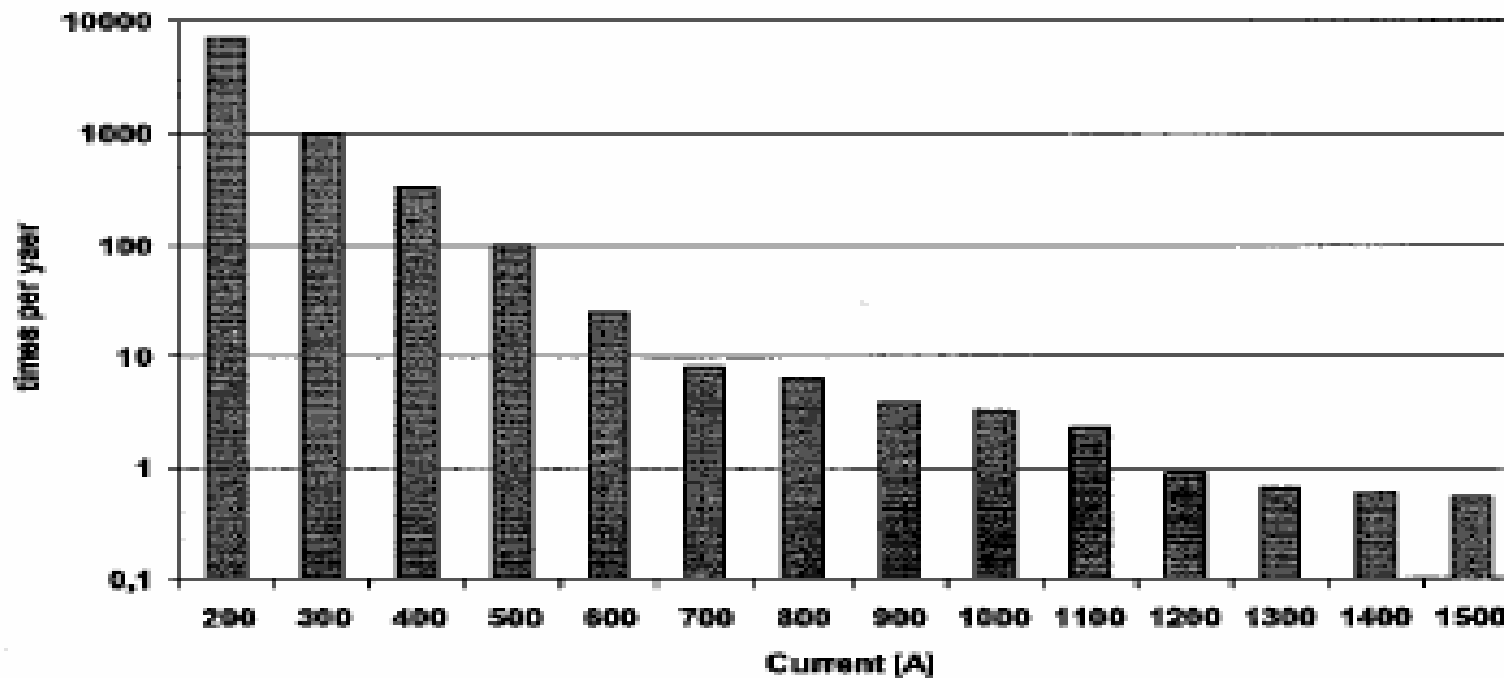
About the available models:

- models based on realistic ionospheric current models and spatially inhomogeneous geoelectric fields
- realistic inhomogeneous multi-layer earth models applied
- geoelectric field calculated directly from magnetic data of BEAR and IMAGE magnetometer arrays, 161 cases, 11 with K-index 9, 20 with K=8 (worst case not seen yet?!)
- the registration network is not dense enough to cover well all parts of Finland
- four events causing maximum GIC's analysed in detail
- geoelectric field distributions vary greatly from event to event and so does the correlation of GIC's through transformers
- $\Sigma I_{GIC} > 2000 \text{ A}$ (400 & 220 kV) occurs 4 times in one 11-year sunspot cycle, largest currents in Alajärvi (237 A) and Kristiina (188 A)
- GIC is large in regions with poor conductivity of the earth



