Hardware-in-the-loop (HIL) Test of Demand as Frequency controlled Reserve (DFR)

QIUWEI WU/Associate Professor
Center for Electric Power and Energy (CEE)
Technical University of Denmark (DTU)

15th September 2016

Outline

- PowerLabDK
- Wind power in Denmark
- DFR control logics
- Heat pump model
- HIL test
- Conclusions

TECHNOLOGY DEVELOPMENT | TESTING | TRAINING | DEMONSTRATION

PowerLab Combines Experimental Facilities in a Unique Platform

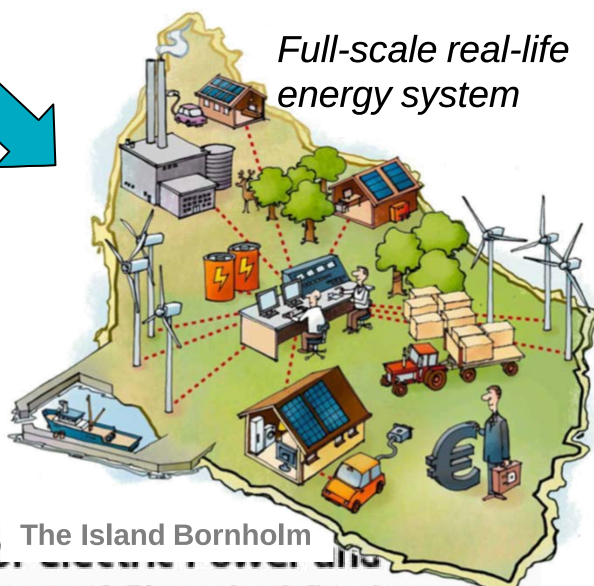
Flexible multi-purpose laboratories

Lyngby & Ballerup Campus

Large-scale test system

Risø Campus

Full-scale real-life energy system



The Island Bornholm

40,000 people
33% wind power
50% renewable energy
Islanding capability

Stakeholders:

ABB, nkt cables, DONG energy, SIEMENS, ENERGINET.DK, VATTENFALL, IBM

Supported by:

GREEN LABS DK, Vækstforum Hovedstaden, EUDP, VÆKSTFORUM SJÆLLAND

Investment:
18 million Euro

PowerLabDK

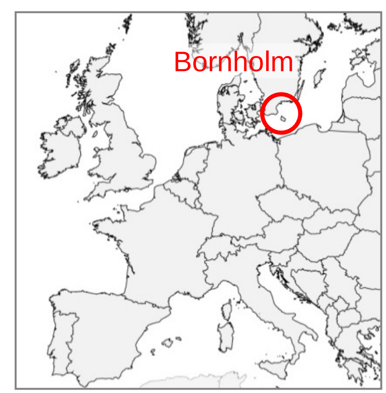
TECHNOLOGY DEVELOPMENT | TESTING | TRAINING | DEMONSTRATION

Bornholm - Full-scale Living Laboratory with 40,000 Inhabitants and 50% Renewable Energy Penetration

BRIGHT GREEN ISLAND
BORNHOLM

Resources:
- *Wind power*
- *Biomass*
- *Biogas*
- *District heating*
- *Combined heat and power*
- *Solar power*
- *eMobility*
- *Active demand*

