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Demand Response Through Point-of-Load Voltage Control

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Agenda

- Background and motivation
- Proposed voltage control device
- Application in Great Britain Network
- Primary frequency regulation
- Distribution network stability analysis

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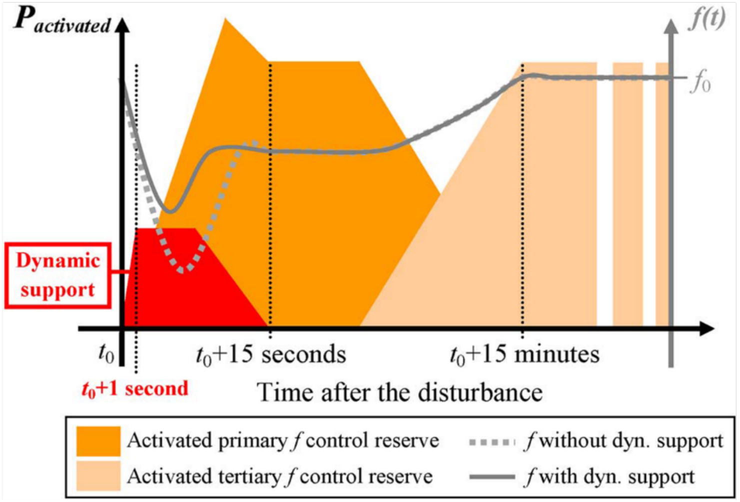
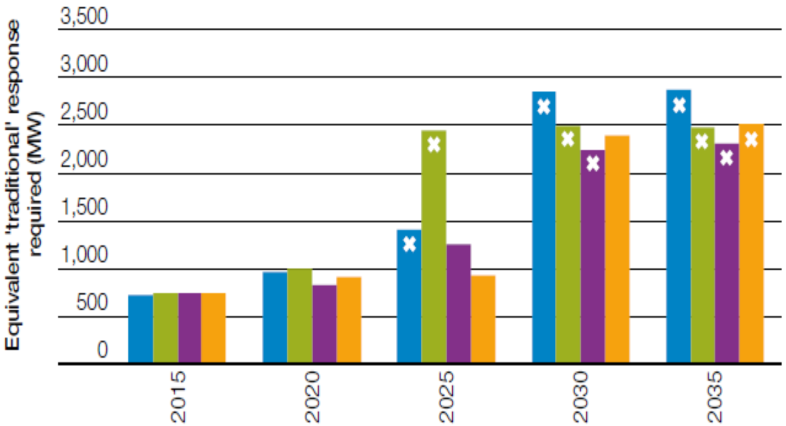
Background and Motivation

- Reduction in effective system inertia and possibility of larger infeed losses
  - Unacceptable RoCoF (>1 Hz/s) and frequency nadir (<49.2 Hz)
- Mitigation - Rapid frequency response (RFR) from
  - Wind farms, HVDC infeed, storage

    AND/OR

  - **Fast load/demand response**
    - On-off (duty cycle) control of **thermostatically controlled loads (TCLs)**
    - Exploit flexibility in other load types using ‘Electric Spring’
      - **Voltage control** of suitable **static loads** (e.g. heating, some lighting)
      - **Frequency control** of suitable **drive-controlled motors** (e.g. blowers)