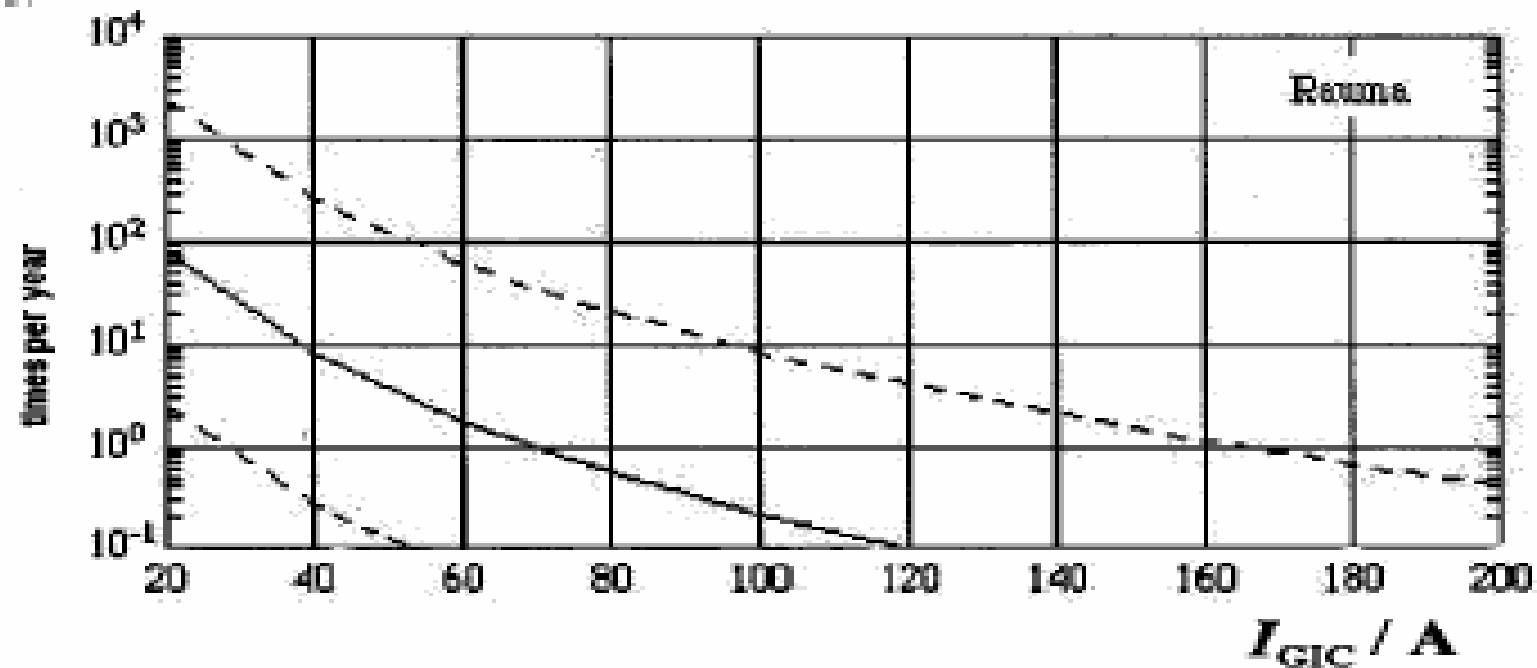
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Annual occurrence probability of different GIC-magnitudes - sum current in 400 kV neutrals of all transformers
- according to FMI (number of trafos abt. 60)



