Application of Smart Monitoring and Control devices in the Low Voltage Utility Grid

Mauro Carpita
Mokhtar Bozorg
In energy transition context, (development of renewable energies, phase-out of nuclear power and reduction of fossil sources, and so on) the low voltage network are facing:

- Stronger penetration of the distributed generation
- Presence of active consumer, or prosumers
- Introduction and continuation of the opening of the electricity market
- Increase in telecommunication and control capabilities

These changes result in the arrival of intelligent network, more often called SmartGrids. This transition is not done instantly but over time, and to plan the upcoming evolution at best it is necessary to have test platforms in order to be able to test proposed solutions.
The ReIne laboratory (ReIne for Réseau Intelligent, French for smartgrid) is a platform that allows the emulation of a great number of different network topologies, in order to test smartgrid control methods as well as power electronic devices under various and controlled load and generation constraints.

**Technical Characteristics**

<table>
<thead>
<tr>
<th><strong>Voltage level</strong></th>
<th>230 / 400V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Topology</strong></td>
<td>8 lines arranged in a controllable matrix and a 9th free</td>
</tr>
<tr>
<td><strong>Line type</strong></td>
<td>Emulated with discrete inductors (resistors and capacitors can be added)</td>
</tr>
<tr>
<td><strong>Nominal Power</strong></td>
<td>100kVA</td>
</tr>
<tr>
<td><strong>Nominal line current</strong></td>
<td>145A</td>
</tr>
<tr>
<td><strong>Equipments</strong></td>
<td>Loads and various production devices, real and simulated</td>
</tr>
<tr>
<td><strong>Standards</strong></td>
<td>NIBT 2015</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>1) Centralized with SCADA; 2) Distributed GridEye modules from DEPsys</td>
</tr>
<tr>
<td><strong>Utilisation</strong></td>
<td>Research and educational</td>
</tr>
</tbody>
</table>
Relne Laboratory

Peculiarities

- **Flexible structure**
  - Reconfiguration of the network topology
  - Connection points of different sources and charges
- **Monitoring with a high frequency sampling (50 kHz)**
- **Data acquisition based on GPS synchronization that allows precise synchronization of each.**
ReIne Laboratory

Reconfiguration capability

The network part of the laboratory is made of 8 lines positioned in a matrix and a 9th line that can be connected freely between two desired nodes.
The configuration of the network to the chosen topology is made via the SCADA and is realized in a remote-controlled wiring board. This board also enable the users to connect all the different devices to the wanted node, every node being available.
Examples of topologies achievable: 1) Partially meshed grid, 2) District, 3) Meshed grid
Relne Laboratory

Power Supply

1. School grid power supply
2. Network simulator

<table>
<thead>
<tr>
<th>4-quadrant REGATRON TopCon TC.ACS</th>
<th>Nominal power</th>
<th>50 kVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-neutral voltage</td>
<td>Up to 280 V</td>
<td></td>
</tr>
<tr>
<td>Nominal current</td>
<td>72 A</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>Up to 1 kHz</td>
<td></td>
</tr>
<tr>
<td>Harmonics</td>
<td>Up to 5 kHz</td>
<td></td>
</tr>
<tr>
<td>Possibility to generate</td>
<td>Asymmetrical voltages</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Short-term failure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flicker</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Balanced or unbalanced voltage drop</td>
<td></td>
</tr>
</tbody>
</table>

Example of a voltage profile obtained with the network simulator

Département des Technologies Industrielles
http://www.heig-vd.ch/tin
ReIne Laboratory

Connected Devices

Smart Home

Aims
• Educational purposes
• Test of industrial devices
  • Measurement devices (e.g., smart-meters)
  • Performance tests on household appliances
  • System service strategy tests, …

Characteristics
✓ Photovoltaic installation (a part of the panels of the solar carport with a converter IMEON 3.6)
✓ AC battery for energy storage (PowerLegato from AUO)
✓ Water-heater that can be connected to the photovoltaic installation (HeatMaster AP 207 CT)
✓ A refrigerator-freezer (TK80LA++ de Kibernetik), cooking plates, dishwasher, and one electric oven
Battery Energy Storage System
Batteries can be connected to the Relne laboratory at any node of the network.

