Energy Research Lab,
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NTVV: ENERGY STORAGE

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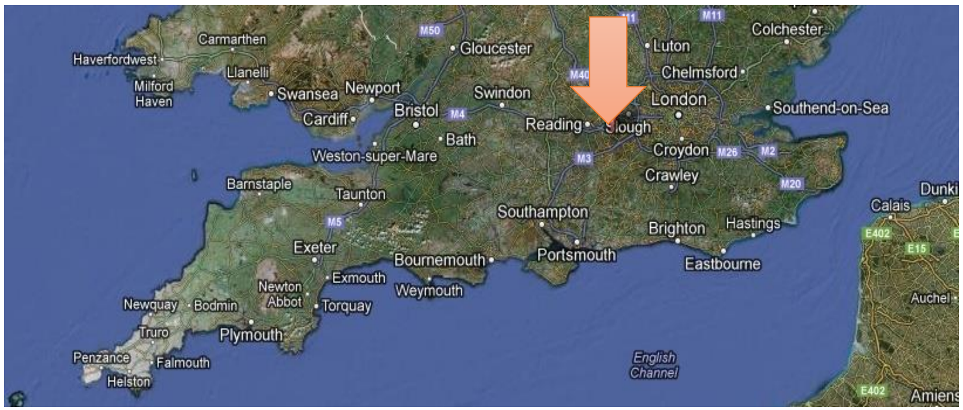
INTRODUCTION

- Project overview
- Energy storage in the New Thames Valley Vision project
  - Objective for energy storage on Low Voltage network
  - Hardware requirements
  - IT requirements and challenges
- Energy storage control system
- Results from trials
- Learning outcomes

NTVV Project metrics

- Focusing on the LV Network
- Bracknell and the surrounding Thames Valley area



THAMES VALLEY VISION

UNIVERSITY OF OXFORD

Bracknell Forest Council

ea technology

Honeywell

DNV·GL

University of Reading

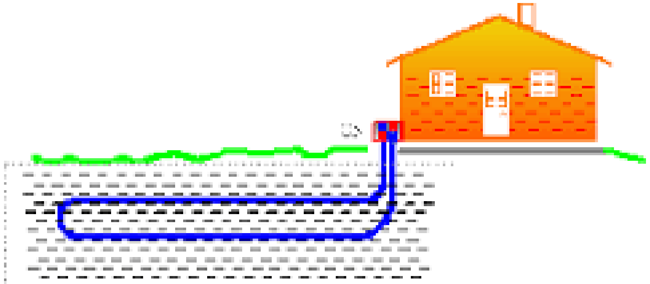
"by better understanding our customers and the loading on the network, we can model the low voltage network and use this to better anticipate and manage the impact of low carbon technology take-up scenarios, allowing timely and targeted investment decisions, minimising disruption and costs to customers"

Introduction - Why use Power Electronics / Storage?

What are the network problems that we are trying to solve?

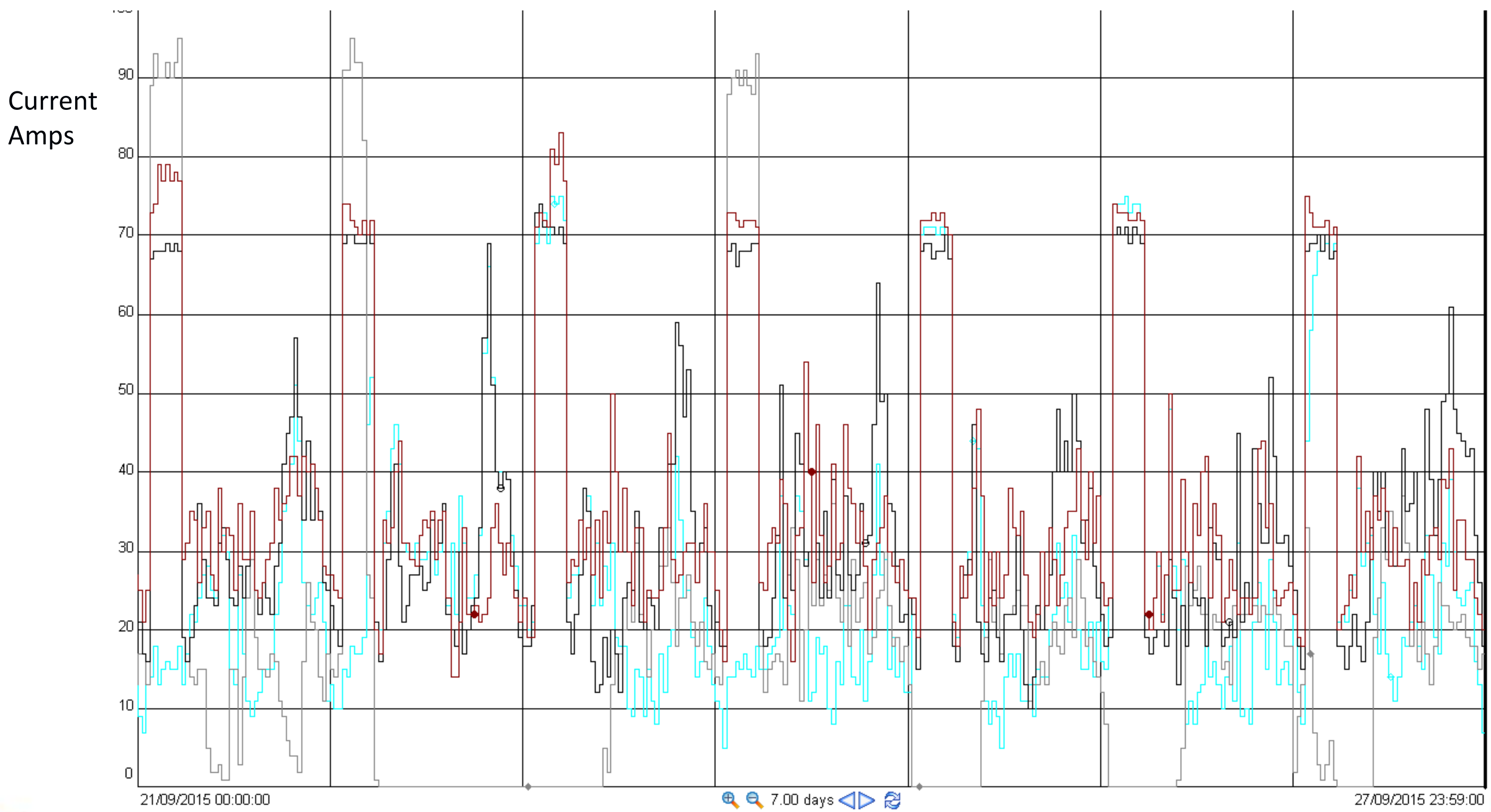
PV panel installations

Domestic **electric vehicle charging**



Retrofitting of **heat pump t**echnology

Understanding LV Networks - Phase Load Balance



Saffron Road Substation Feeder 3 – Mean Current

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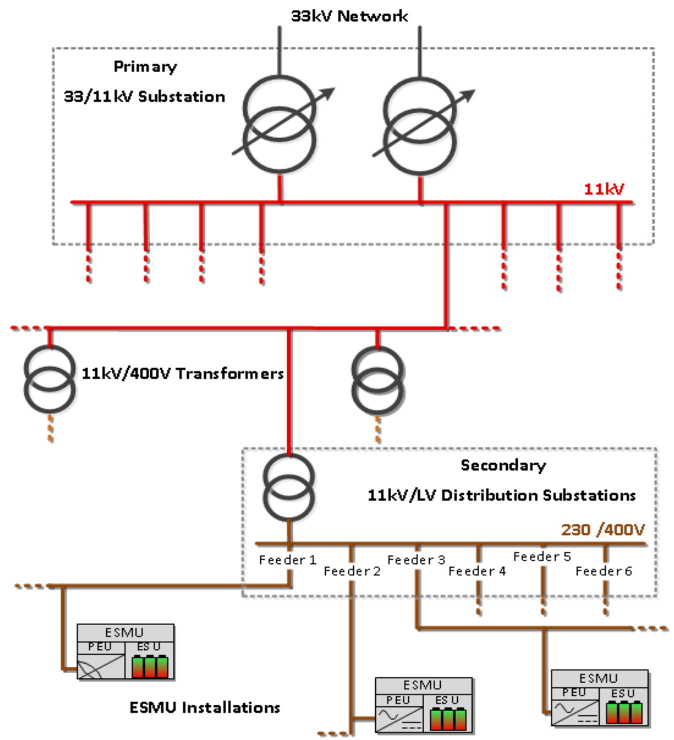
Energy Storage and Management Units

- Functional Expectations
  - **Improve Thermal Performance of Network**
    - Improve phase balance of LV network
    - Manage peaks in demand and generation
    - Demand reduction
    - Power Factor correction
    - Loss Reduction
  - **Improve Power Quality**
    - Improve voltage regulation
    - Reduce Harmonic Content
  - **Grid Support**
    - Frequency Response



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Energy Storage and Management Unit

Power Electronics Unit

Energy Storage Unit

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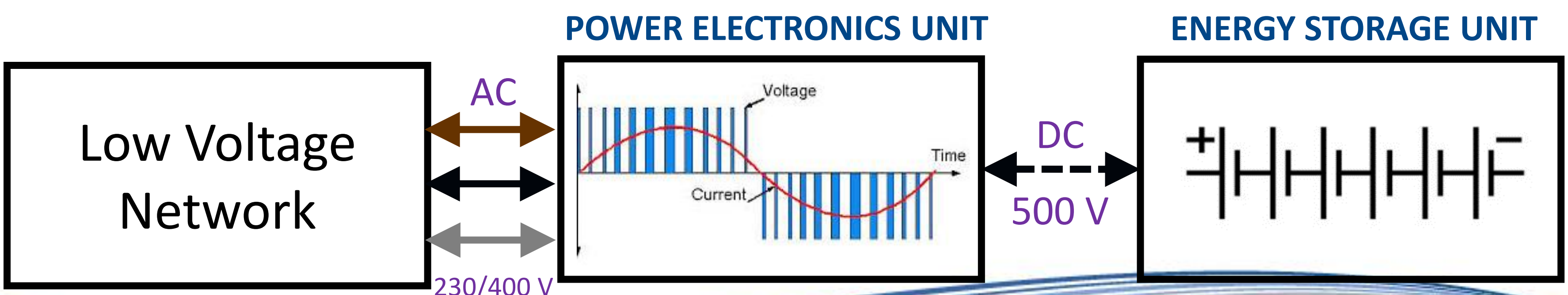
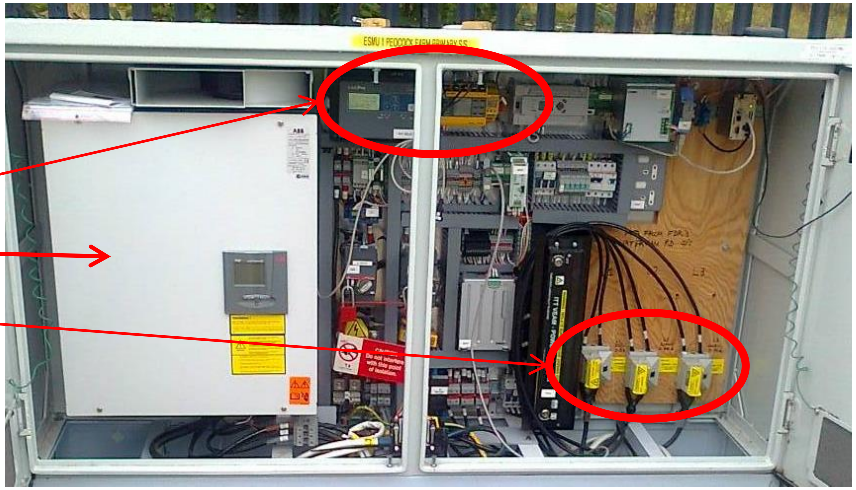
Energy Storage – Design Considerations

- Rating 36kVA (12 kVA per phase)
- Capacity 12.5kWh per ESU
- Size Street Side Cabinet(s)
- Bus Voltage 500V
- Connection 3 x 35sqmm single core cables (allow for neutral currents)
- Connection 400 / 230 V requires interface transformer
- Physical Protection Position / Weather / Mechanical Impact
- Electrical Protection G59 / Ground Fault / AC Isolation / DC Isolation
- Noise
- Communications and Control DNP3



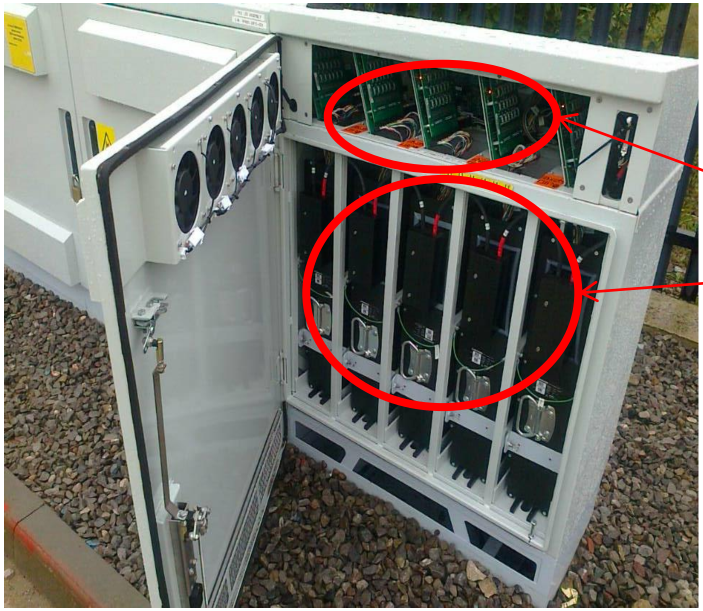
Energy Storage and Management Units

A modular cabinet deployed street side.