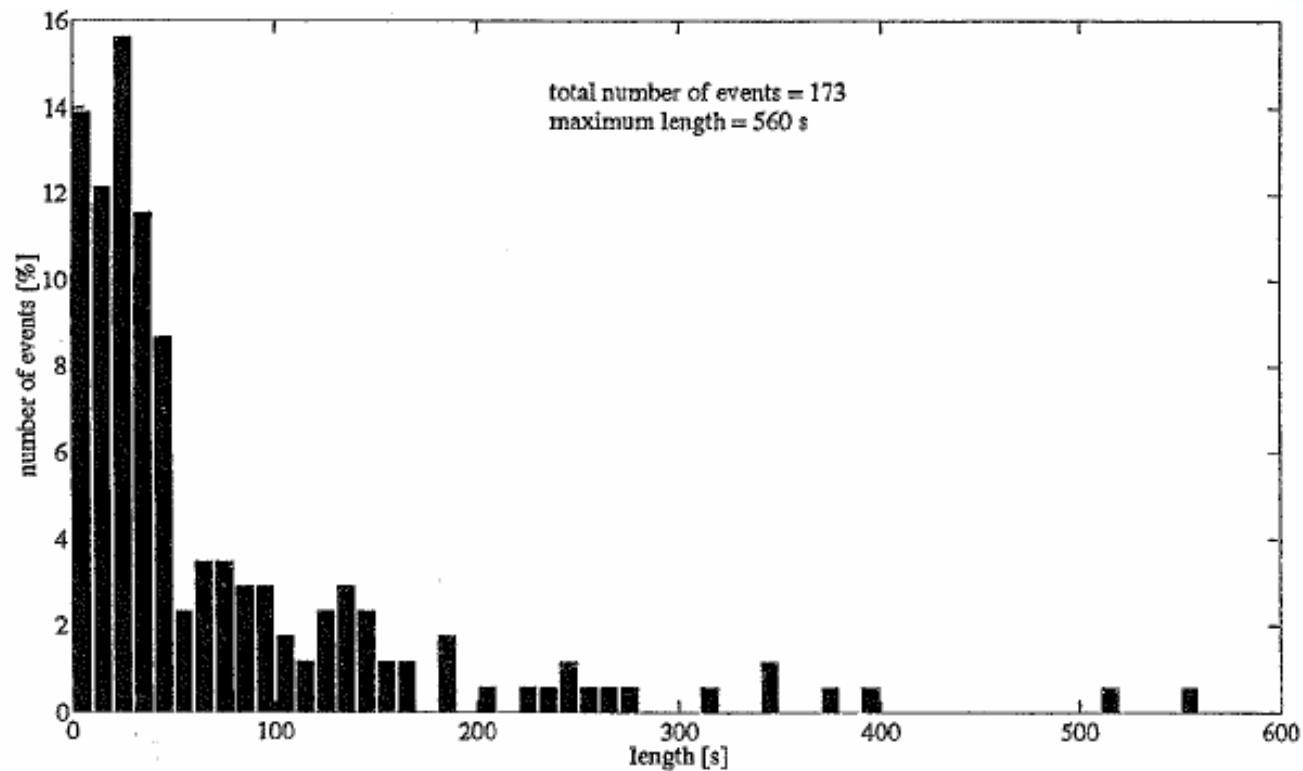
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Annual occurrence probabilities of different GIC-magnitudes in Rauma transformer 400 kV neutral according to FMI (situation 1999)



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Distribution of lengths of peaks $\Sigma I_{GIC} > 400$ A through the transformers (only events $K = 9$ considered)



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S


Finnish and Nordic transmission grid experiences during GIC-events

- up to 2003 GIC's had caused none disturbance nor equipment failure in Finland although the neutral currents have been high
- in 2003 in Finnish Lapland one protective relay caused an erroneous tripping because the relay had been configured erroneously; harmonic content of the current caused the erroneous tripping,
- the Finnish transformers have not overheated during the GIC events nor have they produced gas during these events

FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

- **in Sweden erratic tripping of sensitive earth-fault relays has taken place in several GIC-occasions**
 - **electromechanical relays without harmonic blocking and with constant-time characteristic, some static relays too**
 - **one this kind of event caused a black-out in city of Malmö in October 2003 (too sensitive relay = too low tripping value)**
- **certain transformers are in Sweden of the "GIC-sensitive type" and the operators are worried about the behaviour of these transformers**
 - **Note 1: In USA and UK transformer failures have occurred**
 - **Note 2: in Canada the tripping of the Static Var Systems due to the GIC caused a black-out in the Hydro Quebec -system in 1989 (reactive power unbalance)**



