DIgSILENT Pacific

Power system engineering and software

Transformer saturation and reactive power loss – a case study

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Presentation outline

- Saturation in iron core of transformers
- Saturation:
  - Reactive power
  - Harmonics
- Case study: inverter transformers in solar farm
- Reactive power generation requirement
- Tests on site
- Simulations of saturation
- Conclusions

Saturation in iron core

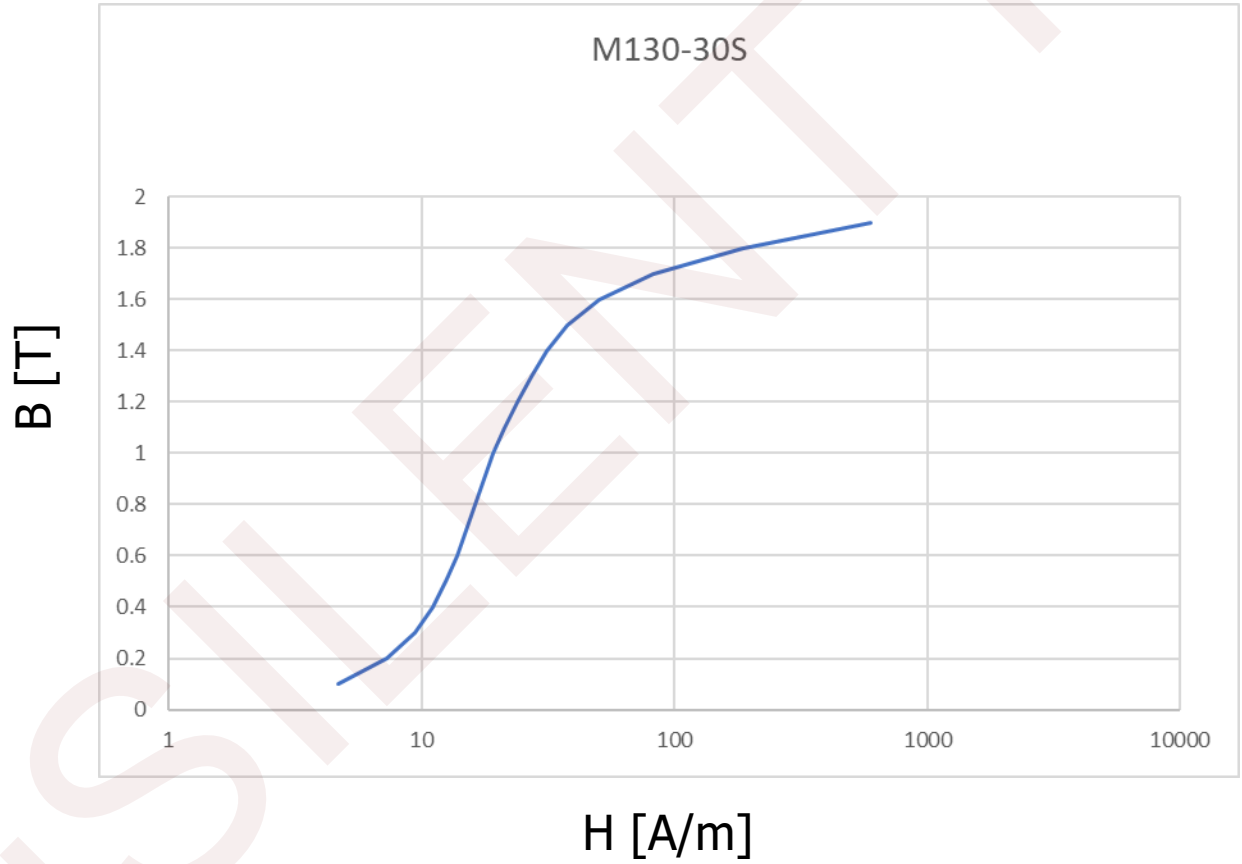
- Occurs when iron is "too full" (saturated) with magnetic flux:
  - The material cannot magnetize more than that
  - The H field to obtain the same B is similar to what is needed in air
  - Magnetization current increases a lot quicker

Some equations:

- Flux is imposed by voltage: $\varphi = \int v(t)dt + \varphi_0$
- Flux in limb of transformer: $\varphi = \mathrm{n} * \mathrm{B} * A_{core}$ (hyp.: B is uniform across core)
- N = number of turns, A = area of core cross-section

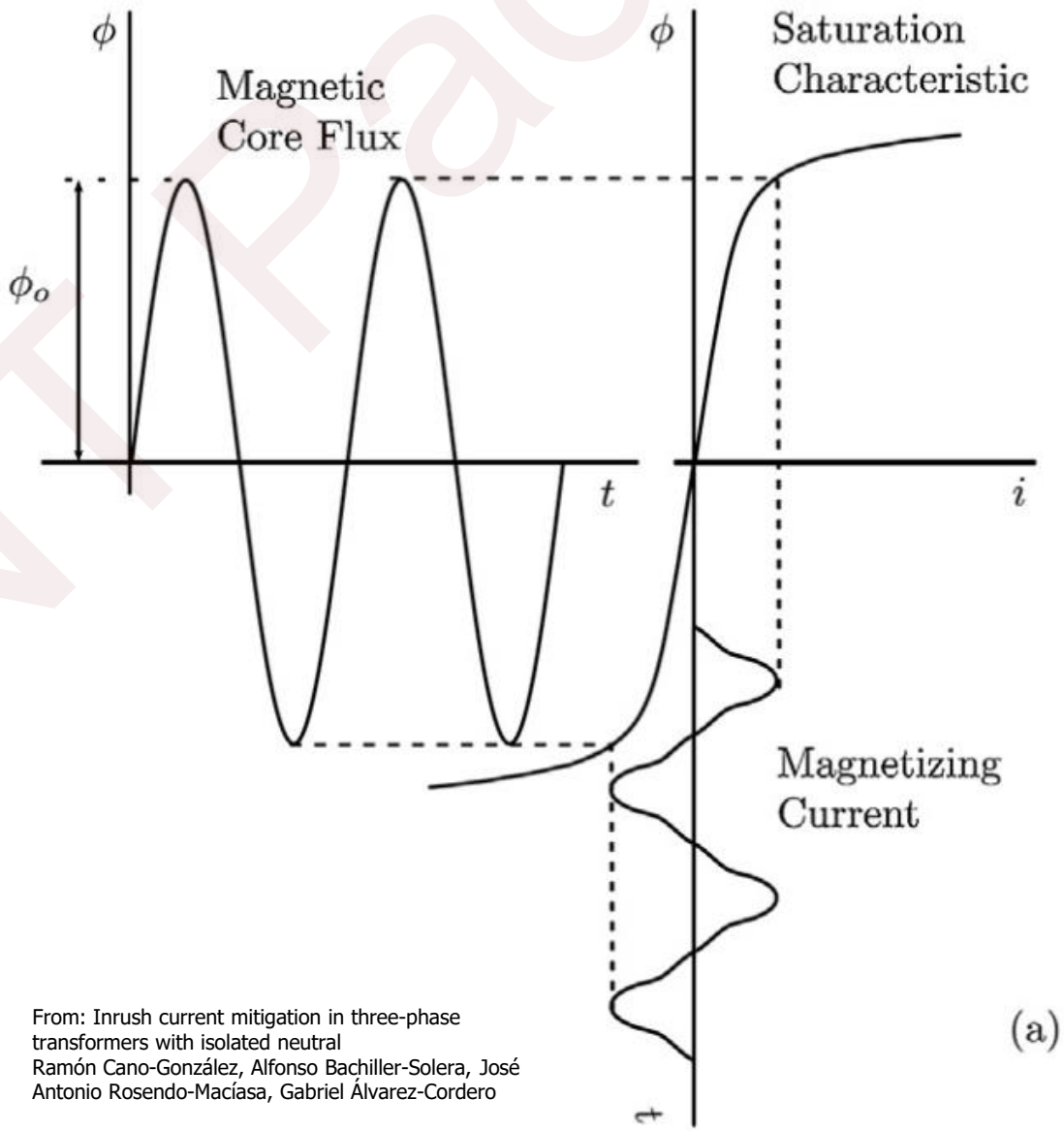
Saturation in iron core

- Example: curve from a steel manufacturer



Saturation in iron core

- Flux is imposed by the voltage
- If the source impedance is high enough, flux is sinusoidal
- Magnetizing current is not
- There are harmonics in the current
- There are harmonics in V if the source impedance is high
- In general saturation causes:
  - Distortion
  - Increase in reactive power absorbed by transformer



