

# **DIGSILENT Pacific**

Power system engineering and software

## **Grid compliance: simple requirements turning into big challenges**

- Power quality (harmonics)**
- Reactive power capability**

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**DIGSILENT Pacific seminar**  
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# Introduction

- Generators need to demonstrate GPS compliance
- Power quality and reactive power capability are two basic requirements which most generators in the past could achieve compliance easily
  - Synchronous generators do not produce harmonic currents
  - Synchronous generators have plenty of reactive capability
- For variable renewables energies (VREs), our commissioning experiences showed proving compliance of these two requirements can be a challenge

# **Part 1**

## **Power quality – Harmonic emission**

# Australian Grid Code – Harmonic voltage distortion

h	Limit	h	Limit	h	Limit
(-)	(-)	(-)	(-)	(-)	(-)
		21	0.10	41	0.14
2	0.11	22	0.10	42	0.10
3	0.15	23	0.19	43	0.13
4	0.10	24	0.10	44	0.10
5	0.46	25	0.19	45	0.10
6	0.10	26	0.10	46	0.10
7	0.31	27	0.10	47	0.13
8	0.10	28	0.10	48	0.10
9	0.16	29	0.17	49	0.13
10	0.10	30	0.10	50	0.10
11	0.41	31	0.16		
12	0.10	32	0.10		
13	0.41	33	0.10		
14	0.10	34	0.10		
15	0.10	35	0.15		
16	0.10	36	0.10		
17	0.27	37	0.15		
18	0.10	38	0.10		
19	0.27	39	0.10		
20	0.10	40	0.10	THD	0.59

- Generator Performance  
Standard requires power quality (harmonics) measures:
  - Generator should aim to meet **auto access requirements**
  - Generator cannot connect if performance is below **minimum access requirement**
- Demonstration of Performance standard compliance required before connection: **simulation**
- Proof of compliance during commissioning: **measurement**

# Inverter harmonics

- Inverters have harmonic currents all over the frequency spectrum
- Harmonic currents vary against output
- (Norton equivalent) harmonic impedance unknown



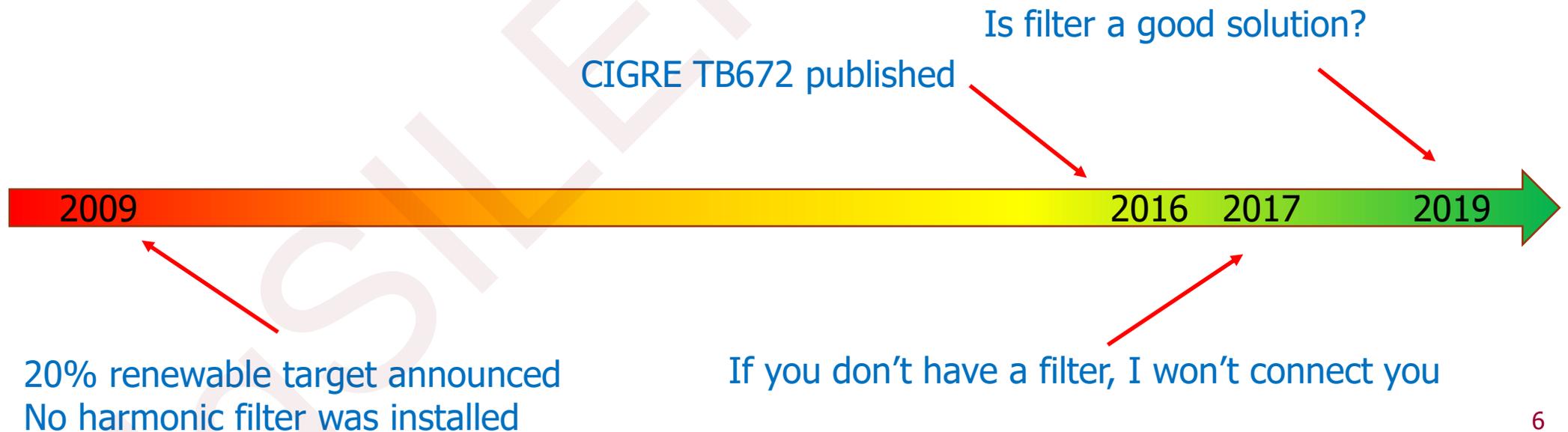
harmonic number	Harmonic Current test results					
	absolute I <sub>n</sub> [A]			relative I <sub>n</sub> / I <sub>1</sub>		
	L1	L2	L3	L1	L2	L3
n						
1	86,72	86,43	86,35	100,00%	99,99%	100,00%
2	0,2860	0,4300	0,4000	0,33%	0,50%	0,46%
3	0,2170	0,1630	0,1190	0,25%	0,19%	0,14%
4	0,1020	0,1120	0,1060	0,12%	0,13%	0,12%
5	0,0420	0,0350	0,0470	0,05%	0,04%	0,05%
6	0,0190	0,0280	0,0230	0,02%	0,03%	0,03%
7	0,0310	0,0230	0,0310	0,04%	0,03%	0,04%
8	0,0190	0,0200	0,0210	0,02%	0,02%	0,02%
9	0,0760	0,0420	0,0410	0,09%	0,05%	0,05%
10	0,0340	0,0380	0,0390	0,04%	0,04%	0,05%
11	0,0990	0,0840	0,1150	0,11%	0,10%	0,13%
12	0,0220	0,0240	0,0240	0,03%	0,03%	0,03%
13	0,0940	0,0920	0,0770	0,11%	0,11%	0,09%
14	0,0140	0,0130	0,0150	0,02%	0,02%	0,02%
15	0,0330	0,0270	0,0120	0,04%	0,03%	0,01%
16	0,0130	0,0120	0,0130	0,01%	0,01%	0,02%
17	0,1520	0,1460	0,1570	0,18%	0,17%	0,18%
18	0,0080	0,0100	0,0110	0,01%	0,01%	0,01%
19	0,1150	0,1140	0,1090	0,13%	0,13%	0,13%
20	0,0080	0,0120	0,0140	0,01%	0,01%	0,02%
21	0,0170	0,0170	0,0110	0,02%	0,02%	0,01%
22	0,0090	0,0090	0,0120	0,01%	0,01%	0,01%
23	0,0900	0,0820	0,0950	0,10%	0,09%	0,11%
24	0,0100	0,0110	0,0100	0,01%	0,01%	0,01%
25	0,0010	0,0070	0,0070	0,00%	0,00%	0,00%

Source:

[https://www.sma-solar.pl/fileadmin/content/landingpages/pl/Falowniki/STP\\_60-10\\_harmonic\\_distorsion\\_15\\_08\\_25\\_EN.pdf](https://www.sma-solar.pl/fileadmin/content/landingpages/pl/Falowniki/STP_60-10_harmonic_distorsion_15_08_25_EN.pdf)

