Applications of wide-area synchronized waveform measurements

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Agenda

1. Technology status
2. Platform for synchronized waveforms
3. Applications
4. Roadmap & challenges

Technology status

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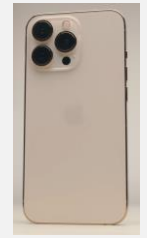
Technology status

Mobile

2000
13 MHz CPU
No data

2007
412 MHz, 1 core ARM11 CPU, 90 nm
2G: 0.1 Mbps

2021
A15, 6-core CPU
15B transitors, 5 nm
5G: >500 Mbps



Computation

1998
MNIST benchmark

2009
ImageNet introduced

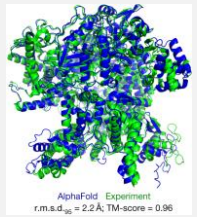
2012
"AlexNet" CNN
GPU deep learning
16% error

2016
ImageNet: 3% error

2016
AlphaGo beats 9-dan human at *Go*

2019
AlphaStar
Grandmaster level
StarCraft II

2020
AlphaFold 2
Predicting protein structures



2021
GitHub Copilot

Digital substations

2000 2010 2020 2022

Platform for synchronized waveforms

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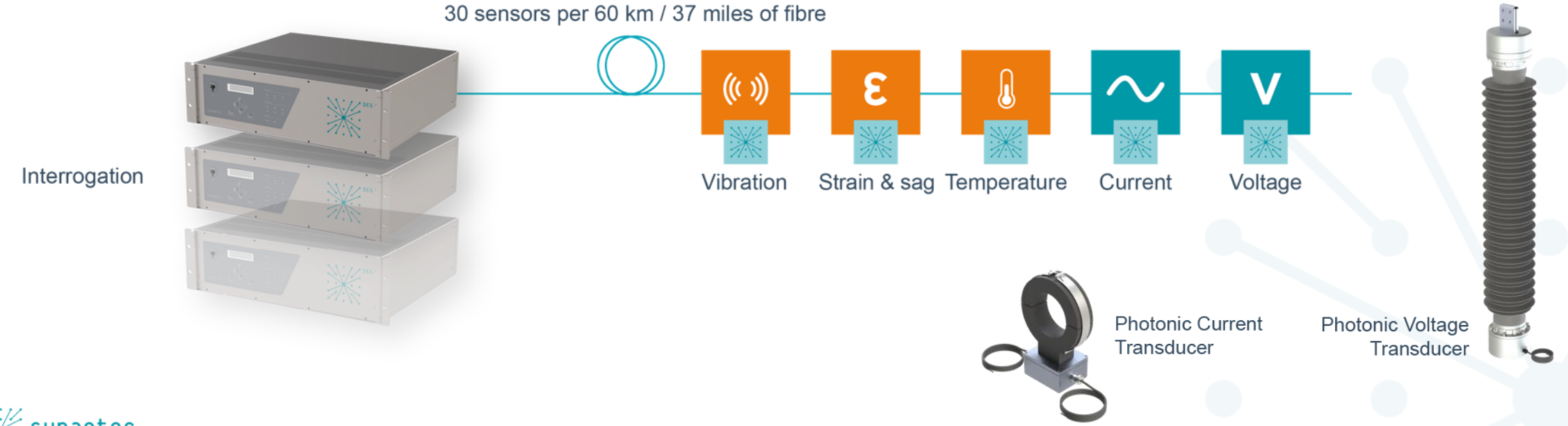
Synaptec – distributed sensing

- **Scalable** Streaming data from up to 30 sensors and up to 60 km per fibre
- **Familiar** Standard CTs and VTs passively networked
- **Reliable** Fit and forget – sensors require no recalibration or maintenance
  Immune to environmental effects like temperature and EM interference
- **Secure** No data, no 4G/IoT
- **Eliminates** Civil works, power supplies and batteries, IEDs, data and sync issues in multiple locations



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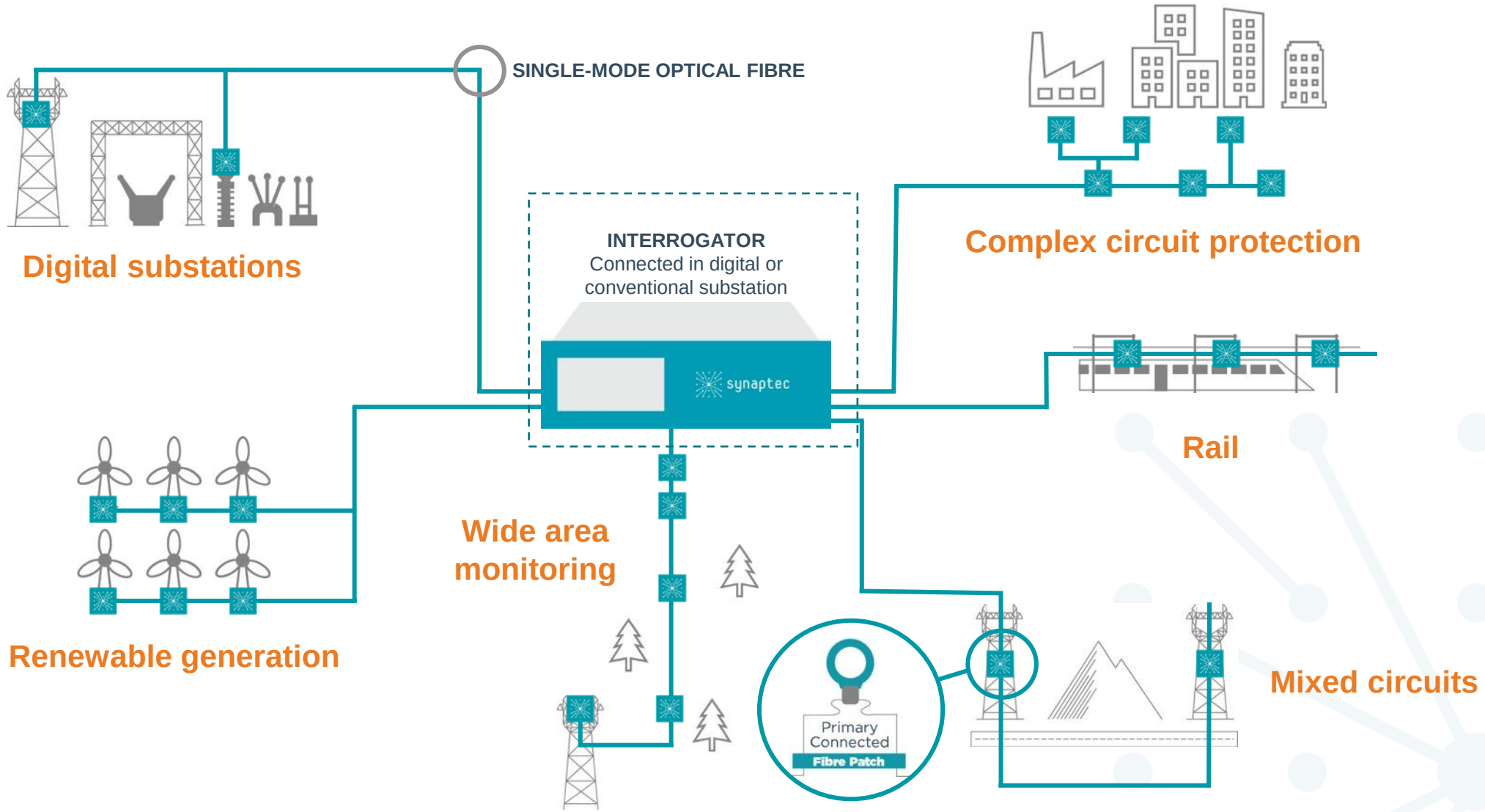
More sensors, better data, smarter decisions



