Microgrids

Microgrid architectures and components

ELENO445-1
Versions

- Version 1: October 11, 2017
- Version 2: October 17, 2017
In the previous lecture

We have seen what is the operation problem in a microgrid, the corresponding objectives, decisions and constraints.
Content of this lecture

In this lecture we review microgrids architectures and components technologies.

We focus on features of microgrids components that are important for operation, both from a technical point of view and from an economical point of view.
Main reference

These slides are partly inspired by chapters 4, 5 and 6 of

Microgrid architectures
Distributed Energy Resources

Distributed energy resource (DER): “sources of electric power that are not directly connected to a bulk power transmission system. Distributed energy resources include both generators and energy storage technologies”

AC grids

- Most microgrids are AC
- Most microgrids are three-phase!
  - three-phase power transfer is a constant expression (if the phases are balanced)
  - Equipments in general require less components per unit of power transferred
Power electronics

Power electronic circuits are interfaces

• between devices (DERs and loads) and the power distribution grid
• between the microgrid and the distribution grid (PCC)

Purpose: enable a controllable (bidirectional) flow between devices
DC microgrids

• The distribution system is DC
  ✦ Requires DC to DC converters to adapt voltage to devices
  ✦ DC to AC to power AC loads, or to inject in the public grid
  ✦ AC to DC to convert AC generation to DC (e.g. from public grid to microgrid)

• DC microgrids are not widespread but gain some interest
DC vs AC: pros

- DC systems enable a simpler integration of DERs, since many of them are either DC by nature or require a DC interface anyway.
- Parallel distributed architectures are simpler to realize in DC:
  - unnecessary frequency control and phase synchronization
- Frequency control is not necessary in DC systems:
  - unwanted harmonic content may be easier to filter too
DC vs AC: cons

- Autonomous distributed control harder in DC than in AC because no information carried through the signal (frequency, phase)
- There are stability issues due to DC-DC conversion stages
- It is more difficult to clear fault currents: the signal “does not go through zero”. Hence protections are more costly and harder to set up.
Most common: radial architecture

• Subject to availability issues (one single path to a load)

• alternatives:
  ✦ provide a redundant path to each load
  ✦ provide spatially diverse paths
  ✦ ring-type distribution
  ✦ ladder type distribution
Characterizing power distribution architectures based on how power conversion is performed

- Centralized: power conversion is performed at a single power electronic interface
- Distributed: power conversion functions are spread among converters
  - may lead to parallel or cascade structures
Storage Systems
Author: Mathias Berger
Introduction
Definition

- A storage system is an object or device allowing to capture energy at a given point in time and restore some of it at a later time.

- Ideally, the amount of energy restored should be as close as possible to the amount of energy captured initially, the ratio of the two defining the efficiency of the system.

- Sources and forms of energy vary widely, leading to the emergence of many different storage system technologies.
Currently Available technologies

• Capacitors
• Batteries
• Supercapacitors
• SMES
• Fuel cells
• Flywheels
• Compressed Air Storage
• Pumped Hydro-Power
• Pumped Heat Storage
Technologies Classification

• Classification criterion: power vs energy density.
  ✦ Energy is proportional to amount of charge available at given voltage.
  ✦ Power is proportional to rate at which charge is made available.
Review of Common Technologies
Capacitors (1/2)

• Energy stored in electrostatic form (electrical field).

• Charge (electrons) stored on electrode surfaces.

• Dielectric inserted between electrodes to increase capacity.

• Two common designs: ceramic/film capacitors and electrolytic capacitors (with much higher capacity).
Capacitors (2/2)

Schematic of common capacitor technologies.
Supercapacitors (1/2)

• Super and ultra capacitors are synonyms. Capacitors and super capacitors are different.

• Energy stored in electrostatic form (electrical field).

• Charge (ions) adsorbed on porous activated carbon electrode surfaces bound to current collector.