Power Electronics Unit PEU

- Protection (G59 and ground fault)
- Inverter (4 quadrant controller)
- Cable connections to LV main



Energy Storage Unit ESU

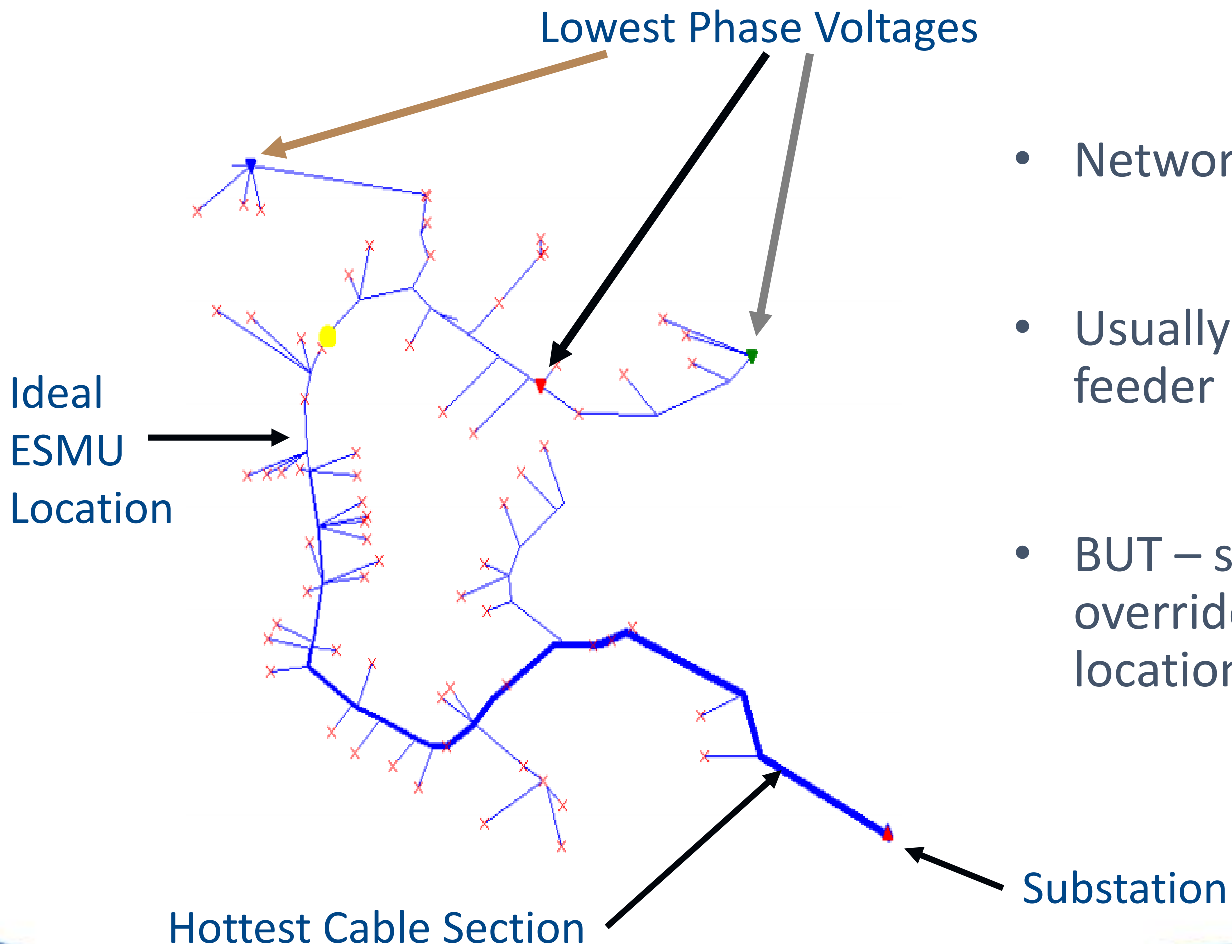
- Battery Monitoring System
- Lithium Ion battery modules

ESMU - Safety Case

Safety Case

- Equipment Specification Review – LVD / EMC / CE
- System Hazards
- Safety Requirements
  - Operational Safety Rules
  - Work Instructions
  - Procedures
  - A Good Practise Guide on Electrical Energy Storage
- Risk Assessment
- Hazard Control / Risk Resolution (HAZID / HAZOP)
- Safety Analysis / Test
- Safety Management System

Energy Storage – Location Selection



- Network specific
- Usually in the middle third of the feeder
- BUT – safety and practicality override the ideal electrical location

ESMU - Installation

Insert base and lay cable

Erect ESMU, connect and commission

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Energy Storage - Installation

- 25 ESMUs Installed during Spring 2015

- 24 ESMUs connected to low voltage cables that provide electricity to customers in Bracknell

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Energy Storage - Commissioning

ESMU – commissioning

- **Factory Acceptance Testing**
- **Type Test**
- **User Acceptance Test**
- **Site Testing**
    - ➢ G59 and safety system(s) calibration and testing
    - ➢ local functional testing of the ESMU under laptop control
    - ➢ 'end-to-end' testing between the ESMU and SCADA system head end (PowerOn Fusion)
    - ➢ Phase Rotation / Connectivity
    - ➢ Impact on the network – operational limits

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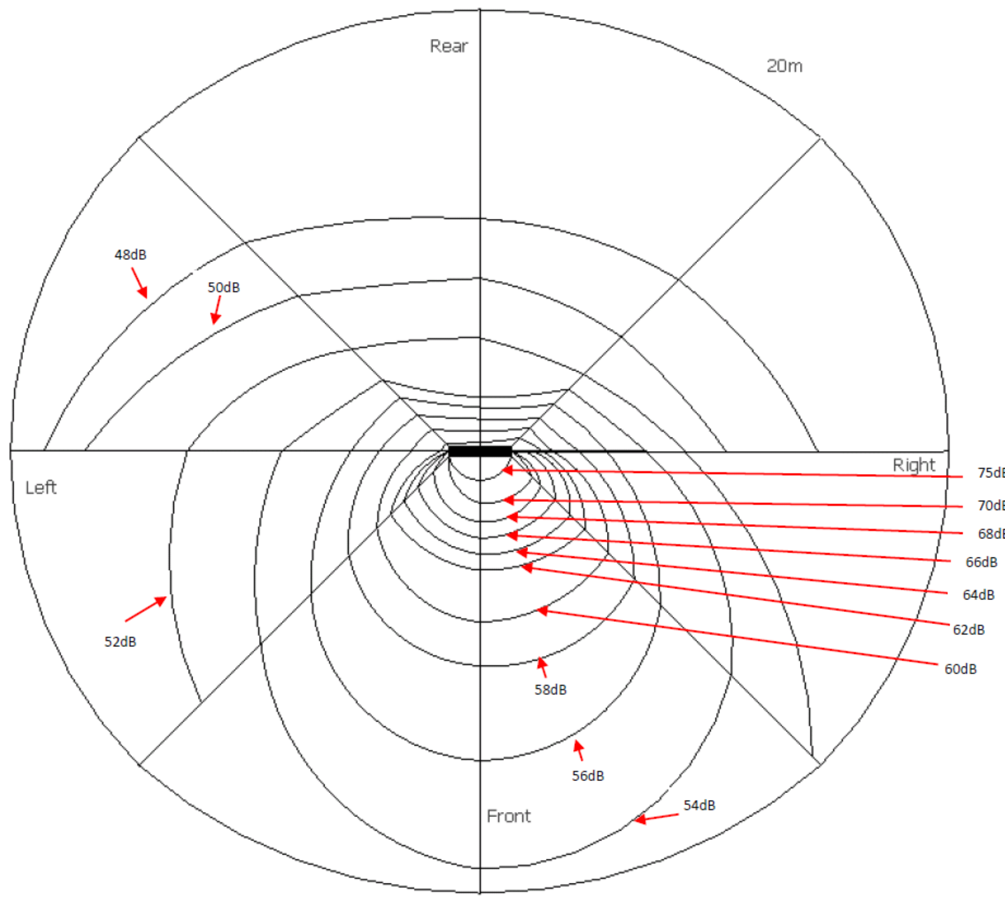
ESMU - Noise

- Design
- Inverter noise
- Cooling fans
- Sound Insulation
- Neighbour Proximity
- Sound Level Contours



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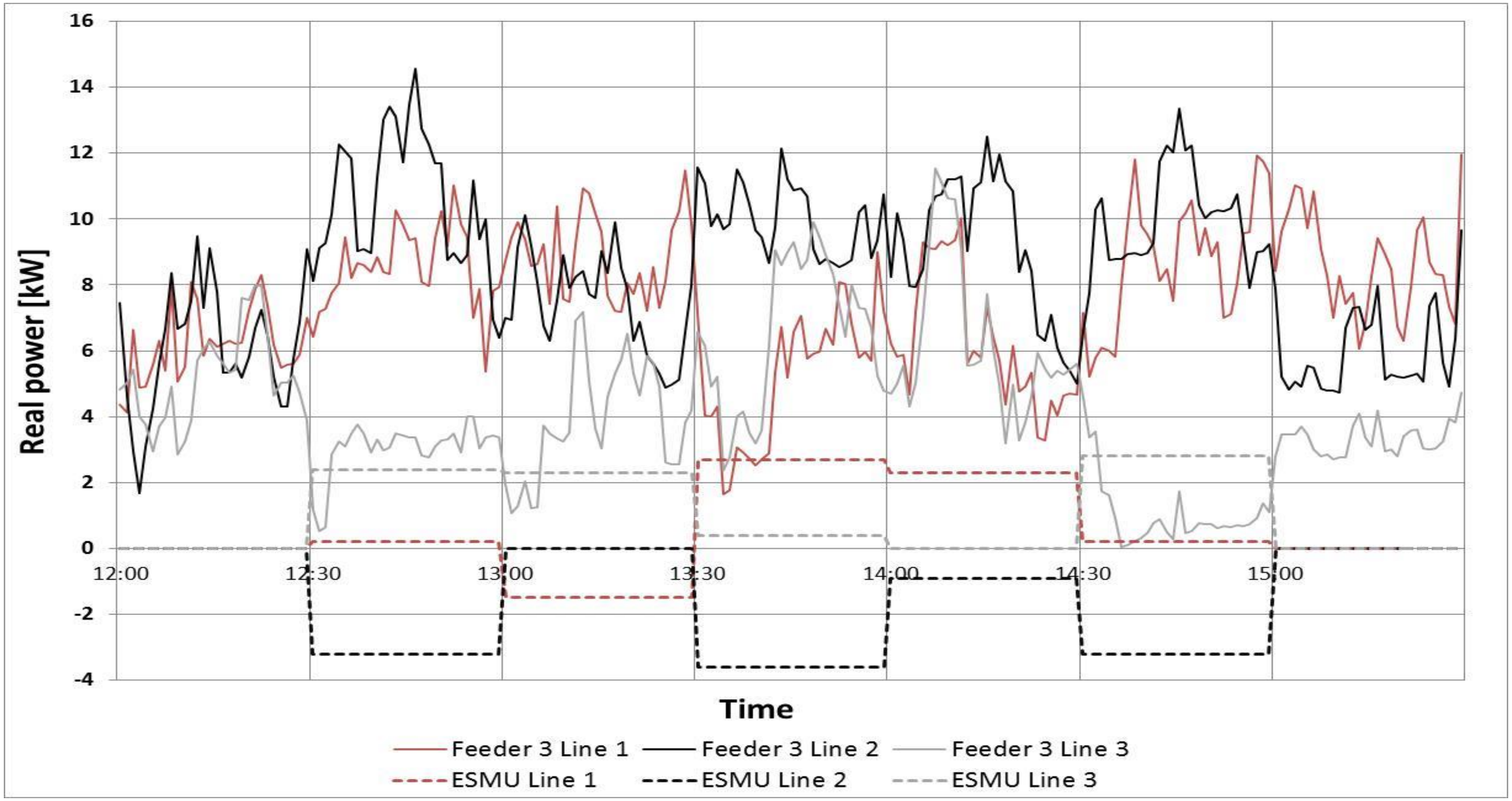
Learning Outcomes