# No one was prepared

- Most developers were not aware of power quality issue
- Some OEMs had no inverter harmonic measurement data
- Some network operators:
  - did not have accurate harmonic impedance data for the network
  - did not know how to determine harmonic allocation

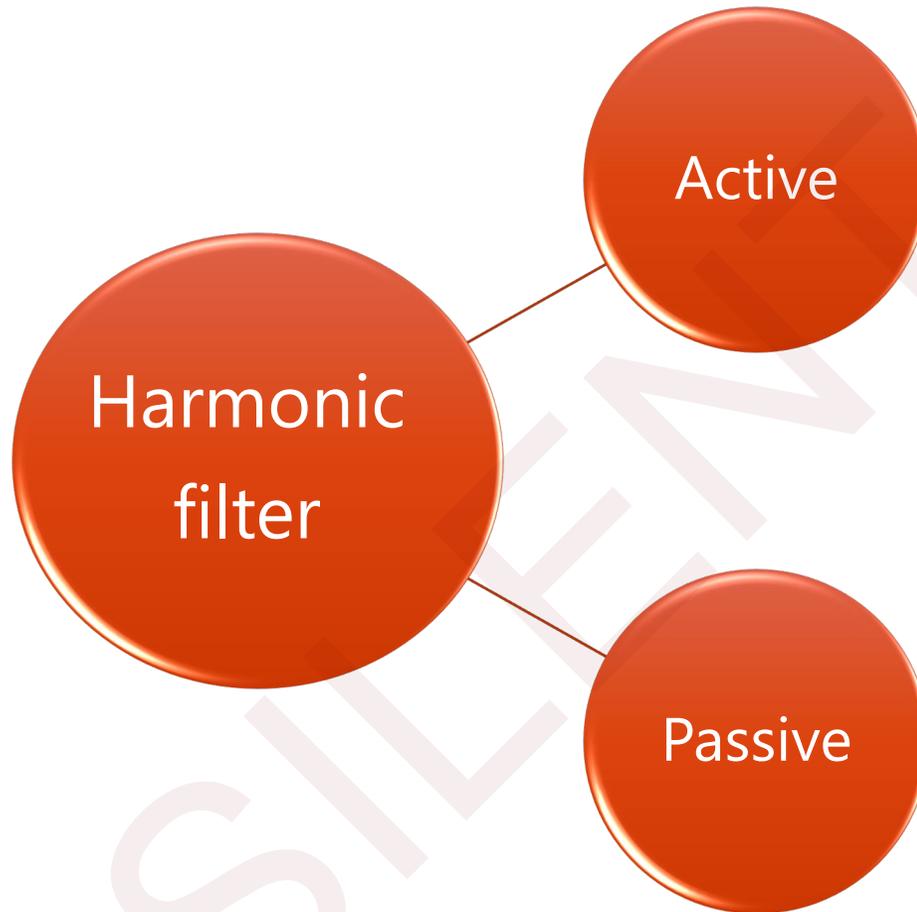


# AEMO's latest findings

Commissioning experience			
Plant	Issue	Action	Resolution
wind farm	<ul style="list-style-type: none"> <li>Turbine blade design issues</li> <li>PSCAD modelling shows non-compliance at full output</li> <li>non-compliance of existing solar farm</li> </ul>	<ul style="list-style-type: none"> <li>Delays to staged testing</li> </ul>	<ul style="list-style-type: none"> <li>Disabled shaft tower damper</li> <li>Plan to rectify blade design issue</li> <li>PSCAD modelling ongoing</li> </ul>
wind farm	<ul style="list-style-type: none"> <li>Inaccurate and inadequate modelling</li> <li>Application of incorrect firmware</li> </ul>	<ul style="list-style-type: none"> <li>Constraints on output</li> </ul>	<ul style="list-style-type: none"> <li>Implementation of additional intertripping schemes</li> <li>Correct firmware applied</li> <li>PSS/E modelling issues addressed</li> </ul>
solar farm	<ul style="list-style-type: none"> <li>fluctuations in output due to cloud movement</li> </ul>	<ul style="list-style-type: none"> <li>Constraints on output</li> </ul>	<ul style="list-style-type: none"> <li>Limit inverter active power based on capability (incl. temp)</li> </ul>
solar farms	<ul style="list-style-type: none"> <li>High high order harmonics</li> </ul>	<ul style="list-style-type: none"> <li>Commissioning delayed</li> </ul>	<ul style="list-style-type: none"> <li>Changed firing angle of some inverters</li> </ul>
solar farms	<ul style="list-style-type: none"> <li>Park controller latency</li> <li>PI settings changed without NSP &amp; AEMO approval</li> </ul>	<ul style="list-style-type: none"> <li>Constraints on output</li> </ul>	<ul style="list-style-type: none"> <li>Replaced meters between inverters and PPC</li> <li>Change PI settings (approved)</li> </ul>
solar farm	<ul style="list-style-type: none"> <li>Transformer tap changer issues</li> </ul>	<ul style="list-style-type: none"> <li>Primary plant commissioning delayed ~6 weeks</li> </ul>	<ul style="list-style-type: none"> <li>Ongoing</li> </ul>

Source: <https://www.aemo.com.au/Stakeholder-Consultation/Industry-forums-and-working-groups/Other-meetings/Generator-Registration-and-Connection-in-the-NEM>

# Challenge 1 – Filter selection



- Easier to target harmonics
- Consume more power
- Cannot control harmonic voltage amplification
- May not be functional at low SCR conditions

- Can control voltage amplification
- Consume less power
- May need multiple filters
- At night time,
  - If filter is **off** :
    - Harmonic voltage amplification
  - If filter is **on** :
    - Introduce higher system voltage when inverters turned off
    - Reduce inverter service lifetime if inverters in service
- Filter switching can cause power quality issue

## Challenge 2 – Determine harmonic contribution

AS/NZS 61000.3.6 recommends:

- Subtraction of percentiles
- Apply exponents to account for phase difference

### Example

Consider 95<sup>th</sup> percentile of 10-minute averaged harmonic components over 7 days of:

- Background = solar farm disconnected
- Operation = solar farm connected

$$\bullet \text{ Contribution} = \frac{1}{\alpha} \sqrt{\text{Operation}^{\alpha} - \text{Background}^{\alpha}}, 1 \leq \alpha \leq 2$$