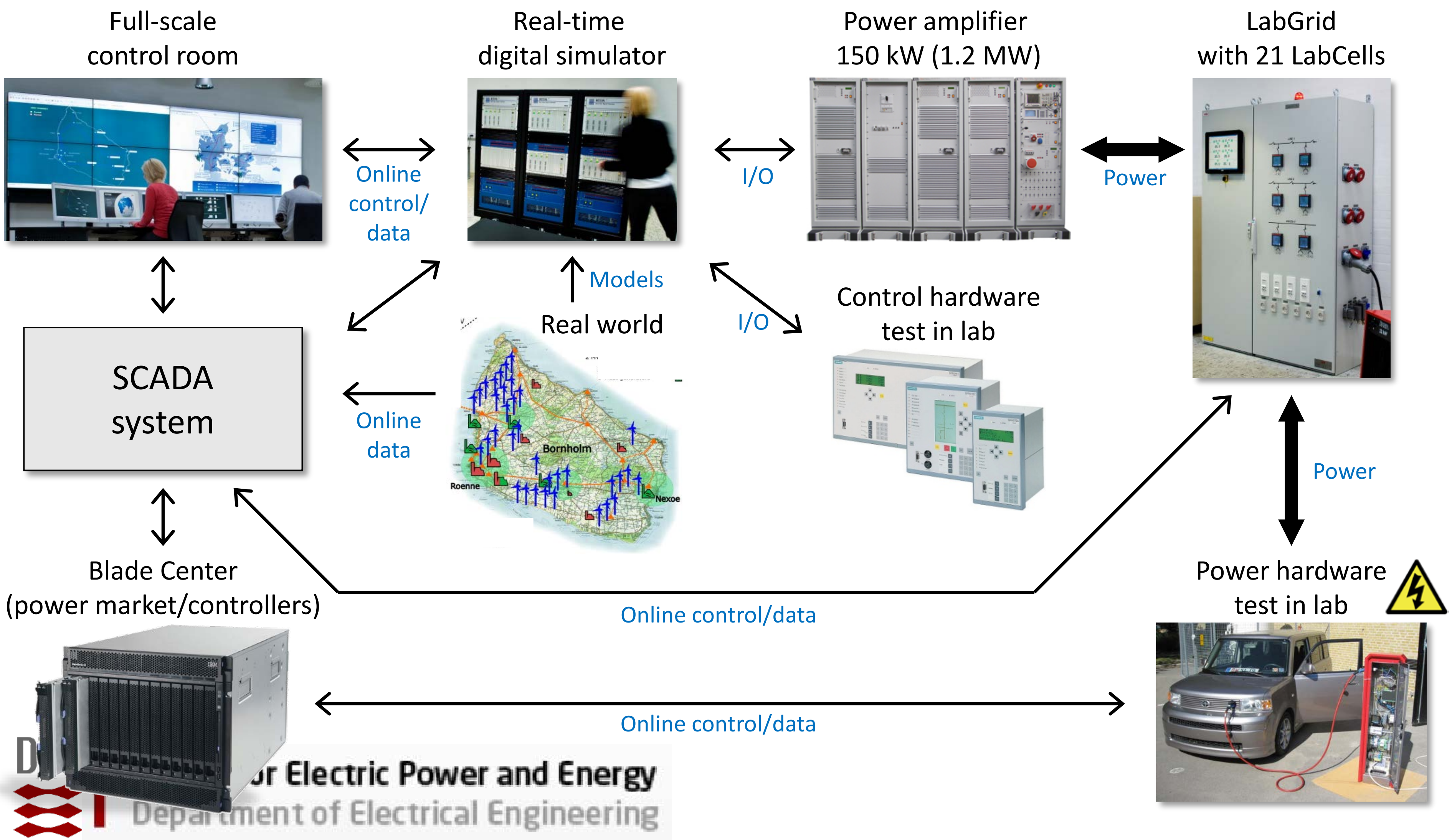
Features:
- *Nord Pool market*
- *Islanding capability*



DTU
Center for Electric Power and Ene...
Department of Electrical Engineering

PowerLabDK

Intelligent Control Lab - Test-bed for Integrated Experiments



Outline

- Intelligent control lab of PowerLabDK
- Wind power in Denmark
- DFR control logics
- Heat pump model
- HIL test
- Conclusions

