Distributed Generation: Benefits & Issues

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Traditional low voltage grid

- Limited number of loads
- Energy supplied top-down from central power station

- Increased loading
- Increased power quality & reliability problems: due to non-linear (power electronic) and sensitive loads
Why are grids changing?

- **3 technological drivers**
  - Power Electronics (PE) becomes ubiquitous in loads, generators and grids
  - More power produced (and stored) near consumers: Distributed Energy Resources (DER)
  - Increased importance of Power Quality (PQ): more disturbances and more sensitive devices

- **3 socio-economic tendencies**
  - Liberalization of energy markets: free choice of supplier
  - More sustainable energy (renewable and ‘high-quality’)
  - Less guaranteed security of supply

Definition of Distributed Generation

- **Distributed Generation (DG)**
  - connected directly to the distribution system or installed at the customer’s side of the meter;
  - non-dispatched by the network operators;
  - not centrally planned;
  - small-scale generators (≤ 50 MW).

- **Distributed Energy Resources (DER)**
  - also including storage, active loads
**DER technologies**

- **Distributed Generation:**
  - Reciprocating engines
  - Gas turbines
  - Micro-turbines
  - Fuel cells
  - Photovoltaic panels
  - Wind turbines
  - CHP configuration

- **Energy Storage**
  - Batteries
  - Flywheels
  - Supercapacitors
  - Rev. fuel cells
  - Superconducting coils

**Current DG penetration**

Forecast: 7.2% DG share in 2004 to 14% in 2012 (WADE)

Wind target in EU: 40.5 GW at present to 75 GW in 2010 (EWEA)
Grid of tomorrow?

- Local generation
- Local storage
- Controllable loads, DSM (‘NegaWatts’)
- Power quality and reliability is a bigger issue

System’s future structure & size?

- **Growth (?)**:
  - Consumption rises annually by several %
  - Investments in production: very uncertain due to liberalisation
  - Limited or no grid expansions are accepted by the public

- **Balancing**:
  - Short-term: make balance by introducing DG?
  - Long-term: more storage and/or ‘activate loads’?

Power electronic dominated grids

Source: KEMA
SmartGrids Vision

- EU Technology Platform preparing FP7
- Involving specialists from industry, academia, …
- Vision paper published in 2006
Enabling Technologies

• Active Distribution Networks
• Improved power flow: FACTS, WAMS, WAPS
• Power electronic technologies
• Smart Metering
• Communication for DSM, on-line services, energy management
• Stationary energy storage

Concepts for the future

• Virtual Utilities: Configure and deliver -> "Internet" model
• Microgrids:
  Low voltage networks with DG sources, local storage and controllable loads, automatic islanding

• Technically, parts of the grid may even separate from central supply
• A Microgrid is a collection of small generators for a collection of users in close proximity
• No net power exchange, total autonomy (Energy Island)?
Is a Microgrid new?

- History of electricity networks:
  - It all started that way, before interconnection

- Today, are they a new concept?
  - **No?**
    - The grid behind certain UPS systems are driven like a microgrid with one generator
    - Multiple UPS units in parallel is not impossible, but not often implemented due to complexity (control, earthing, ...)
  - **Yes!**
    - Intended for longer term operation, not just emergencies
    - Scope of the idea is wider: from a single dwelling to parts of the distribution network (longer connections, multitude of connections, ...)

What makes a Microgrid difficult to operate?

- “Ancillary Services” are all to be delivered internally
  - Balancing the active and reactive power:
    - \[ \text{electricity produced} - \text{system losses} = \text{electricity consumed} - \text{storage} \]
  - Stabilizing the grid: frequency, voltage amplitude and phase angle
  - Providing quality and reliability: unbalance, harmonics, ...
  - Black-start capability
  - ...

- Can a Microgrid become fully separate and deliver these services?
  - How to organize (system operator ↔ fully distributed)?
  - How to reward financially?
What is an optimal deployment of DG technology?

- Distribution grid was *never* built for local power injection, only top-down power delivery
- Technical difficulties:
  - Power Quality & reliability
  - Efficiency
  - Safety
  - Control
  - Economic aspects
- Are there *optima* for the size and location of DER units (generation, storage, active load)?

Power quality & reliability

- Problem:
  - Bidirectional power flows
  - Distorted voltage profile
  - Vanishing stabilizing inertia
  - More harmonic distortion
  - More unbalance
- Technological solution:
  - Power electronics may be configured to enhance PQ
  - DG units can be used as backup supply
PV power is calculated from 5-s average irradiance data measured in Heverlee (B)

Power variation causes voltage fluctuations

Example: MV cable grid

Substation connecting to HV-grid

Location: Leuven-Haasrode, Brabanthal + SME-zone
Impact of wind turbine

Voltage – Power factor relationship at node 406

- Generally, power injected by DG improves voltage profile
- Over-voltage may occur at high level of power injection (especially, synchronous machines)
- Little impact on the voltage rise with the generators operating as induction machine
- Synchronous DG raises system voltage higher due to additional reactive power injection
  - Connect one DG unit at
  - record system voltage

Voltage profile along feeder 4

Voltage – Power factor relationship at node 406
Voltage dips

• Voltage at node 2 – branch 1-2 open

A large induction DG starts up causes severe voltage dips at connected node and nearby nodes → affect sensitivity loads

A soft-start circuit is needed for large induction DG

Voltage stability limit

Critical Point

Normal Operating Point

Voltage stability margin

P_{max} P_{load}
DG Location has significant impact on voltage stability limit.