<table>
<thead>
<tr>
<th>TiRack Leclanché storage with BAT100 FeCon converter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
</tr>
<tr>
<td><strong>Technology</strong></td>
</tr>
<tr>
<td><strong>Converter power</strong></td>
</tr>
<tr>
<td><strong>Available active power</strong></td>
</tr>
</tbody>
</table>
Relne Laboratory

Connected Devices

Carport

✓ 85 solar panels Bisol 295 Wc are installed. 12 panels dedicated to the smart home production (i.e., 3540 Wc).
✓ Possibility to generate capacitive or inductive current.

✓ Charging station for electric vehicle from GreenMotion.
✓ Adjustable power between 3.7 and 22 kW.
Relne Laboratory

Connected Devices

AC Load

Motors

Devices developed at the ISEE institute:
MMC Statcom
PENEGER
DC-Bus
Soft Open Point with Storage (SOPS)

...
Two parallel set of measurement devices and data acquisition systems are installed.

1. National instrument measurement system

<table>
<thead>
<tr>
<th>National Instrument</th>
<th>LEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current measurements (31 x 3)</td>
<td>DHR série (DC...20-6kHz), 1% Acc</td>
</tr>
<tr>
<td>Voltage measurements (10 x3)</td>
<td></td>
</tr>
<tr>
<td>GPS synchronization</td>
<td></td>
</tr>
<tr>
<td>Chasis CompactRIO</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td></td>
</tr>
</tbody>
</table>

- **National Instrument**
  - NI 9220 - 100 kS/s/ch, 16-Bit, Simultaneous Input
  - NI 9244 - 400 Vrms L-N, 50 kS/s/ch, 24-Bit
  - NI 9467 - Pulse per second (PPS) accuracy of ±100 ns, >99 percent typical
  - IC-3173 Linux RT i7; Crio 9035 (x3); REM
  - NI 9263 Pilotage Simulateur réseau
Two parallel set of measurement devices and data acquisition systems are installed.

2. GridEye system from DEPsys

*GridEye* devices from DEPsys are installed in 5 selected nodes/lines of the Relne Laboratory.
Application Projet SMILE-FA
2017-2019

SMILE-FA: The theoretical and application Study on a Metering and Intelligent tool for Low Voltage grid control Enhancement – Flexibility Assessment

Objective
Aim of this project is to develop low voltage network regulation algorithms, to implement in a decentralized measurement and regulating tool, Gridye.

Principal Activities
▪ Improvement of the control algorithms of the LV network based on the estimation of the sensitivity coefficients without grid model.
▪ Testing of new algorithms in the ReIne laboratory. This laboratory allows tests to be carried out in a known environment.
▪ Development of protection strategies against cyberattacks, to be tested also in the new REINE laboratory of the HEIG-VD.

Partners

Département des Technologies Industrielles
http://www.heig-vd.ch/tin
Methods for estimation of Voltage Sensitivity Coefficient with respect to nodal active and reactive power:

\[
K_{PV,ij} := \frac{\partial |\bar{E}_i|}{\partial P_j}, K_{QV,ij} := \frac{\partial |\bar{E}_i|}{\partial Q_j}
\]

\[
\Delta |\bar{E}_i| \approx \sum_{g \in G} K_{P,ig} \Delta P_g + K_{Q,ig} \Delta Q_g
\]

**Model-Aware Methods**

1. Direct computation from the inverse of the Jacobian matrix

\[
J(t) = \begin{pmatrix}
\frac{\partial P}{\partial \theta}(t) & \frac{\partial P}{\partial |\bar{E}|}(t) \\
\frac{\partial Q}{\partial \theta}(t) & \frac{\partial Q}{\partial |\bar{E}|}(t)
\end{pmatrix}
\]

It requires line parameters (Ybus matrix), and voltage phasor at the operation point.
Methods for estimation of Voltage Sensitivity Coefficient with respect to nodal active and reactive power:

\[ K_{PV,ij} := \frac{\partial |\bar{E}_i|}{\partial P_j}, \ K_{QV,ij} := \frac{\partial |\bar{E}_i|}{\partial Q_j} \]

\[ \Delta |\bar{E}_i| \approx \sum_{g \in G} K_{P,i,g} \Delta P_g + K_{Q,i,g} \Delta Q_g \]

Model-Aware Methods

2. A simplified iterative approach based on Gauss-Seidel technique

[Zhou and Bialec, PSCC 2008]