- Installation
  - Safety Case Established
  - Handling lithium ion batteries (Class 9 Hazardous Goods as defined by ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road))
  - Scaled up deployments – consents / excavations / jointing
  - What can be expected from the supplier – firmware / software updates
  - Testing and Commissioning – protection / functionality / end-to-end communications
  - Communications reliability – establishment of heart beat
  - Noise – sound envelope / impact on community

- Operation
  - Functionality expectations - possibilities
  - Real world limitations – capacity limits / communications / data availability
  - Reliability considerations – maintenance requirements / life cycle

Energy Storage – Manual Operation



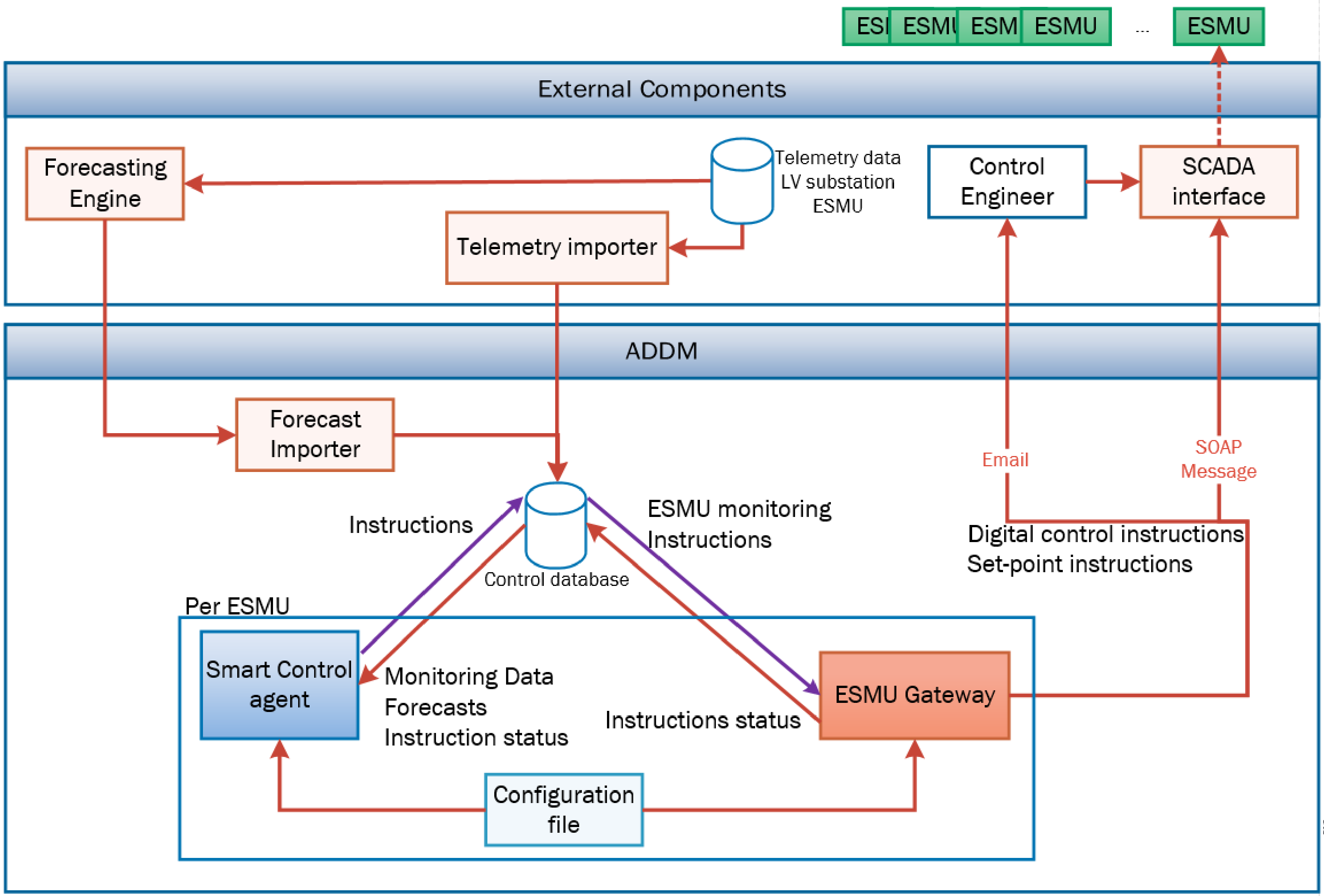
Manual operation – Real Energy charging / discharging – Saffron Road Feeder 3

SMART CONTROL

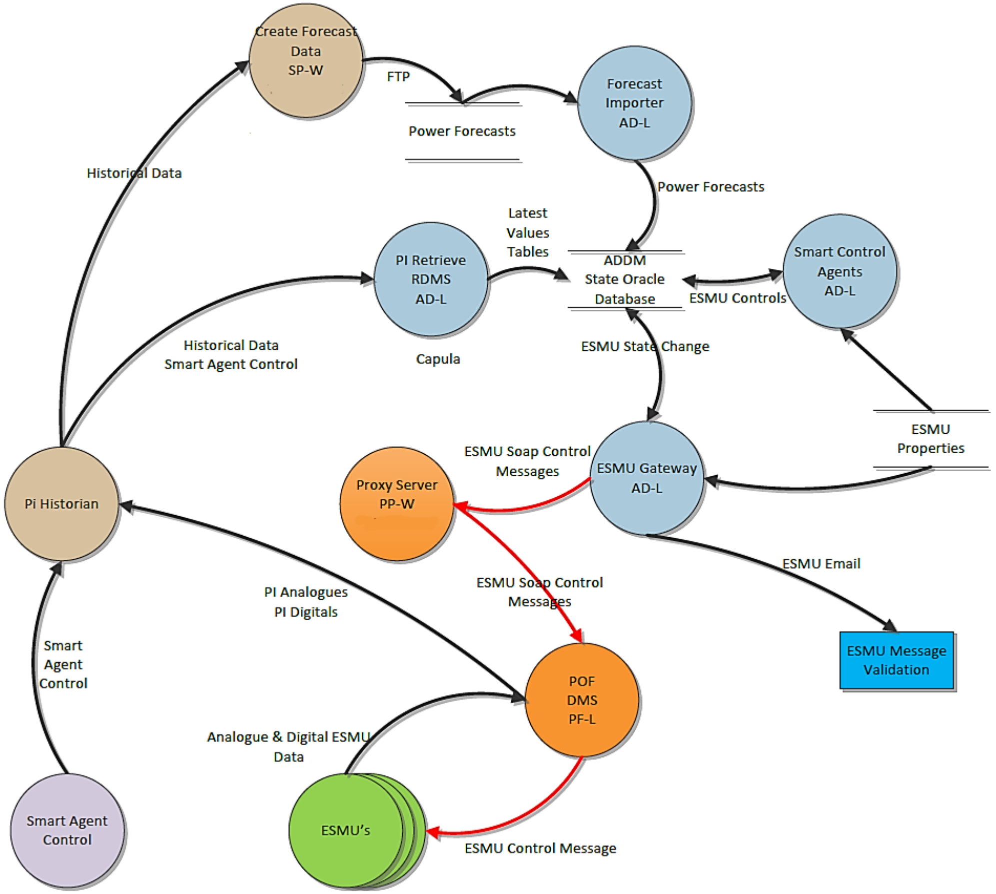
- Automated operation
  - Calculation of instructions:
    - Thermal constraints management
    - Voltage constraints management
  - Utilisation of forecasts and local measurements
  - Regular instructions and continuous operation 24/7
  - Responsive to change in demand (quicker than a human operator!)
  - Modular and scalable structure

EPM and Substation monitoring → Forecasts → Day ahead planning → "Real Time" Control

CONTROL SYSTEM



IT Architecture



Issues and Learning points

Design

- Where to place Intelligence. ESMU or ADDM? Safety case?
- Data flow analysis
- What would we change if done again?

Testing

- Full functional testing (including hardware)

R&D vs BaU process

- Staged development and deployment of increments in complexity
- Production vs Pre-production
- Define a naming convention that brings people on board
- Prototyping vs operational platforms
- Theoretical memory capability may not be exact

Structure of Digital definitions

- Define a library of terms
- Ensure ADDM and ESMU operating from a single source of commands

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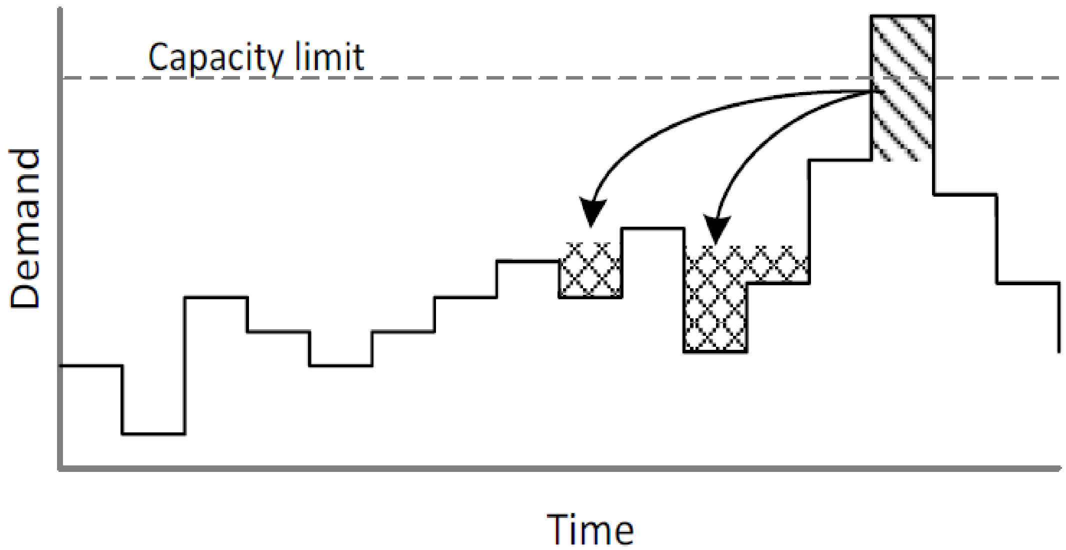
SMART CONTROL AGENT

- Control methods and management of instructions
- Offline – fixed schedule based on forecasts only
- Online – addition of substation monitoring
  - Phase-balancing
  - Power Factor correction
  - Peak reduction combined with phase-balancing
  - Voltage support
  - Voltage balancing

OFFLINE PEAK REDUCTION



- Peak reduction:
  1. Phase-balancing
  2. Energy storage

OFFLINE PEAK REDUCTION

- Half-hourly kW schedule per phase for next 24 hours
- Schedule minimises F (**P**) where