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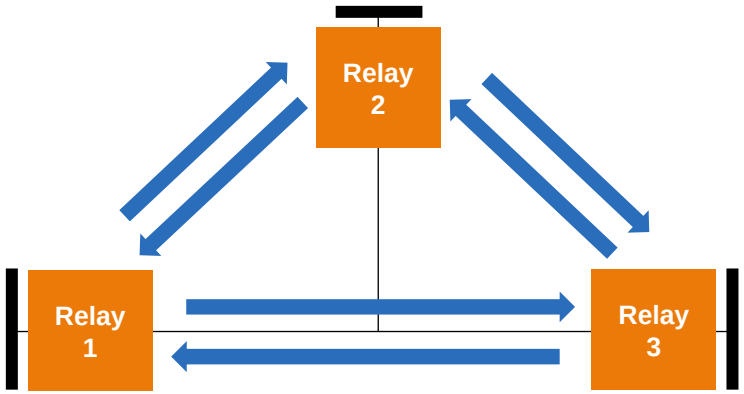
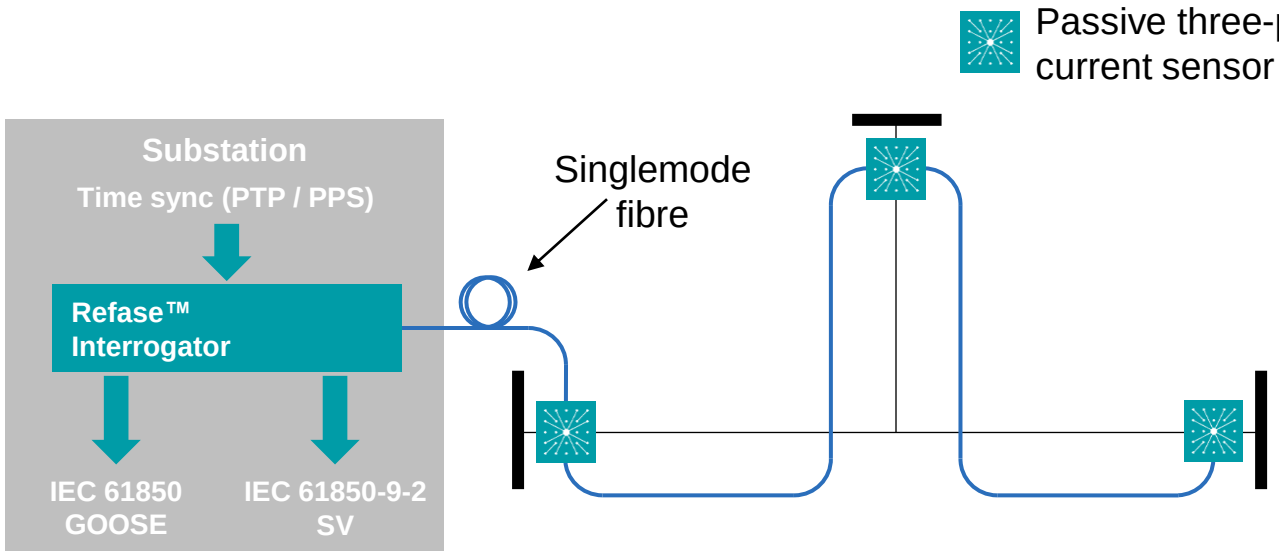
Multi-ended circuit instrumentation scheme





Conventional unit protection scheme

- Protection relays at all terminals
- Complex and expensive telecoms infrastructure for continuous comparison of measurements

Refase™ single-ended unit protection scheme

- Passive current sensors at each terminal
- Existing singlemode fibre for centralised serving of protection-class measurements to local protection relays
- No sync issues
- No data outside substation
- Significant capex savings

