Smart Energy Systems Laboratory
A Real-Time Control, ICT and Power HIL Platform

Dr. Florin Iov
Lennart Petersen

Department of Energy Technology
Aalborg University
Outline

- Background
- Overview
- Smart Grid Applications
- Wind Power Application
- On-going Activities
- Summary and Future Work
Background

**SmartC2Net**, EU-FP7 (€ 4.9M), 2012-2015 [www.smartc2net.eu](http://www.smartc2net.eu)

Mission: To develop, implement and validate robust solutions that enable Smart Grid operation on top of heterogeneous off-the-shelf communication infrastructures with varying properties.

Goals:

i) to provide a reliable energy infrastructure at low infrastructure costs

ii) to position the capabilities of telecommunication operators and energy system integrators in the Smart Grid value chain creating benefits for all stake-holders

External Generation Site UC defined in July 2013
Background

Requirements

• Integration of various hardware platforms as provided by partners
  – Data concentrator for smart meters
  – Hierarchical control
    • Demand response platform
    • Voltage control
    • Loss minimization
• Real-time modelling of a MV/LV grid (more than 60 buses)
• Real components for devices (emulators) -> Power HIL
• Flexible ICT layer
  – Configuring different network technologies
  – Programming data traffic
  – Integration of a monitoring framework (ICT)
    • Adaptivity of controllers to traffic conditions
• Mobility and easy connectivity of components!
Overview

Initial Architecture

- **DSO/Control Center Layer**
  - DR
  - MVGC
  - LVGC
  - Plant Controller
- **Primary Substation Layer**
- **Secondary Substation Layer**
- **Communication Layer**
  - Local High-Speed Ethernet
  - RTDS + Linear Amplifier System
  - DER Emulator
- **Grid Model**
- **Communication Network Emulator**
- **Traffic Generator**
- **Setpoints/measurements**
- **Network Emulator**
- **Transformer**
- **Flexible Load Single Phase SmartMeter**
- **Hardware/SW Plant Controller**
- **Operator/Owner Layer**

**Function & Information Layers**

**Asset Layers**

**July 2013**
Overview

Location #1
October 2013 – March 2014

Location #2
April 2014 - September 2014

Location #3
November 2014 – 20th November 2015

Location #4
1st December 2015 – …
Overview

Final Architecture
Overview

Mapping of Domains/Zones/Layers

- Actors/Applications/Control
- Communication Network
- Electrical grid and assets
- GIS Map
Overview

Network Emulator & Traffic Generator

Technologies: xDSL, 3G, LTE
Traffic generation based on measurements

Delays

Data loss

Modify update rate
Overview

Control Layer
- Various PCs & servers
- Data Concentrator (EFACEC G-Smart)
- Demand Response (EFACEC’s Head-End system)

Power HIL components
Grid Simulator -> Fully 4Q Power Linear Amplifier (Grid simulator) 50 kVA
  - Voltage asymmetries and flickers
  - Harmonics and interharmonics up to 3 kHz

Physical Components
- DER (±20kW/±10kVAR): wind turbine, PV, energy storage
- AC loads - Flexible loads (1Ph, 3Ph)
- Smart meters

Protocols
- IEC 61850 SV/GSE -> protection
- IEC60870 104 -> telecontrol of electric power transmission systems
- DLMS -> smart meters
- oAdr -> demand response
- UDP
Applications

- Application #1 Demand Response Platform
  - Control and Market integration of Low Voltage distribution grids

- Application #2 Smart Grid Control
  - Power Balancing and Voltage Control in distribution grids

- Application #3 Wind Power Plant Control
  - Voltage control for a WPP augmented with STATCOM
Smart Grid Applications

Modified MV/LV grid nearby Aalborg (symmetrical & balanced representation)

Simulink Toolbox for Dispersed Generation and Loads (Opal-RT) -> minute time scale
- Household Models including load profiles
- Small & Large Wind turbines & plants
- Small PV systems and plants
- Energy storage
- Passive reactive power compensators
- Large Industry, Agriculture & Commercial Loads
Application #1 Demand Response