Synchronous DG unit has better contribution to voltage stability limits.

- DG unit: 3 MW
- Voltage stability limit at node 111, is the furthest point from substation (considered to be weakest bus in terms of voltage stability)

**Voltage stability limit @ node 111, impedance load**

**Control, or the lack of**

- Problem:
  - Generators are **NOT** dispatched in principle
    - Weather-driven (many renewables)
    - Heat-demand driven (CHP)
    - Stabilising and balancing in cable-dominated distribution grids is not as easy as in HV grids

  \[
  \begin{align*}
  \text{active power} & \leftrightarrow \text{frequency} \\
  \text{reactive power} & \leftrightarrow \text{voltage}
  \end{align*}
  \]
Networked system operations

- Solutions:
  - Higher level of control required to coordinate balancing, grid parameters?
  - Advanced control technologies
- Future technologies, under investigation
  - Distributed stability control
    - Contribution of power electronic front-ends (see example)
  - Market-based control
    - Scheduling local load and production, by setting up a micro-exchange (see example)
  - Management of power quality
    - Customize quality and reliability level
  - Alternative networks
    - E.g. stick to 50/60 Hz frequency? Go DC (again)?
- Rely heavily on intensified communication: interdependency

Example: fully decentralized control

- Standard method: “droop control”
- KUL method: Virtual Impedance method
  - Emulate a voltage source with internal tunable impedance in the time domain
  - Ref.: K.De Brabandere et al. @ PESC’04
- Advantage: seamless transition from grid-connected to island and reconnect
Experimental results: connection of two independent grids (islands)

Example: tertiary control on local market

- DG units locally share loads dynamically based on marginal cost functions, cleared on market
Safety

- Problem:
  - Power system is designed for top-down power flow
  - Local source contributes to the short-circuit current in case of fault
    - Fault effects more severe
    - Difficult to isolate fault location
  - Bidirectional flows
    - ‘Selectivity’ principle in danger: no backup ‘higher in the grid’ for failing protection device
  - Conservative approach on unintentional islanding

- Solution:
  - New active protection system necessary
Societal issues

• Problems:
  - Environmental effects
    - Global: more emissions due to non-optimal operation of traditional power plants
    - Local effects as power is produced on-the-spot, e.g. visual pollution
  - Making power locally often requires transport infrastructure for (more) primary energy
    - Problem is shifted from electrical distribution grid to, for instance, gas distribution grid!

• Solution:
  - Multi-energy vector approach
  - Open debate on security of supply

Economic issues

• Problems:
  - Pay-back uncertain in liberalized market
    - ‘Chaotic’ green and efficient power production
    - Reliability or PQ enhancement difficult to quantify
  - System costs
    - More complicated system operation
    - Local units offer ‘ancillary services’
  - System losses generally increase
  - Who pays for technological adaptations in the grid? Who will finance the backbone power system?
    - Too much socialization causes public resistance

• Solution:
  - Interdisciplinary regulation, not only legal
  - Need some real ‘deregulation’
System losses example

- DG introduction does not mean lowered losses
- Optimum is 2/3 power at 2/3 distance
- Other injections generally cause higher system losses

Power flow along cable

Evolution of losses

Penetration level of DG
\[ PL_{DG} (%) = \frac{\sum P_{DG}}{\sum P_L} \times 100 \]

First:
- \( PL_{DG} \) increases → Losses decrease

Then
- \( PL_{DG} \) increases → Losses increase

- Synchronous DG units have the largest influence on the reduction of power losses.
Balancing question, again

- Fundamental electrical power balance, at all times is the boundary condition:

  \[ \text{Electricity produced} - \text{system losses} = \text{electricity consumed} - \text{storage} \]

- All sorts of reserves will decrease in the future
- Role of storage? Storage also means cycle losses!
- Next step in enabling technologies
  - \textit{Usable} storage
  - Activated intelligent loads (demand response technology), also playing on a market?
  - Boundary condition: minimize losses

How far can we go?

- Large \textbf{optimization} exercise, making following considerations:
  - Optimal proliferation, taking into account local energetic opportunities, e.g. renewables options?
  - Unit behavior towards grid: technology choice?
  - Control responsibilities?
  - Is the same level of reliability still desired?
  - Level of introduction of new additional technologies (storage, activated loads)?
  - …
Looking for the optimal solution

Where to place DER?