It requires line parameters (Ybus matrix), and iteratively updates the value of sensitivity coefficients based on Gauss-Seidel load flow solution.
Methods for estimation of Voltage Sensitivity Coefficient with respect to nodal active and reactive power:

\[
K_{PV,ij} := \frac{\partial |E_i|}{\partial P_j}, \quad K_{QV,ij} := \frac{\partial |E_i|}{\partial Q_j}
\]

\[
\Delta |E_i| \approx \sum_{g \in G} K_{P,i,g} \Delta P_g + K_{Q,i,g} \Delta Q_g
\]

Model-Aware Methods

3. An analytical method adopted for distribution grids [Christakou et al., IEEE Tr. SG, 2013]
Methods for estimation of Voltage Sensitivity Coefficient with respect to nodal active and reactive power:

\[
K_{PV,ij} := \frac{\partial |\bar{E}_i|}{\partial P_j}, K_{QV,ij} := \frac{\partial |\bar{E}_i|}{\partial Q_j}
\]

\[
\Delta |\bar{E}_i| \approx \sum_{g \in G} K_{P,i,g} \Delta P_g + K_{Q,i,g} \Delta Q_g
\]

Model-Aware Methods

4. An approximate method based on line impedances [Brenna et al., IEEE Tr. SG, 2013]

\[
K_{PV,ij} = \frac{1}{E_n} \left( \sum_{hk \in PT_{ij}} R_{hk} \right) \quad K_{QV,ij} = \frac{1}{E_n} \left( \sum_{hk \in PT_{ij}} X_{hk} \right)
\]

\(PT_{ij}\): The set of nodes contained in the “path” composed of the branches in which flow the active and reactive powers absorbed by node \(i\) and node \(j\).
Methods for estimation of Voltage Sensitivity Coefficient with respect to nodal active and reactive power:

\[ K_{PV,ij} := \frac{\partial |\bar{E}_i|}{\partial P_j}, K_{QV,ij} := \frac{\partial |\bar{E}_i|}{\partial Q_j} \]

\[ \Delta |\bar{E}_i| \approx \sum_{g \in G} K_{P,ig}\Delta P_g + K_{Q,ig}\Delta Q_g \]

Model-Less Method

5. A model-less method based on the Generalized Least Square (GLS) approach using grid measurement data

Test Case Implemented in the Relne Laboratory

**Bus Data**

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Bus Name (Relne)</th>
<th>Nominal voltage (RMS LN) [V]</th>
<th>Connected installation</th>
<th>Installation connection name (Relne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>230</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>N1</td>
<td>230</td>
<td>SOPS Inverter</td>
<td>Resource 9</td>
</tr>
<tr>
<td>2</td>
<td>N3</td>
<td>230</td>
<td>Lamp Panels</td>
<td>Resource 7</td>
</tr>
<tr>
<td>3</td>
<td>N6</td>
<td>230</td>
<td>Cinergia Inverter</td>
<td>Resource 8</td>
</tr>
</tbody>
</table>

**Line Data**

<table>
<thead>
<tr>
<th>Line Number</th>
<th>Line name (Relne)</th>
<th>From bus</th>
<th>To bus</th>
<th>R (pu) Phase 1U</th>
<th>X (pu) Phase 1U</th>
<th>R (pu) Phase 2V</th>
<th>X (pu) Phase 2V</th>
<th>R (pu) Phase 3W</th>
<th>X (pu) Phase 3W</th>
<th>Current Limit per phase (Imax) [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>1</td>
<td>0</td>
<td>1.23 e-3</td>
<td>5.81 e-4</td>
<td>1.23 e-3</td>
<td>5.08 e-4</td>
<td>1.23 e-3</td>
<td>5.08 e-4</td>
<td>33.35</td>
</tr>
<tr>
<td>2</td>
<td>L1+ L2</td>
<td>1</td>
<td>2</td>
<td>7.36 e-6</td>
<td>2.31 e-3</td>
<td>7.42 e-6</td>
<td>2.33 e-3</td>
<td>7.41 e-6</td>
<td>2.33 e-3</td>
<td>34.50</td>
</tr>
<tr>
<td>3</td>
<td>L5</td>
<td>1</td>
<td>3</td>
<td>3.67 e-6</td>
<td>1.15 e-3</td>
<td>3.71 e-6</td>
<td>1.16e-3</td>
<td>3.72e-6</td>
<td>1.17 e-3</td>
<td>34.50</td>
</tr>
<tr>
<td>4</td>
<td>L4+ L6+ L7</td>
<td>3</td>
<td>4</td>
<td>6.73 e-4</td>
<td>3.56 e-3</td>
<td>6.73 e-4</td>
<td>3.55 e-3</td>
<td>6.73 e-4</td>
<td>3.55 e-3</td>
<td>34.50</td>
</tr>
</tbody>
</table>
Test Case Implemented in the ReIne Laboratory

Nodal Power Injections/Absorbtions

Bus 2: Aggregating residential power consumption according to data from a low voltage grid in Chapelle, Switzerland.