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- A tall, grey metal tower for an HVDC power line is visible in the background on the right side of the slide. It has several yellow insulators and cables attached to it, set against a clear blue sky.
- In Sweden GIC's have also caused "unstable" operation of generator voltage controllers and in certain occasions series capacitors have been blocked due to the incorrect operation of their protection systems
 - HVDC-links between the Nordic countries as well as the one connecting the Finnish grid to the Russian grid have not been disturbed due to GIC
 - GASUM (the Finnish natural gas distribution company) is worried about the risk that GIC's deteriorate the corrosion protection system of the buried gas pipes

FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Reasons to good Finnish GIC-experiences

- active limitation of the fault currents by use of relatively great short-circuit reactances in the system transformers and by use of earth-fault current limiting coils in the neutrals of the system transformers
- selected transformer type
- the transformers are specified so that they tolerate relatively high leakage fluxes and their thermal effects
- the sensitive earth-fault protection is set to operate at the fault-resistance of 500 Ω , harmonic blocking is used due to inrush-currents of transformers
- GIC's have decreased due to series capacitors; they reduce the inductive reactance the lines and increase the power transfer capability, **they also block the GIC's!**



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Fault current limitation

- the selection of the transformer type is strongly connected with the fault current limitation
- there might be the need to limit the magnitudes of the fault currents if the resistivity of the soil is too high (like in Finland); otherwise it would be too difficult (even impossible) and far too expensive to limit the ground potential rises during faults to safe values to people and animals
- => increase the short-circuit and zero-seq. impedances
- the system transformers in Finland are of the three-phase, full-wound, five- or three-legged type with the **short-circuit impedance of 20 %** (the resistance is only abt. 0,3 %)

FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Transformer type versus leakage reactance X_k , zero-sequence impedance Z_0 and GIC-sensitivity (= area avail. for DC flux return)

Transformer type	X_k	Z_0/X_k	GIC-sens
full-wound 3-ph, 3-leg core-form	free	5	0
full-wound 3-ph 5-leg core-form	free	$\infty \dots 1$	0,24..0,33
full-wound 1-ph, shell-form	free	1	1,0
autotrafo, 3-ph, shell-form	~ 0	1	0,5..0,67
autotrafo, 1-ph, shell -form	~ 0	1	1,0

Fingrid has only full-wound three-phase core form transformers

FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

- the basic quantities in the fault-current limitation are the short-circuit impedance of the transformer and so called zero-sequence impedance of the fault-current circuit
- e.g. earth-fault current in a single-phase-to-earth fault

$$I_{\text{SPHEf}} \approx 3 \cdot \frac{U_{\Phi\text{toE}}}{2Z_1 + Z_0 + 3Z_n}$$

- here the effect of the short-circuit impedance is included in the quantity Z_1
- the effect of the impedance of the current limiting coil is included in Z_n

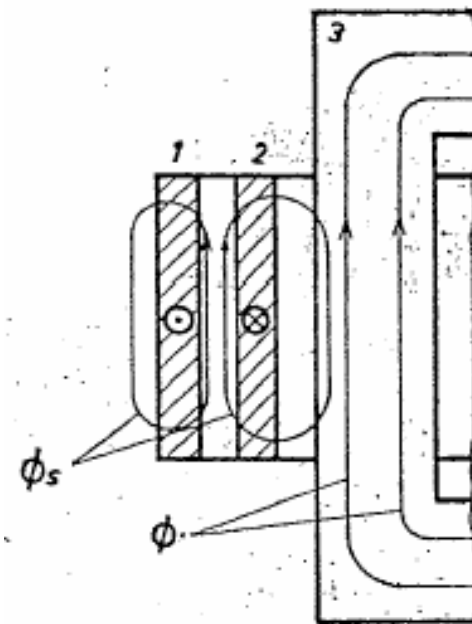
FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