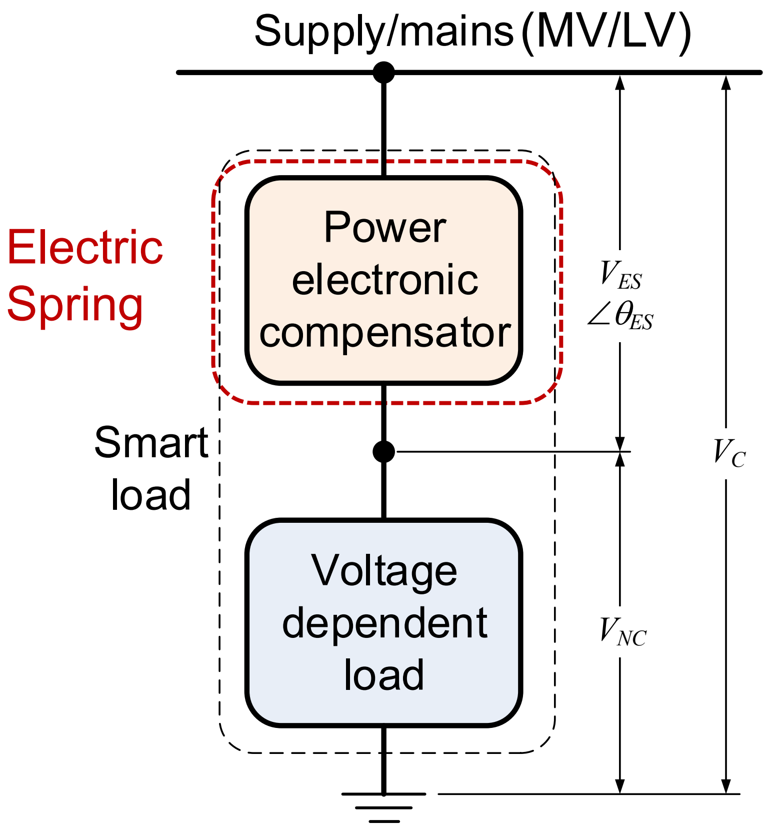


Traditional primary frequency response required in absence of alternatives

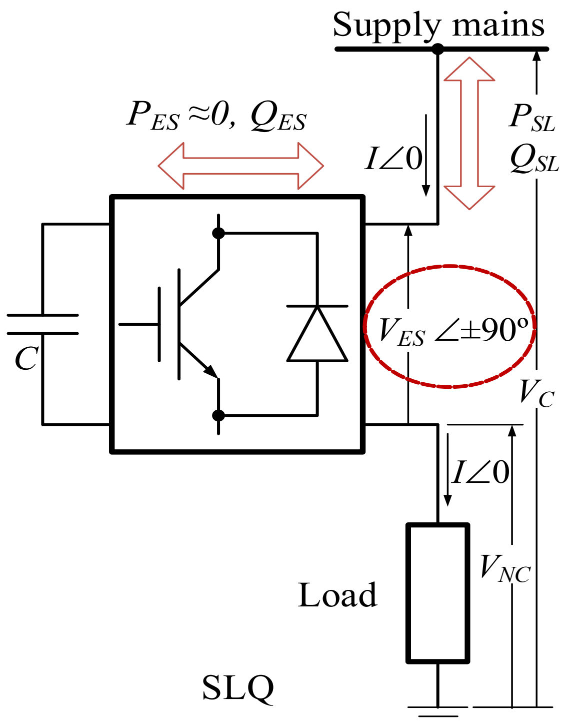
Source: National Grid. System Operability Framework 2015

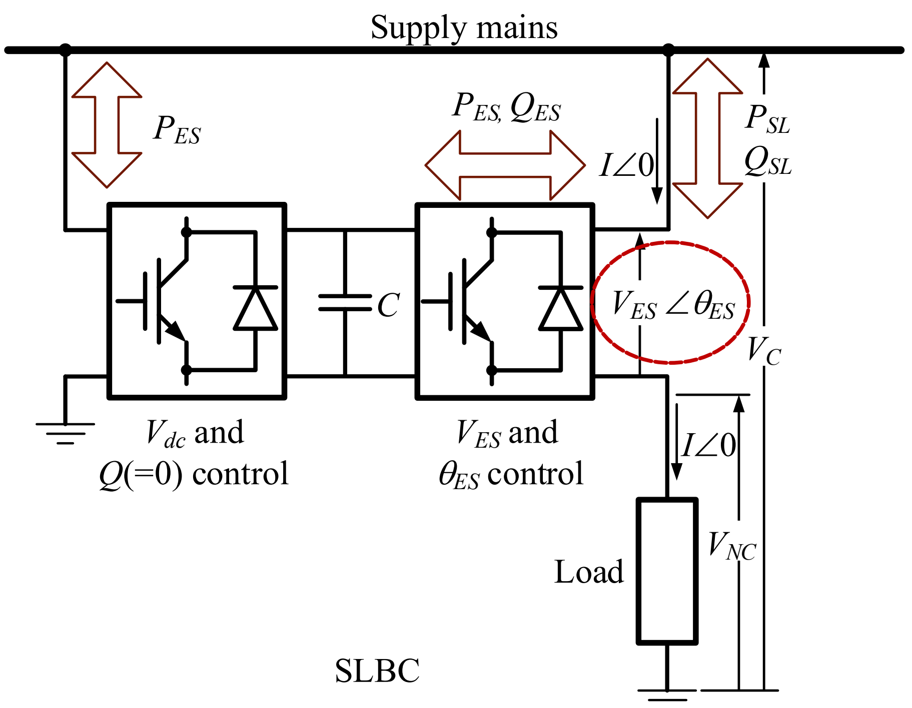
What is Electric Spring?

- Series compensator with cluster of voltage dependent loads
- Inverter rating is part of the nominal load rating
- Injected voltage ($V_{ES}\angle\theta_{ES}$) controlled to regulate mains voltage (V_C) while allowing load voltage (V_{NC}) to vary
- Can provide voltage and/or frequency regulation
- Can be of two types
  - Reactive compensation only (SLQ)
  - Back-to-back inverter arrangement (SLBC)



Smart Load Types





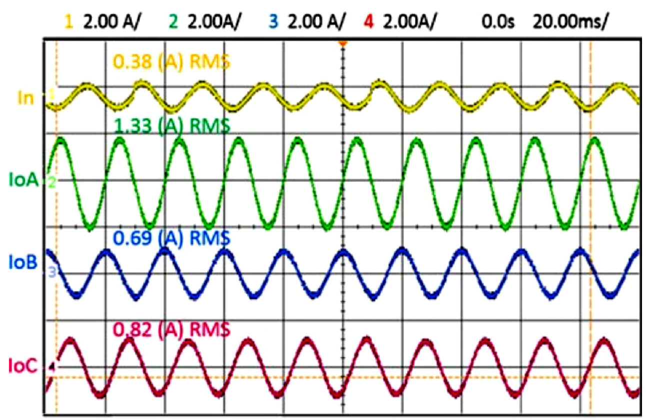
- Single inverter (cheaper, lower losses)
- Only Q support (V_{ES} angle fixed at ±90°)
- Voltage **OR** Frequency regulation
- Limited capability

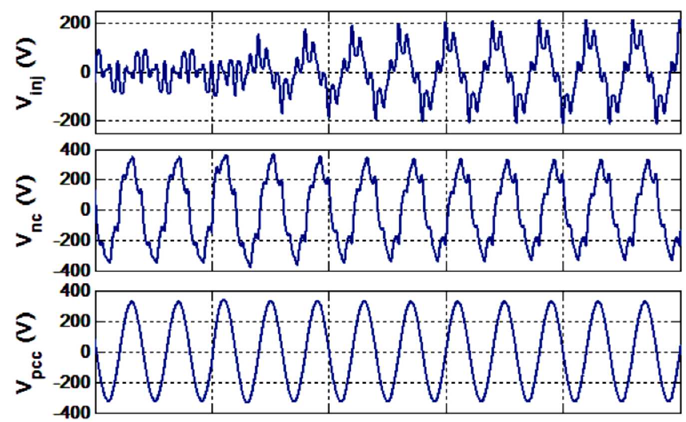
- Two converters (expensive, higher losses)
- Both P&Q support (V_{ES} & θ_{ES} control)
- Voltage and/or Frequency regulation
- Wider capability

Applications of Smart Load

Smart Load applications

- Frequency regulation
- Voltage regulation
- Oscillation damping
- 3-phase power balance
- DC Electric Spring
- Power Quality
  - Voltage harmonic reduction
  - Power factor correction





- Reduction in power imbalance by altering SL line currents both in amplitude and phase. [1]
- Reduce voltage distortion at PCC by dropping harmonic voltage across non-critical load. [2]

[1]. Shuo Yan et al ‘Electric Springs for Reducing Power Imbalance in Three-Phase Power Systems’, IEEE Transactions on Power Electronics
[2]. Parag Kanjiya et al ‘Enhancing Power Quality and Stability of Future Smart Grid with Intermittent Renewable Energy Sources Using Electric Springs’, International Conference on Renewable Energy Research.