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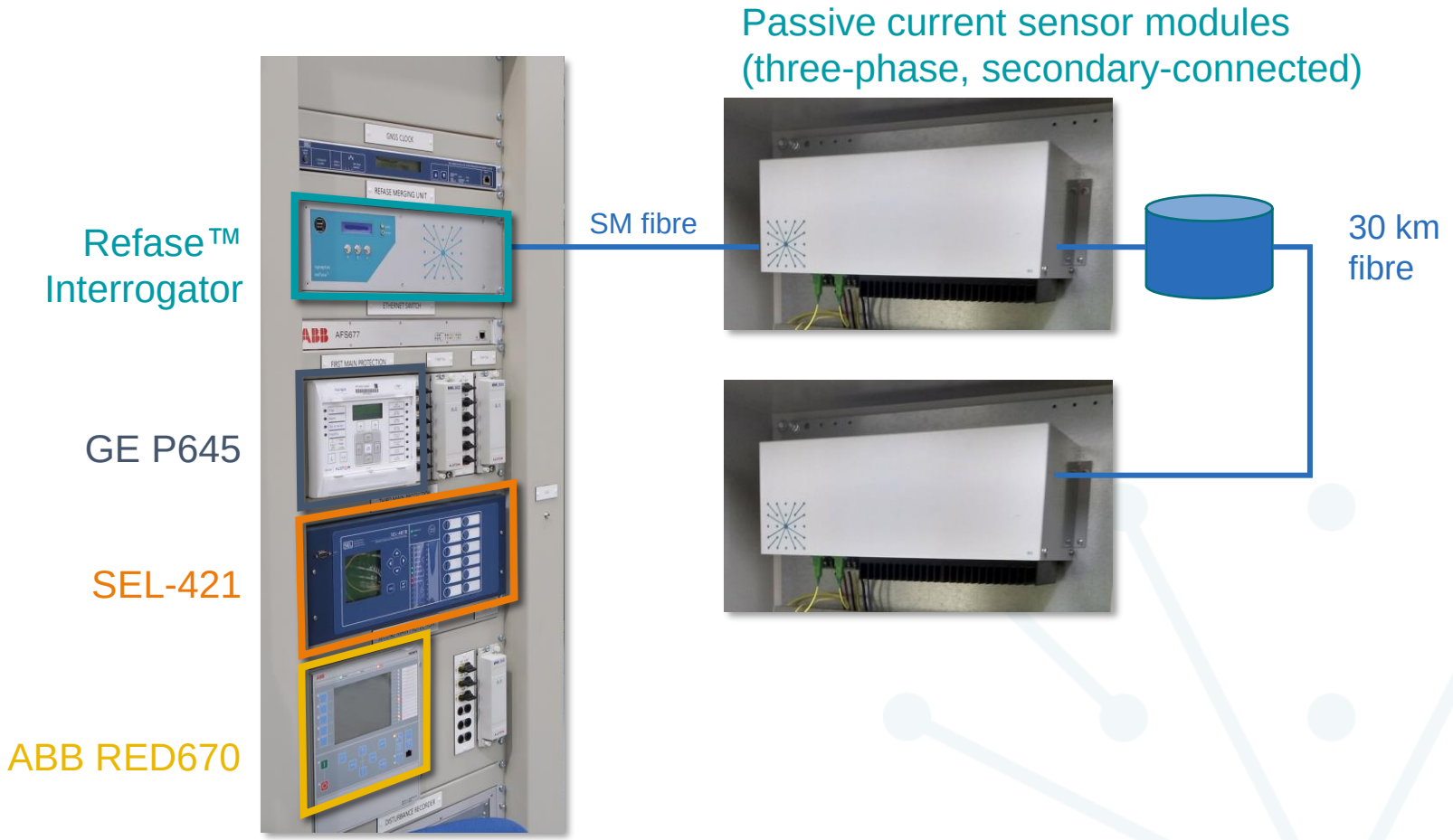
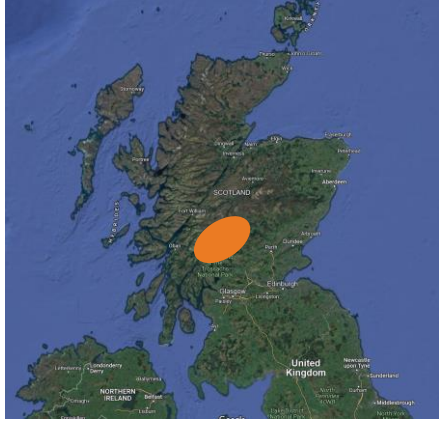
Implementation and testing

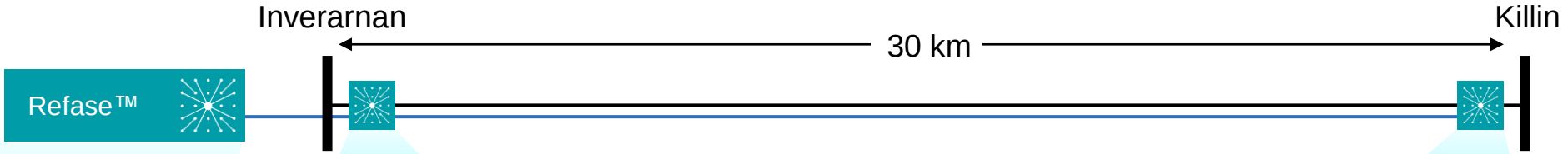
- First demonstration of single-ended unit protection scheme operating over **50 km**
- **Synchronous** SV generated by Refase™ system from every passive current sensor in the network
- **Interoperability** demonstrated between Refase™ platform and protection relays from multiple vendors



Live trial on 132 kV circuit

- System fully commissioned on SSEN two-ended 132 kV circuit during Summer 2021 for operational testing





Applications

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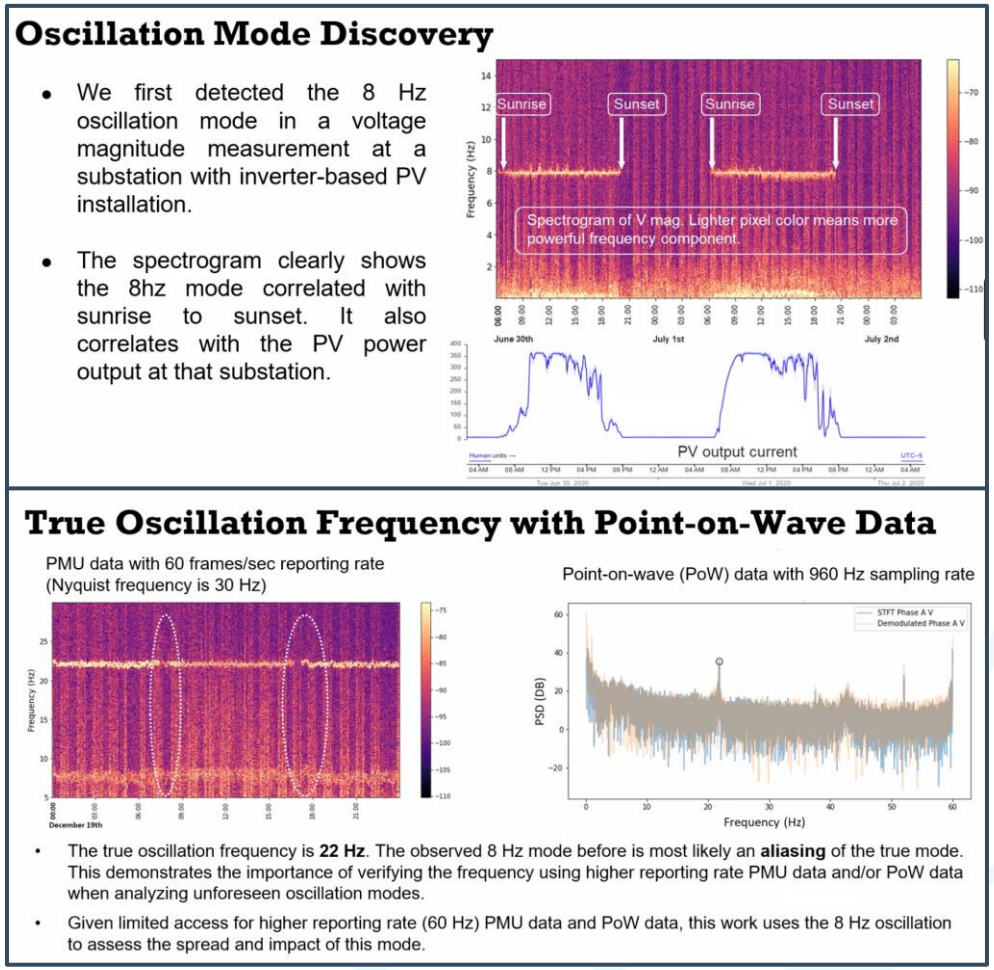
Oscillation monitoring