Forecast per phase

Schedule per phase

Difference in kW between phases

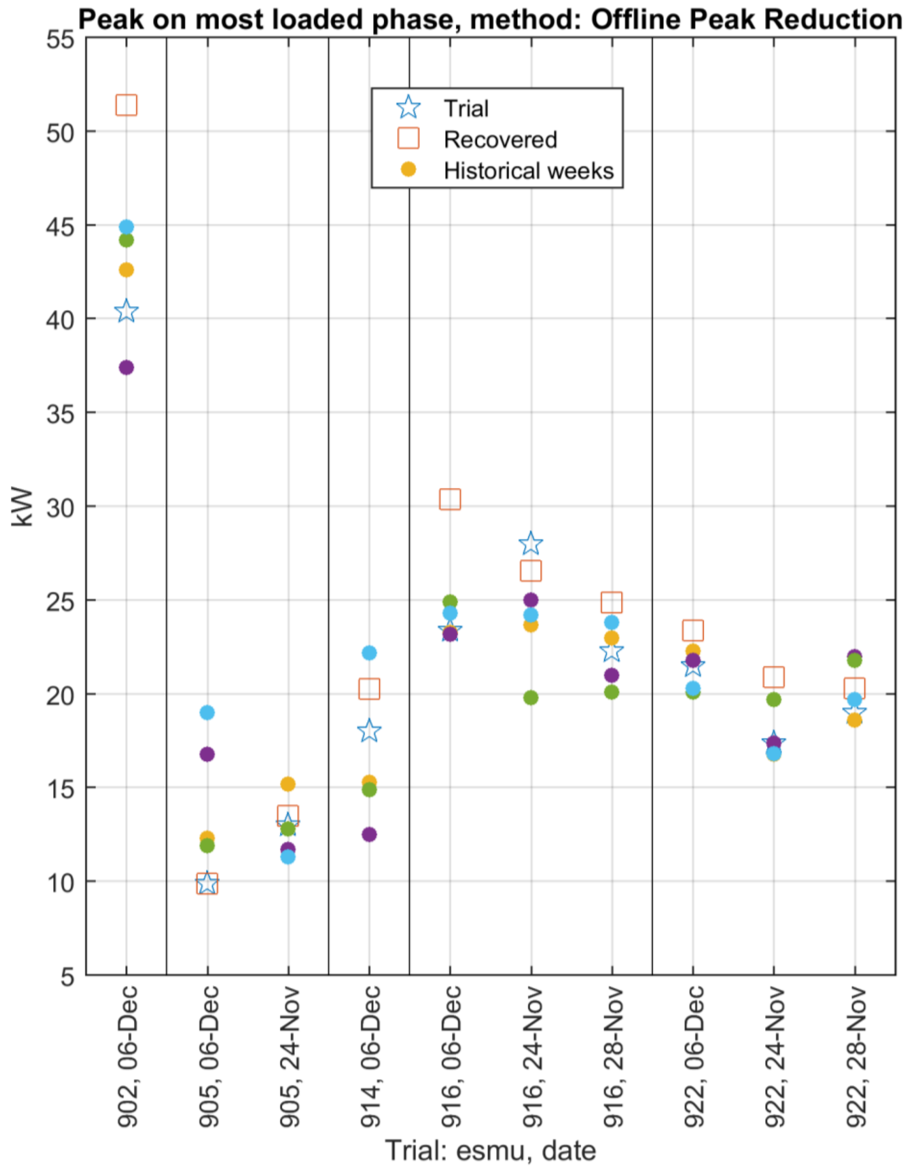
$$
\begin{aligned}
F(\mathbf{P}) = & \max\left((D_f^1(k) - P^1(k)) - (D_f^2(k) - P^2(k))\right)^2 \\
& + \max\left((D_f^2(k) - P^2(k)) - (D_f^3(k) - P^3(k))\right)^2 \\
& + \max\left((D_f^3(k) - P^3(k)) - (D_f^1(k) - P^1(k))\right)^2 \\
& + \max\left(\sum_{p=1}^{3} \left(D_f^p - P^p(k)\right)^2\right) \\
& + (C[48] - 0.5C_{max})
\end{aligned}
$$

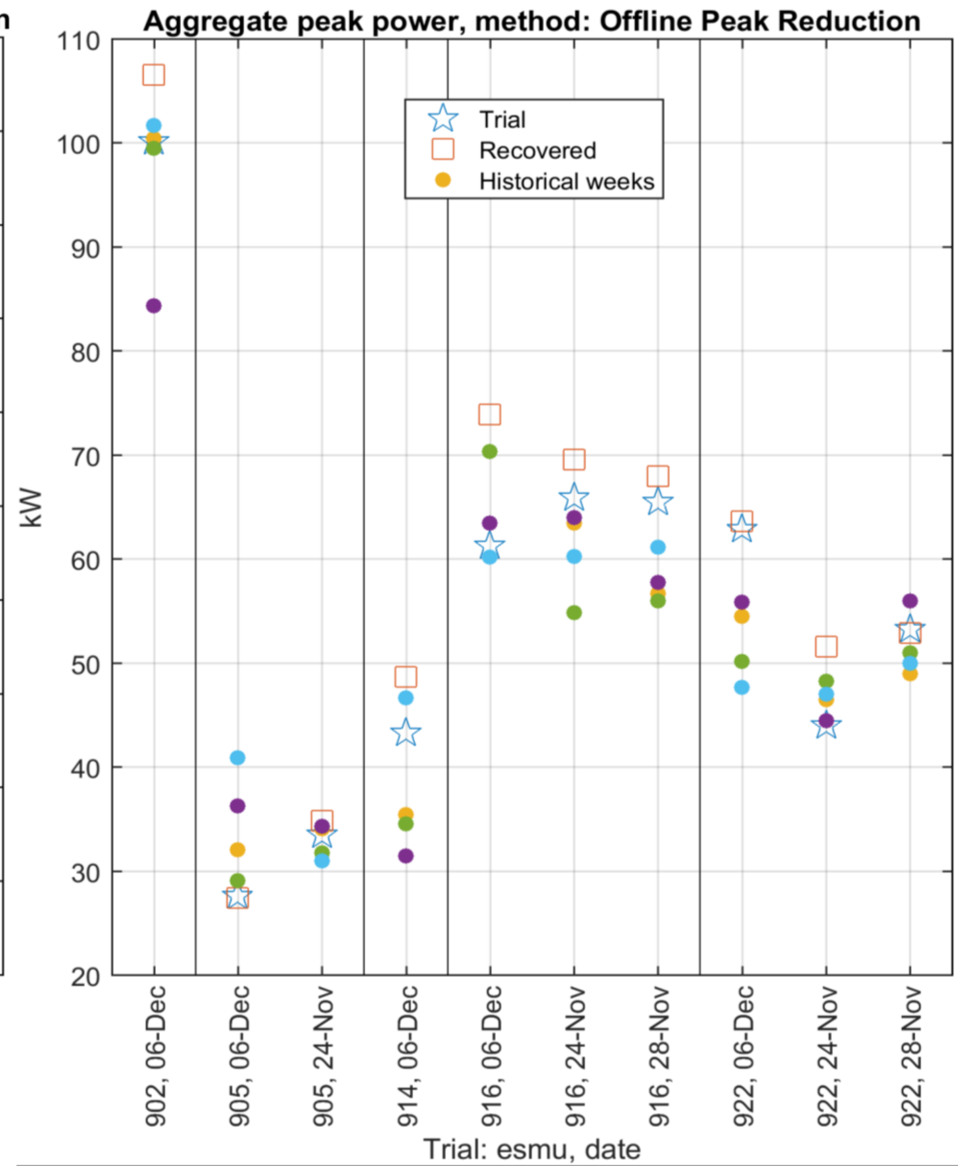
Maximum demand on all phases

End at 50% SoC

- Constraints:
  - Power electronics rating, Energy storage rating and capacity

OFFLINE PEAK REDUCTION



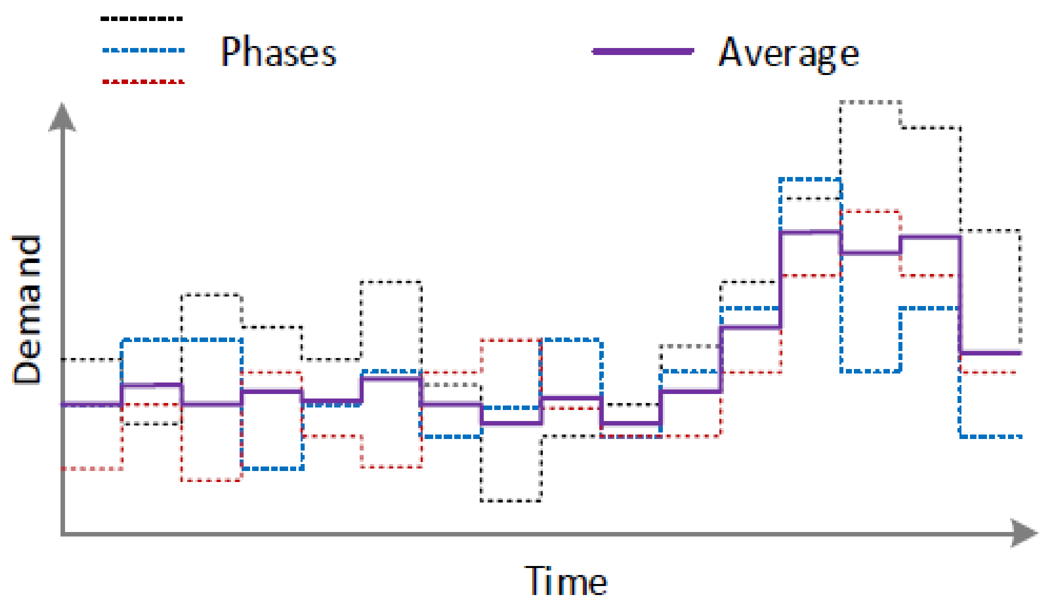


PHASE-BALANCING

- Equalise loading between phases
  - Reduced neutral current
  - Reduced peak on individual phase *
  - More balanced voltages ^