Wind Power in Denmark

Year 2014

Danish wind power generation: 39.1% of the electricity consumption

January 2014

Danish wind power generation: 63.3% of the electricity consumption

December 21th 2013

Danish wind power generation: 102% of the electricity consumption

Single hour July 9th 2015

Danish wind power generation: 140% of the electricity consumption

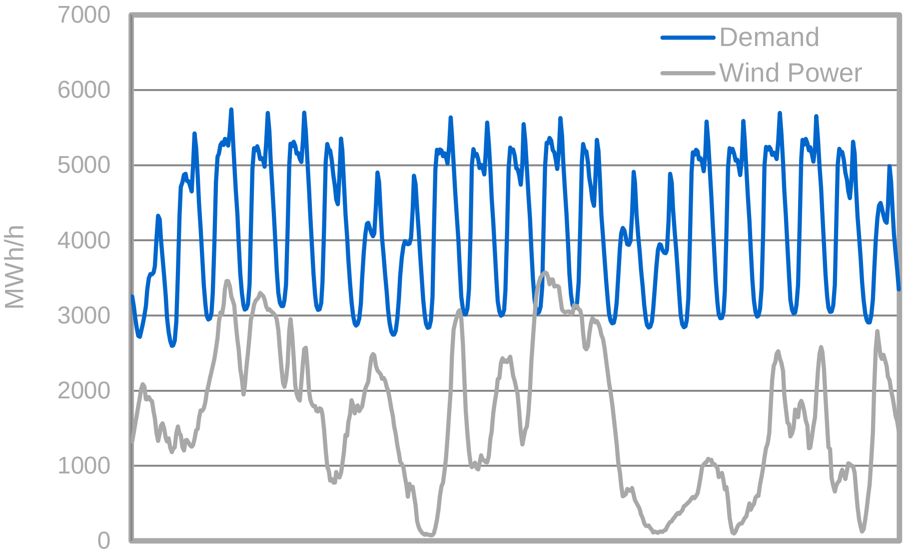
March 11th 2014

only 9 MW wind power generated out of installed 4,900 MW

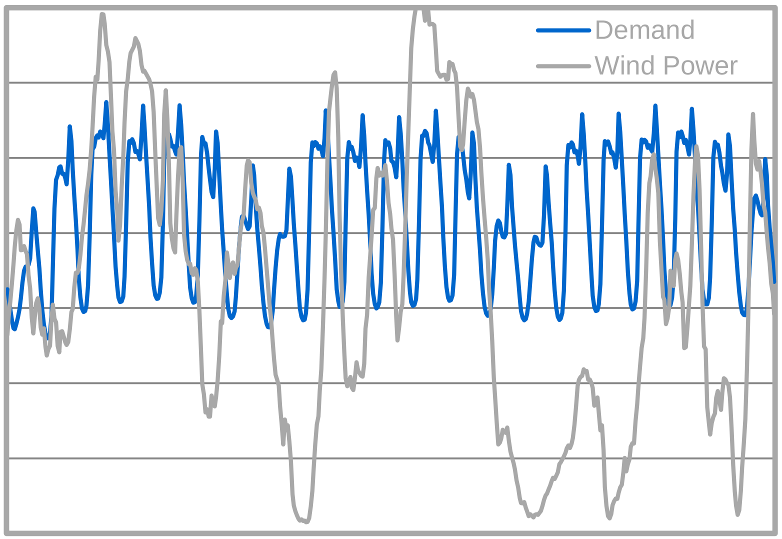
but 480 MW out of 580 MW solar units supplied the grid