## Challenge 2 – Determine harmonic contribution

### Q1: What is the background?

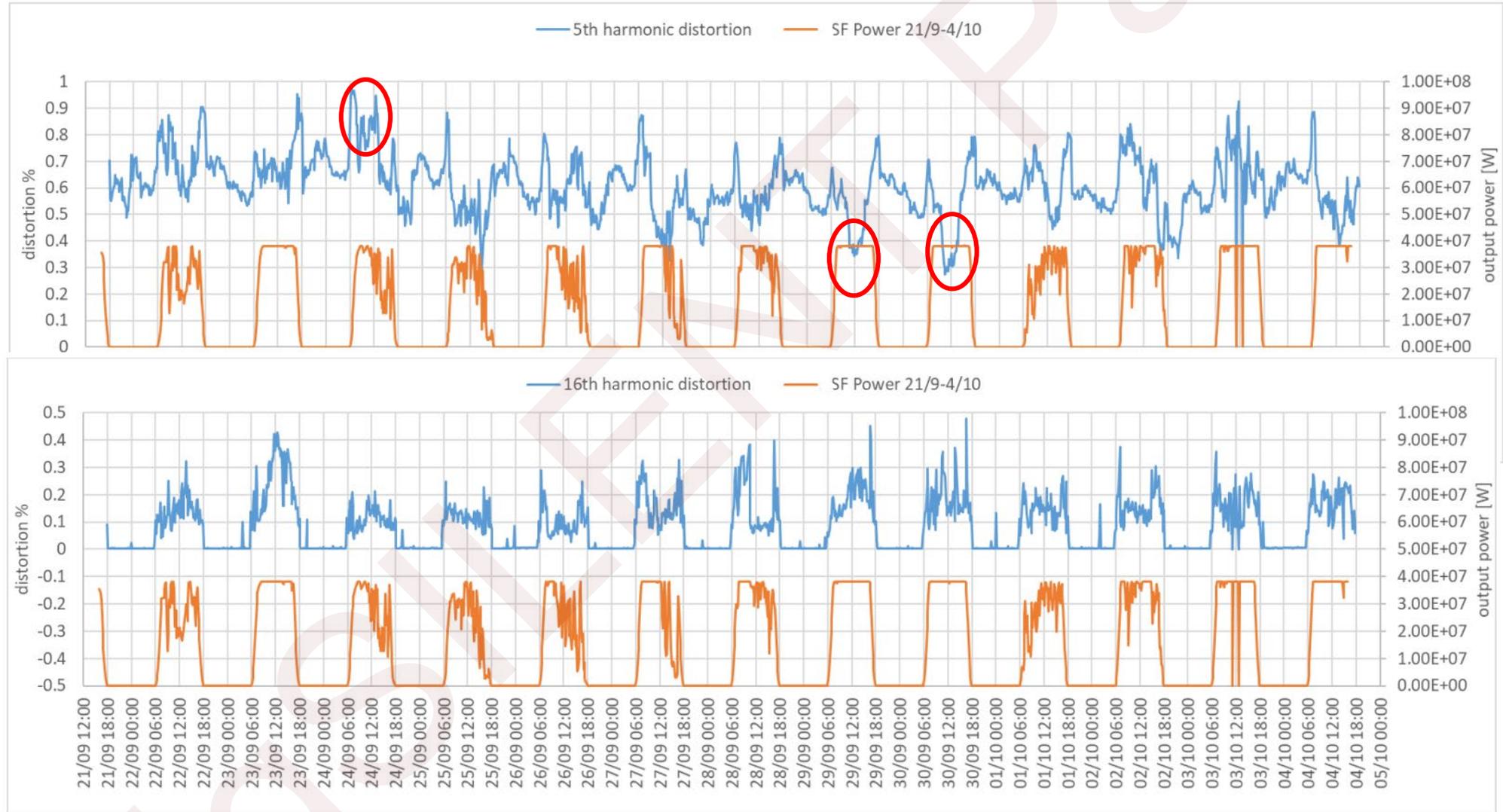
Background harmonics change as more solar farms introduced – what is the relevance of a background reading taken 6 months ago? How do you test ongoing compliance over the life of the plant?

**Q2:** What  $\alpha$  to use for subtraction from background influence? How do you measure the phase angle difference for each harmonic?