- short-circuit impedance X_k
 - describes the magnitude of the magnetic flux between the primary (1) and secondary (2) windings of a transformer
 - this flux is called as stray flux or leakage flux (Φ_s) to separate it from the main flux (Φ) flowing in the magnetic core (3) of the transformer
 - when the core is saturated, main part of the flux uses the path of the stray fluxes
 - is directly proportional to the width of & distance d between the windings
 - in autotransformers $X_k \approx 0\%$, in full transformers it can be selected, in Finland $X_k \approx 20\%$

Fluxes in a transformer

Φ = main flux

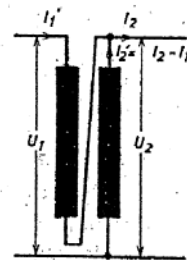
Φ_s = stray flux



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

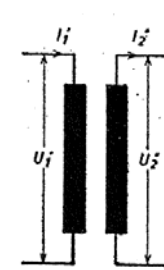
Autotransformer:

- the primary and secondary have a common part
- primary not galvanically separated from secondary
- primary and secondary have similar neutral earthing
- transfo lighter and cheaper
- mechanically low constructions possible



A full-wound transformer:

- all the windings are galvanically separated from each others
- the connection of the primary and secondary windings can be varied according to the needs (connection groups like Y, delta, zig-zag etc.)



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Short-circuit impedance

- due to the value $X_k = 20 \%$ the internal construction and materials to be used in the transformers in Finland have been selected according to high leakage fluxes
- leakage flux generates eddy currents and heat in metallic parts (in autotransformers no need to pay attention to this flux)
- further, the Fingrid's transformer specifications require in addition to the standard heat-run tests also two separate **additional thermal tests** as a type test:
 - a test for the 400/110 kV winding pair with the primary current $1,5 \cdot I_{N1}$ so that hottest spot of the winding reaches $140 \text{ }^{\circ}\text{C}$ and thereafter this temperature is maintained 8 h
 - a corresponding test required to tertiary winding, too



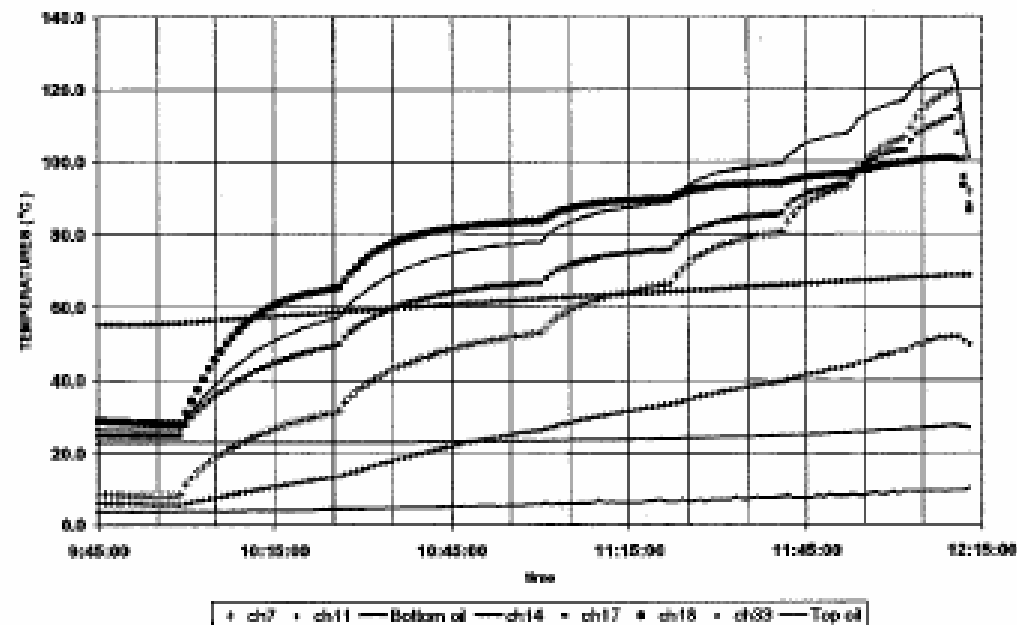
FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

