Internet of Energy
The revolution of distributed generation: from environmental energy harvesting to integration of renewables in smart micro-grids

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Outline

• Part I: Energy Harvesting Research @ UniPD+UniUD
  – Energy Harvesting: Introduction and Foreseeable Applications
  – Research Lines

• Part II: Integration of distributed renewable energy sources in low-voltage smart microgrids
  – Distributed generation scenario
  – Microgrid Architecture
  – Role of Power Electronics
  – Microgrid control
  – Case studies
  – Conclusions
Part I: Energy Harvesting Research
@ UniPD and UniUD
Research in Energy Harvesting @ UniPD+UniUD: People and Departments

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Small-Scale Energy Harvesting

• **General idea** is to absorb, locally store and reuse **ambient energy** from various types of sources such as:
  - Solar, using photovoltaic micropanels,
  - RF, using rectifying antennas,
  - Thermal, using thermoelectric generators,
  - Mechanical, using piezoelectric as well as magnetic devices

• **Purpose** is to operate low-power devices such as sensor nodes and small actuators
## Typical Energy Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Harvester</th>
<th>Typical Voltage</th>
<th>Typical Power</th>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>Photovoltaic Micropanel</td>
<td>0.5 V per cell</td>
<td>Up to 15 mW/cell (outdoors)</td>
<td>Low-complexity MPPT</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Piezoelectric Device</td>
<td>Tens of volts AC @ open-circuit</td>
<td>Tens of mW</td>
<td>Complex Impedance ➔ load-source matching</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Magnetic Device</td>
<td>Few volts</td>
<td>Wide range</td>
<td>Maximum energy extraction</td>
</tr>
<tr>
<td>RF</td>
<td>Rectenna</td>
<td>&lt; 1 V @ Matched conditions</td>
<td>Hundreds of µW to few mW</td>
<td>Coupling</td>
</tr>
<tr>
<td>Thermal</td>
<td>Thermoelectric Generator</td>
<td>0.2 mV/K per cell</td>
<td>Hundreds of µW to few mW</td>
<td>Ultra-low voltage source</td>
</tr>
</tbody>
</table>
Motivating Example: Large Wireless Sensor Networks

• Function of a WSN:
  • **Sense and sample** a scalar field (Temperature, pressure, humidity, motion, vibration, etc...)
  • **Route** sensed information to a central unit or *sink node*

• Large WSN: **tens to hundreds of nodes**
Motivating Example: Large Wireless Sensor Networks

- Application areas:
  - **Industrial**: machine monitoring, fault diagnostics / prevention
  - **Residential**: surveillance, efficient building control
  - **Environmental**: landslide monitoring and prevention

- Practical deployment of large-scale WSN’s implies:
  - **Zero-maintainance nodes** (“Fit and forget” approach)
  - **Prolonged sensor lifetime** (several years)
  - **Low $/Wh**

Research Trend: Embed energy harvesting capabilities into each sensor node
Other Fields of Application of the Energy Harvesting Paradigm

**Wearable technologies and gadgets**
Amiigo wirelessly-charged wristband tracks a number of health parameters

**Avionics**
EH-based wireless engine monitoring vs. conventional wired monitoring

**Automotive**
Rooftop PV’s, Regenerative braking, EH Dampers, Tire Pressure Monitoring Systems

**Wireless Switches for Building Control**
EnOcean ECO-200 Wireless Switch

**Public Places Monitoring**
Underground parking garage occupancy monitoring

@ 2011 Rolls Royce

@ 2011 PowerLeap

@ 2012 EnOcean
The Harvesting-Based Wireless Sensor Node

**Building blocks:**
- Energy harvester
- Storage units: secondary (micro)battery, optional supercapacitor
- Power Processing Unit:
  - Source Matching
  - Storage management
- Sensor loads: Microcontroller Unit (MCU), Transceiver, Sensor(s)
Energy Harvesting Research Lines at UniPD and UniUD

Energy Flow

- Energy Flow Diagram
  - Sensor Node
  - Study of non-conventional harvesting sources
  - Development of power processing techniques for PV and Piezoelectric sources
  - Rechargeable Battery
  - Solar
  - RF
  - Thermal
  - Mechanical
  - Antenna
  - Radio Tx/Rx
  - Temperature/pressure etc...
  - Power Processing Unit
  - Supercapacitor
  - MCU
  - Sensor(s)
  - Definition of energy-aware sensor management policies
  - Power management of hybrid battery/supercap architectures
Non-conventional Harvesting Sources

• Investigated Topics:
  • Study of magnetic energy harvesters for very low-frequency (or one-shot) mechanical energy harvesting

• Challenges:
  • Source characterization
  • Harvester design for optimized energy extraction under realistic battery voltage constraints
  • Different solutions required for continuous vs. one-shot operation
Power Processing Techniques