**Q3:** What if allocation is very small relative to background harmonic? (0.1% against 0.6%)

**Result:** There can be false positives or false negatives in the assessment.

# On-site harmonic measurements



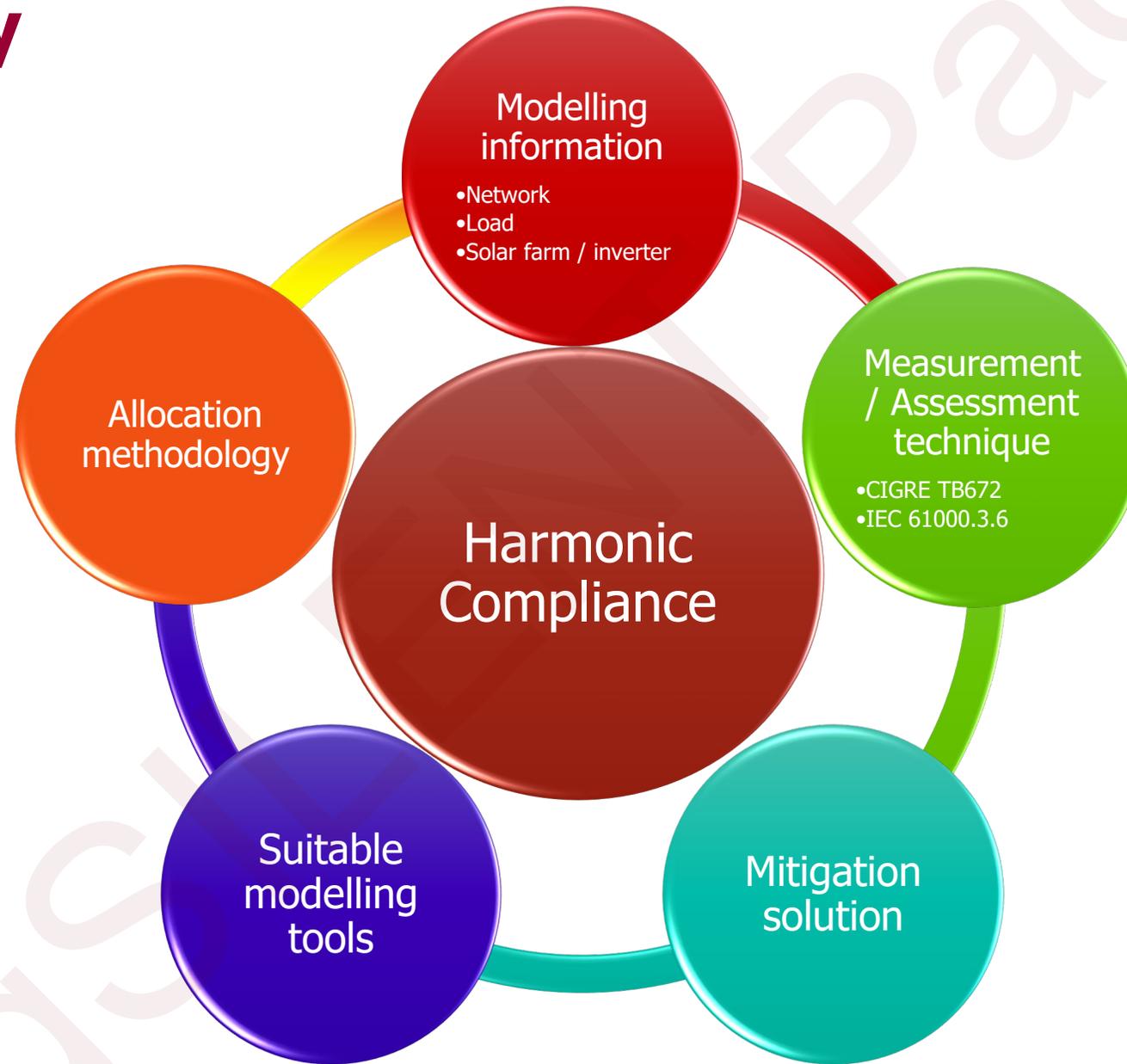
## Challenge 3 – Measurement

- Minimum measurement period: one week of normal business activity
  - Too short to capture seasonal variation
  - Too long for commissioning purpose
  - Many modes of operations during a day
- Measuring instrument accuracy
  - Class 0.2 CT/VT are typically used!
  - 0.1% harmonic allocated?
- Grid Owner/Operator prevents operation at higher output if harmonic levels are greater than allocation – **big commissioning risk**

## Challenge 4 – No national approach

- Different NSPs have different levels of power quality related information
  - Some do not have harmonic impedance network model
  - Some do not have background harmonic measurement
  - Some have different methodologies of harmonic emission allocation
- Different NSPs have different approaches of harmonic emission assessments
- Some NSPs do not allow for negotiation of higher harmonic allocation under the AS61000.3.6 Stage 3 “acceptance of higher emission levels on a conditional basis”

# Summary



# Part 2

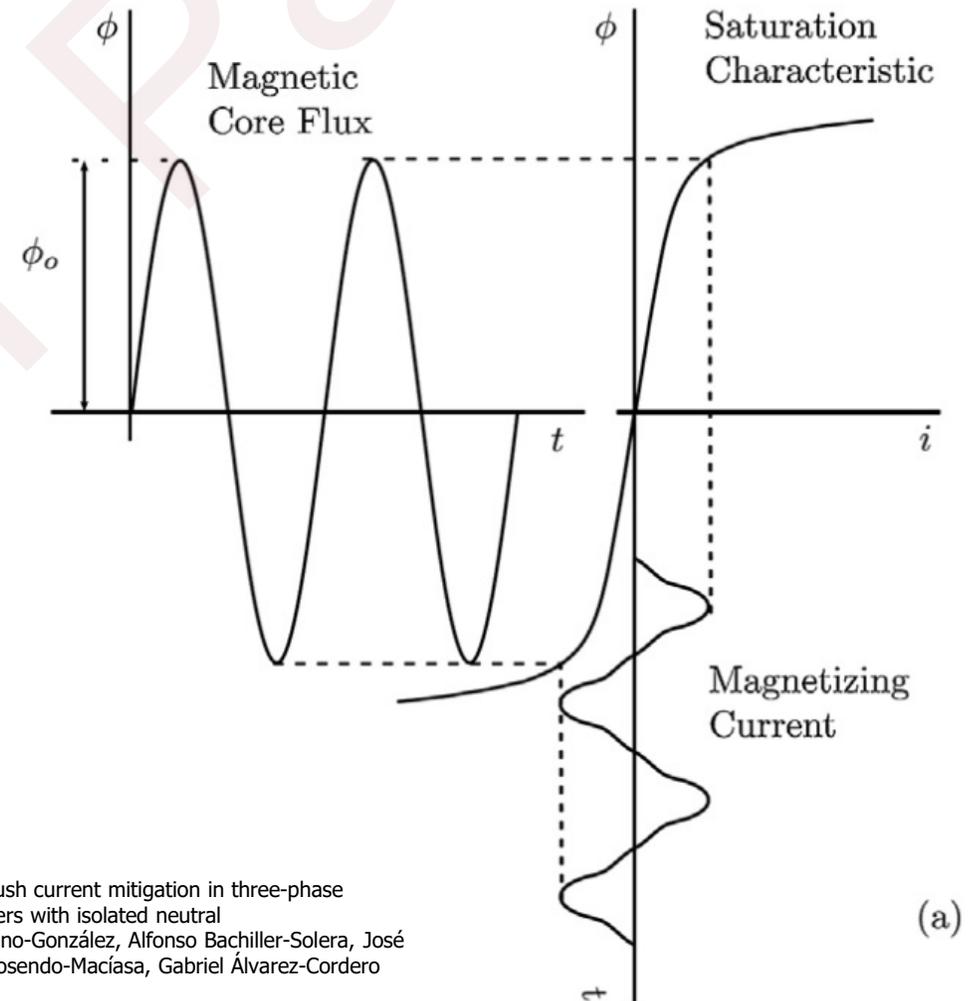
## Reactive power capability

# Presentation outline

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

# Saturation in transformer iron core: distorted current

- Voltage may be a nice waveform...
- ...but why current is not?
- Reason:
  - voltage is too high
  - core can't magnetise that much (saturates)
- A high voltage on a transformer causes:
  - High peaky current
  - High reactive power
- In most situations, neither is wanted



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

(a)