- 9th August 2019 UK partial blackout
  - **10 mins before**: lightly-damped oscillation at 9 Hz – became unstable, tripping Hornsea windfarm (loss of 800 MW)
  - 7.3 Hz oscillation in voltage visible in Scotland ~200 miles away – evidence of power electronic instability
- **CPOW measurement enables** extracting any anomalous frequency from the system voltage

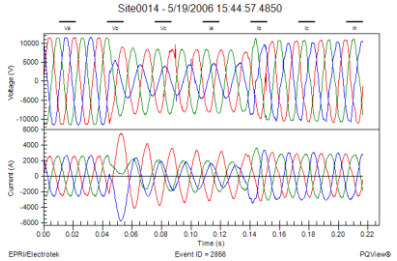
Widespread impact of PV – Dominion Energy, USA

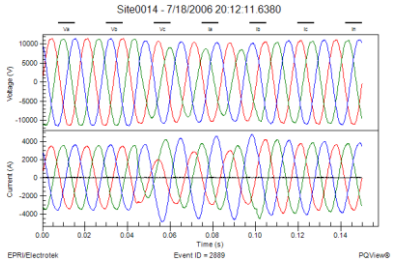


https://www.naspi.org/sites/default/files/2021-04/D1S1_02_wang_dominion_naspi_20210413.pdf

DoE/EPRI CPOW database – root cause of faults

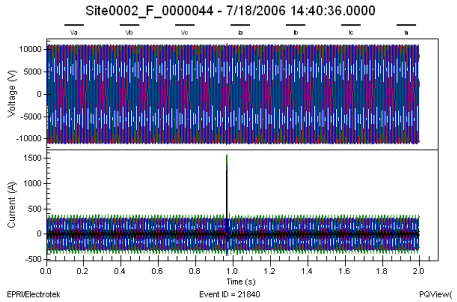
“Simulteneaus lightning on lines during a lightning storm. Both Substations experienced a temporary interruption of 5 seconds.”



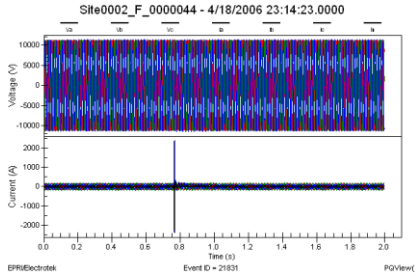


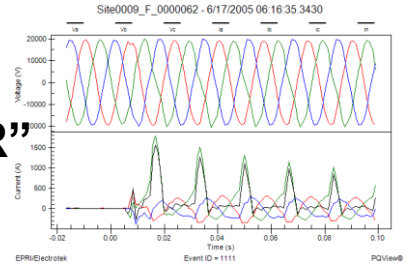
“Transmission Line tripped during a major storm. The cause of this event was likely tree contact. Breakers at Substations tripped and reclosed multiple times.”

“live bird caused trans fuse to blo”

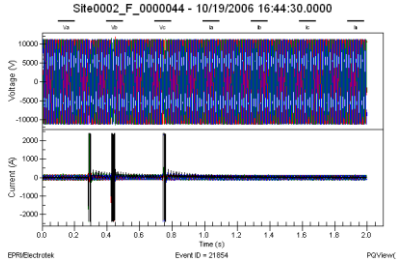


“transformer died under t3309”

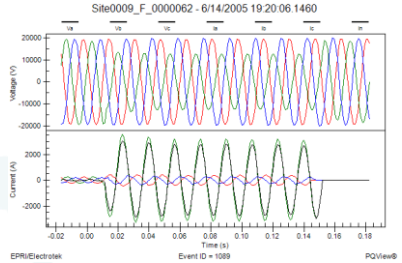




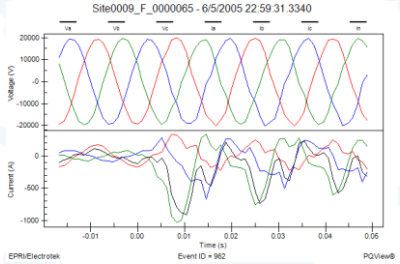
“bad weather blew down a tree that”



“squirrl”



“SNAKE”



“SNAKE ON LIGHTNING ARRESTER”

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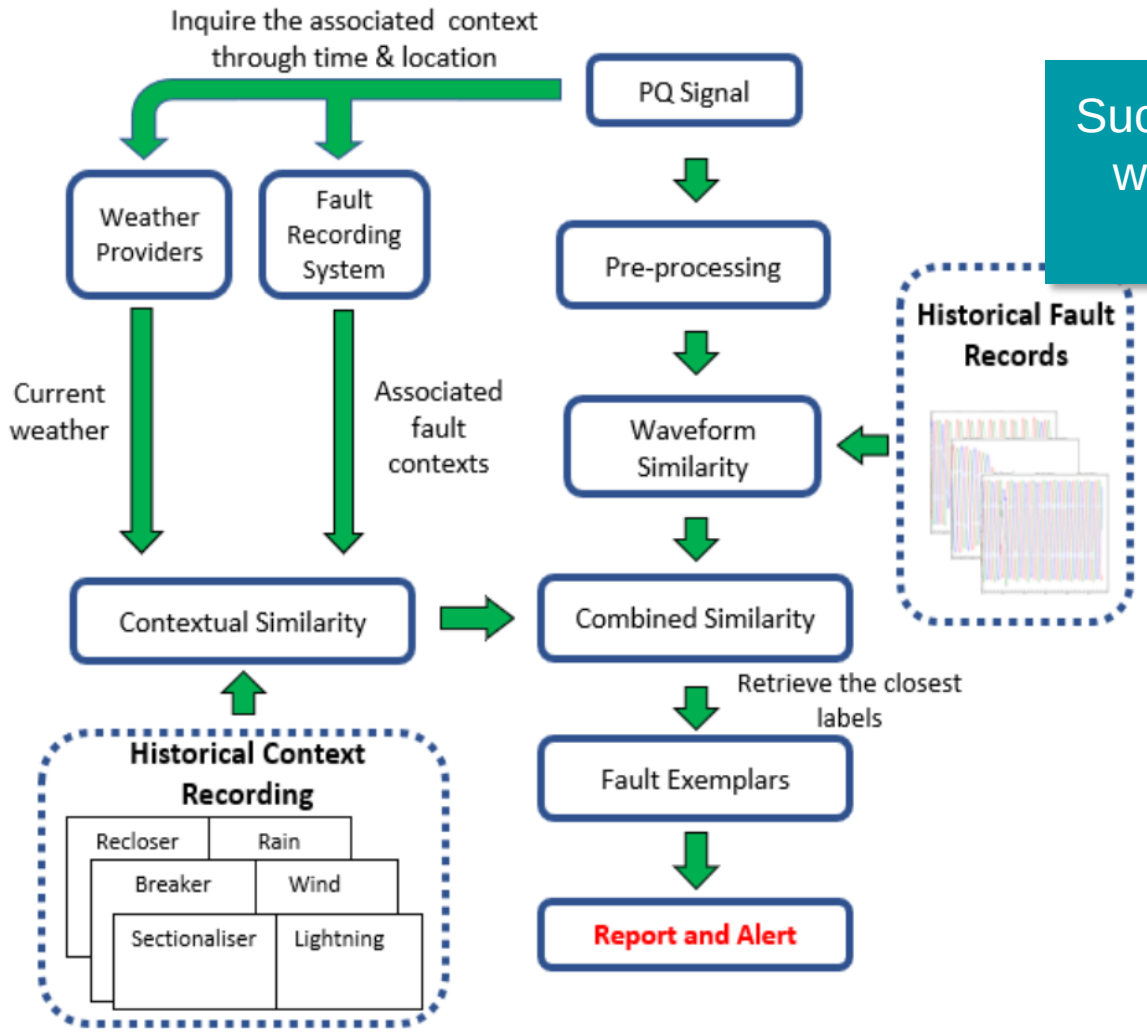
https://pqmon.epri.com/see_all.html