• Ions transferred through electrolyte from one electrode to the other.

• Porous separator inserted between electrodes.
Supercapacitors (2/2)

Schematic & working principle of super capacitor technology.
Batteries (1/3)

Solid-State Batteries

• Energy stored in electrochemical form.

• Charge (ions) stored in electrode bulk through redox reactions.

• Metal oxide cathode and graphite matrix anode.

• Ions transferred between electrodes through electrolyte.

• Porous separator inserted between electrodes.
Batteries (2/3)

Schematic of solid-state Li-ion battery technology.
Batteries (3/3)

Flow Batteries

Schematic & working principle of flow battery technology.
Essential Battery Parameters
Capacity, SOC & Voltage

• Capacity reflects total amount of charge (Ah) that can be theoretically stored in device.

• State of charge (SOC) reflects amount of charge available at given time instant, usually expressed as percentage of capacity.

• Voltage (V) at cell/pack terminals is measurable operating parameter providing indirect information about SOC.
Current & C-rate

• Current (A) is the main excitation signal in batteries as voltage is imposed by system physics.

• C-rate is a standardised metric quantifying applied current intensity. This alternative scale is derived from the constant current intensity needed to fully charge/discharge the battery over a given time period, usually 1h.

• Battery charge/discharge behaviours vastly differ across C-rate range.

• In particular, in Li-ion cells, much less charge can be retrieved from discharge at high C-rates. This phenomenon is called the rate capacity effect.
Degradation & Health

- Battery performances typically decrease over lifetime, in a process known as degradation.

- Main degradation types:
  - Power fade: peak power decreases over time.
  - Capacity fade: capacity decreases over time.

- Several metrics quantifying degradation exist, e.g. remaining capacity or internal resistance. Those quantities then allow to define state of health indicator in fashion similar to SOC.
Batteries in Practice
Battery Packaging (1/2)

- Several Li-ion battery cell geometries exist, e.g. prismatic, pouch and cylindrical.

- The most common cell geometries are the cylindrical 18650 (18mm diameter & 65mm height) and 21700 designs.

- To reach desired voltage and current specifications, battery cells are matched and assembled in series and parallel configurations, thereby forming a block. Several blocks form a pack.

- Temperature plays a critical role in operation and degradation, so that each block is equipped with cooling system.
Battery Packaging (2/2)

Typical Cylindrical Li-Ion Cell Geometry

Tesla Model S Battery Pack
(Panasonic 18650 cells assembly)
Battery Management System

• Modern battery storage systems are equipped with a battery management system (BMS).

• The BMS serves two main purposes:
  
  ✫ Monitoring: harvest data to be fed to control systems and graphical user interface.
  
  ✫ Safety: ensure battery does not operate in dangerous regimes, e.g. severe overvoltage or high temperature.

• Old BMSs used inaccurate heuristics to estimate operating parameters and stop operation if needed whereas new generations exploit high-fidelity electrochemical models solved in real-time.
## Comparison of Li-Ion Battery Technologies

| Lithium Nickel Manganese Cobalt Oxide: LiNiMnCoO₂ cathode, graphite anode |
|---|---|
| Short form: NCM (NCM, CMN, CNM, MCN similar with different metal combinations) | Since 2008 |
| **Voltages** | 3.60V, 3.70V nominal; typical operating range 3.0–4.2V/cell, or higher |
| **Specific energy (capacity)** | 150–220Wh/kg |
| **Charge (C-rate)** | 0.7–1C, charges to 4.20V, some go to 4.30V, 3h charge typical. Charge current above 1C shortens battery life. |
| **Discharge (C-rate)** | 1C; 2C possible on some cells; 2.50V cut-off |
| **Cycle life** | 1000–2000 (related to depth of discharge, temperature) |
| **Thermal runaway** | 210°C (410°F) typical. High charge promotes thermal runaway |
| **Applications** | E-bikes, medical devices, EVs, industrial |
| **Comments** | Provides high capacity and high power. Serves as Hybrid Cell. Favorite chemistry for many uses; market share is increasing. |