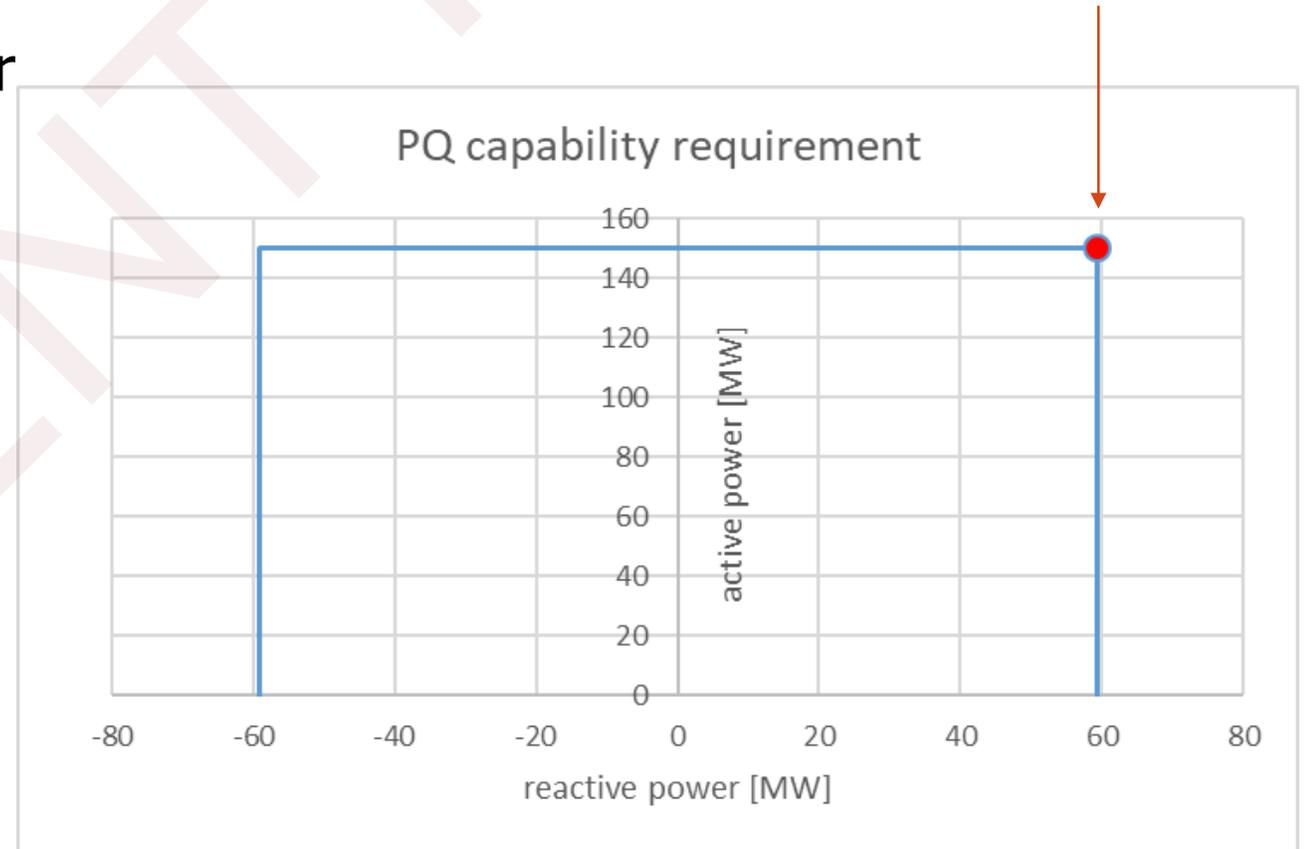
# Case study: reactive power capability in solar farm

- Problem occurred to a solar farm during testing
- Could not meet Q capability = not enough reactive power
- Where was it going?
- Suspect: saturation
- DIgSILENT analysed test data to find the root cause:
  - Test data
  - PowerFactory simulations
  - Conclusions

# Reactive power capability requirement

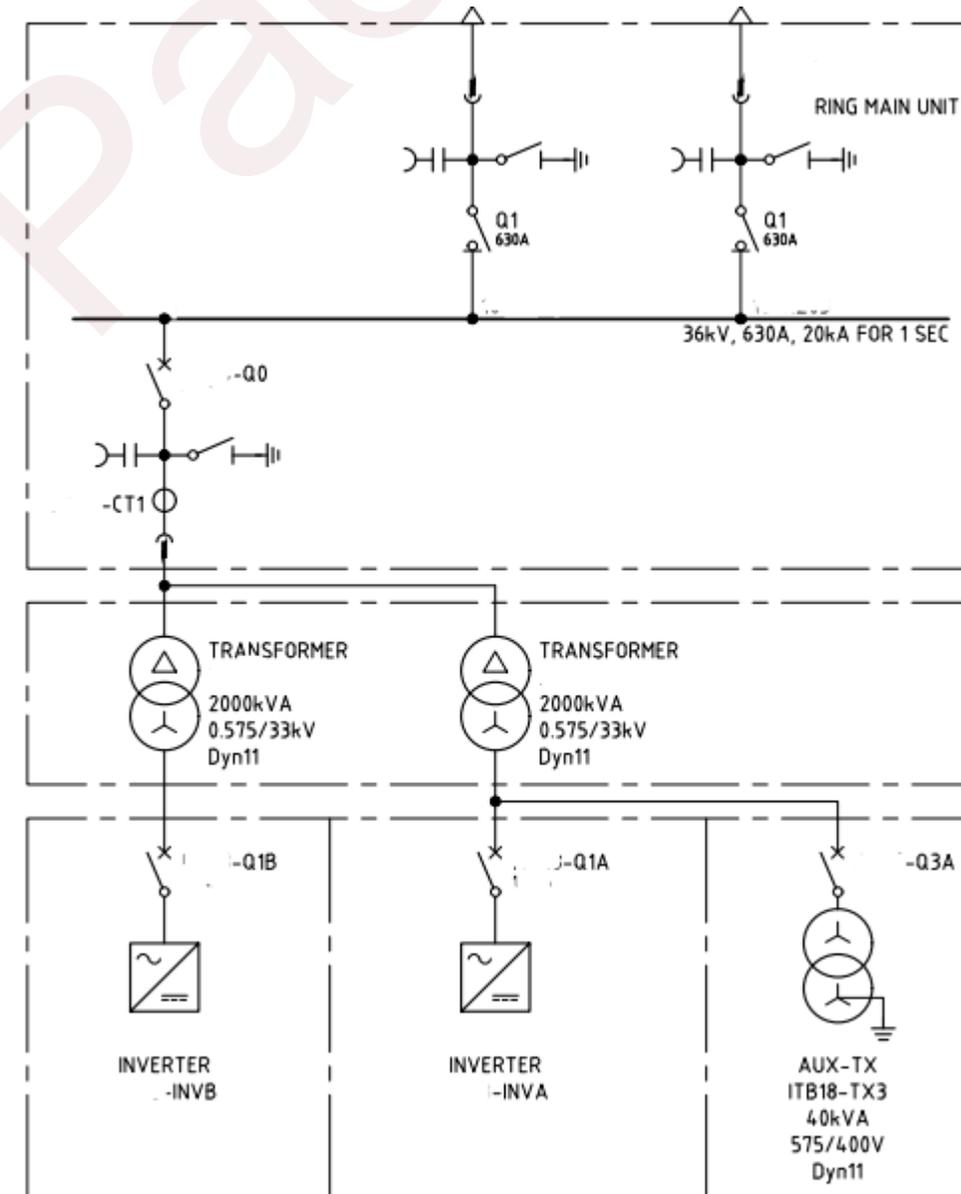
- Clause S5.2.5.1 of National Electricity Rules (NER)
- Ideally: capability maintained for voltage at connection point between 0.9 and 1.1 pu
- Injecting max Q at 1.1 pu makes inverter terminal voltage rise above 1.1 pu
- High voltage = saturation may kick in
- Not enough Q to meet S5.2.5.1
- Test failed!