Bus 3: Piece-wise constant load

Bus 4: PV generation
Pre-Validation Simulations – NR Load Flow

Model Aware Methods (Kvp)

<table>
<thead>
<tr>
<th>Kvp(i,j) – Reference (Jacobian)</th>
<th>i = 1</th>
<th>i = 2</th>
<th>i = 3</th>
<th>i = 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>j = 1</td>
<td>0.2722</td>
<td>0.2725</td>
<td>0.2719</td>
<td>0.2686</td>
</tr>
<tr>
<td>j = 2</td>
<td>0.2723</td>
<td>0.2751</td>
<td>0.2720</td>
<td>0.2687</td>
</tr>
<tr>
<td>j = 3</td>
<td>0.2721</td>
<td>0.2725</td>
<td>0.2725</td>
<td>0.2643</td>
</tr>
<tr>
<td>j = 4</td>
<td>0.2714</td>
<td>0.2718</td>
<td>0.2718</td>
<td>0.4070</td>
</tr>
</tbody>
</table>

Relative differences between the sensitivity coefficients computed based on the Gauss-Seidel method and the reference values in [%]

Département des Technologies Industrielles
http://www.heig-vd.ch/tin
Pre-Validation Simulations – NR Load Flow

Model Aware Methods (Kvq)

Relative differences between the sensitivity coefficients computed based on the Gauss-Seidel method and the reference values in [%]

Département des Technologies Industrielles
http://www.heig-vd.ch/tin
Measurement data processing

Raw measurement sampling: 50 kHz (20 us)

10-cycle data
For currents and voltages, 10000 samples are recorded, RMS values are calculated according to:

\[ x_{10\text{-cycle},\text{rms}} = \frac{1}{n} \left( \sum_{0}^{n=10000} x_{n}^{2} \right) \]

For active power, instantaneous values of current and voltage are multiplied and aggregated over 10000 samples:

\[ P_a = \frac{1}{n} \sum_{0}^{n=10000} u_n i_n \]

10 minutes data
10 min RMS values are calculated according to the IEC 61000-4-30. Real power is assessed according to power triangle formula:

\[ |S_{10\text{-cycle}}| = I_{10\text{-cycle},\text{RMS}} \times U_{10\text{-cycle},\text{RMS}} \]

\[ |Q_{10\text{-cycle},\text{RMS}}| = \sqrt{S_{10\text{-cycle},\text{RMS}}^2 - P_{10\text{-cycle},\text{RMS}}^2} \]
Validation Tests in the Relne Laboratory

DASRIL voltage measurements vs power flow simulation results. $V(b, \varphi)$: voltage at bus $b$, phase $\varphi$
Validation Tests in the ReIne Laboratory - SC Computation Results

Model Aware Methods (Kvp)

Relative differences between the sensitivity coefficients computed based on the model-less method and the reference values in [%]
Real field validation – DEPsys contribution

Voltage Control Based on Sensitivity Coefficients

In this case, the PV installation has caused the risk of overvoltage within the network. The DSO needs to ensure that voltages remain within the acceptable levels while the production of the PV installations are maximized. Here, the reactive power capability of the inverters are initially used for the voltage control and then if it is needed the active power curtailment is considered.
Real field validation – DEPsys contribution

Voltage Control Based on Sensitivity Coefficients

Results

Voltage profiles at node 2 as well as the PV inverters active and reactive power outputs for the case without control (left) and the case using the GridEye “optimal” control (right).
Conclusions and Future Works

• The methods of computation of voltage sensitivity coefficients with respect to active and reactive power injections are tested and validated under known operational conditions in the Relne laboratory of HEIG-VD.

• The results of validation test shows that the relative differences between the sensitivity coefficients are good and testify the worthy performances of the model-less method.

• Next step: Further tests for resistive networks to emulate more realistic LV distribution grids.
Thanks for your attention!