Automated event classification

CPOW data from DoE/EPRI library: https://pqmon.epri.com/



Successful classification without large training dataset

Sampling frequency	Overall accuracy
960 Hz	77.6%
3840 Hz	**94.4%**

Higher CPOW sampling rate improves classification accuracy

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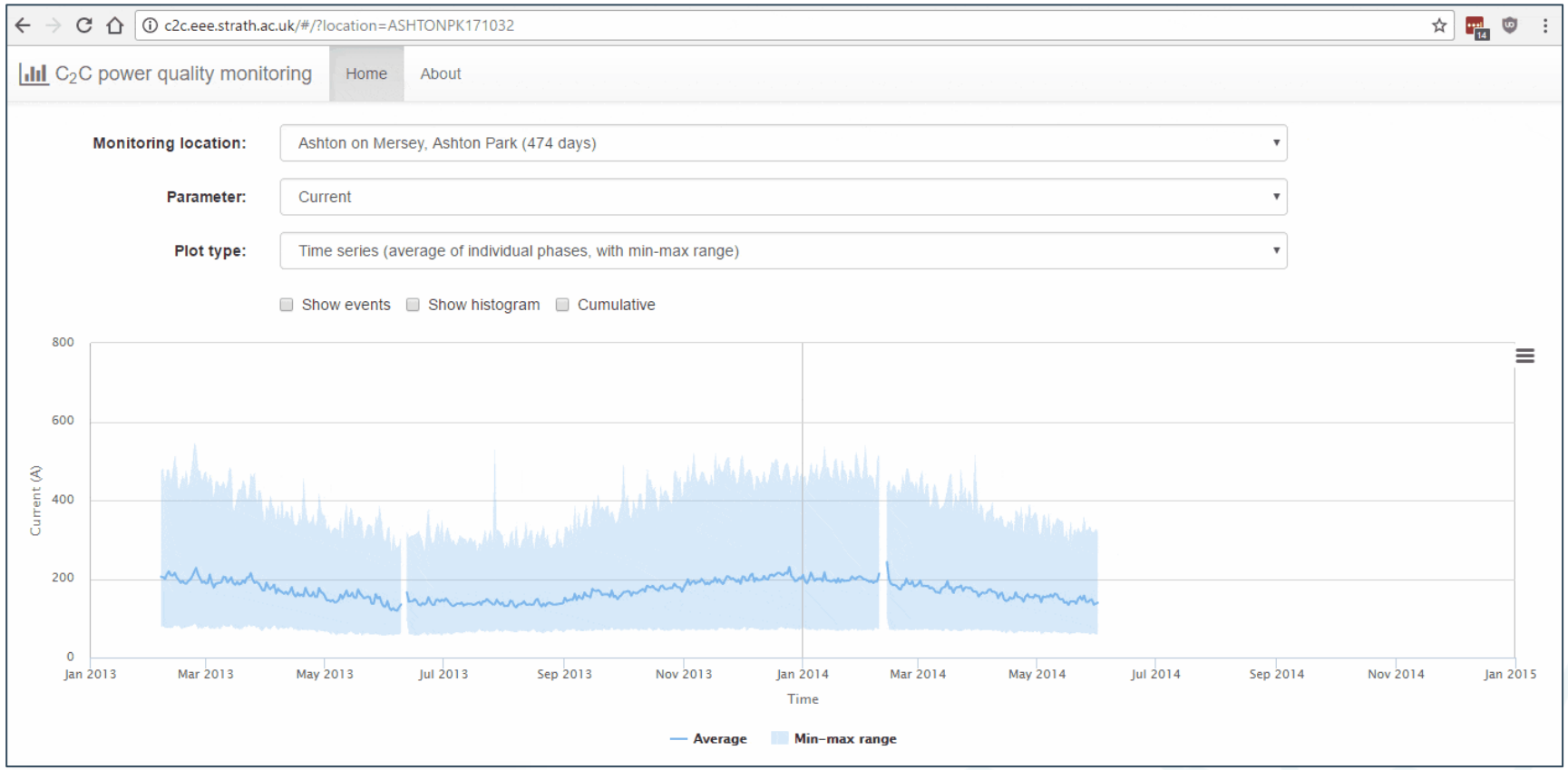
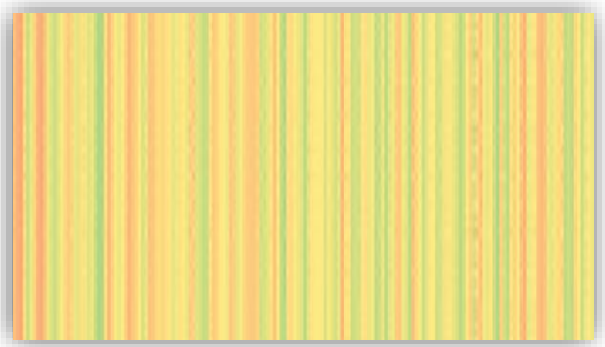
Jiang, et al, "Automated Distribution Network Fault Cause Identification with Advanced Similarity Metrics", 2020: https://doi.org/10.1109/TPWRD.2020.2993144

