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Smart Distribution System Control Over Heterogeneous Communication Networks – SmartC2Net

SmartC2Net Consortium
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### Background

**Goal:** robust smart grid control utilizing heterogeneous (third-party) communication infrastructures

**Robustness against**

- Variability of network performance impacting
  1. Quality of the input data obtained from energy related information sources
  2. Timeliness/reactivity of the performed control actions (downstream communication)

- Security threats due to additional network interfaces and the use of off-the-shelf communication technology.
Case study
- MV and LV case from Støvring (DK)
  - Area covered: 100-200 km²

Contains
- Supermarkets
- One 2 MW industry
- PV’s
  - One 15 MW
  - 1-38 6 kW
- Windturbines (MV)
- 15 Secondary substations
- Households & buildings
  - 133 households
  - 4 commercial buildings
  - 3 agriculture farms
- Smart meters (~133)

No. of buses
- MV busses: 1-7
- LV busses: 8-48

No. of power lines
- MV: 8
- LV: 42
Use-cases & Control Architecture (2)

- **Medium Voltage Control and External Generation Site:**
  Periodic controllers determine set-points targeting
  - Energy Balancing (Reference Tracking)
  - Loss minimization
  - Voltage quality
  → LVGC and MVGC

- **Demand Management**
  Use demand and generation flexibility in order to
  - Realize economic benefit from dynamic prices
  - Avoid grid overflow
  → CEMS and Demand Management Control

CEMS = Customer Energy Management System

*SMART C²NET*
Use-cases & Control Architecture (3)

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  **Control Periods**
  - 1…15min
  - 1…5min

  **Control Period**
  - 15min
Impact of off-the-shelf communication technologies?

- Lab measurements of cellular 2G-4G, WLAN 802.11 type, narrow-band PLC, DSL
- Extrapolation to reference grid scenario in simulations
- Observations: when in ‘good’ conditions
  - delays mostly in sub-second regime and no loss
    - Cellular 2G/3G with eventual delays up to several 10s of seconds
  - All technologies have sufficient throughput to carry the Smart Grid control traffic when using ‘lean’ protocols

**2G statistics:**
Average RTT delay: 449.2ms, packet loss: 0%
Min. RTT: 161ms, Max. RTT: 6360ms

**3G statistics:**
Average RTT delay: 1013ms, packet loss: 0%
Min. RTT: 46ms, Max. RTT: 49138ms
Core Questions

1) Control Performance: What benefits (wrt. use-case KPIs) can be achieved by such control over ideal networks?

2) ICT impact: How do different communication technologies and ICT threat/fault scenarios impact control performance?

3) Robustness: How can control performance be assured despite variable communication behavior and ICT threats/faults?
Energy balancing in MV and LV grid
(part of use-case External Generation Site)
Energy balancing in Distribution Grid
Energy balancing in Distribution Grid

MVGC Reference Tracking

- Power Reference
- Ethernet Com.
- PLC Com.

Time of Day
4:00 8:00 12:00 16:00 20:00

Power [kW]
-1500
-1000
-500
0
500
1000
1500

MVGC

High Voltage Transmission Grid
60 kV
B1 - Slack

Control Signal

20 kV
B2
Industry

B3

B4
SPP

B5
Commercial

B6

B7
Agriculture

B8

B9
Residential

B10
Supermarket

B11
WPP

LVGC

0.4 kV

Residential
Energy balancing in Distribution Grid

MV Solar Power Plant

MV Wind Power Plant

Time of Day

Power [kW]

Available Power
Ethernet Com.
PLC Com.
Energy balancing in LV Distribution Grid

- Tracking error with ideal and imperfect communication in the LV grid
  - Control performance is not affected significantly
Energy balancing with higher control frequency

- Execution in Communication Technology test bed
  - over different real comm. tech.
  - with 10sec control periods
  - 16 minutes of real-time evaluation
    \((P_{\text{ref}}=-10kW \ [0-8\text{min}], \ P_{\text{ref}}=5kW \ [8-16\text{min}])\)
  - QoC = reference tracking deviation (RMSE) relative to case with ideal network

Small degradations observed only for EDGE
Increase of cross-traffic (here WLAN example)