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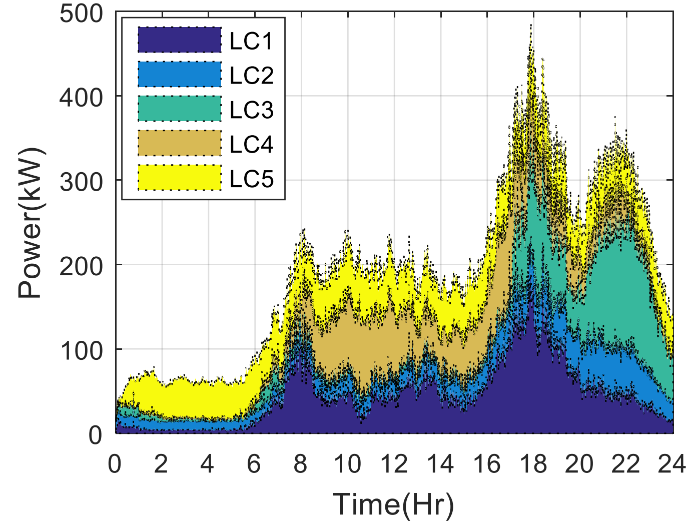
- ❑ Distribution network stability analysis

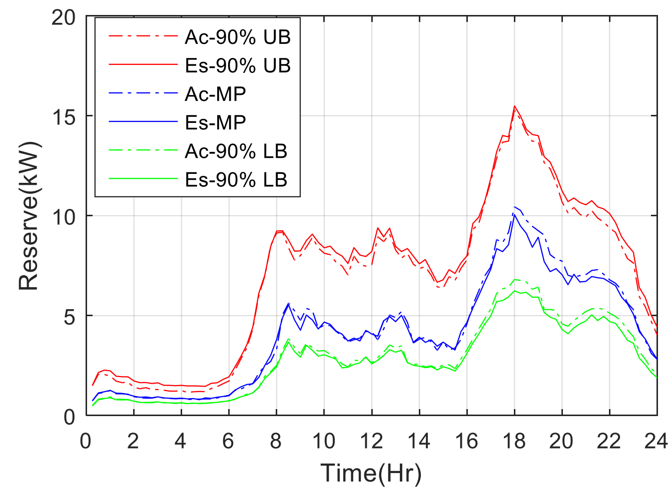
Load disaggregation using substation measurement

Load disaggregation using ANN

- Offline training process
- Real time estimation of reserve within certain confidence bounds
- Only substation P,Q & V measurements needed
- Does not rely on smart meter data, customer surveys or high resolution load signatures
- Does not require knowledge of distribution network topology

BSP Load disaggregation



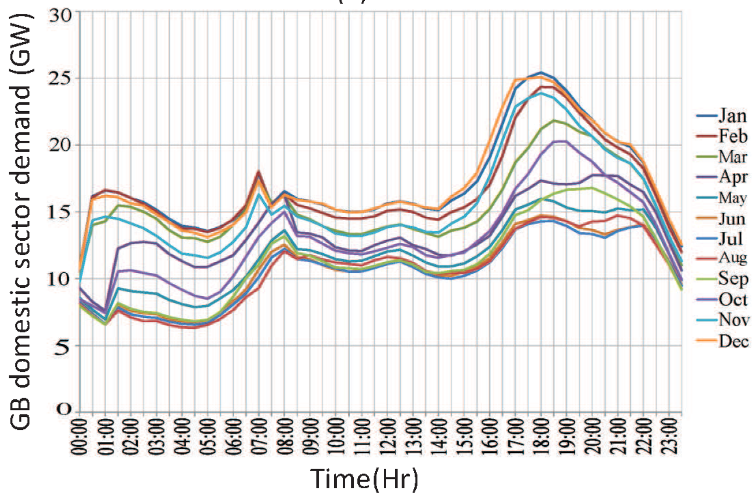


Reference: D. Chakravorty; B. Chaudhuri; S. Y. R. Hui, "Estimation of Aggregate Reserve with Point-of-Load Voltage control," in IEEE Transactions on Smart Grid , pp.1-10

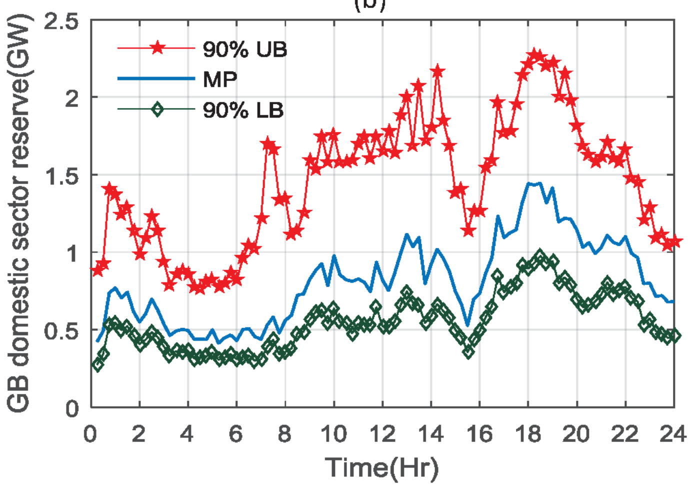
Estimated Enhanced Response from domestic sector