LV Grid

- 38 houses in a low voltage (LV) grid
  - 8 electric cars charging in 1-2 intervals per day
  - 5 kW electric heating in winter
  - PV generation in every house

Scenarios

- No control (no DMC)
- Baseline DMC: no loading limit in secondary substation transformer & fixed prices.
- Excessive consumption: reduce load if demand exceeds loading limit
- Excessive generation: limit overall injected power into LV grid
- Interruption – communication failures
- Spot price used for demand control
Application #1 Demand Response

Real-Time Digital Simulator

HV Transmission System
MV Distribution System
LV Distribution System

Constraints
Market Prices

Load Diagrams oADR

Flexibility oADR

Setpoints oADR

CEMS 01
CEMS 02
CEMS 38

CEMS 01
CEMS 02
CEMS 38

VM 01
VM 02
VM 38

Measurements DLMS

Measurements UDP

Virtual Smart Meters

Household models
Local Energy Management using Gurobi Suite

Power output UDP

Multi-physics domain modelling

Multi-physics domain modelling

Load Diagrams oADR

Flexibility oADR

Setpoints oADR

CEMS 01
CEMS 02
CEMS 38

CEMS 01
CEMS 02
CEMS 38

VM 01
VM 02
VM 38

Measurements DLMS

Measurements UDP

Virtual Smart Meters

Household models
Local Energy Management using Gurobi Suite

Power output UDP

Multi-physics domain modelling

Load Diagrams oADR

Flexibility oADR

Setpoints oADR

CEMS 01
CEMS 02
CEMS 38

CEMS 01
CEMS 02
CEMS 38

VM 01
VM 02
VM 38

Measurements DLMS

Measurements UDP

Virtual Smart Meters

Household models
Local Energy Management using Gurobi Suite

Power output UDP

Multi-physics domain modelling
Application #1 Demand Response

Results

Demand limit set to 70 kW
Reference power is always below limit
Results: Impact of temporary energy price increase

+10€/MWh
impact of increased price +10 between 18:00-19:00
on total load
Application #1 Demand Response

Results: Resilient Operation

Interruption scenario:
- Household become suddenly disconnected from DMC.
- Benefit: Cached plan is followed by local algorithm
Changes in consumption cannot be coordinated by the DMC
Application #2 Smart Grid Control

Control Objectives
Loss minimization
Power balancing
Voltage control
Application #2 Smart Grid Control

Functional focus
- Control functionality
- Monitoring framework functionalities
  - Reliable connections
  - Information access scheduling
Application #2 Smart Grid Control

Power Balancing

Objectives:
• Activate flexibility of assets in low voltage grid
• Follow power setpoints as results of bidding process on energy markets
Application #2 Smart Grid Control

Power Balancing

High Voltage Transmission Grid

Control Signal

MVGC

B1 - Slack

P_{ref}

P_{max}

20 kV

60 kV

B2

B3

B4

SPP

B5

Commercial

B6

B7

L6

Agriculture

B8

Supermarket

B9

Residential

B10

LVGC

B11

WPP

B12

Industry

B13

Industry

0.4 kV

0:00 6:00 12:00 18:00 24:00

Power [kW]

0

100

500

1000

0:00 6:00 12:00 18:00 24:00

Power [kW]

0

100

500

1000

0:00 6:00 12:00 18:00 24:00

Power [kW]
Application #2 Smart Grid Control

Voltage Control

Objectives:
- Activate controllability of LV assets using existing ICT
- Management of voltage profiles in MV/LV grids
Application #2 Smart Grid Control

Voltage Control

High Voltage Transmission Grid

60 kV

20 kV

B1 - Slack

LV PV System

Power [kW]

0:00 6:00 12:00 18:00 24:00

0 2 4 6

Power [kVA]

0:00 6:00 12:00 18:00 24:00

-4 -2 0 2 4

Voltage [PU]

0:00 6:00 12:00 18:00 24:00

0.0 0.8 1.0 1.2

Time [hrs]