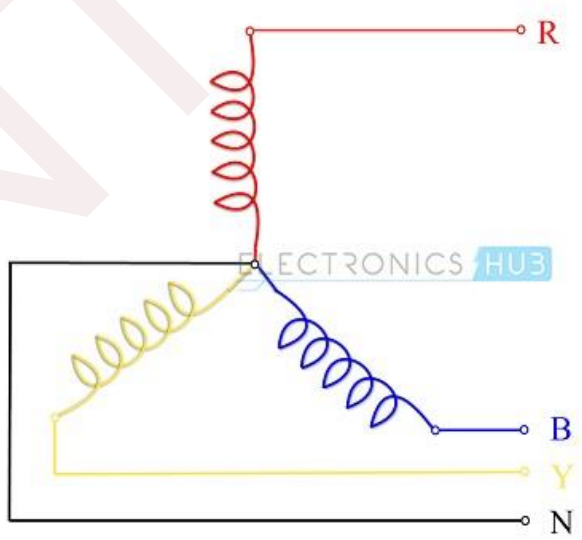
From: Inrush current mitigation in three-phase transformers with isolated neutral
Ramón Cano-González, Alfonso Bachiller-Solera, José Antonio Rosendo-Macíasa, Gabriel Álvarez-Cordero

Saturation: reactive power and distortion

- The current absorbed by a saturating transformer is distorted
  - The 50 Hz component causes increase in Q absorption
  - The harmonic components cause distortion of the voltage
- Spectrum:
  - The waveform is symmetrical with respect to time axis
  - Hence only odd harmonics
- How about inrush then? LR transient
  - There is a large amount of φ_0, or residual flux
  - φ_0 causes the zero of the waveform to move up/down
  - Current is asymmetrical now: even (order 2n, n=1,2…) harmonics can be high (“chopped” appearance)

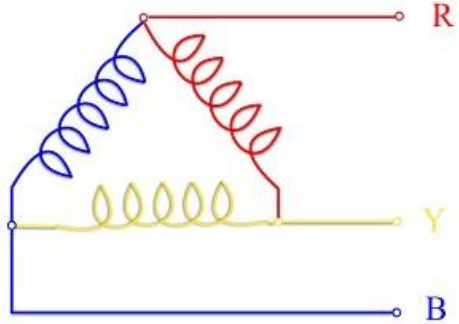
Saturation: transformer connection

- The waveform (or the harmonics) of a saturation current can change with the connection of the windings:
- Δ: voltage (flux) is imposed on the limb; currents are added
- Y: voltage (flux) results from limb impedance, current in limb is line current
- Different waveforms of current
- Flux is in common to primary and secondary, unless distortion is very high



Star Connection (Y or WYE)

From: https://www.electronicshub.org/wp-content/uploads/2017/07/Star-and-Delta-Connections.jpg



Delta Connection (Δ)

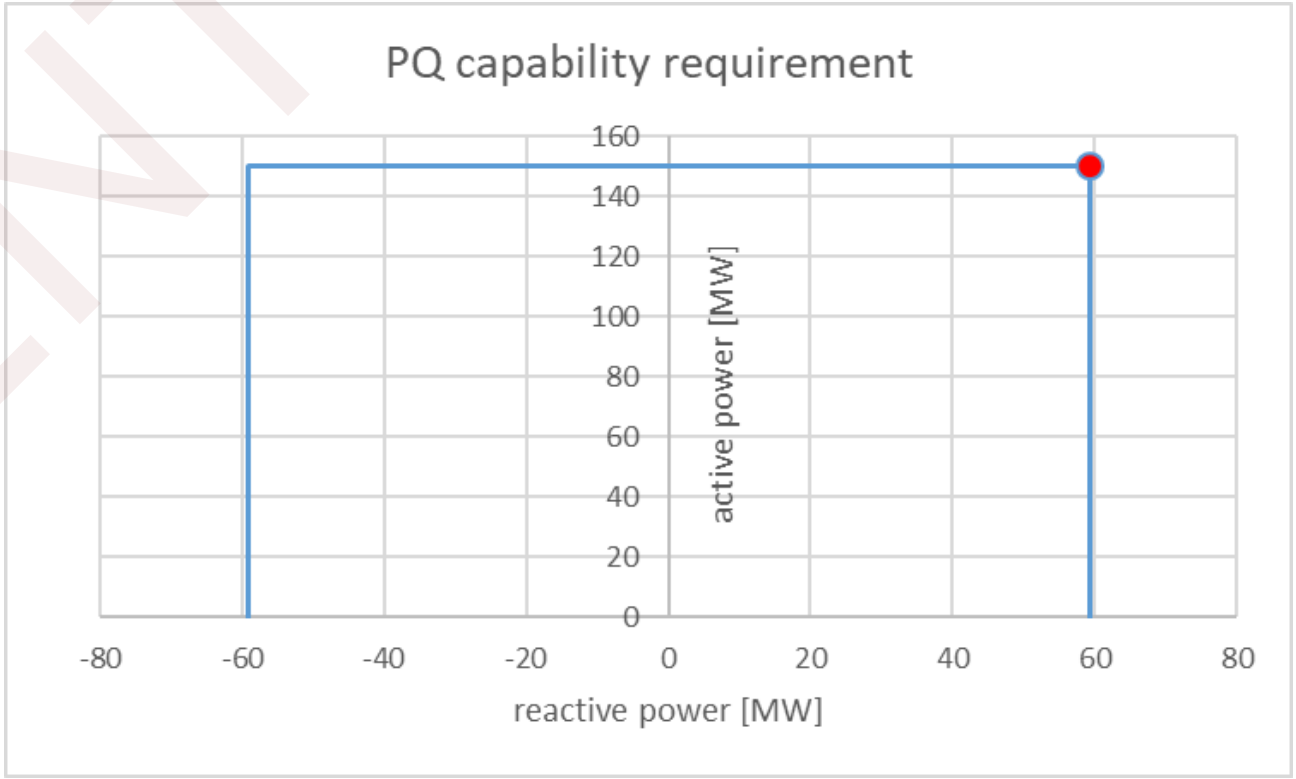
Case study: reactive power capability in solar farm

- Analysis of a problem occurred to a solar farm
- Could not meet Q capability
- Saturation was suspected to cause the problem

- DIgSILENT conducted analysis of test data to find the root cause:
  - Test data
  - PowerFactory simulations
  - Conclusions