A case study in GB domestic sector

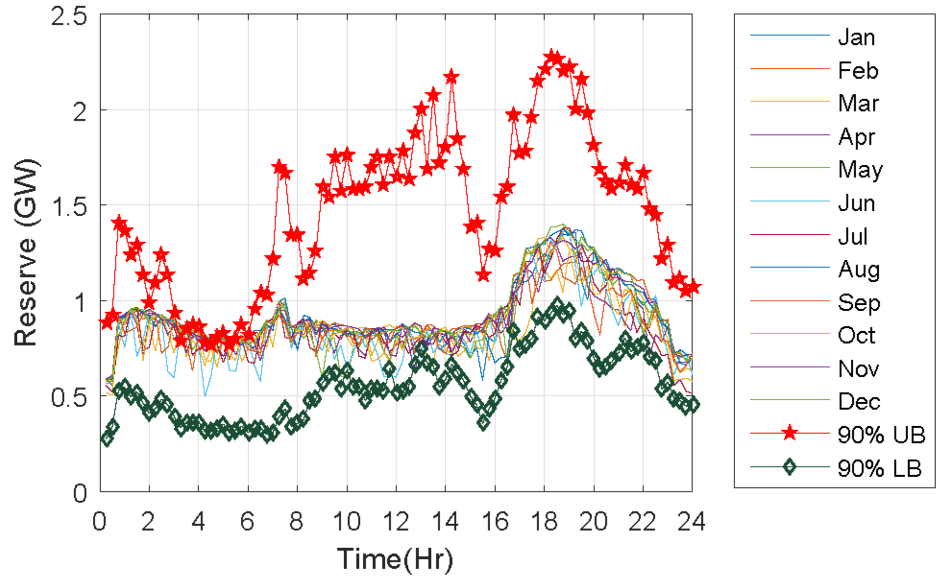
(a)



(b)

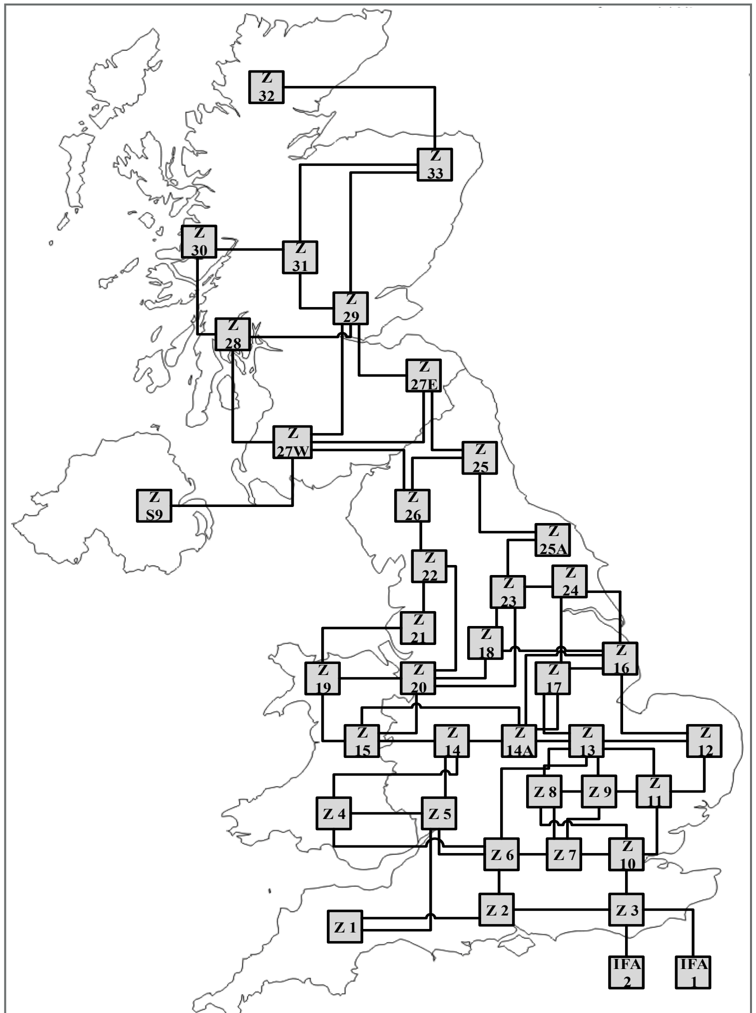


Validation of bounds on estimated reserve



- Most probable estimated reserve around 0.5GW from midnight till 8am and a peak value of **1.5GW around 6pm**
- GB domestic sector alone could provide significant part of 800-950MW enhanced response required under future low inertia scenario