PQ meters – data correction and visualization

- 77 PQube monitoring devices
- Deployed for 1.5 years
- 400 V, three-phase voltage and current measurements
- Extensive data validation:
  - Correlation of frequency trends, and re-alignment
  - Correct phase sequence and polarity





http://c2c.eee.strath.ac.uk

Paper:
http://dx.doi.org/10.1109/TPWRD.2016.2602306

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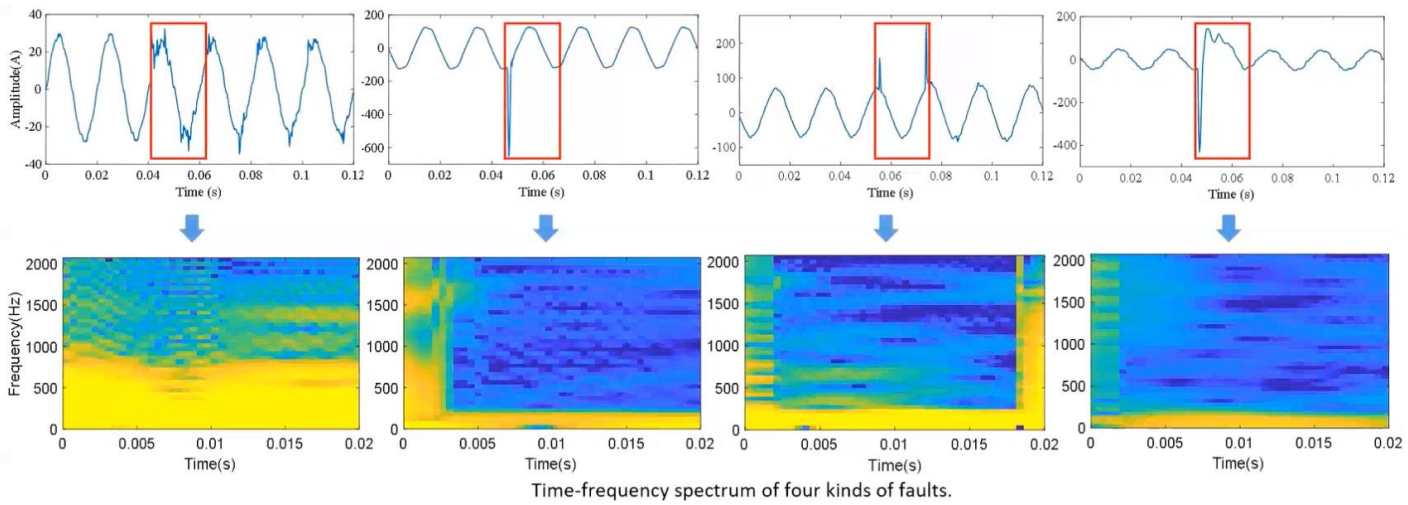
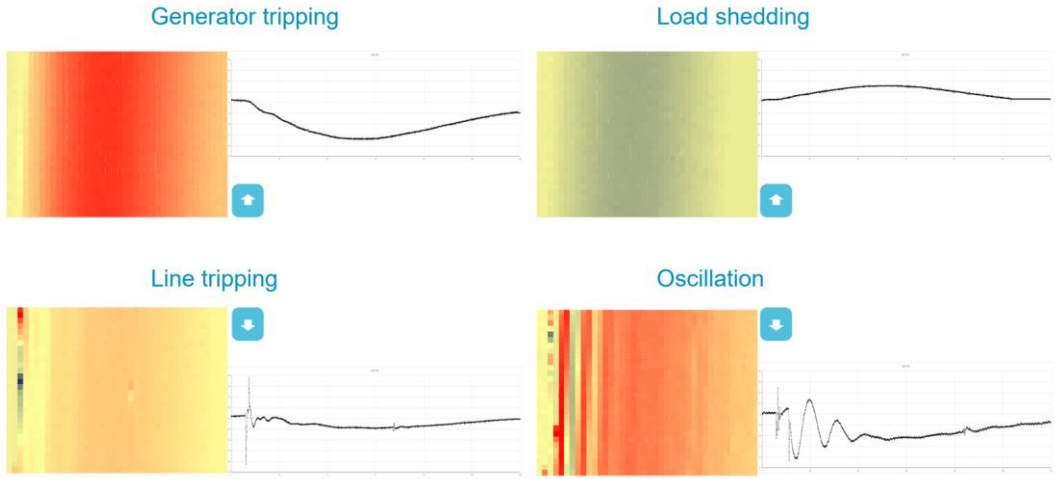
Signature detection: distil complexity into images



Time-frequency spectrum of four kinds of faults.

Tianshu Bi, NCEPU, IEEE SGSMA 2021



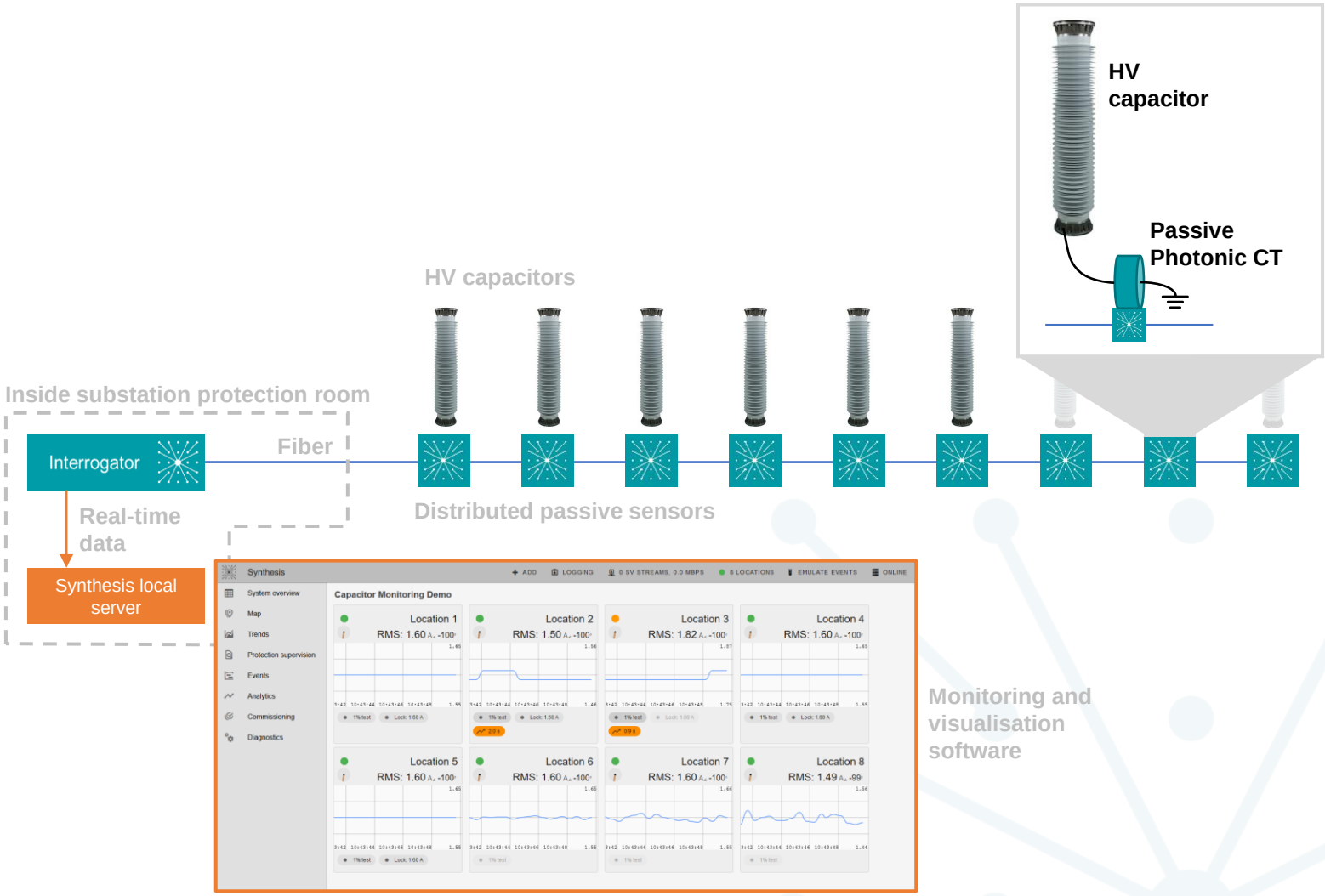
http://sites.ieee.org/pes-powertech/files/2017/07/PowerTech-2017-Vladimiro-Miranda.pdf