Reactive power capability requirement

- Clause S5.2.5.1 of National Electricity Rules (NER)
- Power characteristic for a generator
- Marked point: Q>0 at max P
- Ideally: characteristic for voltage at connection point between 0.9 and 1.1 pu
- Injecting max Q at 1.1 pu makes inverter terminal voltage rise above 1.1 pu



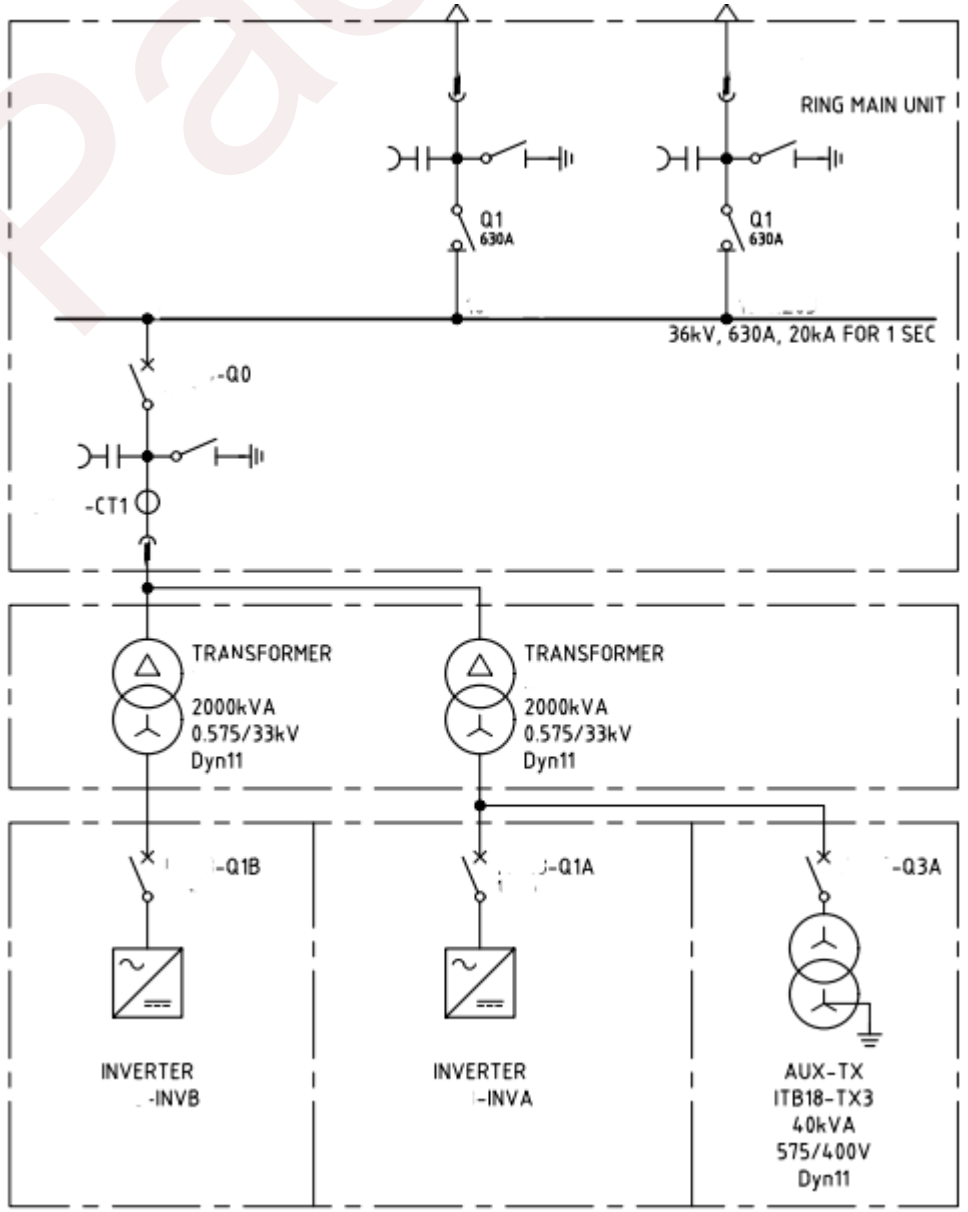
Reactive power capability test

- Capability required by electricity rules (NER)
- Transmission network provider (TNSP) to check capability
- Requirement:
  - Demonstrate Q supply to grid capability for a point of connection voltage of 1.1 pu
- Issue:
  - Supplying Q increases the voltage
  - The voltage at grid was high (not 1.1 pu, but as high as practical)
  - The voltage at the inverters had to be even higher…
  - …saturation occurred?
  - Question: saturation absorbed too much Q?
  - Fact: solar farm could not supply agreed amount

Connection of inverters to transformers

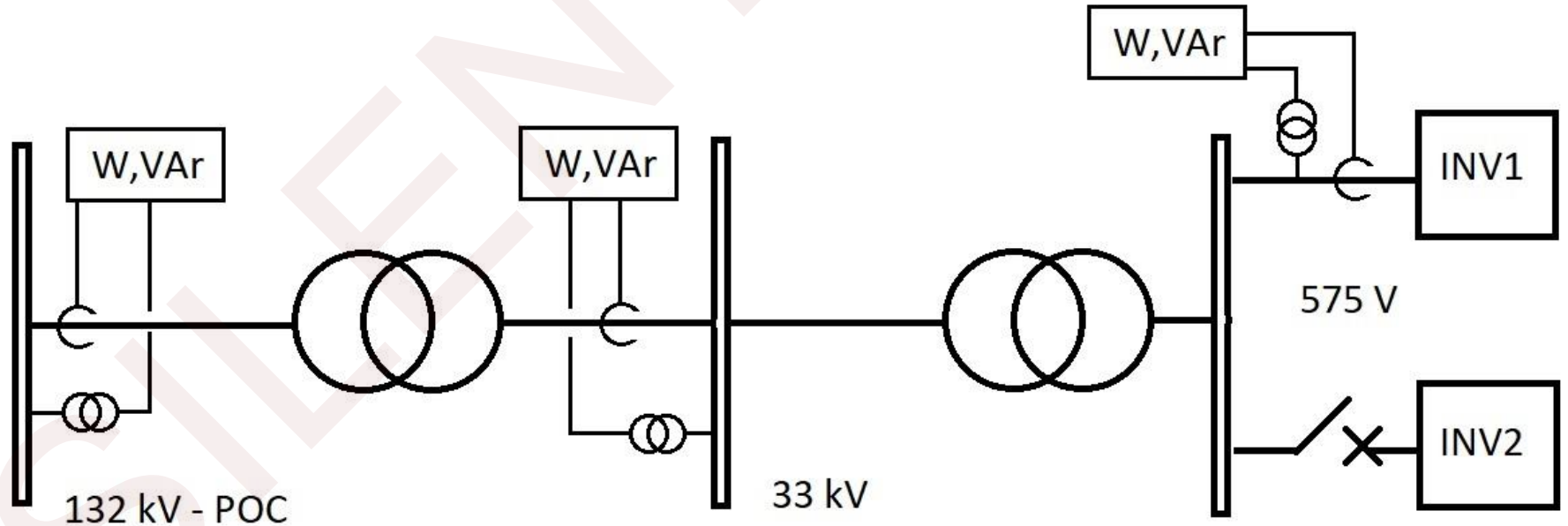
- Each inverter has its own transformer
- HV: 33 kV
- LV: 575 V
- S = 2 MVA
- Group: Dyn 11

- Each pair of inverters and transformers is connected to 33 kV solar farm cables
- Cables terminate on a 33 kV bus
- 33/132 kV transformer connects bus to the grid
- Point of connection (POC) at 132 kV