- **Optimization goals:**
  - voltage quality penalty
  - minimum losses
  - minimum costs
  - ...

- **Constraints:**
  - net balance
  - load flow equations
  - acceptable voltage profile
  - ...

**Optimization**
- non-convex
- multiple objectives
- mixed discrete-continuous
- long term vs. short term interactions

DER Planning

- **Single objective**
  - \( \text{Min (Energy Loss)} \)
    - very straightforward
    - does not represent the real problem

- **Multi-objective**
  - **Weight factors → single objective**
    - \( \text{Min (} \alpha \text{ Energy Loss + } \beta \text{ Voltage penalty + } \gamma \text{ Installation Costs)} \)
    - value of weight factors?
    - useful if objectives are comparable, e.g. all costs (€)

  - **True multi-objective → trade-offs**
    - \( \text{Min (Energy Loss; Voltage penalty; Installation Costs)} \)
    - selection based on Pareto ranking
DER Planning

Long term planning problem efficiently handled by using **Genetic Algorithms**
- Optimization based on evolutionary computing techniques
- Able to deal with mixed discrete (placement) – continuous (sizing) problem
- Global optimum not guaranteed!! Rather a target-oriented tool
- Often difficult to obtain sufficient data sets → use Markov models

Test case

2 generator types used: PV & CHP
- each represented by a 5-string bit
- network chromosome = 20 x 2 x 5 = 200 bits
  (2⁴⁰ siting options)
Test case

Load data are based on actual measurements
- residential buildings
- period of 1 year
- on a 15-minute basis

4 load scenario types are available
- each scenario consists of 4 typical one-day load profiles
- 5 times repeated over the 20-node grid

Summer, high load

- Load data are based on actual measurements
- residential buildings
- period of 1 year
- on a 15-minute basis

4 load scenario types are available
- each scenario consists of 4 typical one-day load profiles
- 5 times repeated over the 20-node grid

High load (e.g. working day)

Low load (e.g. weekend)

Summer

Winter
Test case

- Evolution of total power loss in the optimal solution of each generation in the Summer–Low scenario
  - Optimal and stable solution reached after 100 generations

Test case

Optimal solution in the Summer-Low scenario
Test case

Cross-comparison test:
use solution of scenario $i$
in fitness function of scenario $j$

<table>
<thead>
<tr>
<th>Total power loss [kWh]</th>
<th>Load scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SH</td>
</tr>
<tr>
<td>Using optimal DG of scenario</td>
<td></td>
</tr>
<tr>
<td>SH</td>
<td>23.4</td>
</tr>
<tr>
<td>SL</td>
<td>26.9</td>
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<tr>
<td>WH</td>
<td>59.1</td>
</tr>
<tr>
<td>WL</td>
<td>36.9</td>
</tr>
<tr>
<td>No DG</td>
<td>63.5</td>
</tr>
</tbody>
</table>

DER Planning

Instead of single-objective optimization, the use of true multi-objective optimization is proposed

Single objective
* only one “optimal” solution
* significance?

Multi-objective
* pool of solutions
* trade-offs between objectives
* insight in the potential of the grid
* which objectives are conflicting?

Decreasing objective value with each generation

Pareto front between conflicting objectives
What is a trade-off?

Rank topologies according to dominance:
If topology A is at least equal in all objectives compared to B
and better in at least one objective,
then topology A dominates topology B

Aim of the optimization:
Identify as much non-dominated topologies as possible

Fitness of a DER topology is calculated by running
a scenario with assumed loads and grid topology

What if
✓ Storage is to be optimized?  ⇒ Control?
✓ Load has an elastic behavior?  ⇒ Demand Response?
✓ Production is dispatchable?  ⇒ Forecasting?

⇒ What if Local Markets exist?

Long-term planning interacts with short-term planning problem!!
Conclusion

• Current grid:
  ◦ Interconnection
  ◦ Higher PQ level required
  ◦ DER looking around the corner
• History repeats: after 100 years the idea of locally supplied, independent grids is back
  ◦ Microgrids, being responsible for own ancillary services
• Maximum (optimal?) level of penetration of DER = difficult optimization exercise
  ◦ Whose optimum?
• Special (technological) measures are necessary
  ◦ ancillary services are a challenge
    ◦ e.g. in system control, balancing
  ◦ role of loads?
• Not only technology push, but also customer pull required

more information:
http://www.esat.kuleuven.be/electa

check publications sections, e.g.:
Pepermans G., Driesen J., Haeseldonckx D., Belmans R., D’haeseleer W.:
“Distributed Generation: Definition, Benefits And Issues,” Energy Policy, Elsevier,
Vol.33, Issue 6, April 2005, pp. 787-798

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Thank you!
(now, let’s discuss)