| Lithium Iron Phosphate: LiFePO₄ cathode, graphite anode |
|---|---|
| Short form: LFP or Li-phosphate | Since 1996 |
| **Voltages** | 3.20, 3.30V nominal; typical operating range 2.5–3.65V/cell |
| **Specific energy (capacity)** | 90–120Wh/kg |
| **Charge (C-rate)** | 1C typical, charges to 3.65V; 3h charge time typical |
| **Discharge (C-rate)** | 1C, 2S5C on some cells; 40A pulse (2S); 2.50V cut-off (lower that 2V causes damage) |
| **Cycle life** | 1000–2000 (related to depth of discharge, temperature) |
| **Thermal runaway** | 270°C (518°F) Very safe battery even if fully charged |
| **Applications** | Portable and stationary needing high load currents and endurance |
| **Comments** | Very flat voltage discharge curve but low capacity. One of safest Li-Ions. Used for special markets. Elevated self-discharge. |

| Lithium Manganese Oxide: LiMn₂O₄ cathode, graphite anode |
|---|---|
| Short form: LMO or Li-manganese (spinel structure) | Since 1996 |
| **Voltages** | 3.70V (3.80V) nominal; typical operating range 3.0–4.2V/cell |
| **Specific energy (capacity)** | 100–150Wh/kg |
| **Charge (C-rate)** | 0.7–1C typical, 3C maximum, charges to 4.20V (most cells) |
| **Discharge (C-rate)** | 1C; 10C possible with some cells, 30C pulse (5s), 2.50V cut-off |
| **Cycle life** | 300–700 (related to depth of discharge, temperature) |
| **Thermal runaway** | 250°C (482°F) typical. High charge promotes thermal runaway |
| **Applications** | Power tools, medical devices, electric powertrains |
| **Comments** | High power but less capacity; safer than Li-cobalt; commonly mixed with NMC to improve performance. |

| Lithium Nickel Cobalt Aluminum Oxide: LiNiCoAlO₂ cathode (~9% Co), graphite anode |
|---|---|
| Short form: NCA or Li-aluminum | Since 1999 |
| **Voltages** | 3.60V nominal; typical operating range 3.0–4.2V/cell |
| **Specific energy (capacity)** | 200–260Wh/kg; 300Wh/kg predictable |
| **Charge (C-rate)** | 0.7C, charges to 4.20V (most cells), 3h charge typical, fast charge possible with some cells |
| **Discharge (C-rate)** | 1C typical; 3.00V cut-off, high discharge rate shortens battery life |
| **Cycle life** | 500 (related to depth of discharge, temperature) |
| **Thermal runaway** | 150°C (302°F) typical. High charge promotes thermal runaway |
| **Applications** | Medical devices, industrial, electric powertrain (Tesla) |
| **Comments** | Shares similarities with Li-cobalt. Serves as Energy Cell. |
Power electronics interfaces
3 main categories of power electronics devices

**Rectifiers:** AC to DC, are typically used at the output of small wind turbines or micro-turbines.

**DC-DC converters** e.g. to interface photovoltaic modules and achieve their maximum power operating point

**Inverters:** DC to AC e.g. to connect PV modules to the AC distribution grid.
Components
The main components of power electronics devices

Controllable switches that can be actuated at a high frequency, without excessive losses, and with a large lifetime

Ideal switch model:
- no losses
- switches without delay
Realistic switch model

Current

Voltage

Closed

Open
Diode models: ideal diode

- Current flows from anode to cathode when forward biased: $i > 0 \Rightarrow v = 0$
- No current when reversed bias: $v < 0 \Rightarrow i = 0$
Diode models: realistic diode in the forward bias region

- Piecewise linear approximation of “true exponential model”.