Summary of value:

- Comprehensive monitoring of assets in an area
- Automated fault/event classification to find root cause of disturbances
- Find trends in asset performance over time – and highlight deviations
- Electrical + mechanical: multiple perspectives, simultaneously
- Reduce risk and exposure of workforce to hazardous environments unnecessarily – target assets before scheduled maintenance

HV capacitor health monitoring

- Detect subtle changes in HV capacitor operation
- Early warning of insulation failures
- Can be combined with PQ/waveform monitoring of voltages and currents to discover root cause



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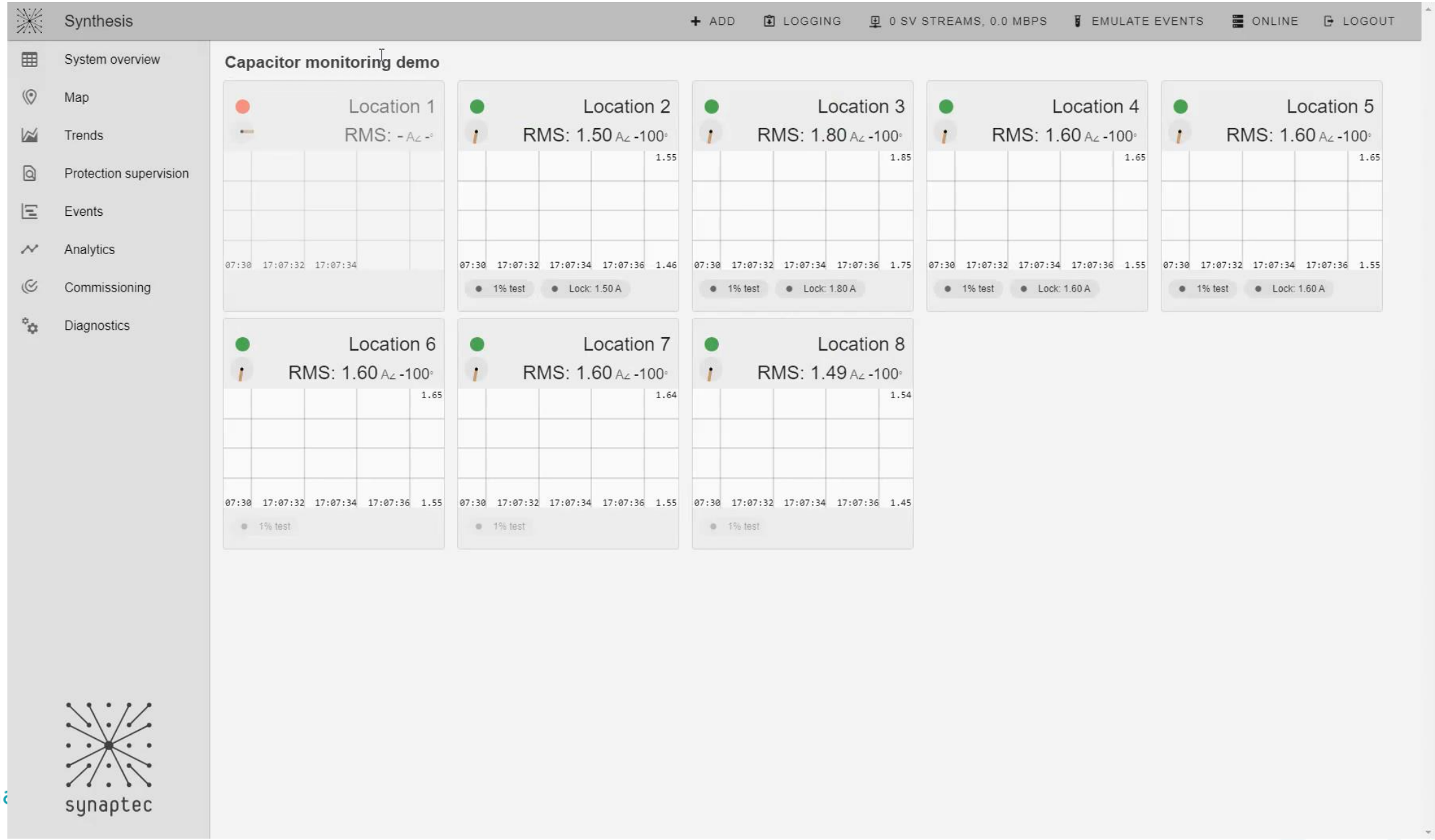
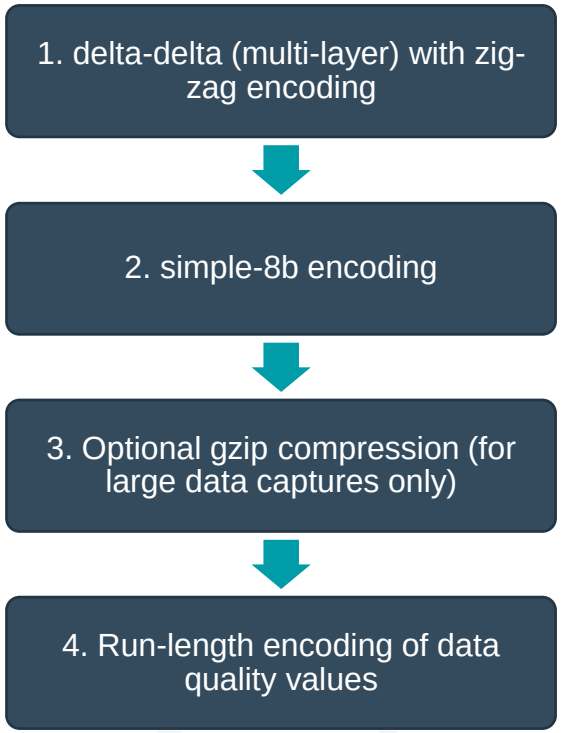
“Simple” analytics, high impact