Marked point:  $Q > 0$  at max P



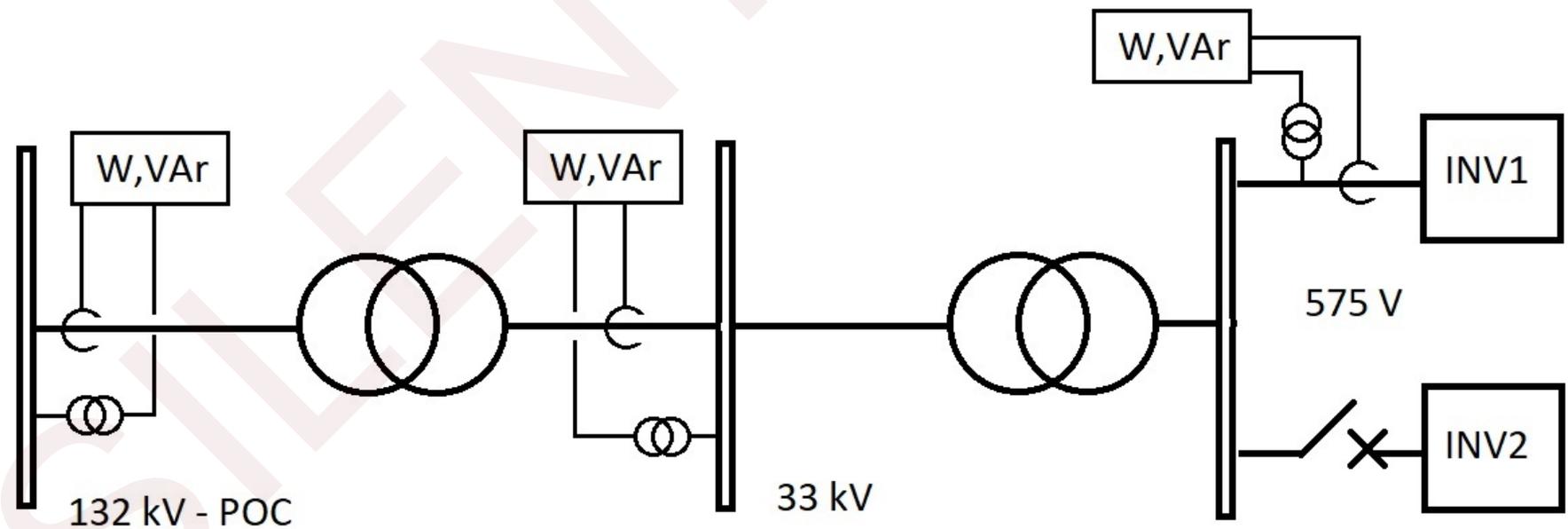
# Connection of inverters to transformers