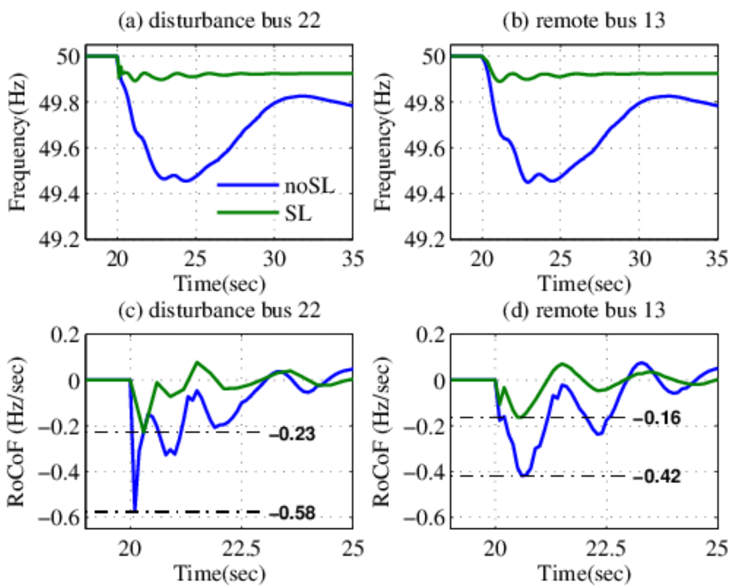
37 zone reduced equivalent GB system



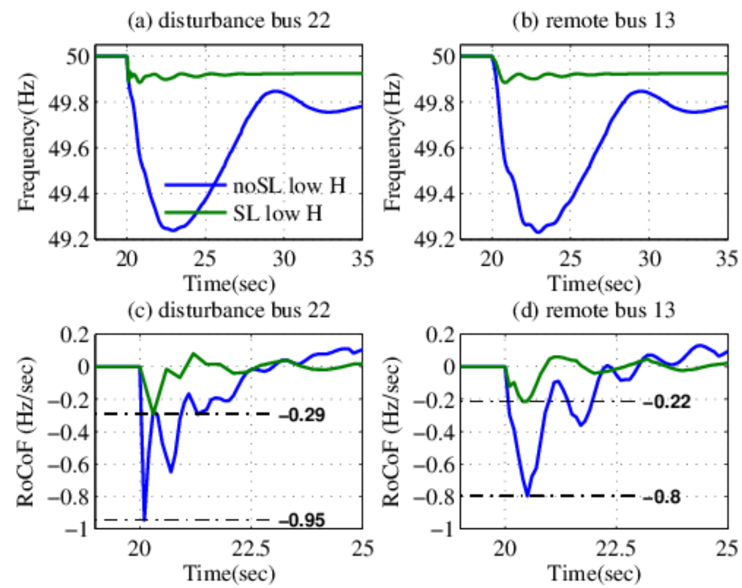
- Aggregated load at each bus divided into critical and non-critical/controllable loads in proportion to the actual load classification
- Non-critical loads operated as smart loads
- Nuclear plant in Zone22 tripped
- Outage is around 2GW, slightly higher than spinning reserve of 1.8GW

Frequency/RoCoF: Dynamic variations

Base case (6.5% NSG)



Low inertia scenario (20% NSG)



- SLs effectively arrest frequency nadir and **improve RoCoF**
- RoCoF values calculated using 100 ms sliding window

- Similar disturbance results in more severe frequency excursion and RoCoF
- **More primary reserve required to tackle disturbance in future**

Reference: D. Chakravorty; B. Chaudhuri; S. Y. R. Hui, "Rapid Frequency Response From Smart Loads in Great Britain Power System," in IEEE Transactions on Smart Grid , pp.1-10

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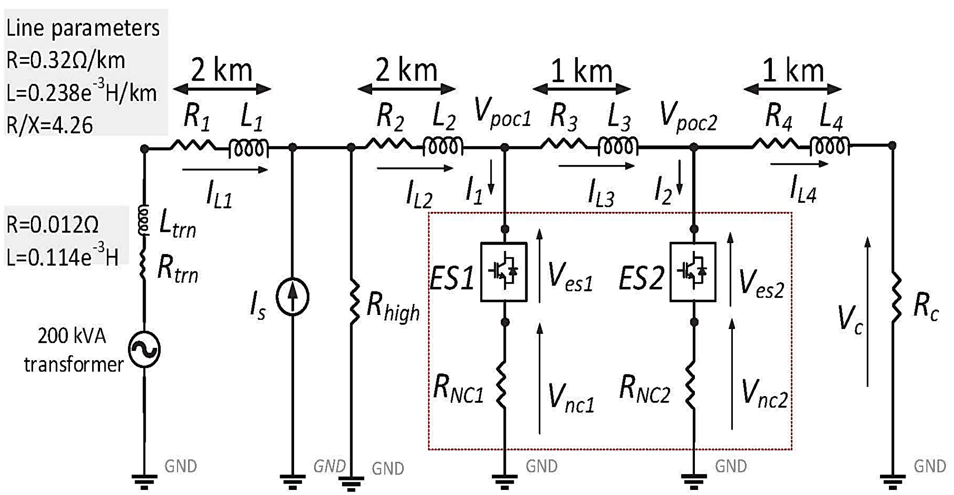
Frequency Domain Analysis