Wind Power in Denmark

2012
25% wind power



2020
50% wind power

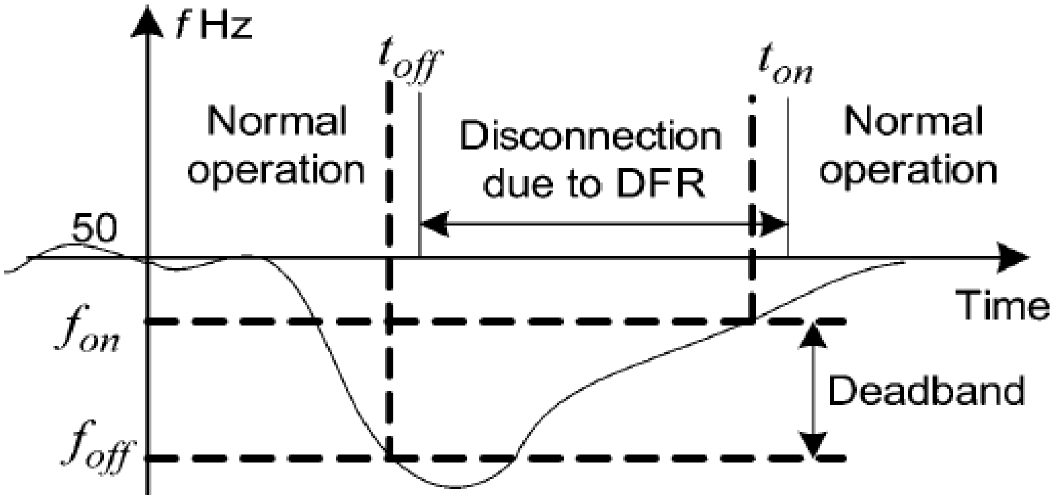


Outline

- Intelligent control lab of PowerLabDK
- Wind power in Denmark
- DFR control logics
- Heat pump model
- HIL test
- Conclusions

DFR Control Logic

The DFR control logic type I disconnects and reconnects electric appliances to the grid when the system frequency falls below f_{off} and recovers above f_{on}, respectively

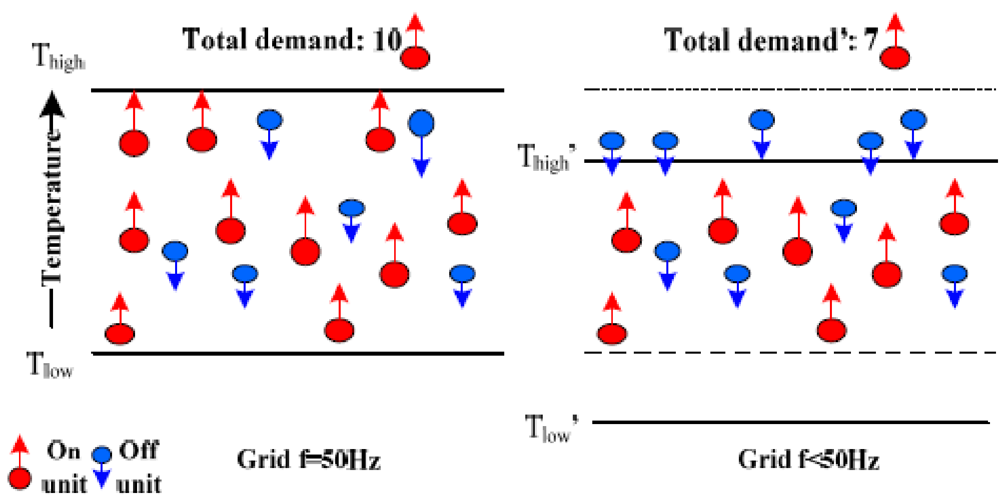


DFR Control Logic

The DFR control logic type II is customized for switching the thermostatically controlled loads by adjusting the nominal temperature set points T_{high}^{normal} and T_{low}^{normal} .