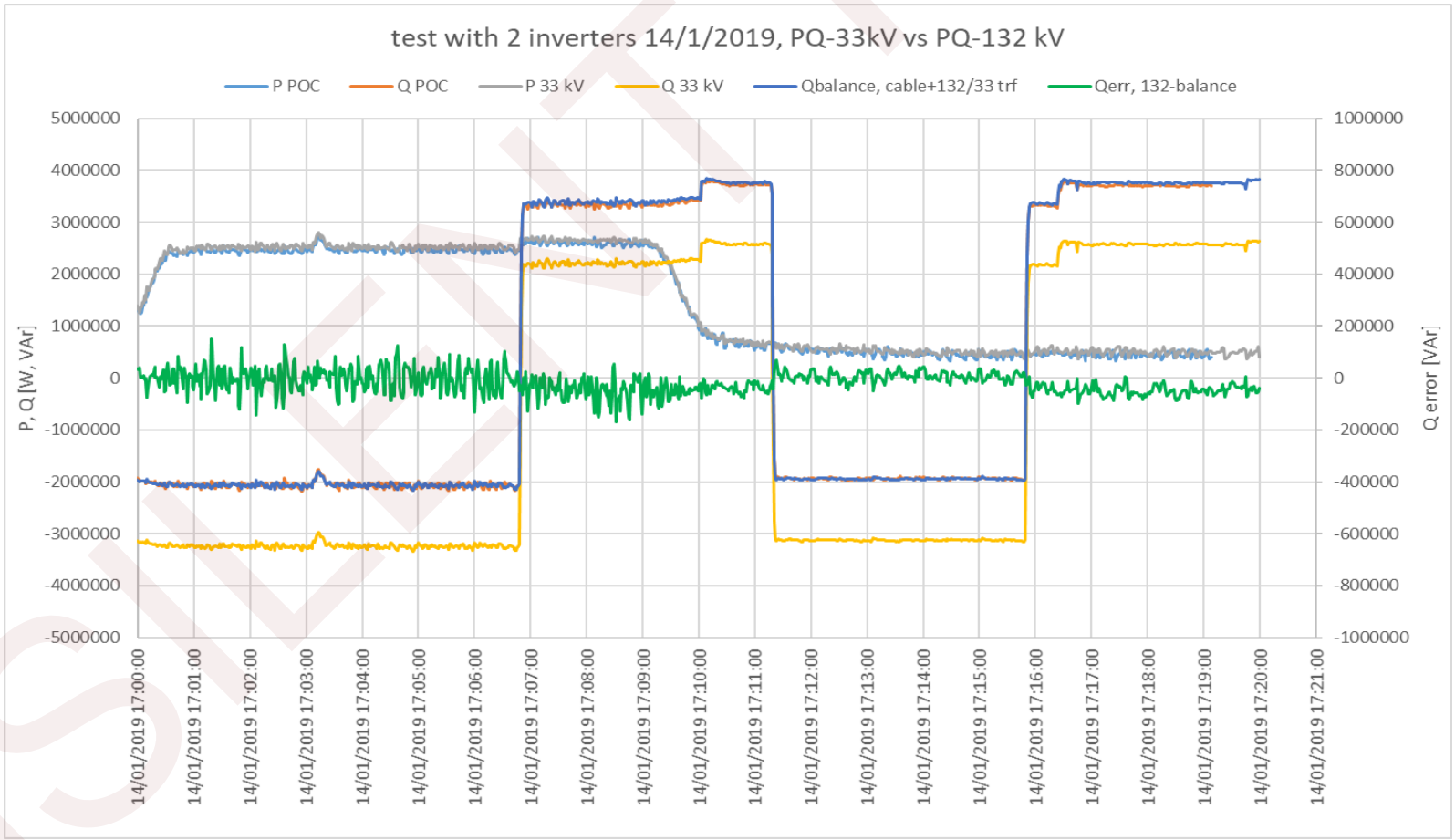
Power balance test: meter connection

- P and Q measured either side of main transformer and inverter transformer
- Only one inverter and one inverter transformer are connected
- All other cables and plant disconnected



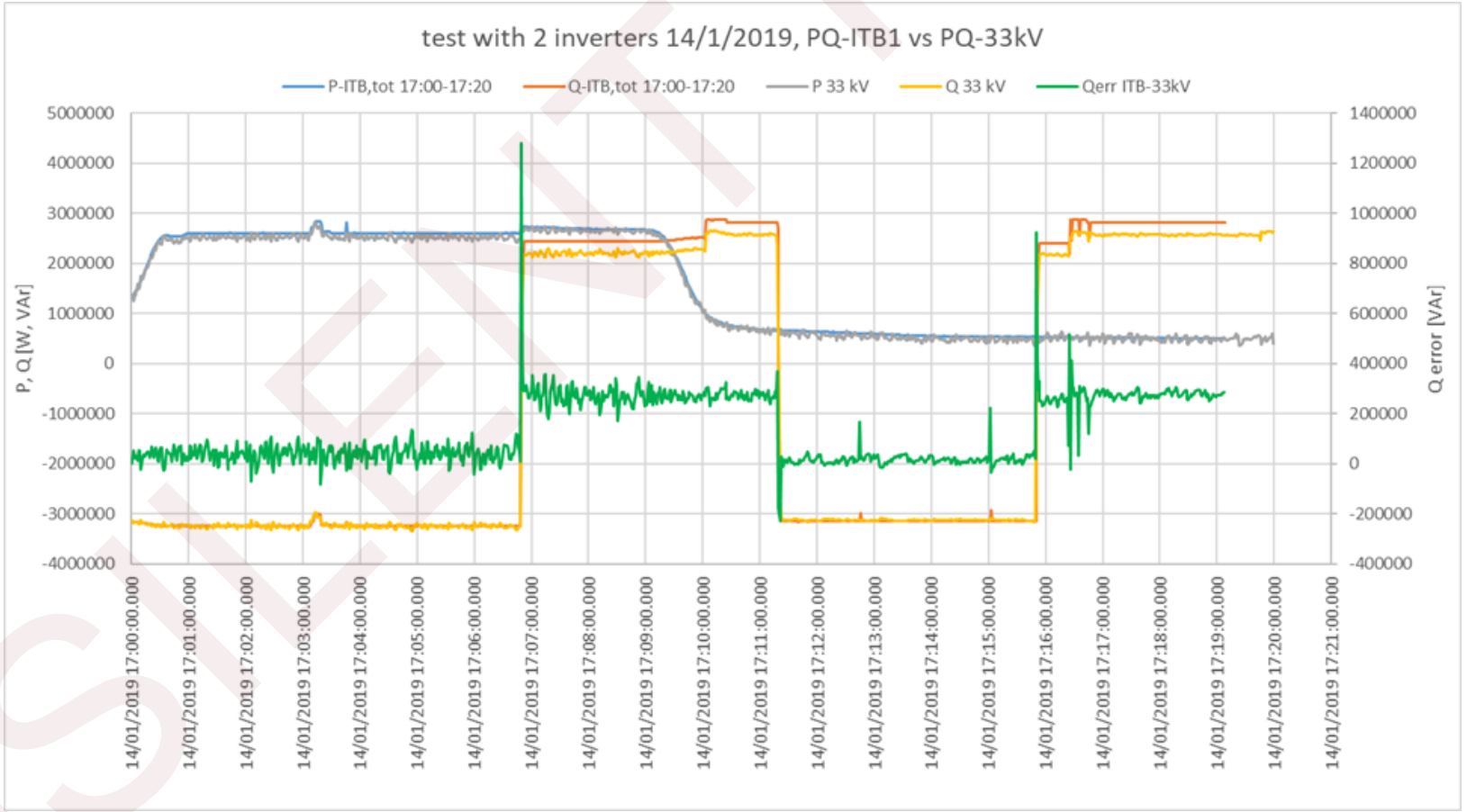
Power balance test

- P and Q measured either side of main transformer and inverter transformer
- Main trf:



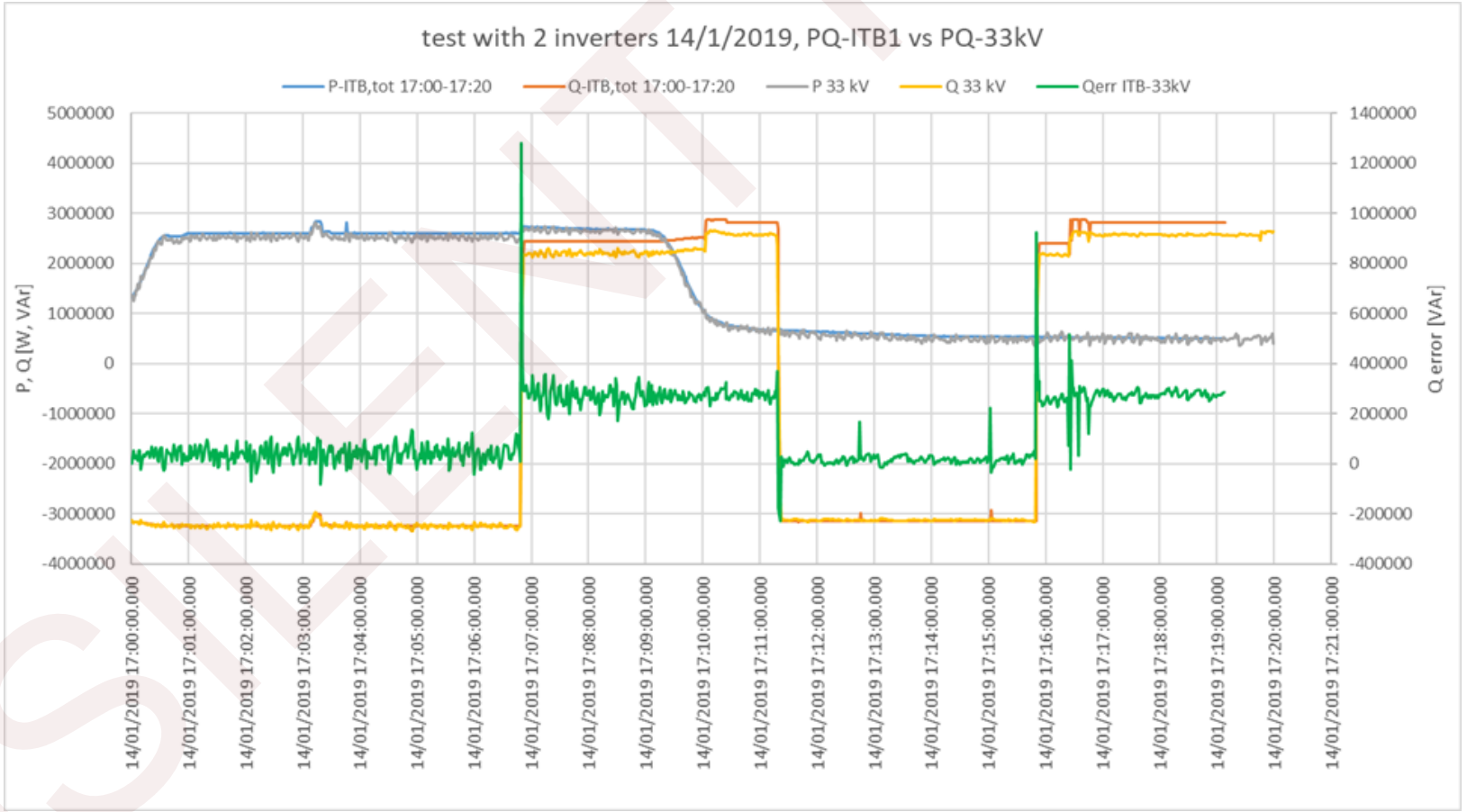
Power balance test

- P and Q measured either side of main transformer and inverter transformer
- Inverter trf:



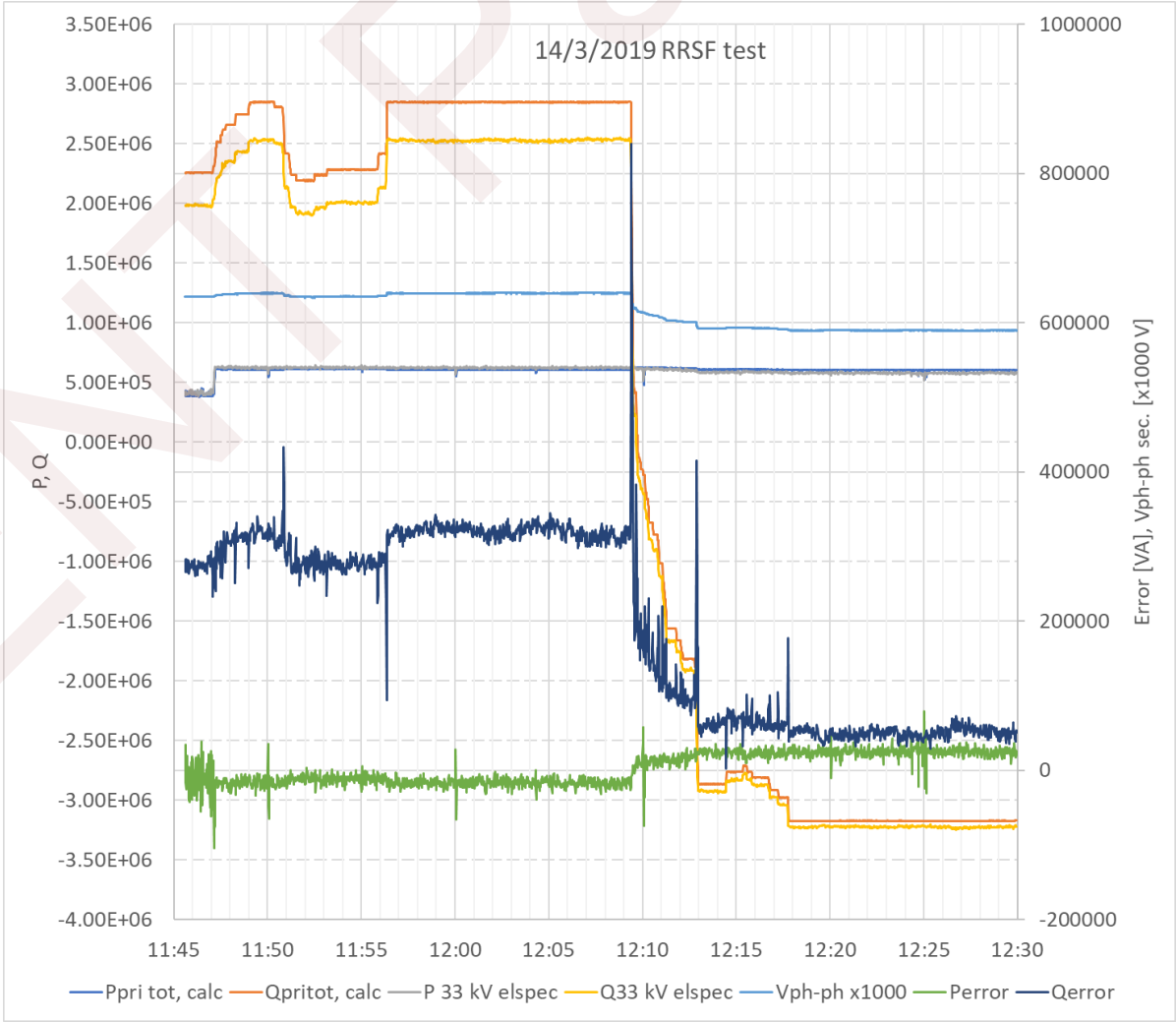
Power balance test

- P and Q measured either side of main transformer and inverter transformer
- Inverter trf:
- Q error high with higher Q supply