Investigated Topics:
- Maximum power point tracking for PV and Piezo sources

Challenges:
- Low-complexity algorithm required due to limited power budget
- Two-parameter load matching required: voltage / switching rate (PV) or load equivalent R and L (Piezo)
Power Management of Hybrid Systems

- Investigated Topics:
  - Multi-converter power management system of a combined Li-Ion + Supercap architecture

- Challenges:
  - Best exploitation of batteries (low power, large Wh) and supercaps (high power, low Wh) in hybrid systems
  - Prolong / optimize battery lifetime
Energy-Aware Sensor Management

- Investigated Topics:
  - Exploitation of SoC information *at network level* for:
    - Improved battery management (depth of discharge vs. degradation)
    - Understanding quality of service vs. energy autonomy tradeoffs
  - Challenges:
    - Development and study of Markovian models for sensor management including battery degradation and SoC information
Ongoing Activities

• Study of electronic oscillators for cold-start operation from ultra low-voltage sources (e.g. thermoelectric)

• Maximum power harvesting of industrial thermal waste using thermoelectric panels

• Optimized energy harvesting circuits for wireless switches
Part II: Integration of distributed renewable energy sources in low-voltage smart microgrids
PV Installations in Europe / Italy

- High density of distributed generation
- 49% Low Voltage (LV) installations
- Further increase up to 300 GW in 2020

Global solar capacity (GWp)

2012: 100 GWp

Legend:
- >450 W/hab.
- 300-450 W/hab.
- 150-300 W/hab.
- 100-150 W/hab.
- 50-100 W/hab.
- 10-50 W/hab.
- 0-10 W/hab.

Source: www.pvgrid.eu
Effects of PV penetration in LV Grids

- **Intermittent** power generation
- Possible **overload** of distribution lines due to uncontrolled power sharing
- Alteration of **voltage profiles** due to local power injection
- Possible detrimental **interaction** among distributed generation systems
- Reduction of **power quality** due to circulation of reactive currents, injection of unbalanced power by single-phase equipment, increase of THD due to resonances
- Other issues: protection, islanding detection...
- **Solution:** to aggregate distributed loads and power sources to form LV microgrids, where energy resources are shared so as to improve local and global performances, i.e., energy efficiency, power quality, robustness against faults and transients, etc.
LV Microgrid Architecture

Elements:
- LV distribution grid
- ICT infrastructure
- Passive loads
- Distributed (renewable) power sources
- Energy storage devices
- Smart meters
- **Energy gateways** (EG)
- **Utility Interface** (UI)
Role of Power Electronics

Energy Gateways
- Interface local sources and grid
- Behave as current sources
- Perform as control slaves (two-way communication to UI)

Utility Interface
- Interfaces microgrid and mains
- Behaves as voltage source
- Performs as control master (two-way communication to SMs, EGs and DSO)

The Utility Interface is the key element to ensure safe dynamic operation of the microgrid and effective interaction with the mains.
Control Hierarchy

**Tertiary (global) control**
(DSO + UI + EGs)
- Optimization of interaction between microgrid and mains: harmonic, reactive and unbalance compensation, demand response, fault management, islanding detection and management, etc.

**Secondary (microgrid) control**
(UI + EGs)
- Load power sharing
- Full exploitation of DERs
- Reduction of distribution and conversion loss
- Optimization of \(\mu\)G operation on-grid and off-grid, black start ...

**Primary (local) control**
(EGs)
- Management of local energy sources (smoothing of power profiles, control of ES device, ...)
- Reactive and harmonic compensation of local loads
- Local voltage stabilization
- Emergency supply to local loads

Primary loads: PV gen., Energy storage
Secondary loads: Local Loads
Tertiary loads: Mains, LV distribution grid, PCC
Power-based control of microgrid

Poll of all $K$ microgrid nodes

Communication

Computation of the total consumed and generated power

Computation

Selection of control strategy

Control algorithm

Dispatch of power commands to EGs

Time

$\Lambda_n$

$P_{Ln}, Q_{Ln}$

$P_{Gn}$

$E_{in,n}^{\max}, E_{out,n}^{\max}$

$P_{Gn}^{\min}, P_{Gn}^{\max}$

$P_{S_{n}}, P_{S_{n}}^{\max}$

$P_{Ltot} = \sum_{k=1}^{K} P_{Lk} = \sum_{m=1}^{M} P_{Lm} + \sum_{n=1}^{N} P_{Ln}$

$P_{Gtot} = \sum_{n=1}^{N} P_{Gn}$

$P_{Gtot}^{\min} = \sum_{n=1}^{N} P_{Gn}^{\min}$

$P_{Gtot}^{\max} = \sum_{n=1}^{N} P_{Gn}^{\max}$

Grid conn.