→ Reduced losses

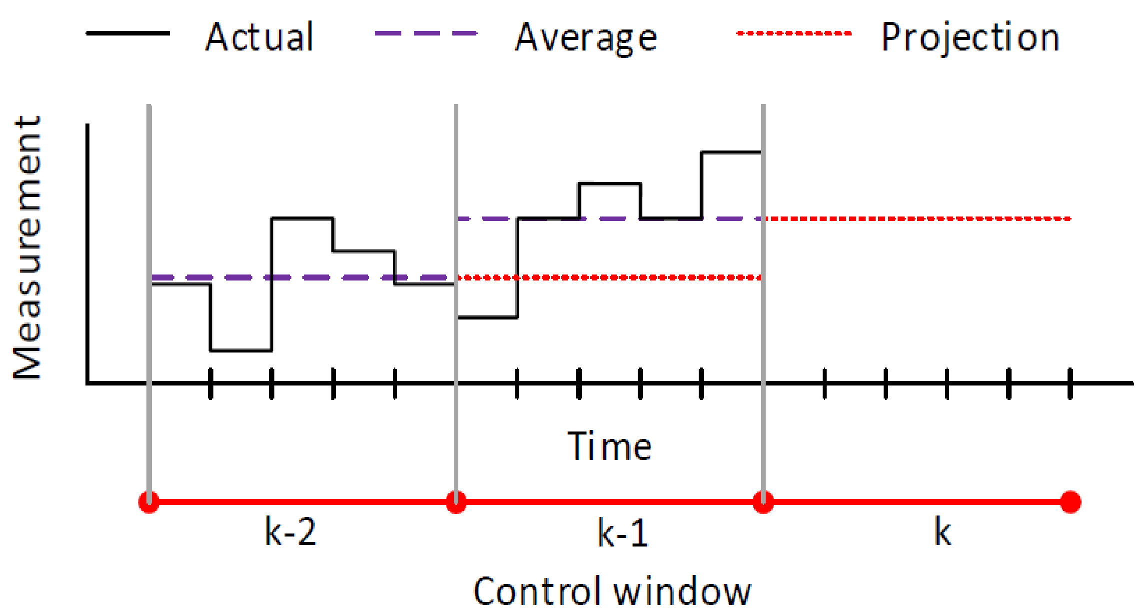
Better utilisation



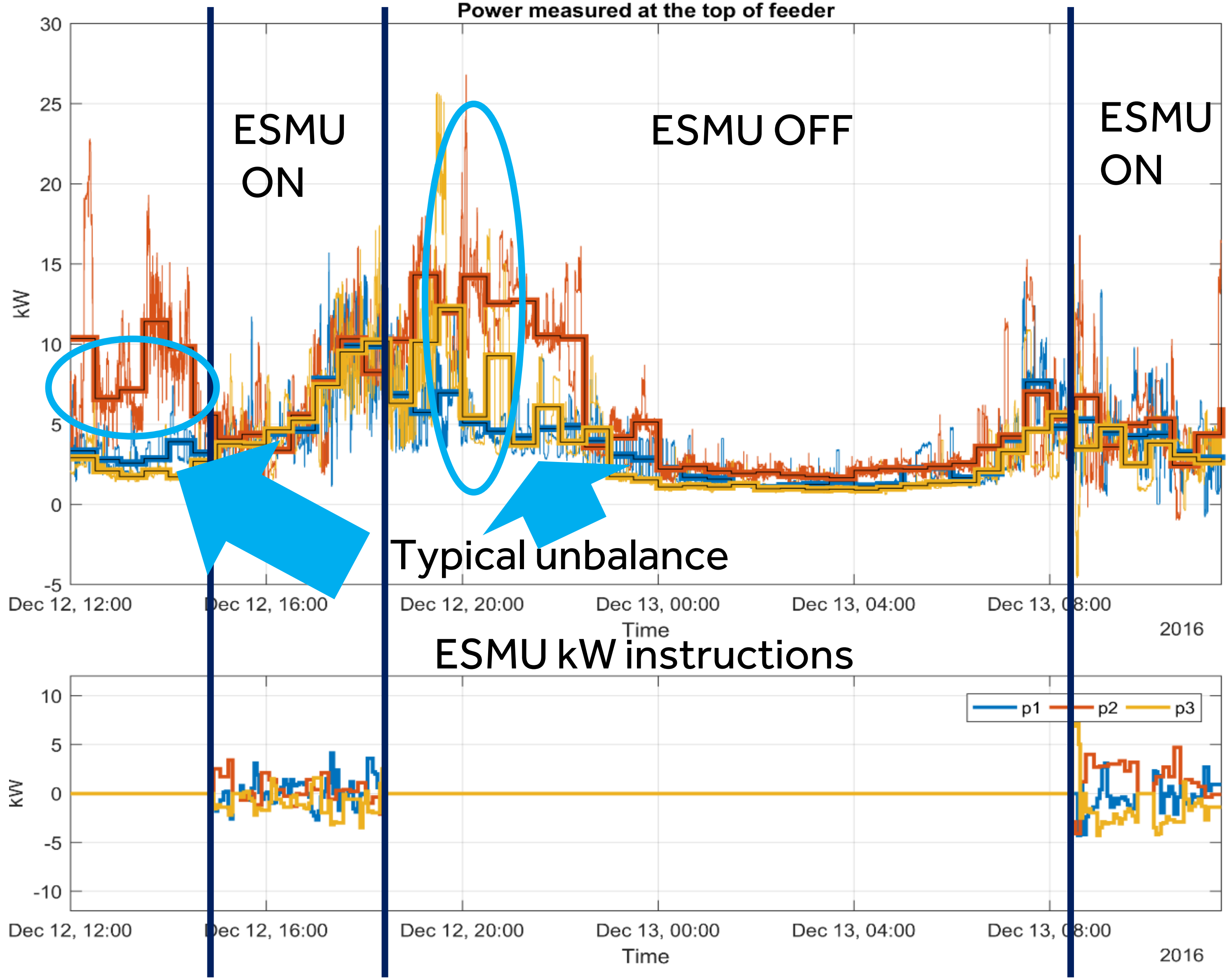
* Assuming no simultaneous peaks .
^ Depends on ESMU location and distribution of loads along feeder.

PHASE-BALANCING

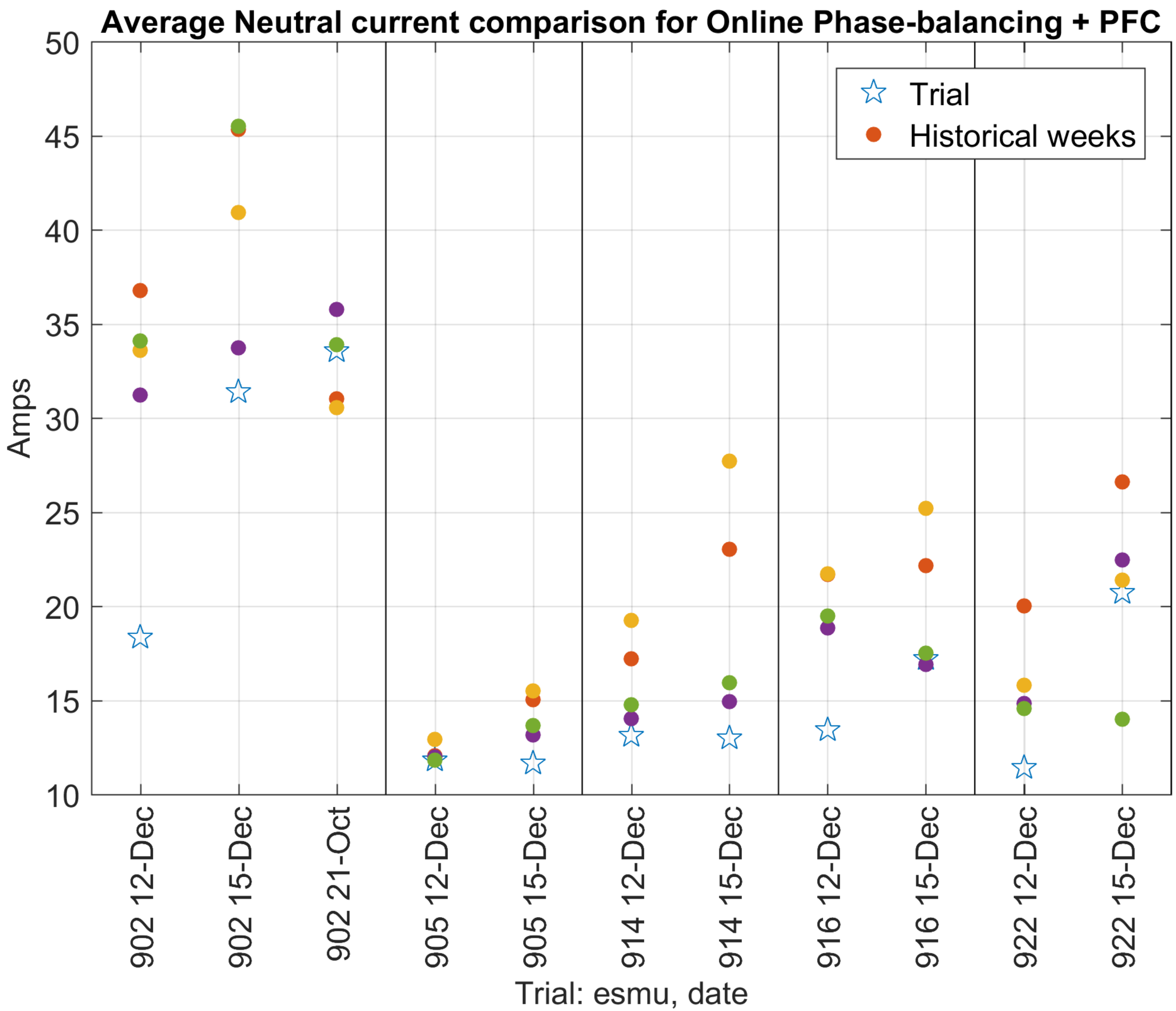
- ADDM is not a true "real-time" system:
  - SCADA 5 second polling
  - ESMU Gateway 1 minute job cycles
  - Smart Control Agent 10-30 seconds state change cycles
- Approximation by projection over 3-10 minutes