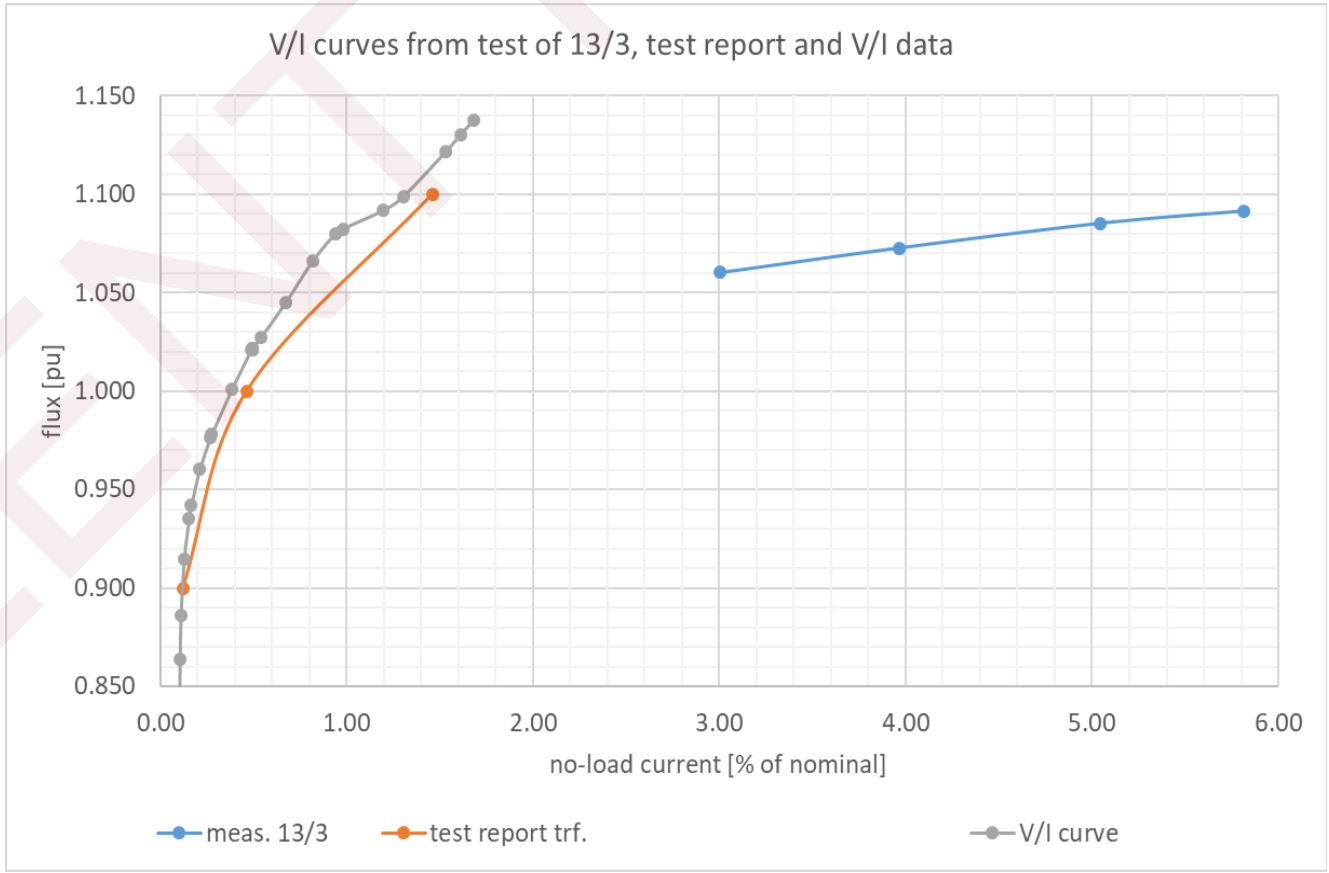
Power balance test, repeated

- Q error high with higher Q supply and higher voltage
- This indicates that the inverter transformer changes its Q absorption significantly
- Is it saturation?
- Check for distortion
- Compare Q absorption with trf V/I no-load curves



V/I no-load curves

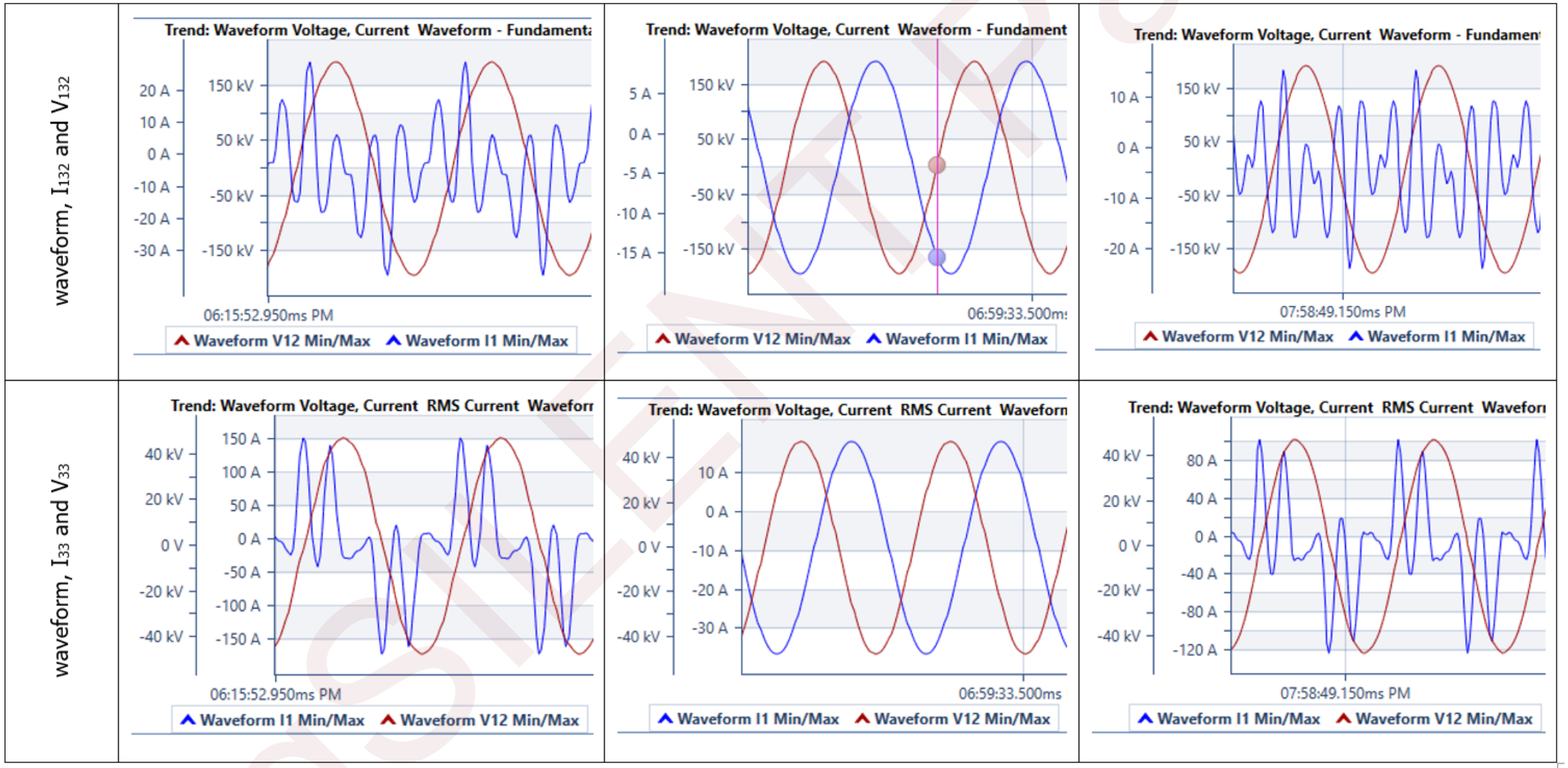
- Curves relating RMS current and voltage at no-load
- Difference between type test and field test data
- Steel data and factory test coincide
- Site measurement differs
- Transformers saturating more than expected?