- 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



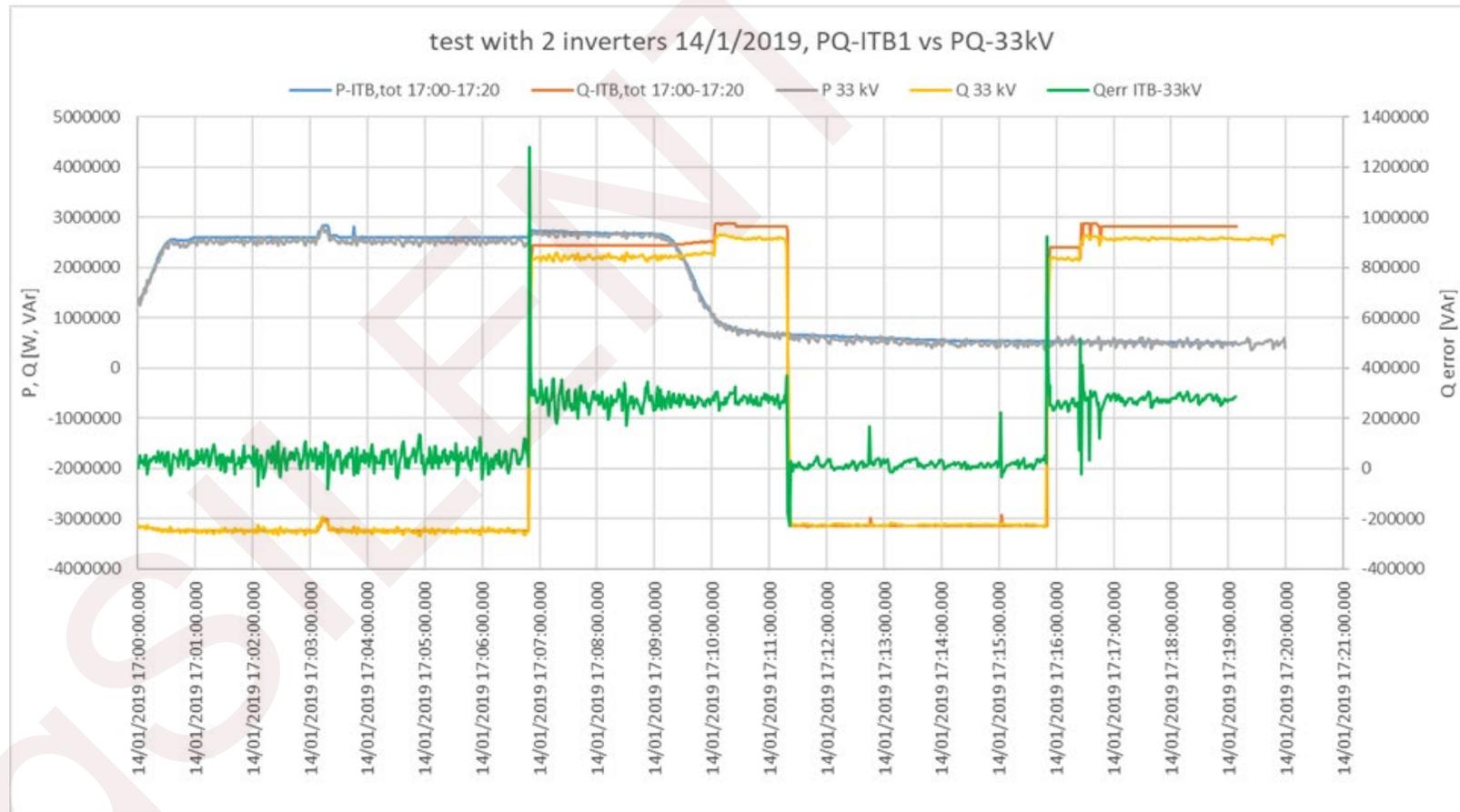
## Power balance test: meter connection

- 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



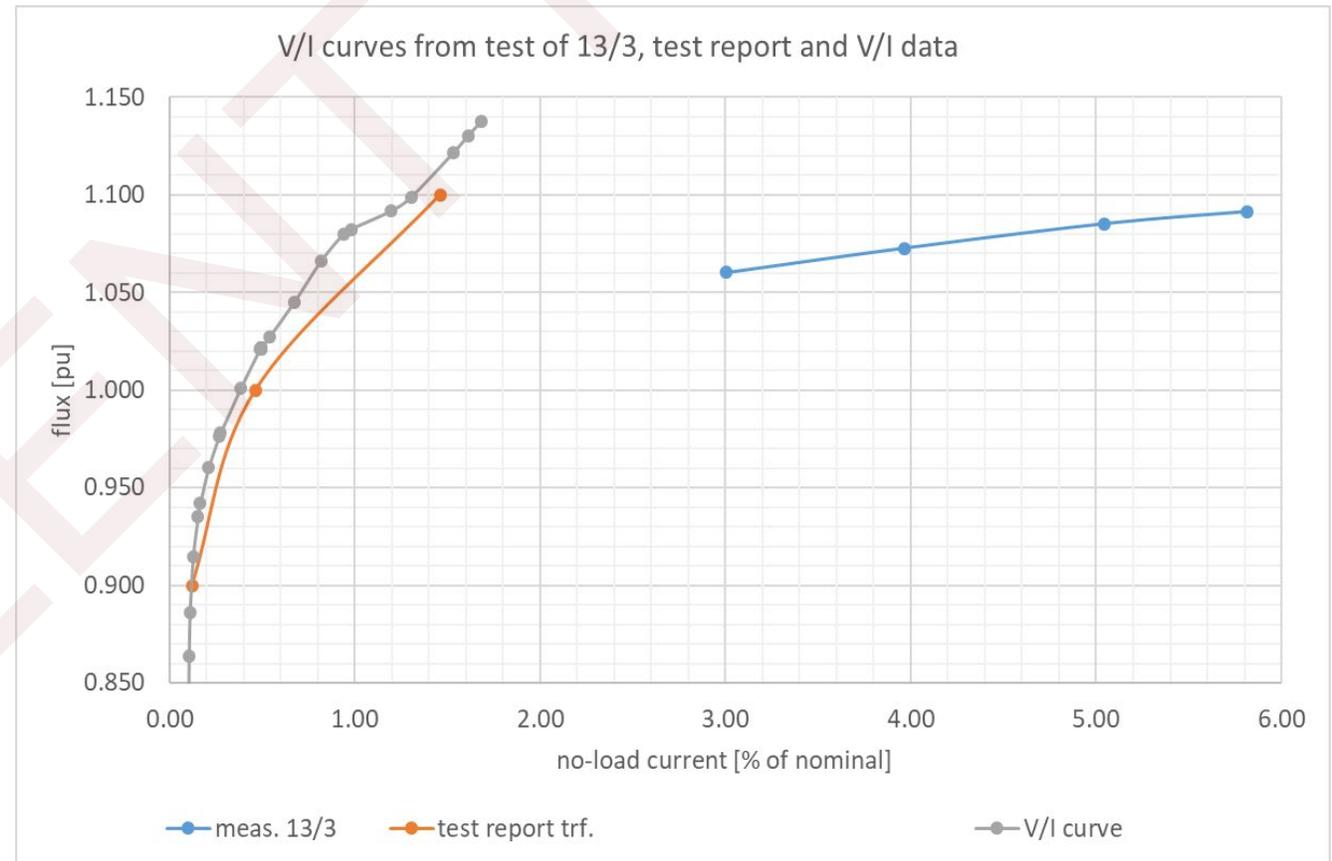
# Power balance test on inverter transformer

- P and Q measured either side of inverter transformer
- Q error high with higher Q supply (higher voltage)
- Transformer is absorbing Q: is it saturation?



# Check trf: factory data vs test results

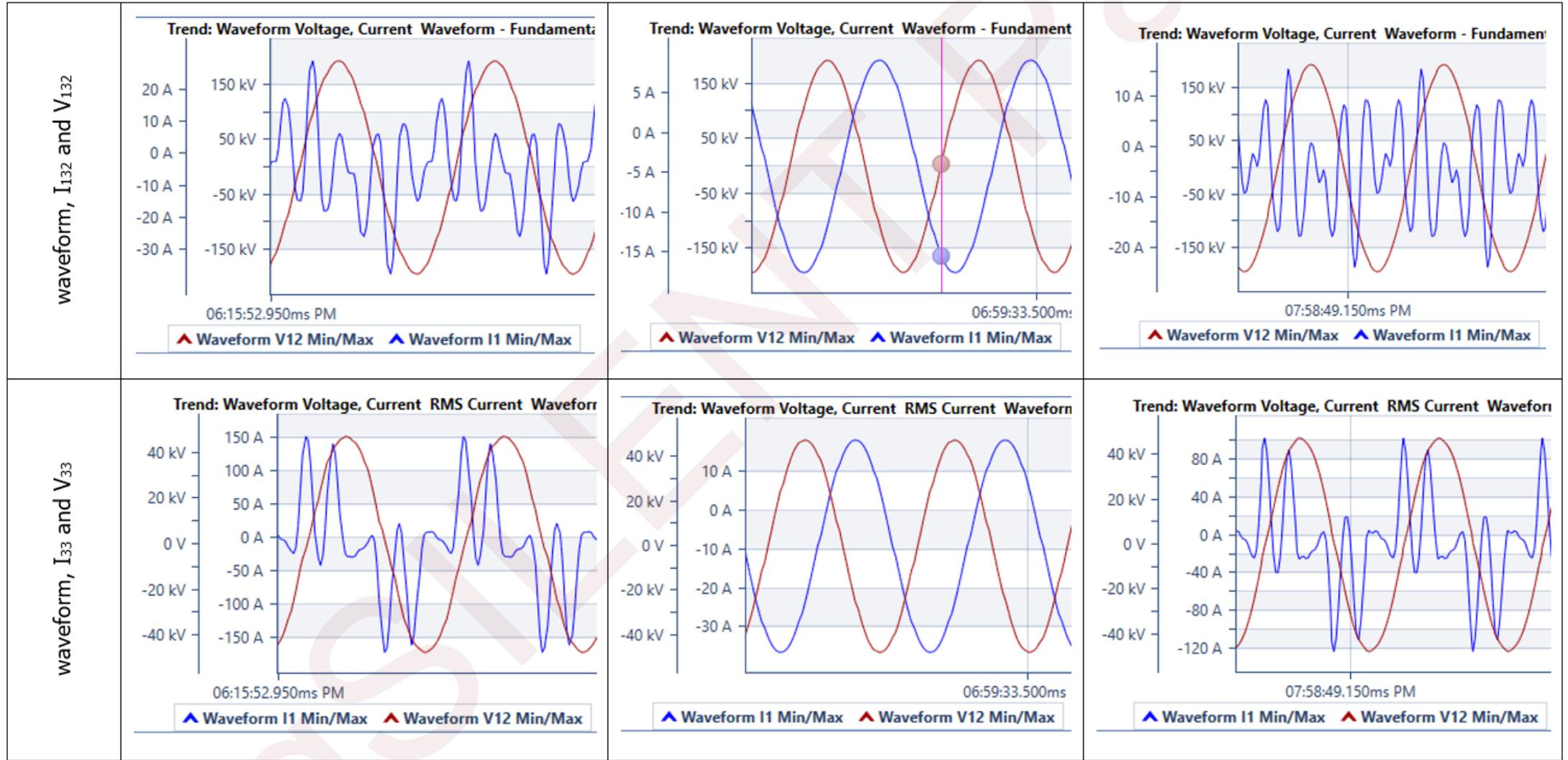
- Magnetization curves: voltage applied vs. current absorbed (no-load test)
- Difference between type test and field test data
- Core material data and factory test coincide
- Site measurement differs
- Transformers saturating more than expected?