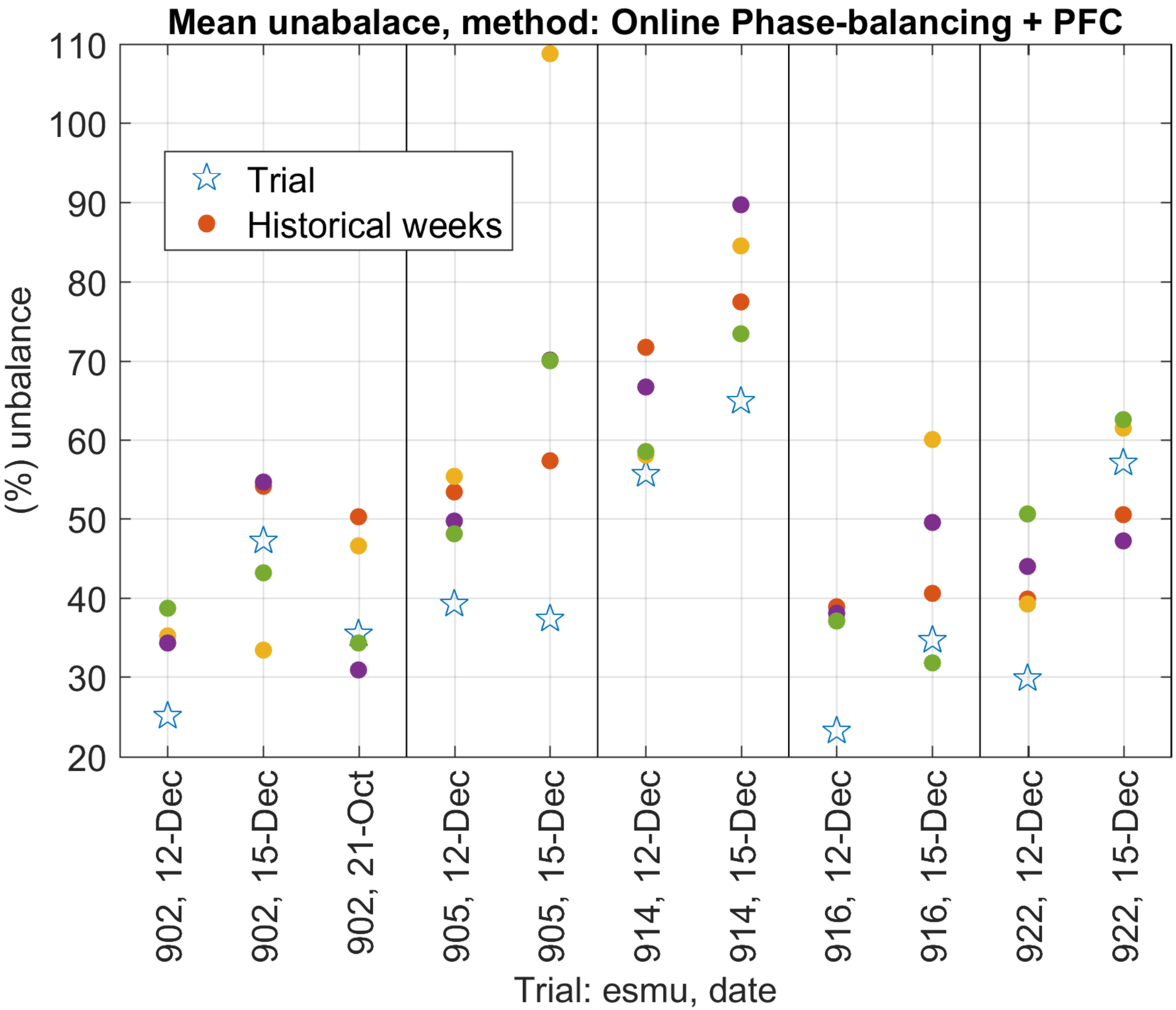
PHASE-BALANCING



PHASE-BALANCING



PHASE-BALANCING



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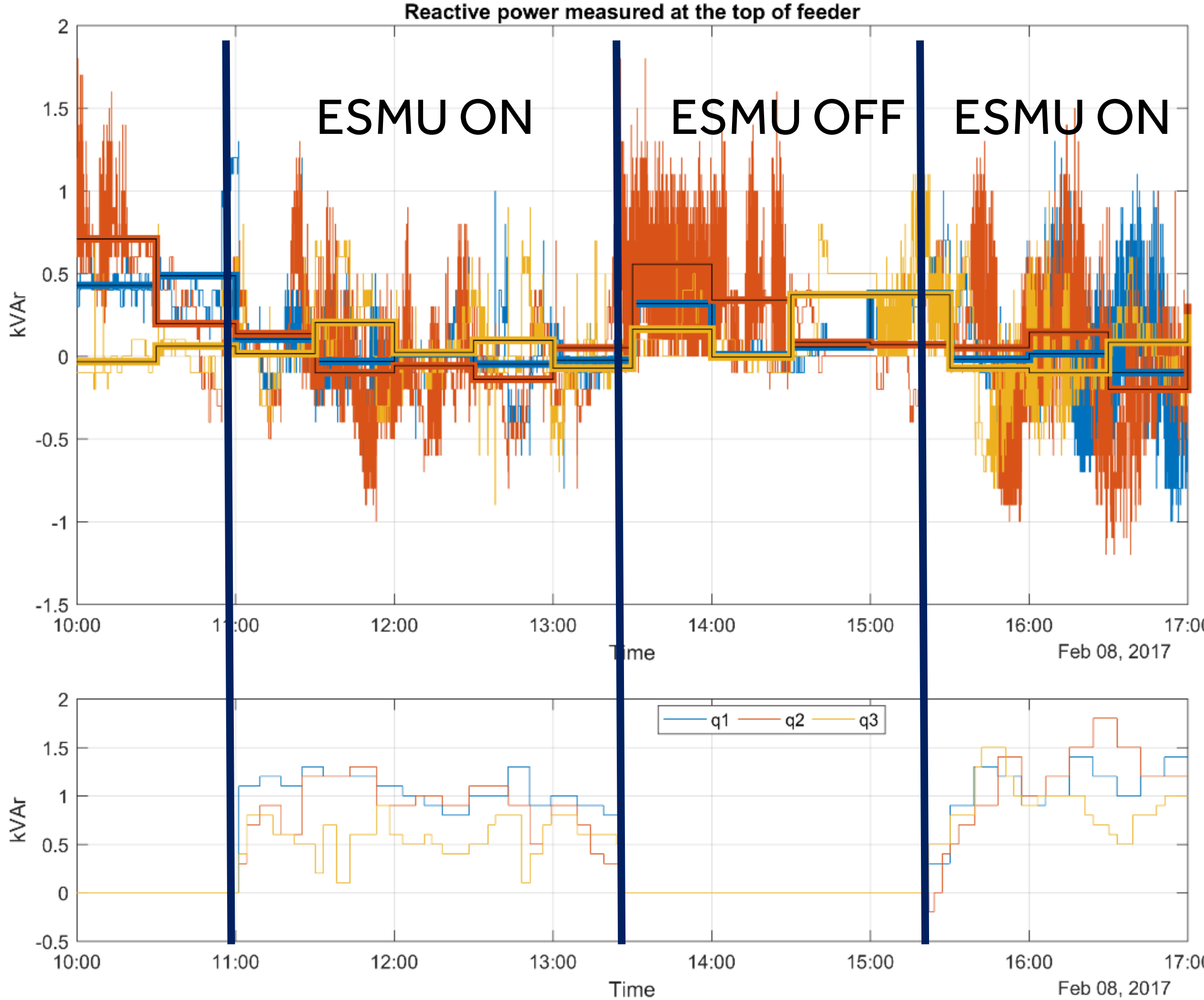
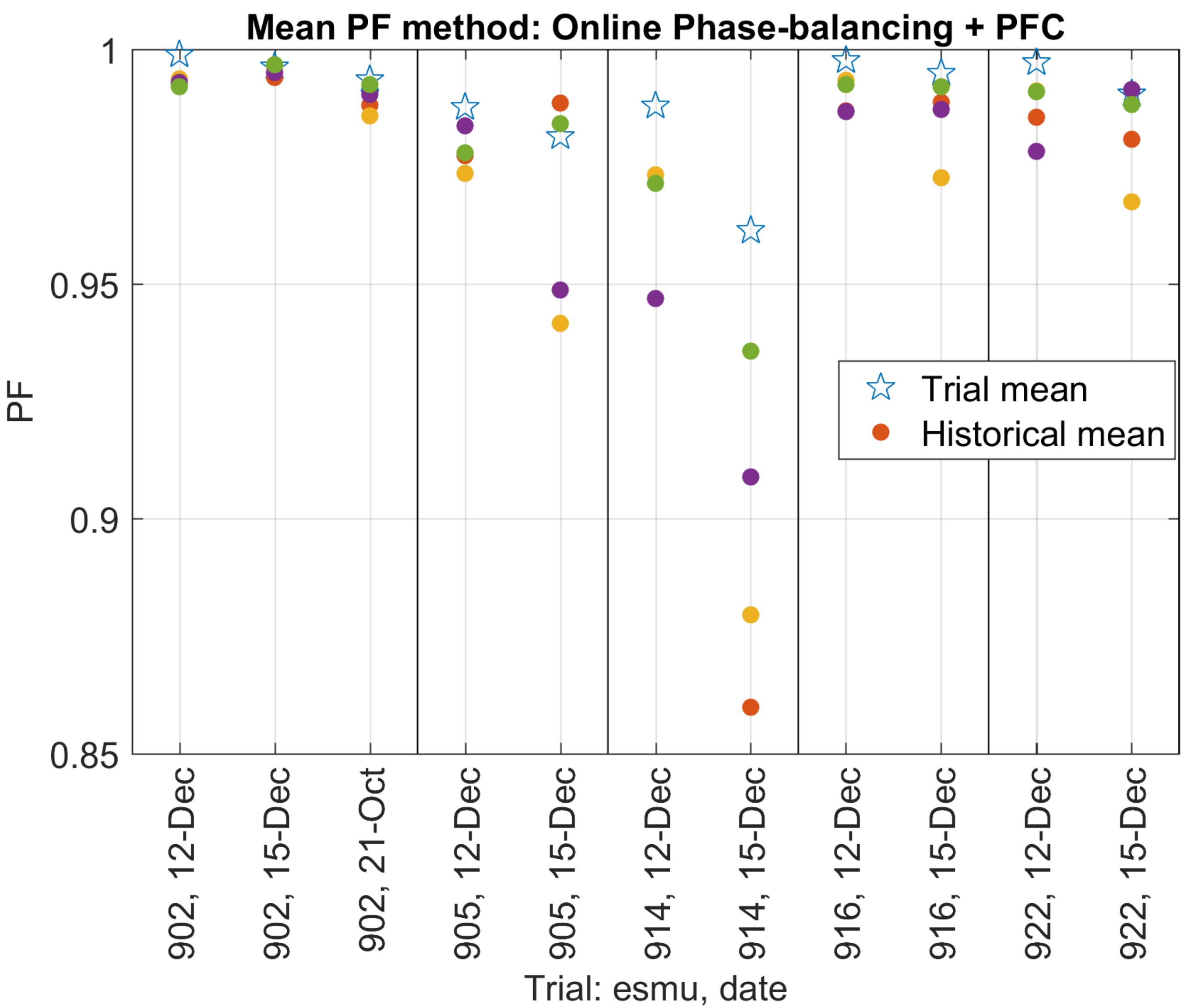
POWER FACTOR CORRECTION

- Combined with phase-balancing

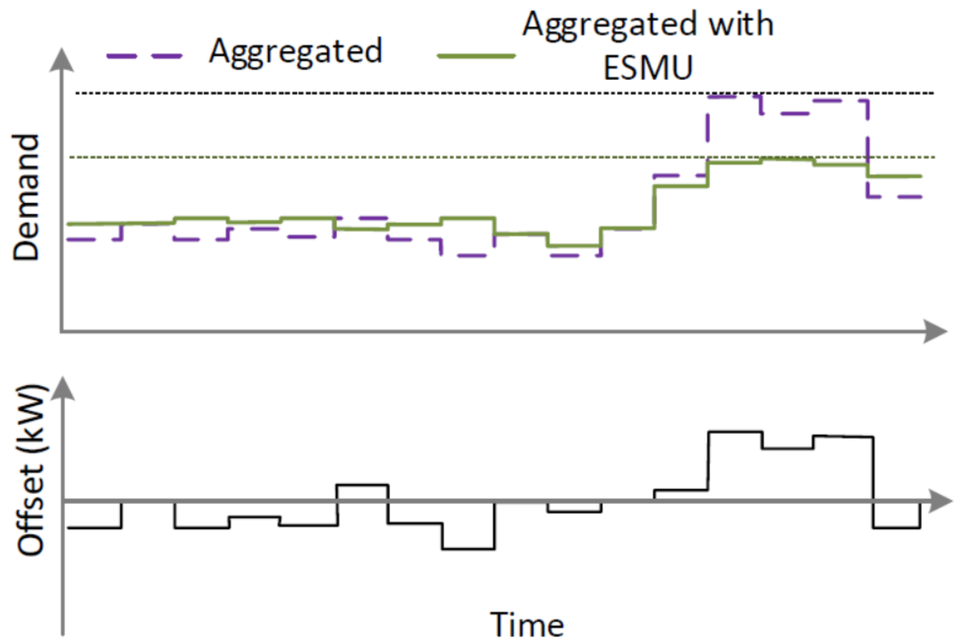


POWER FACTOR CORRECTION



ONLINE PEAK REDUCTION

- Half-hourly schedule based on aggregated forecast



- Schedule used as offset for phase-balancing
  - Load on balanced phases equally reduced or increased according to schedule

ONLINE PEAK REDUCTION

- Schedule minimises $F(\boldsymbol{p}, \boldsymbol{d_f})$:

Peak-to-average cost

$$\xi_p(\boldsymbol{p}, \boldsymbol{d_f}) = \frac{\left(\frac{\max\limits_{t=[1,N]}(d(t)+p(t))}{\sum_{t=1}^{N}(d(t)+p(t))/N}\right)^2}{\xi_p(\boldsymbol{p_i}, \boldsymbol{d_f})}$$

Storage cycle

$$\xi_{sc} = \frac{\sum_{t=1}^{N}\left|\frac{\delta I_{(0,p_{max}]}(\boldsymbol{c})}{\delta t}\right| + \sum_{t=1}^{N}\left|\frac{\delta I_{[-p_{max},0)}(\boldsymbol{c})}{\delta t}\right|}{2}$$

Forecast

Schedule

$$F(\boldsymbol{p}, \boldsymbol{d_f}) = \xi_p(\boldsymbol{p}, \boldsymbol{d_f}) + \frac{\alpha\xi_{cd}(\boldsymbol{p})}{w} + \frac{\beta\xi_{sc}(\boldsymbol{c})}{w} + \frac{\gamma\xi_{ts}(\boldsymbol{c})}{w}$$

Smoothen charge dynamics

$$\xi_{cd} = \frac{\max\left(\left|\frac{\delta I_{[0,p_{max}]}(\boldsymbol{p})}{\delta t}\right|\right)}{p_{max}}$$

Scaling factors:

$$w = \alpha + \beta + \gamma$$

End state-of-charge

$$\xi_{ts}(\boldsymbol{c}) = \frac{(c(N) - 0.5C_{max})^2}{\xi_{ts}(\boldsymbol{c_i})}$$

- Constraints:
  - Power electronics rating, Energy storage rating and capacity

Publication under review.