$$T_{high} = T_{high}^{normal} + kf(f - f_0)$$

$$T_{low} = T_{low}^{normal} + kf(f - f_0)$$



Outline

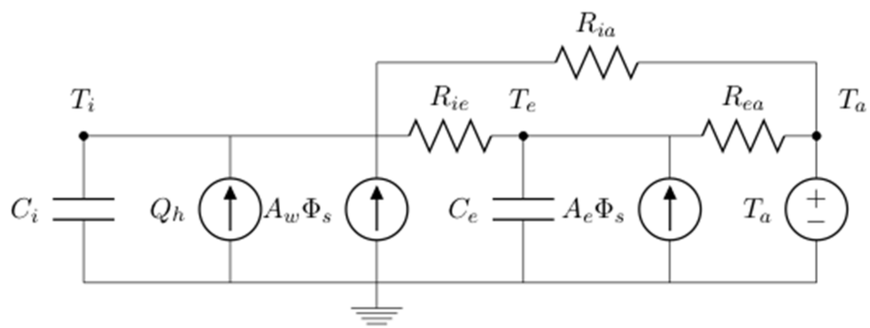
- Intelligent control lab of PowerLabDK
- Wind power in Denmark
- DFR control logics
- Heat pump model
- HIL test
- Conclusions

Heat Pump Model

- The dynamics of a direct air heating system can be sufficiently described by three thermal masses.
- The ambient air of the building interior has smaller storage volume, and defines a faster dynamics of the system.
- the larger storage volume of the building envelope, or structure, describes a slower dynamics of the system

$$\dot{T}_i = \frac{I}{C_i}\left(\frac{1}{R_{ie}}(T_e - T_i) + \frac{1}{R_{ia}}(T_a - T_i) + Q_H + A_w\Phi_s\right)$$

$$\dot{T}_e = \frac{I}{C_e}\left(\frac{1}{R_{ea}}(T_a - T_e) + \frac{1}{R_{ie}}(T_i - T_e) + A_e\Phi_s\right)$$