Test at night

- Transformers gradually disconnected and reconnected during the night
- To make sure that distortion:
  - Was there if inverters were off
  - Disappeared if transformers were off
  - Was not due to the grid
- Test results were also compared to simulations

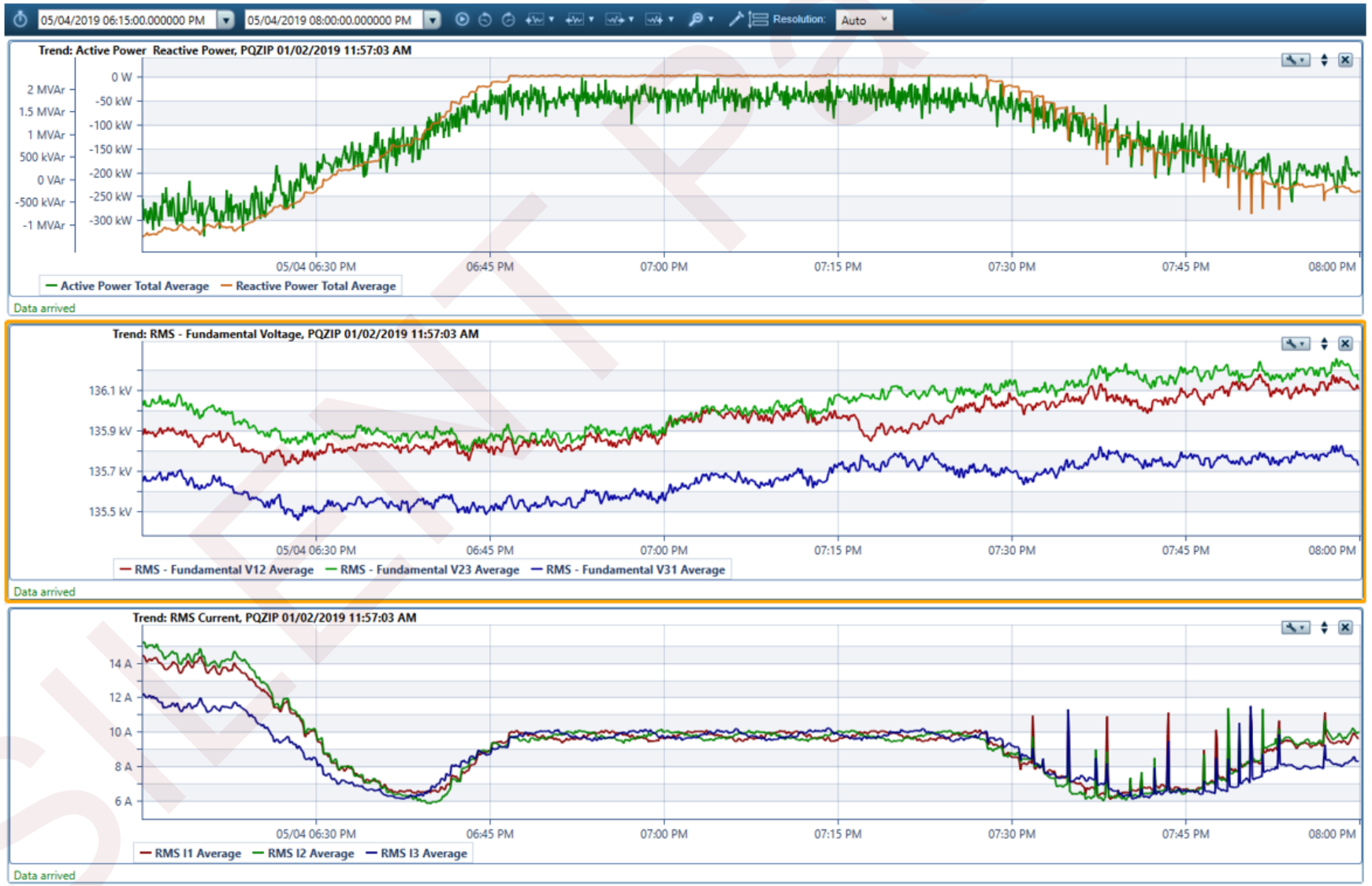
Test at night



currents and voltages before (left), during (centre) and after (right) transformer de-energisation