ONLINE PEAK REDUCTION

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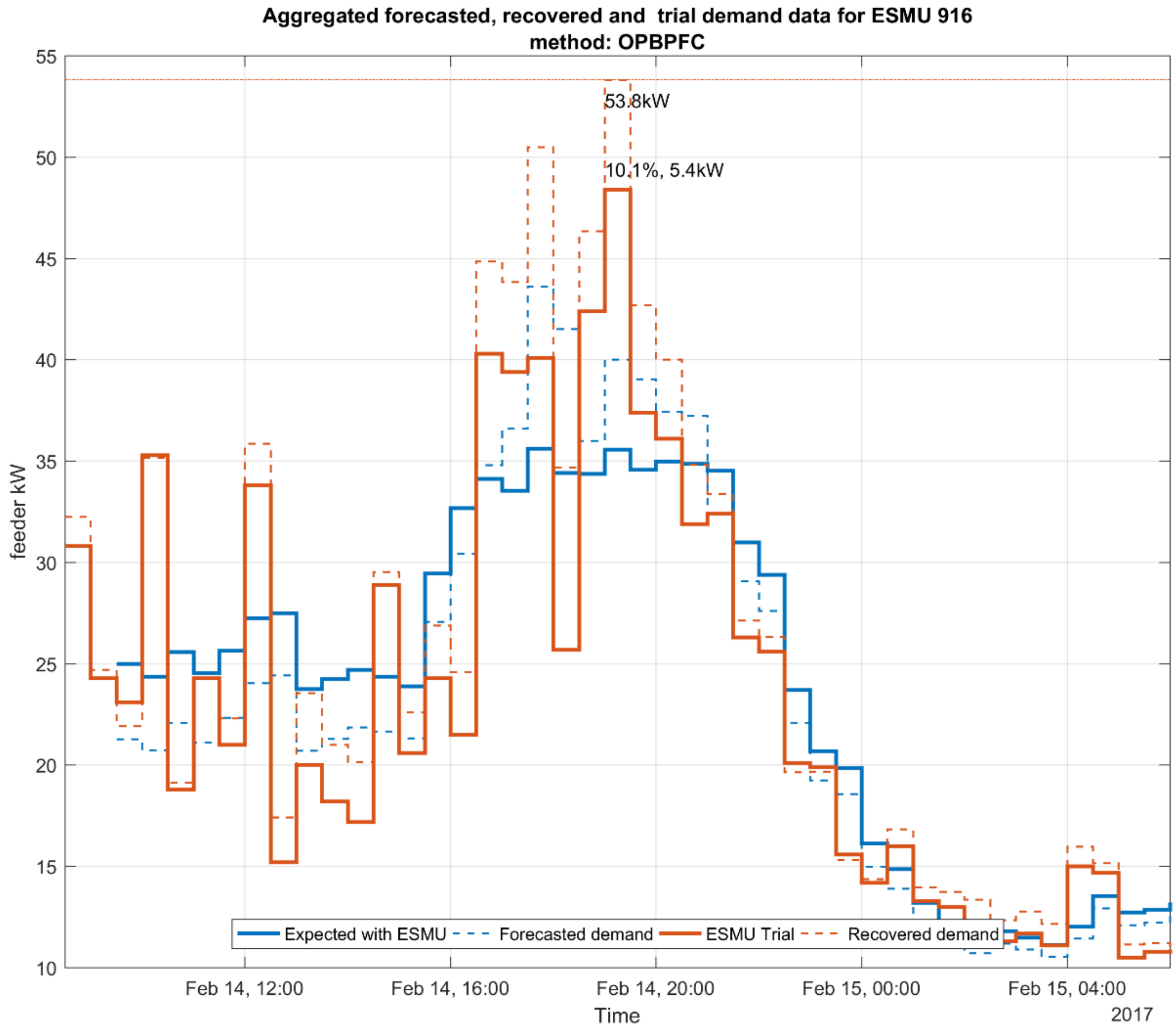

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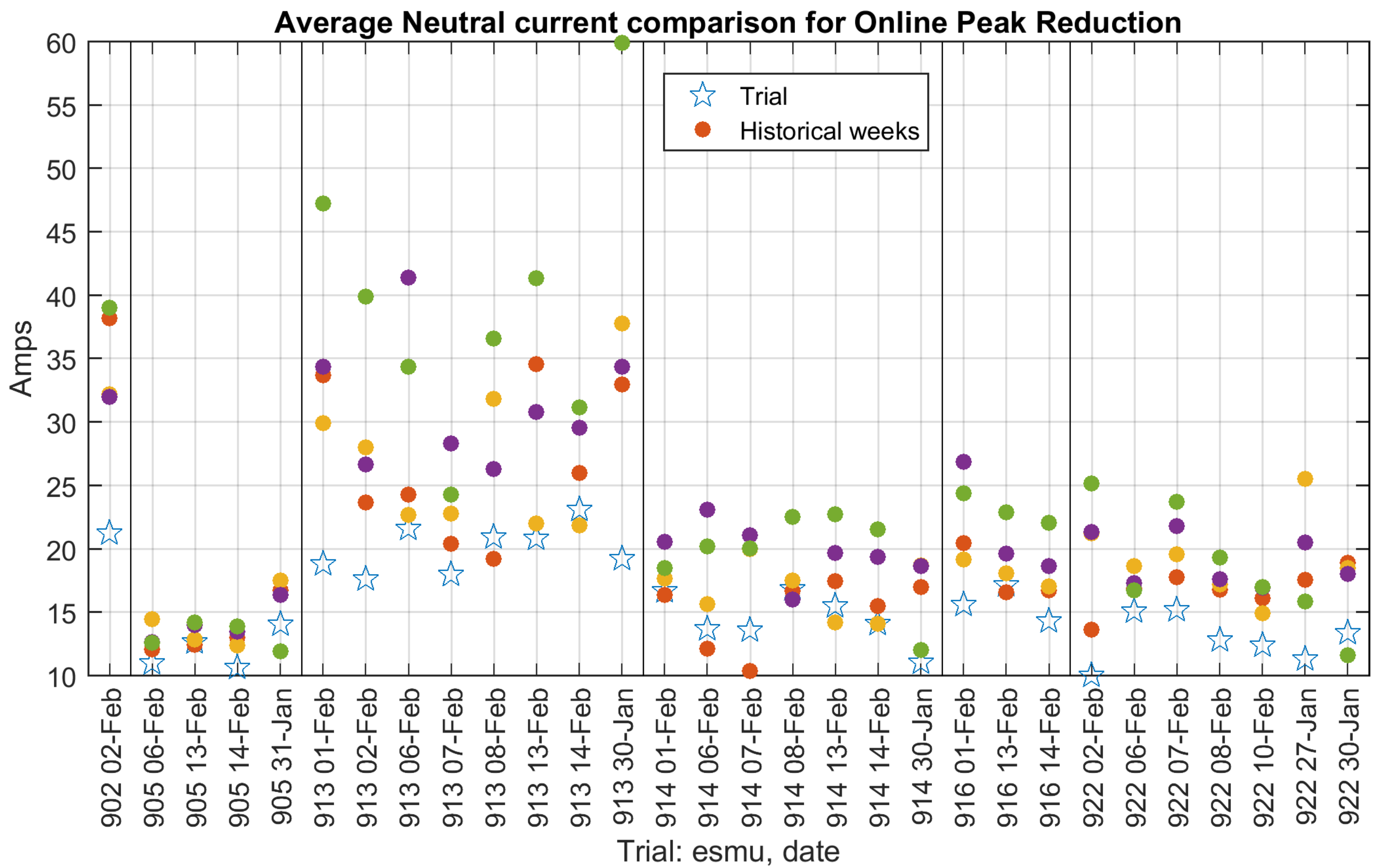

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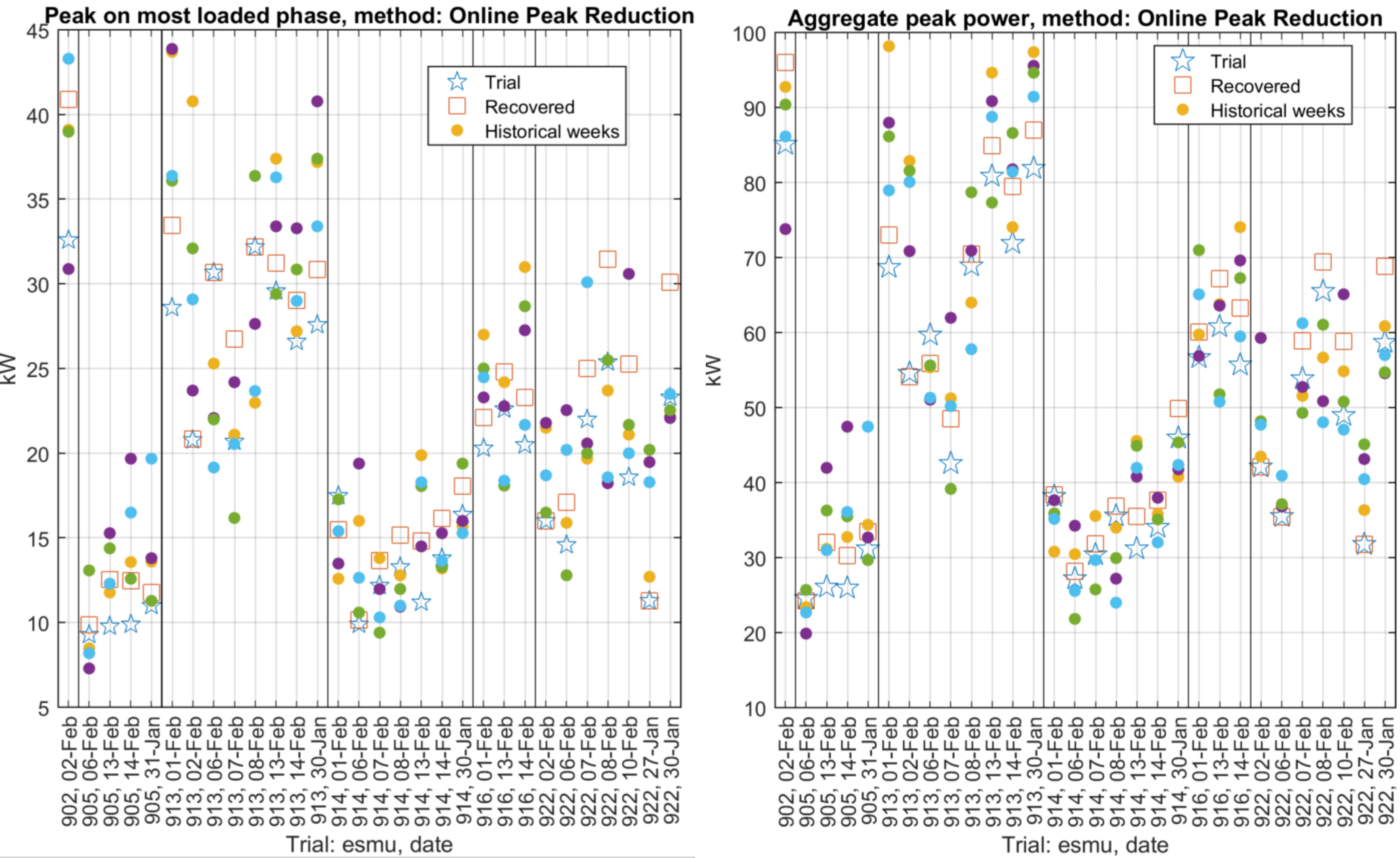

COMPARISON OF METHODS

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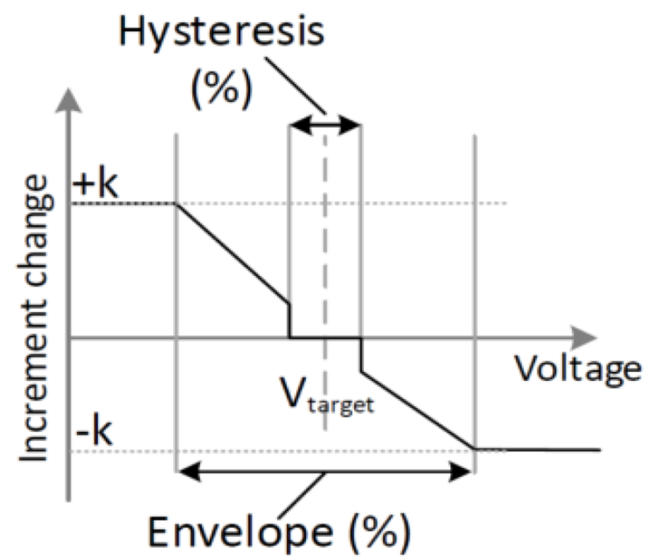
	Offline peak reduction	Phase-balancing + PFC	Online Peak reduction
Neutral current	13.1%	20.2%	21.67%
Demand unbalance between phases (phase compared to average)	Mean: reduced by **13.1%**, from 48.6%unb to 41.1%unb. Max: reduced by **10.6%,** from 139.9%unb to 110.5%unb.	Mean: reduced by **20.2%**, from 52.6%unb to 40.9%unb. Max: reduced by **15.9%**, from 122.9%unb to 95.5%unb.	Mean: reduced by **22.4%**, from 53%unb to 39.1%unb. Max: reduced by **16%**, from 128.4%unb to 92.6%unb.
Peak difference (peak during trial compared to historical peaks)	15.9%	13%	20.6%
Power Factor	Min: from 0.7 to 0.53. Mean: from 0.98 to 0.98.	Mean: from 0.66 to 0.9. Max: from 0.98 to 0.99.	Mean: from 0.71 to 0.86 Max: from 0.97 to 0.99

VOLTAGE SUPPORT

- Additive Increase Multiplicative Decrease (AIMD)
  - Voltage trigger points for
    - Additive increase to:
      > Further absorb when voltage is above upper voltage threshold

      > Further inject when voltage is below lower voltage threshold
    - Multiplicative decrease to:
      > Reduce intake of power when voltage is below the lower threshold