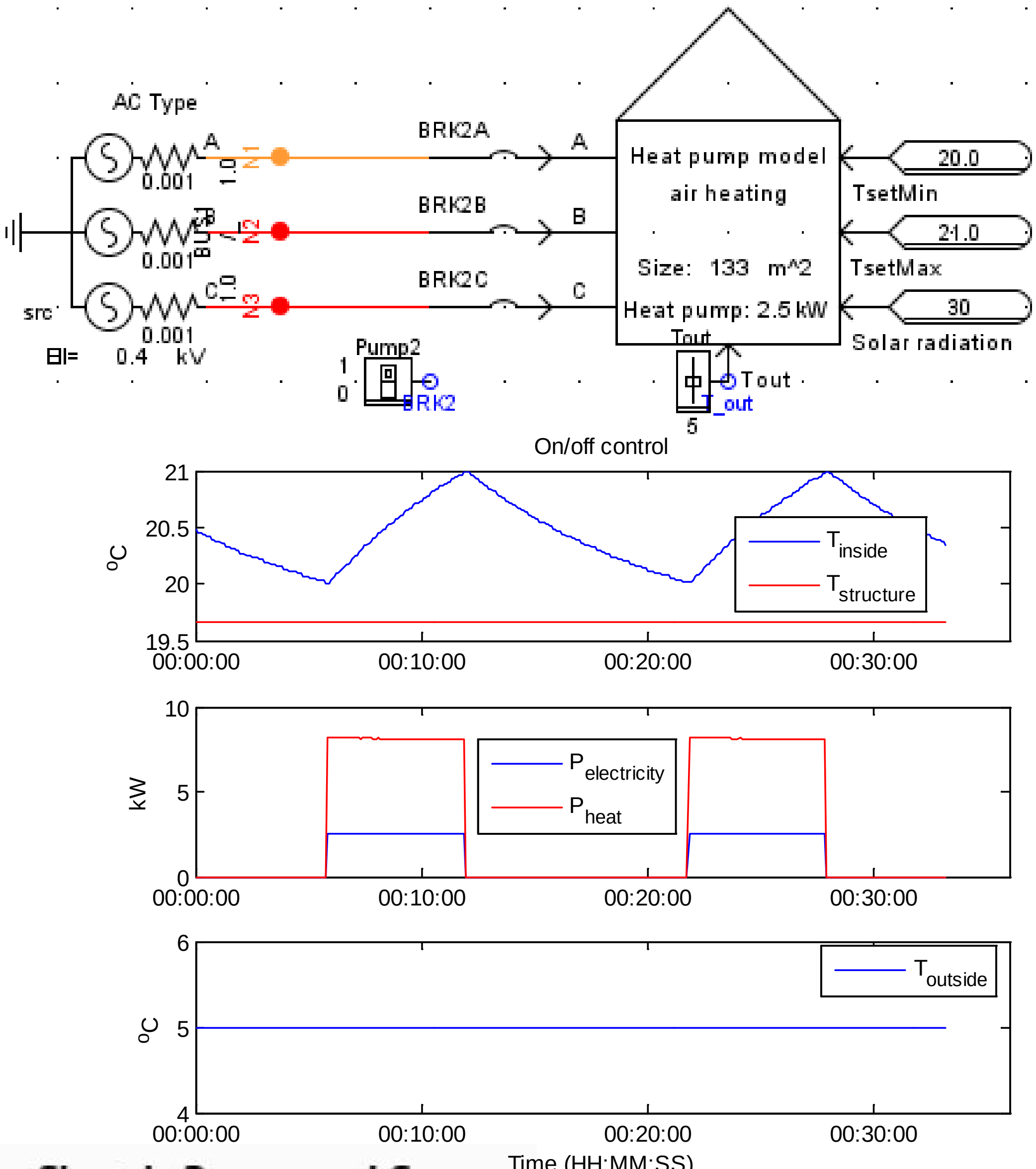
Outline

- Intelligent control lab of PowerLabDK
- Wind power in Denmark
- DFR control logics
- Heat pump model
- HIL test
- Conclusions

HIL Test


RTDS
GTAO
GTDI
Freq, current and voltage (analog)
Relay (digital)
Smartbox

HIL Test



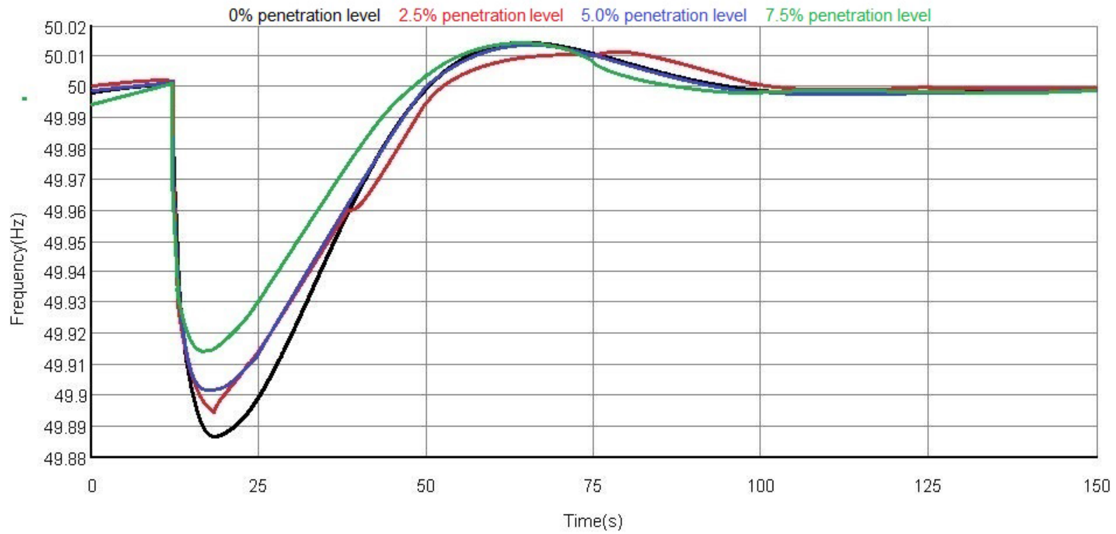
AC Type
BRK2A
BRK2B
BRK2C
A
B
C
Heat pump model
air heating
Size: 133 m^2
Heat pump: 2.5 kW
20.0
TsetMin
21.0
TsetMax
30
Solar radiation
Tout
Pump2
0.4 kV
On/off control
T inside
T structure
P electricity
P heat
T outside
Time (HH:MM:SS)