Study Network



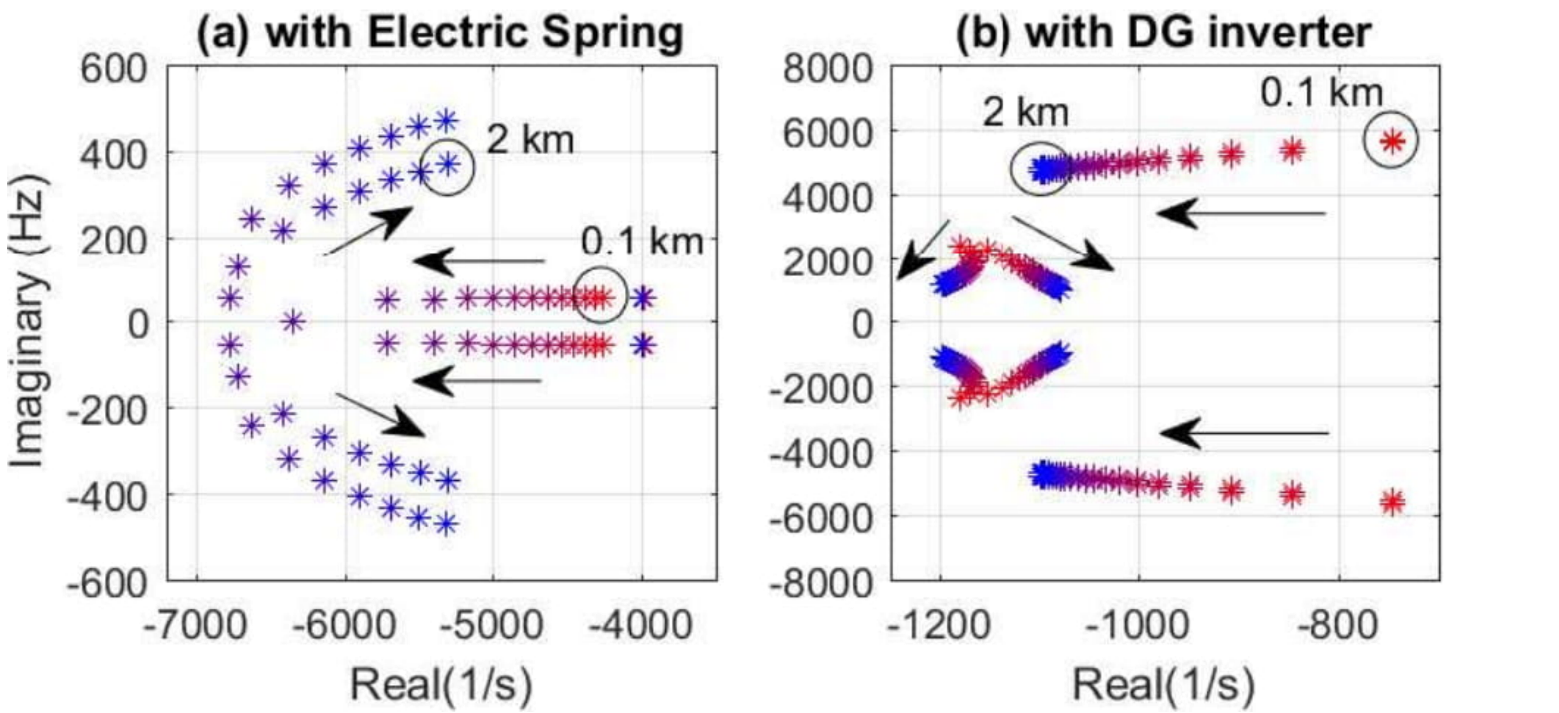
Studied Scenarios

Parameter Variation	Scenario
L1 & L2	Location of Electric Spring with respect to the substation
L3	Proximity of adjacent Electric Springs
R/X ratio	Dense urban (R/X≈4) to sparse rural (R/X≈10) LV network as well MV network (R/X≈1)

- Small signal stability analysis of distribution network with (a) ESs (**series converter**) (b) STATCOM or DG inverter (**shunt converter**)
- Dynamic response of state variables in linearized model validated with non-linear model
- Network parameters varied to see movement of critical system modes

Reference: D. Chakravorty; B. Chaudhuri; S. Y. R. Hui, “Small Signal Stability Analysis of Distribution Networks with Electric Springs," in IEEE Transactions on Smart Grid , pp.1-10

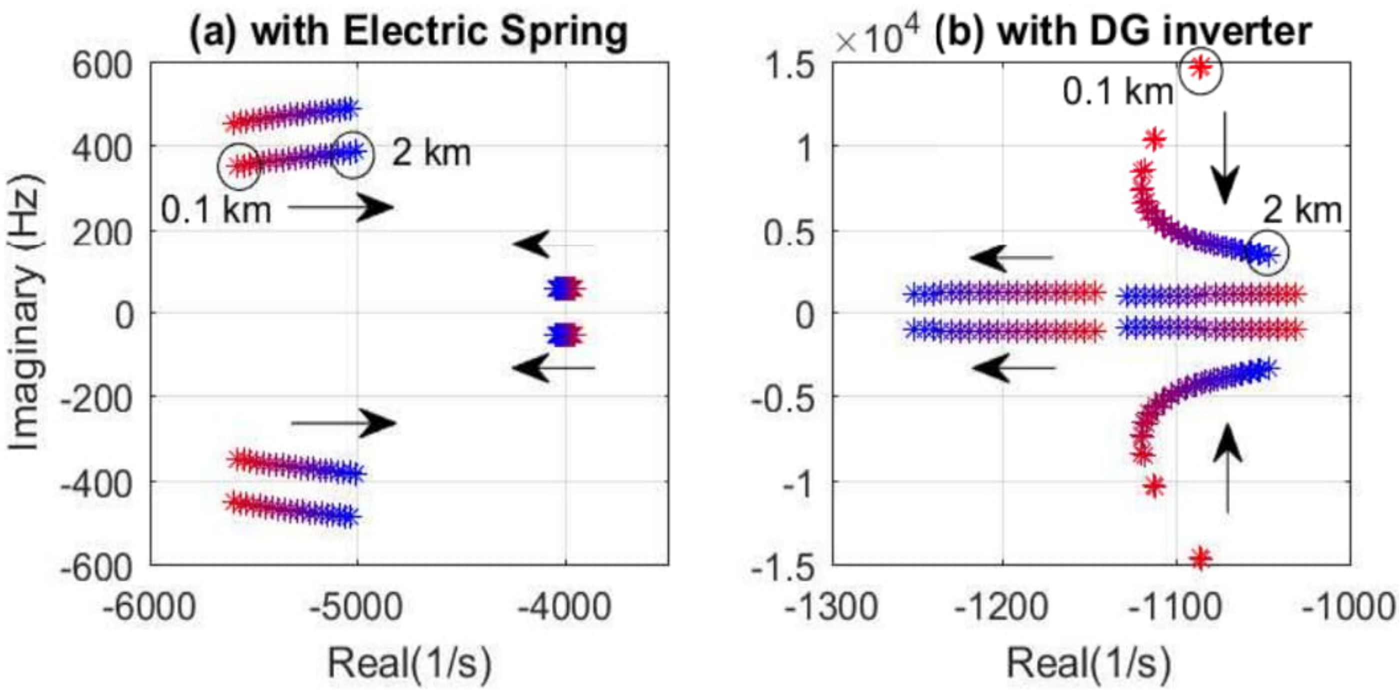
Distance from Substation



- Length of line segments **L1 & L2 varied** keeping everything else constant
- Movement of 472 Hz & 369 Hz modes **away from the imaginary axis**
- With ES, modes are much further away compared to the case with DG inverters