- during the additional thermal tests the temperature rise of the windings, iron core, structural parts and transformer tank are monitored with the help of thermo-optical sensors connected to optical fibres, with conventional thermo-couples and by IR-scanning the tank
- as a whole, these additional tests have been very useful
- during GIC-events these additional tests have turned out to be important because in the saturated transformer a major part of the main flux takes the path of the stray flux (in normal operation conditions the transformers work with a main flux density 1,8 T which is about 80 % of the value where saturation starts to occur)



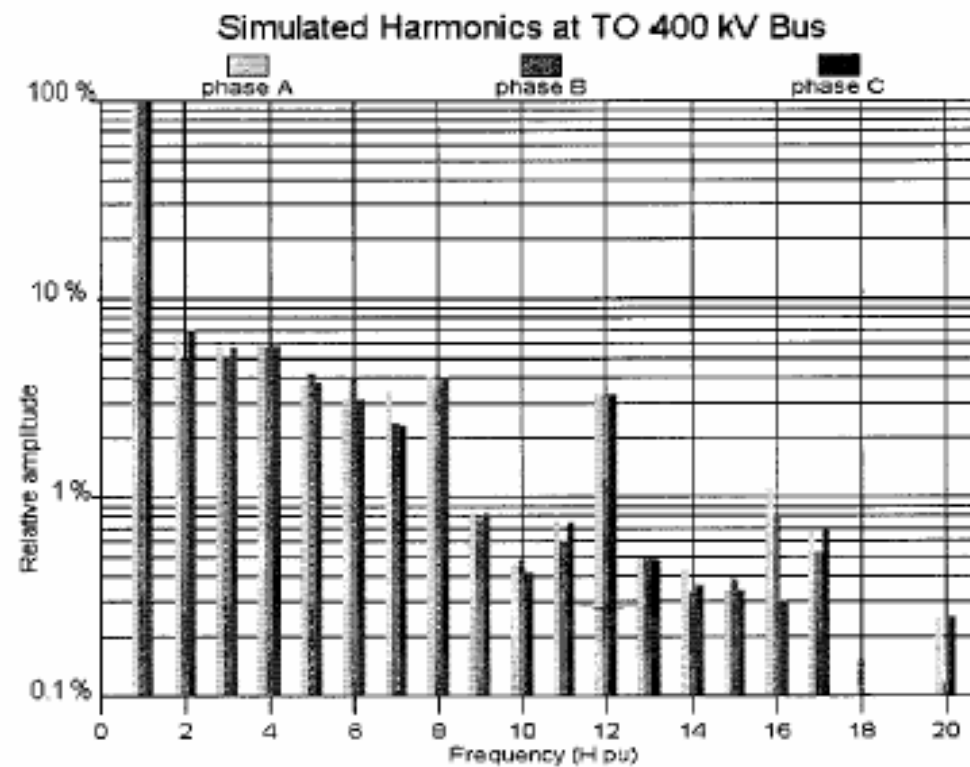
FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Temperature rises in a Finnish 400 MVA transformer under various DC-magnetizations (50...200 A) (Ch.7: Inside bottom yoke clamp; Ch.11: Non-magn. winding support; Ch. 14: Inside top-yoke clamp; Chs.17 &18: Flitch plate; Ch.33: center phase iron core mid-point)



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

**Production of harmonic voltages in two 3-phase 3-winding
5-leg 400 MVA transformer under 200 A DC-magnetization**



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Note!

- the GIC through an earthed transformer is significantly greater than the 50 Hz magnetization current of the transformer (for a 400 MVA transformer typically of the order of 2...3 A, i.e. 0,3...0,4 % of rated primary current)
- because the **GIC** is a pseudo-stationary current, it **must not be compared directly with the magnetization current!**
- when the magnetization effect of the GIC is studied, the **voltage drop**, which the GIC causes in the winding, has to be taken into account together with the **hysteresis loop** of the saturated transformer (otherwise incorrect conclusions; e.g. magnetization current reaches also values <0)



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Finnish transformers and GIC's:

- highest temperature 130 °C measured but in favourable climatic conditions (ambient temp. -2 °C)
- highest temperature rise (ΔT) about 110 K
- time constant of this temperature rise about 10 min
- if transformer is, at a start of an GIC-event, already in normal load with high ambient temperature, internal temperatures 170...180 °C can be reached => **No risk because no cellulose material in the vicinity**
- some gassing of oil might occur, even gas bubbles, but the risk is low (200 A appr. 1 time per 50 years)
- winding temperatures do not reach critical values



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

GIC's and the Finnish grid:

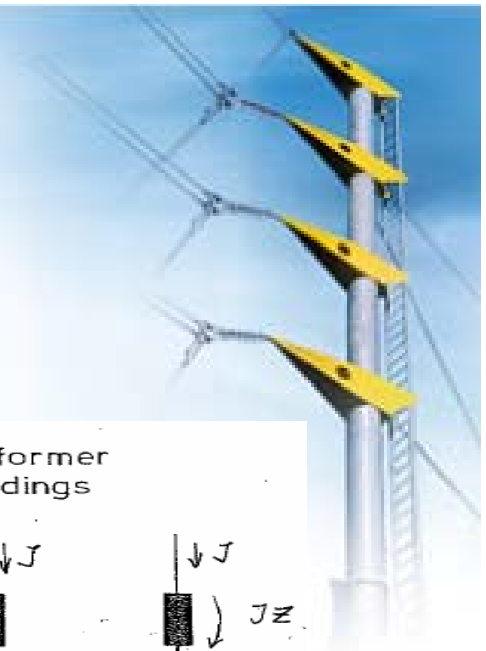
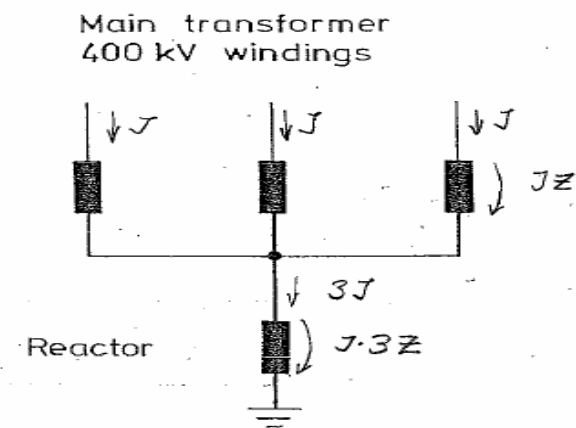
- in weak points of the system the distortion level of the voltages can be very severe
- the possibility of component failures is not excluded
- voltage control problems a potential risk , too
 - one transformer consumes abt. 55 Mvar at 200 A DC-magnetisation
 - $\Sigma I_{GI}=1200 \text{ A}$ would require extra reactive power capacity of 660 Mvar => abt. 95 % of time there is enough reactive power resources available <=> one voltage collapse per 20 a
- the GIC's are becoming smaller due to the evolution of the grid (e.g. series compensation of longer lines with series capacitor banks)
- **Risks acceptable; no mitigation, no warning systems**



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

Current limiting coils in transformer neutrals

- The impedance in the neutral branch is 3 times as "effective" than in phases
- The 400 kV winding neutral point coils
 - are of air-core type and
 - have typically reactance of 120Ω and resistance of $2,4 \Omega$
- the resistance of the neutral branch does not affect in the losses and its value can be selected on the basis of the thermal aspects
- the **resistance $3 \cdot 2,4 \Omega$ has** a significant magnitude when compared to the typical zero-sequence resistance of a 400 kV overhead line ($r_0 = 0,067 \dots 0,075 \Omega/\text{km}$) and transformers ($0,3 \Omega$) and has **importance in limiting the GIC in the grid**



FINNISH EXPERIENCES ON GRID EFFECTS OF GIC'S

About the future:

- no special measures needed if the dimensioning principles and equipment kept similar as now
- if large single-phase transformers will be installed in the grid, mitigation methods might become necessary
 - capacitor between the earth and the neutral of the transformer, or
 - use of a resistor in series with the current limiting coil
- reactive power reserves of the grid shall be maintained
- the equipments should withstand high harmonic voltages and currents (esp. protective relais worth of special consideration)