Slipstream: synchronized waveform data compression

- Designed for **streaming waveform data**, similar to IEC 61850-9-2 or IEC 61869-9 SV
- Optimised for **smallest message size**
- **Low overhead** compared to SV
- **Lossless**: must not add errors or distortion
- **Flexible**: variable number of samples per message for different applications
- Compress each data stream separately
- Open source project: **https://github.com/synapteccltd/slipstream**



Sampling rate (Hz)	Samples per message	Message size (bytes)	Size
4000	10	236	**18.4%**
4000	4000	123738	**12.1%**
14400	6	141	**18.3%**
14400	14400	123213	**6.7%**
150000	150000	779918	**4.1%**

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Roadmap & challenges

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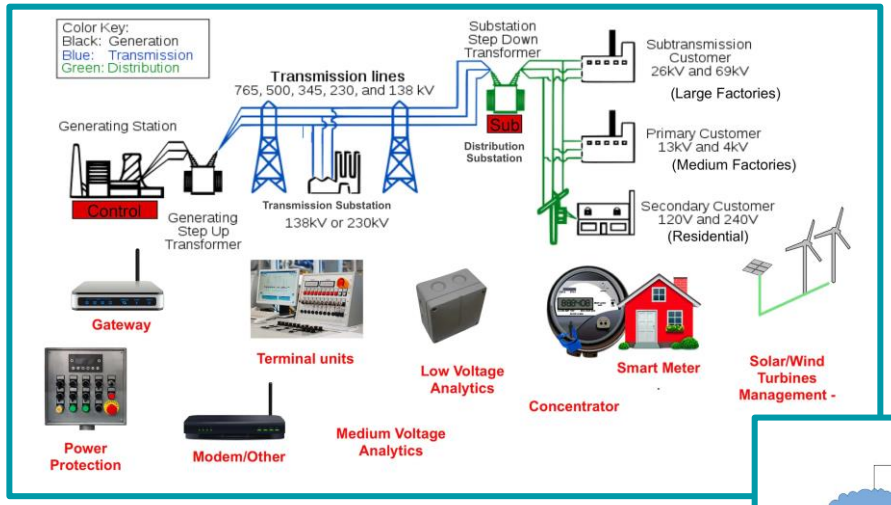
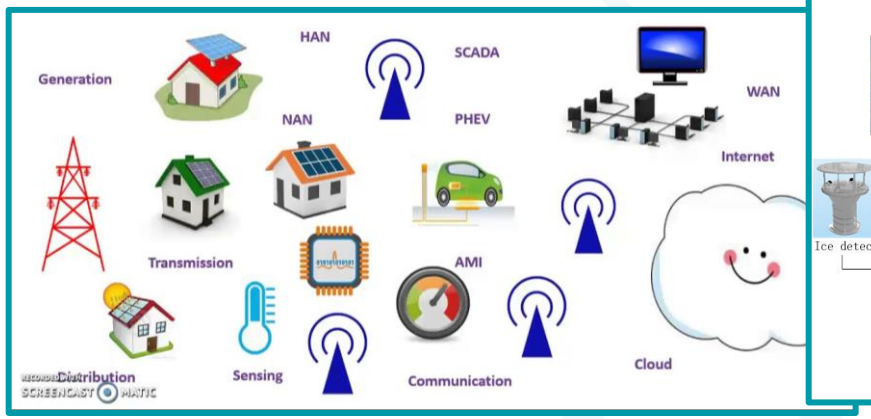
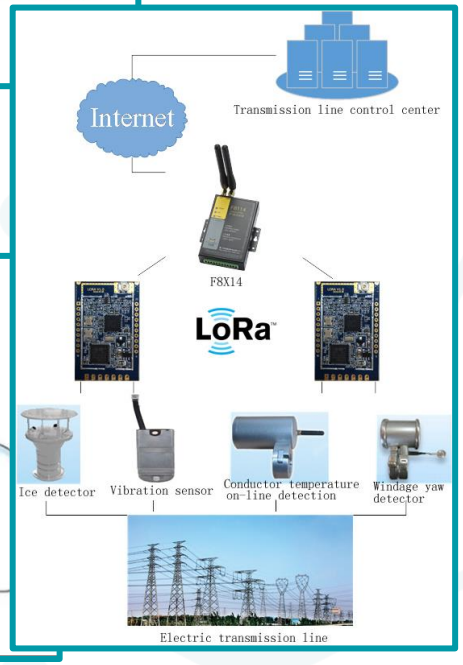
Paradox of condition-based maintenance

- **Maintenance is a huge, expensive problem for many utilities**
- Need to see what's happening with remote assets, which are large, expensive, and critical
- Wireless communications and sensors:
  - Jammable
  - Need power/batteries
  - Poor signal from underground locations
  - Security concerns
  - Low data rate
- But these are minor, may improve over time
- **The main problem for utilities is the lifespan: 5-10 years**
- Paradox: adding devices to monitor other devices only adds to the problem!



Solutions?





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Open questions…

Phasor-based protection may not be suitable in the near future?

Substation digitalisation is happening slowly?

High performance wide-area networking & PTP are expensive

Distance protection is less effective

Need user engagement and sharing of results

Cybersecurity is complex

Not enough utility experts driving standards

DG/DER protection can impact major events?

Conclusions: solution architecture

Data-driven applications

Ability to sift through data “firehose”

Need R&D in new approaches, assuming data can be available:

- Real-time control
- Condition-based maintenance
- Forecasting
- Many other applications…

WAN infrastructure

Core network must be designed for forward-looking applications

Assume network-wide streaming PMUs, but also allow for CPOW transfer

Own the WAN

Embrace cloud infrastructure for challenging compute, storage, and security requirements

Local/edge building blocks

Upgrade last-mile sensor networks

Minimise new devices in/outside substations

Make decisions as close as possible to the assets they influence

Distributed/decentralised control & protection

Resilience

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