![Diode model diagram]
Thyristors

- Thyristors are “controllable diodes”, through a gate where a signal is applied

- Different types:
  - GTO (gate turn off) can be turned on and off, less than 1kHz switching frequency
  - SCR (silicon-controlled rectifier): can be turned on, turns off when forward current goes through zero
  - TRIAC (Triode alternating current): two SCR back to back with one gate (AC-AC conversion)
Transistors

- Bipolar junction transistors (BJT)
  - Historically used as amplifiers in their active region of operation
  - Can also be used as a switch, in the saturation region
  - High power, but high losses

- Field effect transistors (MOSFET)
  - High speed and high efficiency at low voltage.
  - Isolated gate (field effect)
  - Commonly used for low voltage converters
Insulated Gate Bipolar Transistor (IGBT)

- Most common device for high power DC-DC converters and inverters from medium to high voltages
- Combination of BJT and MOSFET
- Now replaces thyristors in most medium to high power applications
Characterization of power electronics devices
DC component

• Integral of the output signal over a full AC input cycle.

• In case of a rectifier, this is the power that is really transmitted from source to load.
Total Harmonic Distortion

- THD = ratio of the total signal, including harmonics, to the desired frequency component

\[
THD = \sqrt{\frac{F_{\text{RMS}}^2 - F_{\text{RMS,1}}^2}{F_{\text{RMS}}^2}}
\]

- IEEE standard 519–1992, “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”, states that the voltage THD is limited to 5% for general systems and is only up to 20% for dedicated systems
Rectifiers
Definition

- Rectifiers: large subclass of topologies for AC to DC conversion
- Single-phase or three phase voltage source to DC current load
- Power-electronic is “only” the front end:
Half bridge single phase topology

\[ v_{AC} = V_p \sin(t) \]

DC component:

\[ V_{DC} = \frac{V_p}{2\pi} \int_0^{\pi} \sin(t) d\theta = -\frac{V_p}{2\pi} \cos(t)|_0^\pi = \frac{V_p}{\pi} \]
Full-bridge single phase topology

- DC component twice of the half bridge
- But Large harmonic current in the input AC current
- DC output not controllable
Full-bridge single phase topology with low pass filter

- Improves output harmonics content
- Better if capacitor size increases
  - which in turn degrades harmonic content of input
- Bad power factor => LC topology
- Active power factor correction => DC-DC after the rectifier

Plot generated with PySpice
Recap with more realistic components

Plots generated with PySpice
Multi-phase topologies

• Power from source to load is constant!
  ✦ Not any of the frequency components seen in a single-phase system
  ✦ Reduce peak currents, hence systems are more compact and efficient

• Main reason why AC microgrids are three-phase systems
DC - DC converters
Definitions

- DC-DC converters are present in many devices,
  - from mW power level to MW level
- Made possible by MOSFET and IGBTs
- Can be unidirectional, from low voltage to high voltage or the inverse, or bidirectional
  - \( v_h > v_l, \ i_l > i_h \)
Basic bloc: two switches

Only one switch ON at a time
Pulse Width Modulation (PWM)

- Process that actuates the switches
- Duty cycle signal compared to a reference triangular waveform of a chosen frequency
Buck converter

- $q_1$ is a controllable switch and $q_2$ is a diode
Boost converter

- q2 is a controllable switch and q1 is a diode
Inverters
Definition

• Voltage source inverter: $v_{AC} < v_{DC}$

• Current source inverter: $v_{AC} > v_{DC}$

• Impedance source inverter: for a wide variation of $v_{AC} \leq v_{DC}$
Power generation sources
Wind turbines
Wind turbines

1. Wind turbines convert the mechanical power of wind into electrical power.
2. The power of the wind can be derived from its kinetic energy

\[ E_w = \frac{1}{2}mv^2 \]

As power is the time derivative of energy, we have, assuming the speed is constant:

\[ P_w = \frac{dE_w}{dt} = \frac{1}{2} \frac{dm}{dt} v^2 \]