      > Reduce injection of power when voltage is above upper threshold



VOLTAGE SUPPORT

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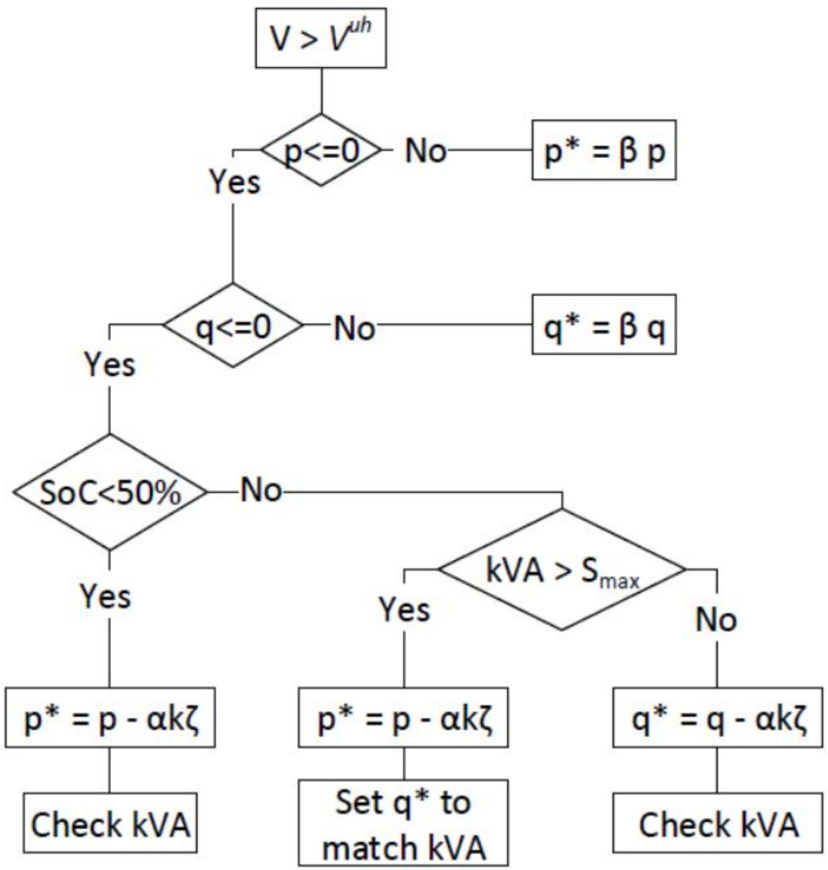
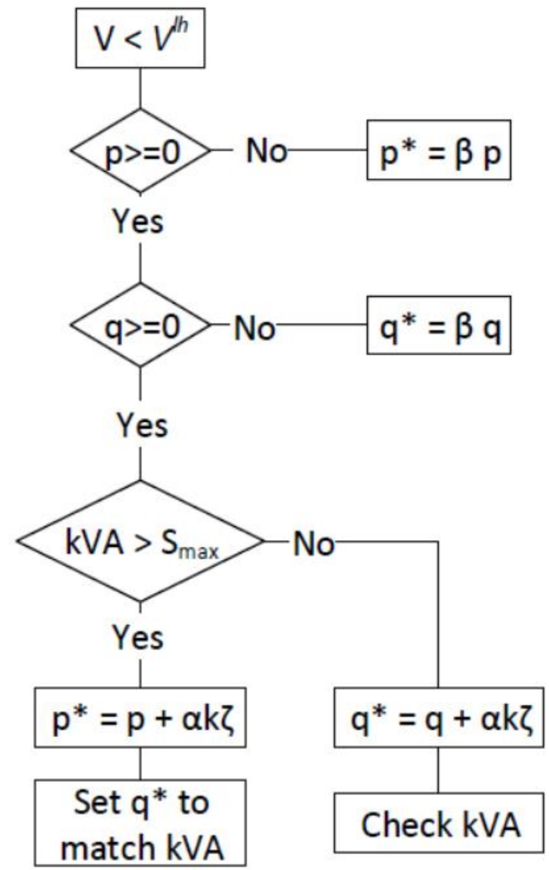
High voltage events



Low Voltage Events



VOLTAGE SUPPORT

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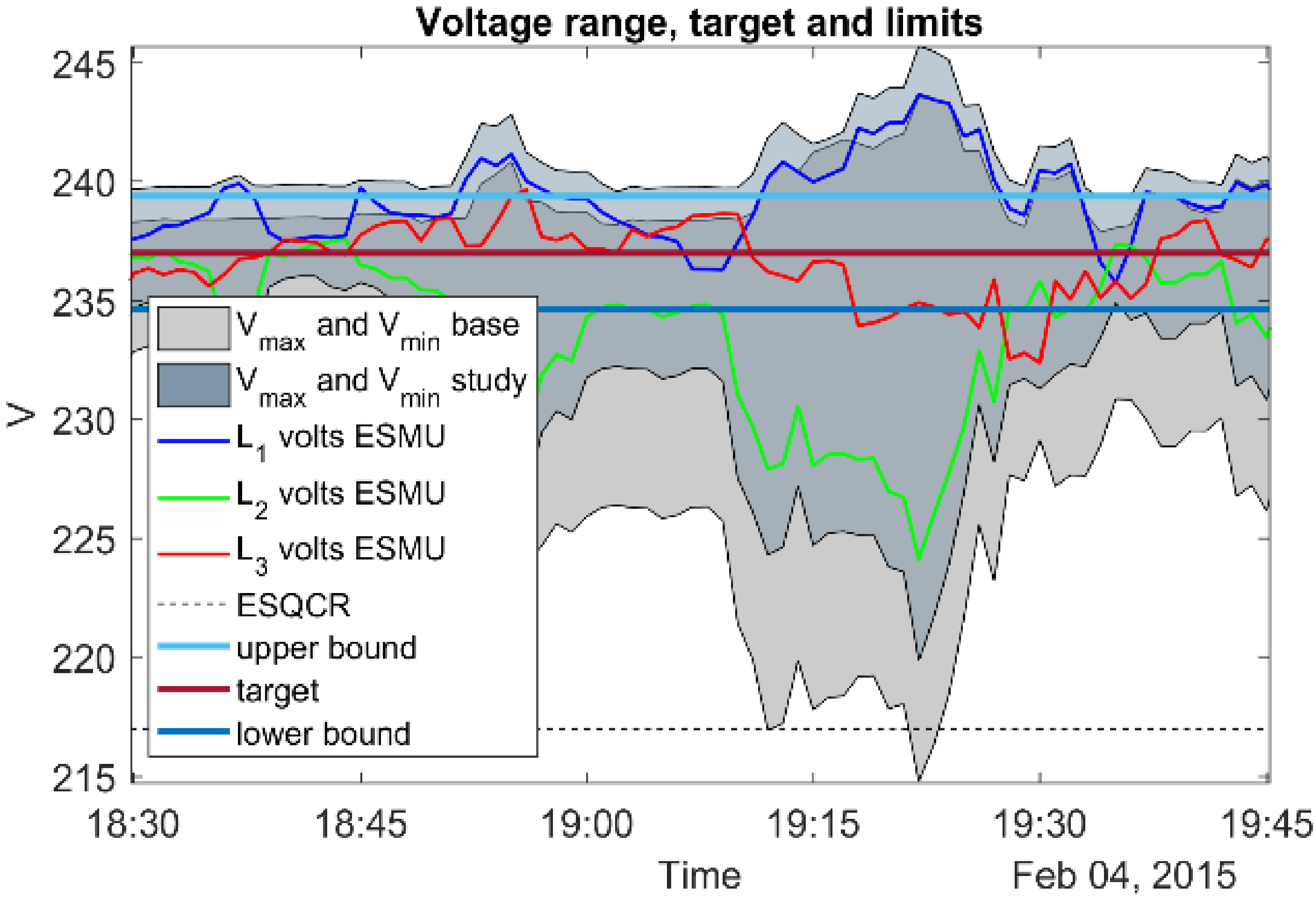
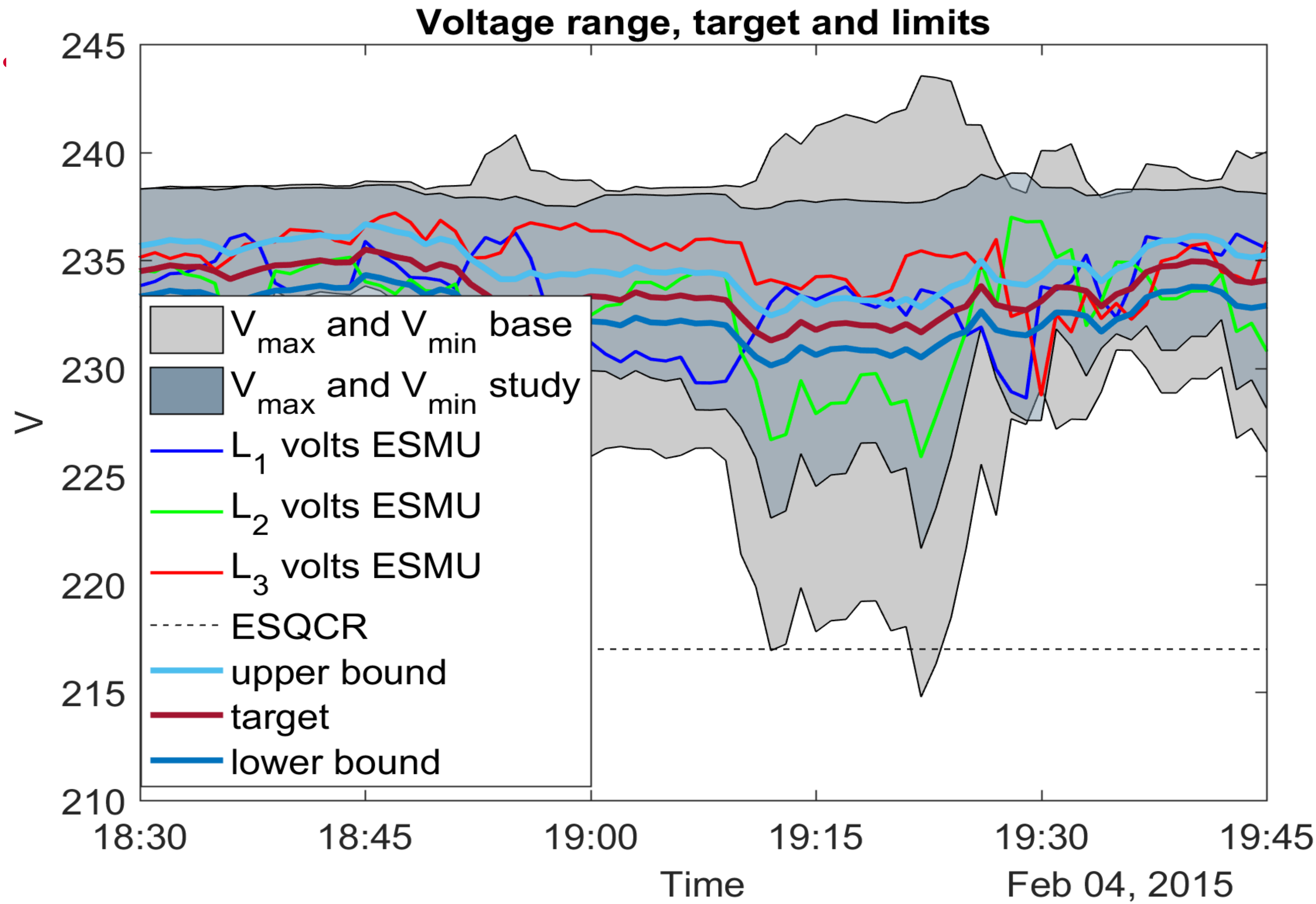


VOLTAGE BALANCING



LEARNING OUTCOMES

- Loading is unbalanced
  - Phase-balancing operation demonstrated
    - Reduction in neutral current -> better efficiency
    - Reduction in peaks on individual phases
  - Lower storage capacity required to manage thermal and voltage constraints

- Online (sub-half-hourly operation) outperforms half-hourly operation
  - Better response to change in demand
  - Compensation for forecast inaccuracy
- Smoother forecasts deliver better chance of peak reduction

FUTURE WORK

- Integration of uncertainties
  - Demand forecasts
  - Control algorithms
- Rolling forecast and scheduling
  - Updating forecasts and schedules on live information
- Distributed control
  - Local fast response control
  - Centralised forecasting

FUTURE WORK

- Combination of services
  - Network support
  - Aggregated operation for high level impact
    - Frequency response
    - Constraint managed zones
  - Coordination with other services
    - Demand response
    - V2G
  - Targeted management of embedded generation

THANK YOU!

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- http://www.thamesvalleyvision.co.uk/