Test at night

- P and Q
- V 50 Hz
- I 50 Hz

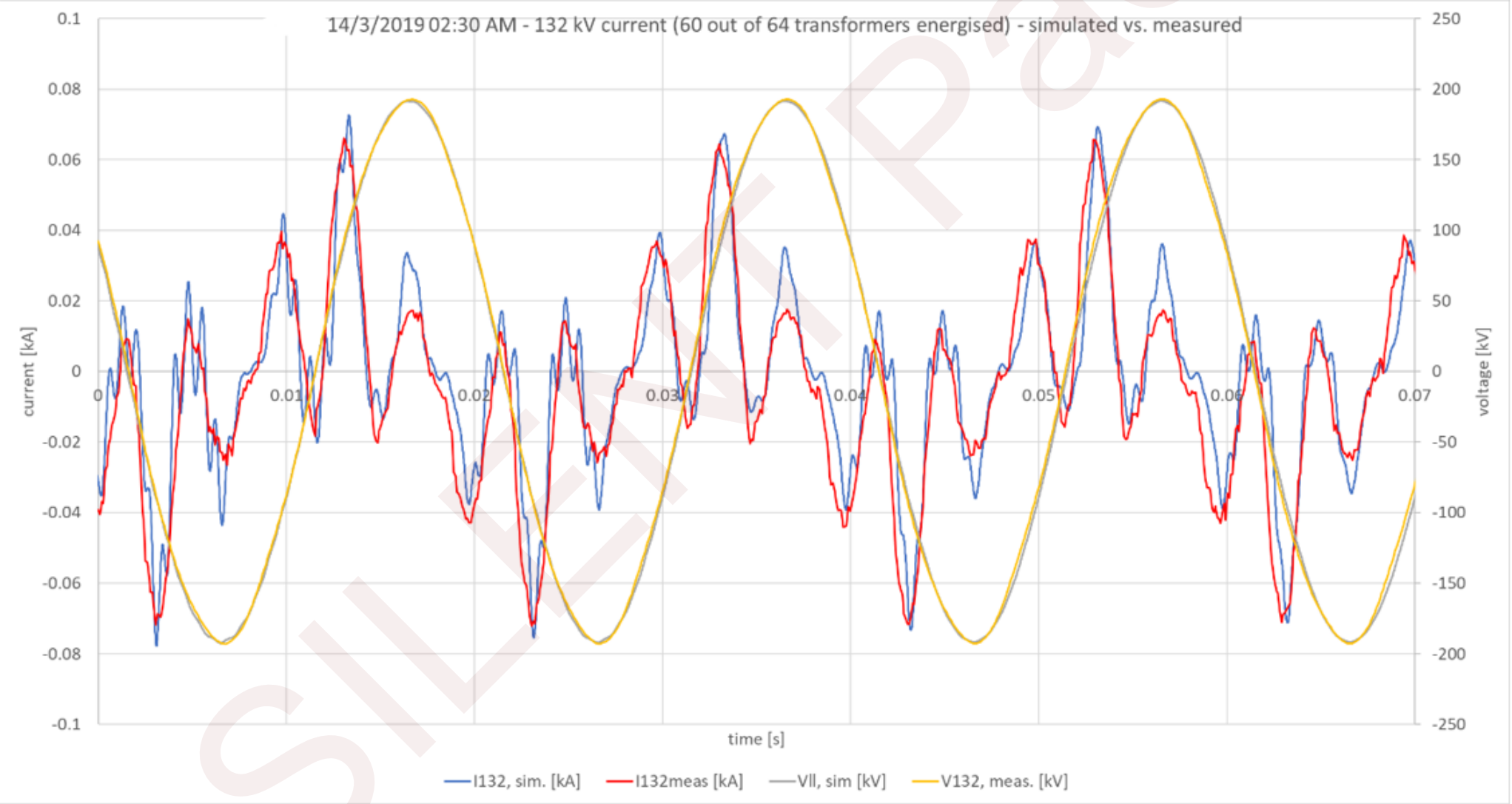


132 kV, P Q V and I during the test of 5/4/2019; the current spikes are the re-energisations of the transformers; current dips during de- and re-energisation when reactive power absorbed by transformers is balanced by reactive power contributed by cables (Q_{net} = 0)

Test results

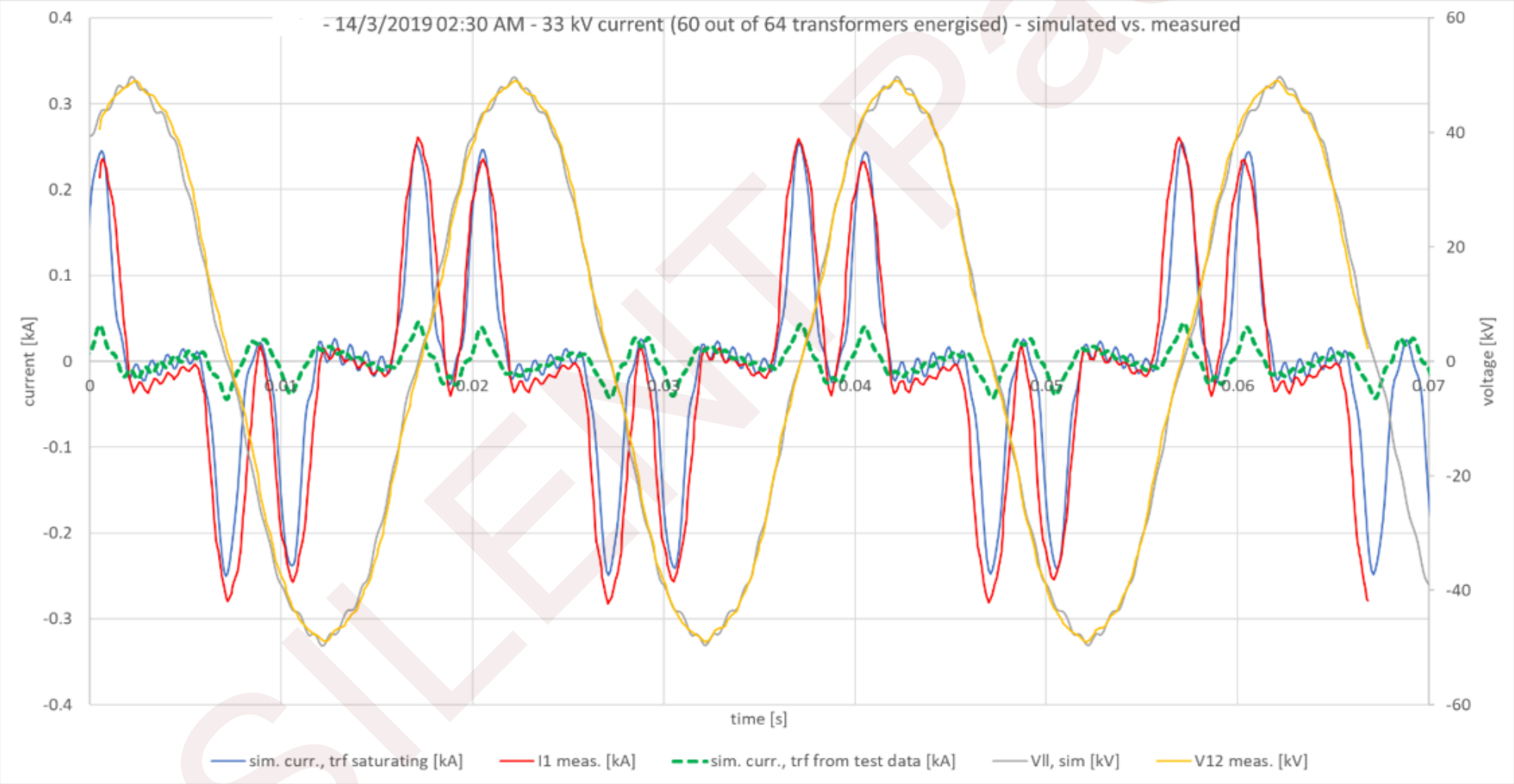
- The test demonstrated that:
  - The transformers are absorbing more reactive power than expected (total Q absorbed / transformer number > $Q_{type\text{-}test}$
  - Distortion is caused by the transformers, not inverters and not grid
- It is necessary to:
  - Demonstrate that there is a mismatch between V/I characteristic of installed transformer and V/I supplied in test data
- Power Factory time-domain simulation of transformer with:
  - declared V/I curve from type test
  - modified V/I curve, where B values are increased by a factor, to model higher saturation

Simulation



simulated and measured current and voltage waveform at 132 kV

Simulation



simulated and measured current and voltage waveform at 33 kV; the green dotted line is the simulated current obtained by using the model of the type-tested transformer

Simulation results

- The simulation demonstrated:
  - Good agreement between model with “modified” V/I curve and measured waveforms
  - That type-test V/I curve was not compatible with measured data
- Waveform simulation is a tool suitable for saturation investigation:
  - Waveform is closely related to curve
  - Oscillations between stray capacitance and non-linear inductance can be reproduced
  - Peak amplitude of current can be reproduced and checked (peak A/m)
  - Eventual ferro-resonance phenomena can be predicted

Conclusion

- Transformers will be replaced – awaiting for feedback
- Usage of extensive site tests and simulation technology:
  - Identified a problem
  - Provided information on which all parties could discuss and agree
  - Made a strong case for a solution
- Questions?

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