- Causing losses 2%,...82% and longer delays from few ms to hundreds of ms to few seconds
- TCP (yellow) can compensate smaller fraction of losses

<table>
<thead>
<tr>
<th>Cross-traffic</th>
<th>Min. delay (ms)</th>
<th>Avg. delay (ms)</th>
<th>Max. delay (ms)</th>
<th>Packet loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 kbit/s</td>
<td>127.9</td>
<td>160.1</td>
<td>559.4</td>
<td>0%</td>
</tr>
<tr>
<td>6 kbit/s</td>
<td>809.4</td>
<td>1509.4</td>
<td>2029.9</td>
<td>73%</td>
</tr>
<tr>
<td>7 kbit/s</td>
<td>1222.5</td>
<td>1787.9</td>
<td>2495.4</td>
<td>91%</td>
</tr>
<tr>
<td>1.4 Mbit/s</td>
<td>4.1</td>
<td>6.5</td>
<td>12.2</td>
<td>0%</td>
</tr>
<tr>
<td>1.5 Mbit/s</td>
<td>28.7</td>
<td>29.0</td>
<td>30.9</td>
<td>66%</td>
</tr>
<tr>
<td>1.6 Mbit/s</td>
<td>28.8</td>
<td>29.1</td>
<td>37.1</td>
<td>81%</td>
</tr>
<tr>
<td>3.5 Mbit/s</td>
<td>109.0</td>
<td>117.1</td>
<td>182.0</td>
<td>2%</td>
</tr>
<tr>
<td>3.6 Mbit/s</td>
<td>660.1</td>
<td>1613.9</td>
<td>1912.7</td>
<td>25%</td>
</tr>
<tr>
<td>3.7 Mbit/s</td>
<td>1624.8</td>
<td>1629.7</td>
<td>2654.3</td>
<td>40%</td>
</tr>
<tr>
<td>3.8 Mbit/s</td>
<td>1221.1</td>
<td>1646.7</td>
<td>2097.2</td>
<td>70%</td>
</tr>
<tr>
<td>3.9 Mbit/s</td>
<td>1360.1</td>
<td>1749.5</td>
<td>2654.3</td>
<td>82%</td>
</tr>
</tbody>
</table>

WLAN with application Layer cross traffic (blue: UDP, yellow: TCP)
Impact of non-ideal communication on energy balancing

- Control interval of one minute
- Packet losses from around 65% for UDP based communication leads to significant degradation of control performance
  - Controller is robust against packet losses up to around 65%
- For TCP, packet losses are either leading to lost connectivity or excessive delays

The controller shows robustness of communication delays up to around 7 minutes (7 control cycles)
- Failure and attack scenarios may lead to such scenarios that leads to control performance degradation

Based on DiSC tool simulation
### Controller gain adaptation using Monitoring framework

- Via monitoring framework delays are provided to the LV controller
- LVGC adapts gain according to the delays
- For this case
  - only the overshoot is negatively affected by the long delay
  - by chance the tracking error is not
- The maximum overshoot can be decreased by adapting the gains of the controller

<table>
<thead>
<tr>
<th>Control Scenario</th>
<th>LVGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy balancing with ideal communication</td>
<td>Tracking Error (RMS)</td>
</tr>
<tr>
<td></td>
<td>15.61 kW</td>
</tr>
<tr>
<td>Energy balancing with 2-3 min. delay</td>
<td>14.03 kW</td>
</tr>
<tr>
<td>Energy balancing with gain adaption</td>
<td>17.03 kW</td>
</tr>
</tbody>
</table>
Monitoring and mitigation of imperfect networks

- Monitoring framework functionalities:
  - The controllers are able to receive notification from the monitoring framework in order to adapt internal parameters (Gain adaptation)
  - Reliable TCP connections for grid data access (UDP vs. TCP control performance)
  - Data access scheduling (Toffset parameter) based on network delays

- Automatic adaption of access to information over imperfect networks
  - Alleviates the need for manual or time consuming reconfigurations when networks degrades (e.g. cyber attacks, faults, congestions or other situations)
Conclusions: Energy balancing and voltage control

- Controllers enables new services
  - Energy balancing and loss reduction in low and medium voltage grids
    - Allows using grids as services by following references
  - Voltage control in distribution grids
    - Allows to alleviate voltage constraints violations
    - Allows more energy to be produced by renewable energy resources.