Reference: D. Chakravorty; B. Chaudhuri; S. Y. R. Hui, “Small Signal Stability Analysis of Distribution Networks with Electric Springs," in IEEE Transactions on Smart Grid , pp.1-10

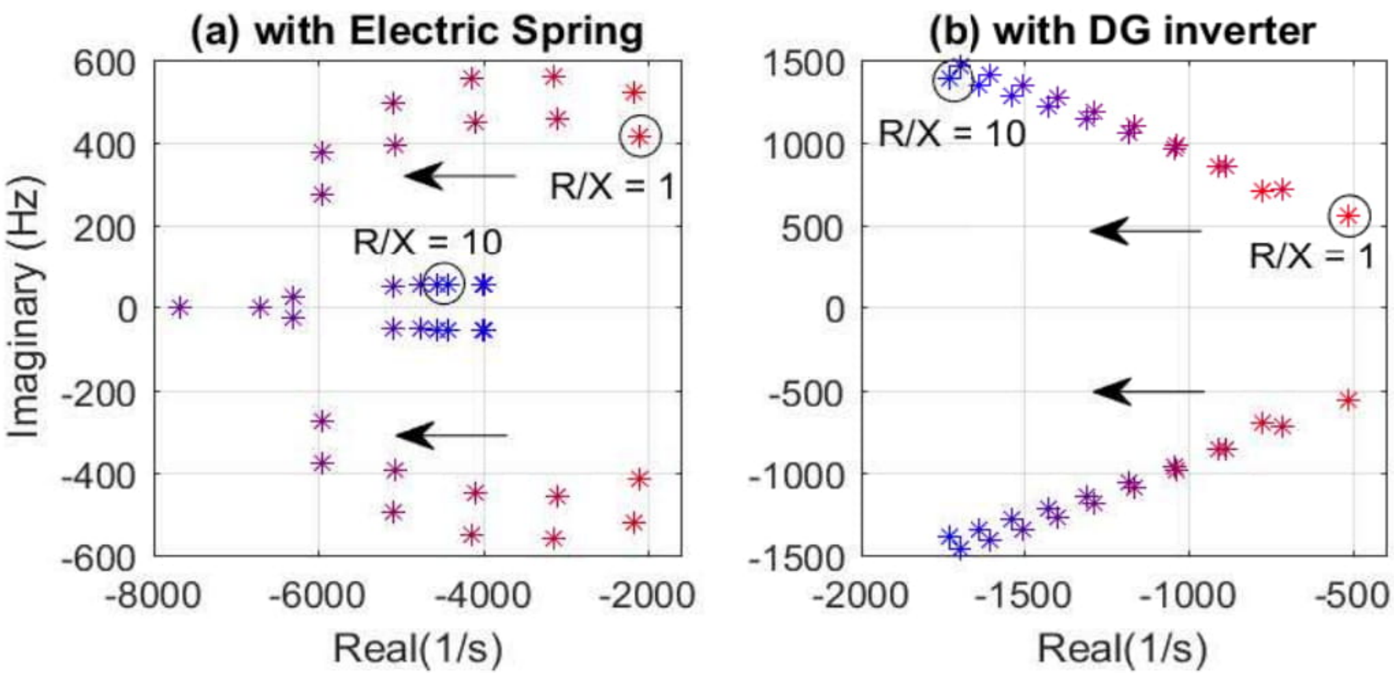
Proximity of Adjacent Converters



- Length of line segment **L3 is varied** to represent electrical proximity of adjacent ES or DG inverters (installed at POC of a cluster of customers)
- Separation distance has **hardly any influence** on the modes
- DG inverters in close electrical proximity will result in modes > 10 kHz

Reference: D. Chakravorty; B. Chaudhuri; S. Y. R. Hui, "Small Signal Stability Analysis of Distribution Networks with Electric Springs," in IEEE Transactions on Smart Grid , pp.1-10

Distribution Network Voltage Level



- R/X ratio of line segments varied between 1 (MV) to 10 (LV-sparse rural network)
- Dominant participation in the 472 Hz & 369 Hz modes
- With **higher R/X ratio**, modes move further to the left due to **higher damping**
- Similar effect is observed in case of DG inverter

Reference: D. Chakravorty; B. Chaudhuri; S. Y. R. Hui, “Small Signal Stability Analysis of Distribution Networks with Electric Springs," in IEEE Transactions on Smart Grid , pp.1-10

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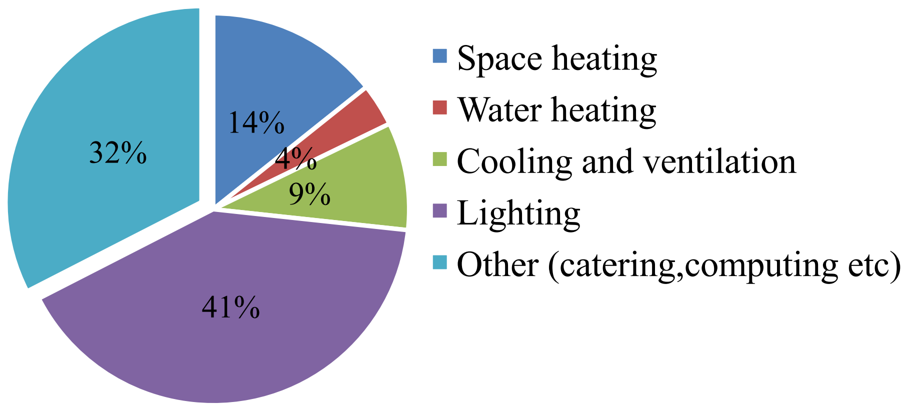
Conclusion

- Electric Springs are not likely to threaten the small signal stability of the network.
- Stability margin of Electric Spring is higher than equivalent penetration of DG inverters
- Significant reserve can be unlocked through point-of-load voltage control
- Enhanced response from smart loads can effectively support the grid frequency in the event of a large disturbance