## More tests: test at night

- Check again if transformer is really saturating more than expected
- 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: check distortion



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

# Test at night: P, Q V and I

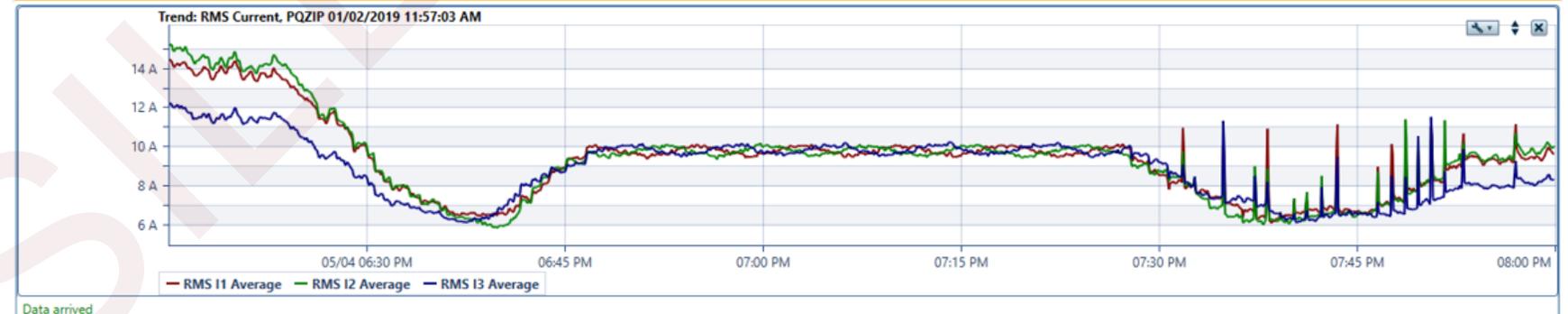
- P and Q



- 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

- Transformers absorb more Q than expected:  
total Q absorbed / transformer number  $> Q_{\text{type-test}}$
- Distortion is caused by the transformers, not inverters and not grid

### Next test:

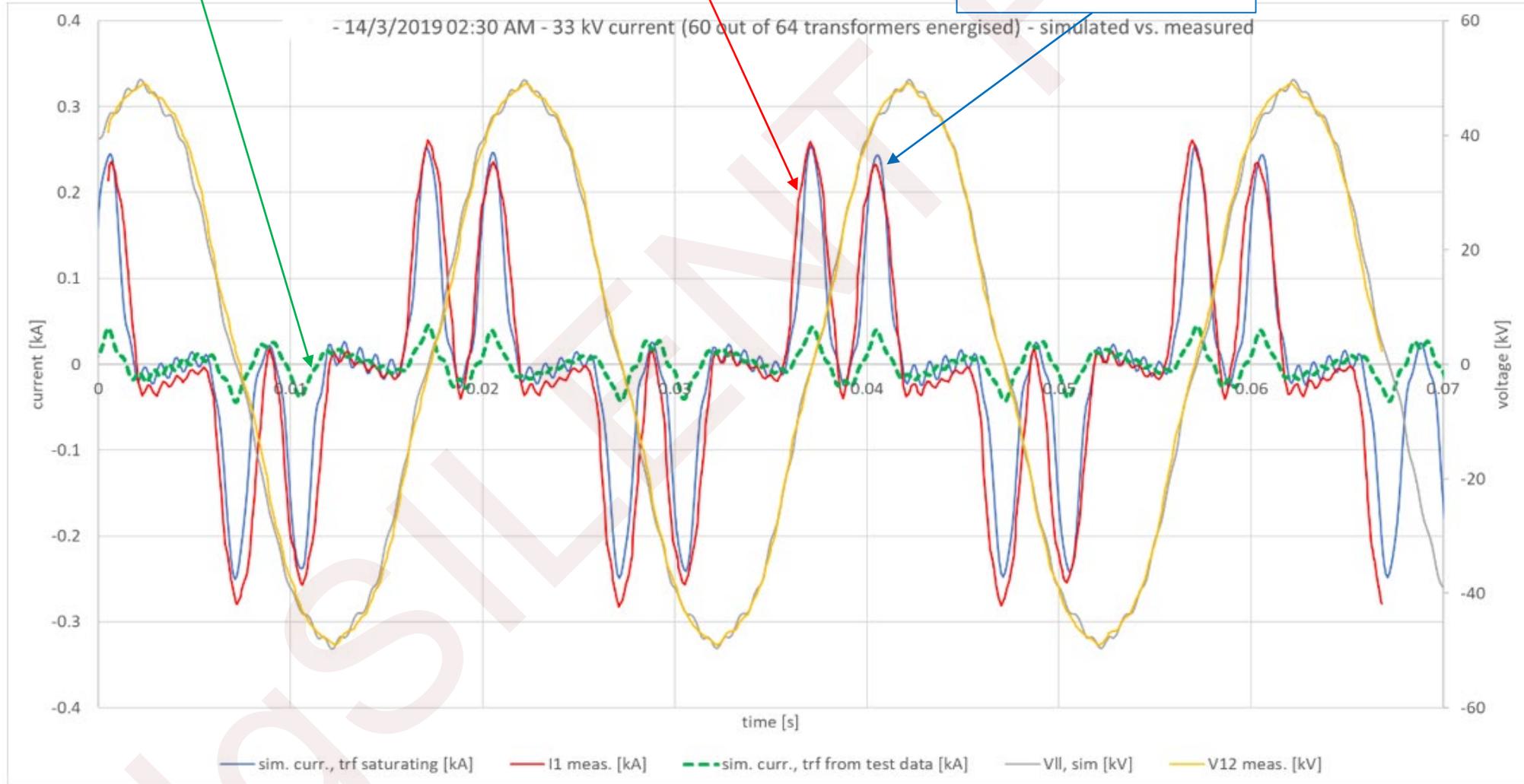
- Prove that no-load curve of installed trf  $\neq$  curve in test data
- Tool: Power Factory waveform simulation, comparing transformer with:
  - declared V/I curve from type test
  - V/I curve shifted down until simulated waveform = measured waveform
  - Amount of shifting indicates a difference in transformer construction

# Power Factory: distorted waveform, 33 kV

Green dotted = type test characteristic

Red = measured

Blue = type test base, shifted to match measured



# 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 replacement
- 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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