- Under normal conditions evaluated network technologies supports grid control functionalities. Controllers are inherently robust towards
  - Long delays
  - High packet drop rates (up to 60-65% using UDP)

- For abnormal cases, e.g. faults and cyber attacks, results shows an impact and need for mitigations

- Monitoring framework developed to actively react upon changes in the network condition and reconfigure access to information dynamically
MV Grid realization and analysis (only briefly)

.... so far 'lean' communication solution via UDP/TCP sockets

- **For voltage control in medium voltage (MV) grid**
  - IEC 61850 communications using MMS (Manufacturing Message Specification)
  - Including TLS-based security

- **Analysis of larger set of performance metrics**
  - Including attack scenarios (mainly DoS) and fault management/recovery strategies
  - 2G networks not any more adequate

[see D5.3 and D6.3]
Demand Management – Key findings

- Price-based indirect control of prosumers at customer sites
  - Operated e.g. by an aggregator
  - Using input from DSO on total power limitations
- **Energy cost optimization** shifts the load to the low price energy periods, and saves in the tested scenario around 11% compared to the fixed price.
- Independently of its cause, excessive total demand can be controlled at the DMC to **avoid overloading the grid**, however with impact on economic savings
- **Resilience via Controller/Communication design:** If the control communication network fails, cached plans allow for resilient operation of CEMS’s during several hours.

[see D6.3 and D4.2]
Summary: ICT Deployment Recommendations

Full deployment recommendations given in D5.3 and final report

**DSL**
- Suitable for all Use Cases and future requirement increases. Enforcement of QoS and customer interference (i.e. can shut off the connection) need to be considered.

**Fibre/Ethernet**
- Suitable for all Use Cases and future requirement increases. Cost considerations apply, recommended for backhaul and long-term deployments.

**2G GPRS**
- Limited suitability for SmartC2Net use cases. Not suitable for use with security features (e.g. TLS). Recommended to use in small short-term (phase out around 2020) deployments without alternatives.

**3G UMTS (HSPA)**
- Suitable for all Use Cases and future, limited requirement increases. Recommended for use outside of MVC deployments in the medium term.

**4G LTE**
- Suitable for all Use Cases and future requirement increases. Recommended as long-term solution due to cat.0 device class for Smart Grids, evolution towards 5G networks and option of including SDN.*

**IEEE802.11g**
- Suitable for all Use Cases and future increases in ITT and transmission size. Deployment recommended for point-to-point RF backhaul due to required dense infrastructure and potential interference problems (ISM band).

*VDE ITG Positional Paper “Communication for the Smart Grid”, March 2015*
Summary: Key Outcomes

- Distribution grid controllers
  - Voltage control
  - Energy balancing (and loss minimization)
  - Demand Management

- Resilience functionality
  - Adaptive controllers
  - Middleware functions: adaptive monitoring & fault mgt.
  - Adaptive communication: prioritization and recovery, e.g. via SDN

- Assessment approaches and tools
  → Analyze other use-cases
  → Support SLA definition and realization
  → Support tender preparation
SmartC2Net: Key Figures

- 4 Use-cases defined and analysed
- 4 Controllers defined and implemented
- 7 Communication technologies analysed
- 5 Middleware and communication layer functionalities for increased resilience
- 6 Evaluation instruments
- 7 DSOs from 5 countries supported the project execution
- 40 Publications (several more in progress)
- Over 40 Presentations to stakeholders

More info:
- High-level overview: [http://smartc2net.eu/brochure/smartc2net_booklet](http://smartc2net.eu/brochure/smartc2net_booklet)
  - Including references to papers and deliverables at [http://smartc2net.eu/public-deliverables.html](http://smartc2net.eu/public-deliverables.html)
The SmartC2Net results clearly show that intelligent distribution grid operation can be realized in a robust manner over existing communication infrastructures even despite the presence of accidental faults and malicious attacks.