No Control
30% Curtailment
P/Q Control
P Available

Residential

B14

B10

20 kV

0.4 kV

B14

B10

20 kV

0.4 kV

B17

B19

B20

B21

B22

B23

B26

B29

B30

B31

B32

B33

B34

B35

B36

B37

B38

B39

B40

B41

B42

B43

B44

B45

B46

B47

B48

B49

B50

B51

B52

B53

B54
SmartC2net Applications

Challenges
• Protocol interfacing Opal-RT vs. Industrial platforms
  – DLMS for Smart meters
  – oAdr for Demand response
• Setup UDP communication
• Implementing historic profiles for assets (wind, temperature, solar irradiation, load, etc) in Opal-RT
• Time frame -> 4 months to realize all implementation and running the tests

http://www.smartc2net.eu/public-deliverables.html

Application #3 WPP Control

MSc Thesis "Wind Power Plant Control Optimisation with Embedded Application of Wind Turbines and STATCOMs” *

- Dynamic voltage control
- Challenges of incorporation of WTGs and STATCOMs
- Tuning and optimization of park control

Control Design Criteria
- Dynamic response of the reactive power output
  - Delay time
  - Rise time
  - Settling time
  - Overshoot

Motivations for RT implementation:
- Control Validation
- HIL Testing
- Communication Properties

Application #3 WPP Control

- WPP Network
  - ePHASORsim

- Wind Turbines
  - Discrete State-Space Models for small voltage changes
  - In future: Dynamic simulation mode acc. to IEC 61400-27

- WPP Controller
  - 1\textsuperscript{st}: Simulation in Opal-RT
  - 2\textsuperscript{nd}: HIL testing
Application #3 WPP Control

System Implementation on Opal-RT Simulator

Implementation challenges:
- Different sampling times
- Splitting models
- Model discretization
Simulation Results

Validation of control tuning:
Closed-loop discrete RT system in vs. linearized state-space model in s-domain

Impact of discretization method:
Backward Euler vs. Tustin

Impact of control sample time:
Selected control sample time depends on communication technology (protocols & delays)
Application #3 WPP Control

Simulation Results

- Monitoring internal behavior of whole wind power plant
  → Voltage constraints within wind power plant
  → Reactive power capability limits of wind turbines
Application #3 WPP Control

System Implementation into RT-HIL Framework

Implementation challenges:
• Asset communication via UDP/IP (sampling rate, data format etc.)

Future opportunities with Bachmann controller system ↔ Opal RT:
• Testing with standardized communication protocols (e.g. IEC 61850 MMS)
• Voltage/current sampling via grid measurement module
### On-going Activities

**PSO-ForskEl RePlan**

**Control Centre**

**Primary Substation Control**

**Secondary Substation Control**

**Renewable Plant Control**

**Focus**
- Renewable generation plants HV & MV
- Coordinated Grid Support

**Control Functionalities**
- Frequency
- Voltage
- Rotor Angle Stability

**Partners:** AAU-WCN, DTU-VES, DTU-Elektro, Vestas

[http://www.replanproject.dk/](http://www.replanproject.dk/)
On-going Activities

PSO-ForskEl RemoteGrid

**Focus**
- Advanced Metering Infrastructure LV Grids
- Increase Visibility of LV grids in DSO Control Centre

**Functionalities**
- Near RT State Estimation
- Advanced Monitoring Functionalities and Warning System

**Partners:** AAU-WCN, Kamstrup, Thy-Mors Energi
Acknowledgement

Financial support

• Det Obelske Familiefond (www.obel.com)
• Aalborg University
• EU FP7 through SmartC2net Project
• PSO-ForskEl through EASE Wind Project
• PSO-Forskel through Control, Protection and Demand Response in Low Voltage Distribution Grids project
• PSO-Forskel through RePlan Project
• PSO-Forskel though RemoteGrid Project

Technical support and in-kind contributions

• Opal-RT Support Team: Ahmed Daher & Francois Tempez
• Bachmann Electronic Denmark (www.bachmann.info)
• EFACEC (www.efacec.pt)
• Regatron
• Danfoss Drives
• Kamstrup
Contact Info

Coordinator Smart Energy Systems Lab
Dr. Florin Iov fi@et.aau.dk

www.smart-energy-systems-lab.et.aau.dk