HIL Test

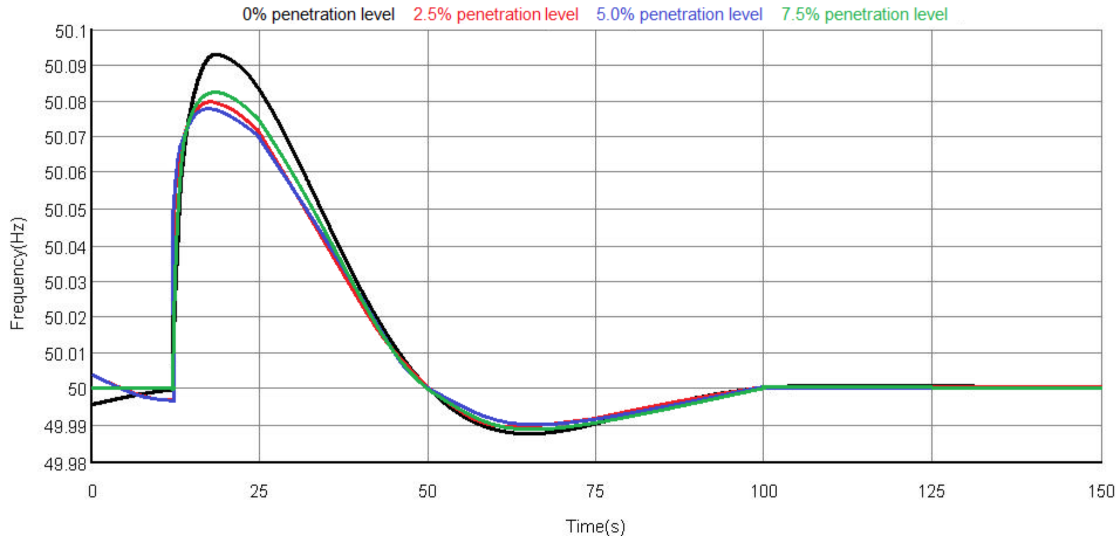
Table 1: Test Scenarios

Contingency Type	Ratio of Demand Change	DFR penetration level			
Demand increase	5%	0%	2.5%	5%	7.5%
Demand decrease	5%	0%	2.5%	5%	7.5%

HIL Test


0% penetration level
2.5% penetration level
5.0% penetration level
7.5% penetration level
50.02
50.01
50
49.99
49.98
49.97
49.96
49.95
49.94
49.93
49.92
49.91
49.9
49.89
49.88
Frequency(Hz)
0
25
50
75
100
125
150
Time(s)

(a)


0% penetration level
2.5% penetration level
5.0% penetration level
7.5% penetration level
50.1
50.09
50.08
50.07
50.06
50.05
50.04
50.03
50.02
50.01
50
49.99
49.98
Frequency(Hz)
0
25
50
75
100
125
150
Time(s)

(b)

Outline

- Intelligent control lab of PowerLabDK
- Wind power in Denmark
- DFR control logics
- Heat pump model
- HIL test
- Conclusions

Conclusions

- The DFR technology has been developed to utilize the demand side resources to provide fast reserves needed in the future renewable based power system.
- The DFR technology has been tested by offline simulations in the previous work.
- The real time HIL tests were conducted to verify the effectiveness of the DFR technology.
- The HIL test results show that the DFR technology can successfully arrest the system frequency and illustrate the efficacy of the SmartBox.

Thank you for your attention