Islanded

$P_{tot}^{G} > P_{tot}^{L}$

$P_{tot}^{G} < P_{tot}^{L}$

Over-generation

Under-generation

$P_{Ltot} \leq P_{Gtot}^{\max}$

$P_{Ltot} > P_{Gtot}^{\max}$
Real-Time Simulation Setup

Development PC

Programming
Datalog
HM interface

Communication link

Grid voltage emulator

230 V, 50 Hz socket

I/O connector fixture

Simulation output

Scope

RT simulation model

Real-Time simulator

UI model

Instantaneous simulation variables

Grid voltage
Dynamic operation of Utility Interface

- Connection of non-linear load
- Variation of grid voltage
- Transition from grid-connected to islanded operation and *vice-versa*
• Connection of non-linear load
• **UI compensates only for distorting currents** generated by the load
• Load power fed by the grid at **unity power factor**
Return to grid-connected operation

- Reconnection to main grid (& black start)
- UI voltage keeps synchronized with grid voltage
- Grid current adapts in few line cycles and shows limited deviations
Case study – Distribution efficiency

Power System Parameters

<table>
<thead>
<tr>
<th>$V_{\text{grid}}$</th>
<th>$f_{\text{grid}}$</th>
<th>$P_{\text{load}}$</th>
<th>$Z_{B1}$</th>
<th>$Z_{B2}$</th>
<th>$Z_{B3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>230 V</td>
<td>50 Hz</td>
<td>6 kW</td>
<td>0.17 + i0.04 Ω</td>
<td>0.26 + i0.06 Ω</td>
<td>0.71 + i0.16 Ω</td>
</tr>
</tbody>
</table>
Power generation and consumption

Typical data of residential installations:
- generation and load profiles
- inverter and energy storage parameters

<table>
<thead>
<tr>
<th></th>
<th>$EG_1$</th>
<th>$EG_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{EG}$</td>
<td>4.2 kVA</td>
<td>5.0 kVA</td>
</tr>
<tr>
<td>$E_{ES}$</td>
<td>3.6 kWh</td>
<td>5.4 kWh</td>
</tr>
<tr>
<td>$P_{S_{out(max)}}$</td>
<td>2 kW</td>
<td>3 kW</td>
</tr>
<tr>
<td>$P_{S_{in(max)}}$</td>
<td>1 kW</td>
<td>1.5 kW</td>
</tr>
<tr>
<td>$\eta_{EG}, \eta_{ES}$</td>
<td>0.95, 0.92</td>
<td>0.95, 0.92</td>
</tr>
</tbody>
</table>
Micro-grid performance

- **Power-based control** significantly reduces reactive power flows at PCC and total distribution loss.
- **Automatic overvoltage limitation** maintains voltages within specified limits, though affecting total energy production.
- Proper management of energy storage improves distribution efficiency and voltage stability as well.

<table>
<thead>
<tr>
<th></th>
<th>Produced Energy (kWh)</th>
<th>Distribution losses (kWh)</th>
<th>(v_{EG2} \text{ max overvoltage} ) (%)</th>
<th>Power Factor at PCC (W/VA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No control</td>
<td>36.5</td>
<td>0.83</td>
<td>5.5</td>
<td>0.93</td>
</tr>
<tr>
<td>Power-based control</td>
<td>34.1</td>
<td>0.65</td>
<td>4.0</td>
<td>1.00</td>
</tr>
<tr>
<td>Power-based control +</td>
<td>34.2</td>
<td>0.47</td>
<td>4.0</td>
<td>1.00</td>
</tr>
<tr>
<td>Energy storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
LV Microgrids: a win-win solution

Low-voltage microgrids equipped with Utility Interfaces feature:
- prompt adaptation to load and line variations
- management of intentional and non-intentional islanding
- voltage and fault ride-through capability
- black start and fault recovery
- reactive, harmonic and unbalance compensation
- management of interaction with DSO (demand response, fault recovery, intentional islanding ...)

Final users (prosumers) take advantage of:
- Energy savings, reduced electricity bill, increased power quality
- Upgrade of role in the electrical market, increased negotiation capability

DSOs and ESCOs take advantage of:
- Aggregation of end-users into efficient and programmable macro-users
- Participation of end-users to investments for distributed energy management and storage
- Increased operation flexibility and efficiency of distribution networks
Conclusions

• Distributed generation, from small environmental sources to residential renewable energy, is experiencing a huge diffusion worldwide.

• This will dramatically change some traditional and consolidated markets, like electric distribution, and open entirely new and pervasive application domains, like wireless sensor networks and microgrids.

• The expected investments on distributed generation technologies in the next decade are very high (tens of $B in North-America, Europe, China, Japan, Korea ..) , under the pressure to reduce carbon footprint, preserve environment and improve health and quality of life.

• Key elements of such innovations are power electronic devices and systems, that can provide distributed and effective power management at low cost, high efficiency and compactness.