And \( \frac{dm}{dt} = \rho Av \) with \( A \) the area crossed by the wind, and \( \rho \) is the mass of air by unit of volume. This yields

\[ P_w = \frac{1}{2} \rho Av^3 \]
Power conversion

- Only a fraction of the wind power is harvested by the blades.
- Actually, the energy harvested is function of the speed of the air that enters the blades, $v_u$, and speed of the air that leaves the blades, $v_d$:

$$P_b = \frac{1}{2} \frac{dm}{dt} (v_u^2 - v_d^2)$$

Approximating $\frac{dm}{dt}$ by $\rho A \frac{v_u - v_d}{2}$ and defining the coeffitient $\lambda_w$ as

$$\lambda_w = \frac{v_d}{v_u}$$

Then the power harvested by the turbine can be written as

$$P_b = \frac{1}{2} \rho A \frac{v_u - \lambda_w v_u}{2} (v_u^2 - \lambda_w^2 v_u^2)$$
Turbine efficiency

If we define the coefficient

\[ C_p = \frac{1}{2} (1 + \lambda_w)(1 - \lambda_w^2) \]

Then

\[ P_b = \frac{1}{2} C_p \rho A v_u^3 \]

Betz limit:

- It can be shown that there is a theoretical limit for \( C_p \) at \( \frac{16}{27} = 59.2\% \)
- This limit is reached for \( \lambda_w = 1/3 \).
Efficiency of different technologies as a function of tip-speed ratio (TSR)

TSR = rotor tip speed / wind speed
Electromechanical conversion

So far, we have only been talking about mechanical power conversion!

Several types of generators can be used to convert mechanical power into electrical power:

- Synchronous machine
- DC machine
- Induction machine
- Doubly fed induction machine

Brushless variants of (some of) these machines can be used to decrease maintenance needs, through permanent magnets. Those cannot be used for large size generators (> several hundreds of kW).
Power electronics interface

Most of the time, and especially in microgrids operation, these generators are coupled with power electronics to generate power with an appropriate shape:

- the output of the generator goes through a DC conversion stage (rectifier if AC generator, DC-DC if DC generator) to cope with wind speed variations
- If the distribution grid is AC, then there is an additional inverter stage.

Power electronics are also used

- to maximize the energy harvested, especially for low-to-medium power generators (instead of adapting rotor speed through e.g. controlling blade pitch):
- to limit the power output at high wind speeds to avoid degradation
Wind generator operating characteristic

\[ P_{\text{nom}} \]

\[ P (\text{MW}) \]

\[ v (\text{m/s}) \]

cut-in speed

cut-out speed

Limited rotor efficiency range
PV generation
Photovoltaic generation

A PV cell is composed of semiconductor material. Photons emitted by the sun interact with the semiconducting material in two ways:

1. photons directly transmit energy to electrons and allow them to move into the conduction band.
2. a thermally generated current as in a p-n junction (diode).
Photovoltaic generation

Effect of temperature


Effect of irradiance

Source: https://en.wikipedia.org/wiki/Maximum_power_point_tracking
Photovoltaic generation

Maximum power point

Power

Current

Voltage
PV panels

PV cells are arranged into panels. PV cells are combined in series and in parallel.

PV panels are then arranged in parallel and/or in series:

- Parallel: same open circuit voltage, increased short circuit current
- Series: same short circuit current, increased open circuit voltage, but current limited by PV panel delivering the smallest current.