Thank You

Extra Slides

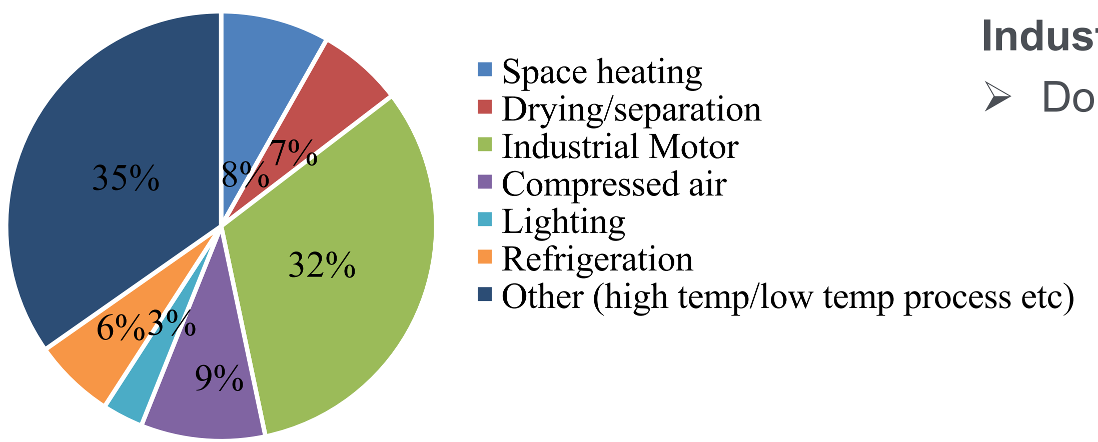
[1]Load Sectors in GB



Service

Service sector loads

- Dominated by lighting load



Industry

Industrial sector loads

- Dominated by industrial motor

1. Department of Energy and Climate Change (2014). Energy Consumption in the UK Overall data tables 2014 update. [Online]. Available:https://www.gov.uk/government/statistics/energy-consumption-in-the-uk

Reserve from smart loads (SLs)

Reserve from non-motor SLs

- Estimated reserve ≈**1.7 GW**
- Lighting load provides maximum reserve
- Essential public service lighting (e.g. healthcare, transport) not included

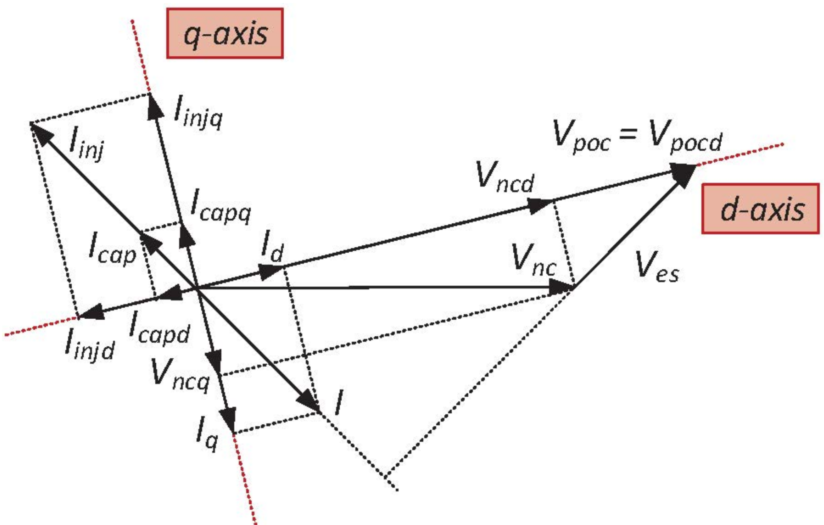
Total reserve from non-motor and motor smart loads ≈ 2.6 GW (considering conservative figures for load factor and node voltages)

Reserve from motor SLs

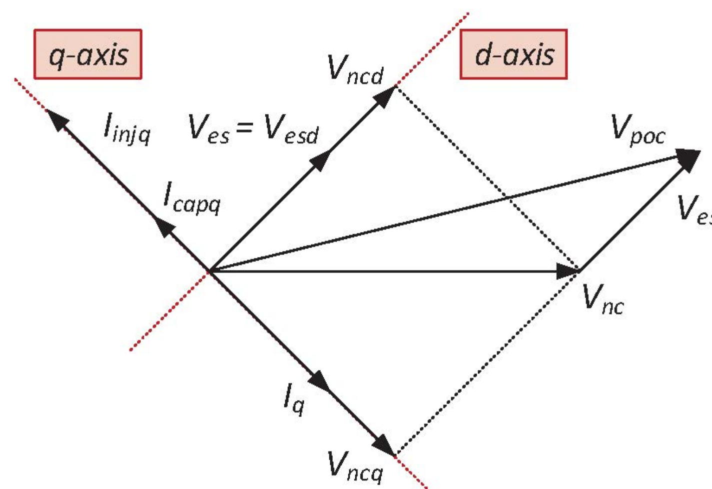
- Estimated reserve ≈ **0.8 GW**
- 80% of (industrial + commercial) motor loads are DOL type.
- Out of remaining 20%, 30% of motor drives are for critical application
- DOL motors and critical application motors not considered

Reference: D. Chakravorty; B. Chaudhuri; S. Y. R. Hui, "Rapid Frequency Response From Smart Loads in Great Britain Power System," in IEEE Transactions on Smart Grid , pp.1-10

Choice of reference frame



(a) D-axis aligned with PoC voltage



(b) D-axis aligned with capacitor voltage

- Aligning d-axis with PoC voltage results in non-zero inverter current on both axes
- Not possible to ensure zero active power exchange in steady state
- Aligning with filter capacitor voltage enables d-axis control loop to maintain dc link voltage while q-axis can be used for regulating PoC voltage