Hence a shadowed or damaged panel can impact the whole array. Hence in practice PV panels arrangement is a mix of series and parallel connections. This trade-off is also impacted by the number and types of power electronics equipment a particular configuration requires.
Integrating PV arrays

Extreme approaches:

1. Single central power electronics interface for entire array:
   - low cost in power electronics,
   - high cost in installation and cabling,
   - low reliability.
   - Highly impacted by damages, shadow
   - cannot reach MPP per panel

2. One interface for each PV panel (module-integrated):
   - High cost in power electronics,
   - low cost in installation and cabling,
   - high reliability.
   - Robust to damages, shadow
   - can optimize MPP per panel

Realistic approaches:

1. One converter per string
2. Multiple-input converters
Power electronics interface

1. A DC-DC converter connected at the output of the panel (or string of panels) aiming at reaching the MPP.
2. An inverter to connect to the grid (or another DC-DC converter if it is a DC bus).
Maximum power point tracking (MPPT)

Assume a PV panel feeds a resistor $R_0$. $R_0$ is almost never equal to $R_{MPP} = \frac{V_{MPP}}{I_{MPP}}$ since:

1. $R_0$ can vary in time depending on the user needs,
2. $R_{MPP}$ is function of irradiance and temperature.

Hence the panel is usually not naturally operating at its MPP:
Maximum power point tracking (2)

To achieve MPP, the DC-DC converter situated between the PV panel and the resistor is configured to maintain a situation such that the PV panel sees a resistance of $R_{MPP}$.

For instance, for a buck converter, it should be $\frac{R_0}{D^2}$ where $D$ is the duty cycle of the converter. Note that this works only if $R_{MPP} \geq R_0$ since $D \leq 1$.

Several algorithms exist to adapt the value of the duty cycle dynamically. Basic idea: at MPP, $\frac{dP_{PV}}{dV_{PV}} = 0$, use an iterative algorithm to identify the value of $V_{PV}$ that achieves this.

Note that this algorithm works well for a single PV panel, but if a converter is connected to a complex combination of PV panels, several local optima may exist and thus require more advanced solutions.
Fuel cells
Fuel cells

A combination (fuel cell + electrolyzer) can be seen as a storage device.

We focus here on the electricity (and heat) generation part, i.e. the fuel cell.

A fuel cell converts chemical energy directly into electricity.

Unlike a battery, it requires a continuous flow of $H_2$ fuel:

- Each $H_2$ molecule reacts at the anode and gives two electrons
- The remaining $2H^+$ ions pass through the membrane and react with oxygen + electrons coming from the cathode to produce water
Proton exchange membrane fuel cell (PEMFC)

These are the most common implementation of fuel cells:

- The anode and cathode catalyst is platinum
- The membrane is made of Nafion

The reversible voltage is

\[ E_r = 1.23 \text{V} \]

From thermodynamics, it can be shown that the maximum efficiency is

\[ \eta_{\text{max}} = 0.83 \]

In practice, its efficiency varies between 35% and 60%. The main factor affecting its performance is the fuel flow.
Fuel cell operation

• Fuels cells have a MPP of operation that corresponds to a cell output voltage of approximately 0.4V

• The power electronics interface must be designed to account for this low cell voltage, hence to provide a high input-output voltage step-up ratio

• Another important factor is that the cell must be operated with a relatively constant current output. Else, it can lead to a loss of performance or even to degradation of the membrane and catalysts
Microturbines
Microturbine

- Moderate cost and efficiency (20% to 30%)
- Failure rate is relatively low
- Moderately fast dynamic response
- Usually fueled with natural gas (NG), but can work with other fuels
- Units of 20 to 500 kW
Working principle of a micro turbine

1. Entering air is compressed
2. It is then mixed with the fuel in a combustion chamber
3. The mix is ignited, hence the temperature increases and the volume of the air increases
4. The expanded air actuates the turbine
5. The turbine drives the shaft of the generator
6. The heat of the exhausted air is reused to warm the compressed air.

Microturbines usually follow a Brayton thermodynamic cycle. Efficiency is affected - by the temperature ratio between the entering air and the compressed air (hence the reuse of exhaust gases to warm up the air in the compression chamber) - the compression ratio
Power electronics interface

The shaft rotates at a high speed, in the range 50,000 to 120,000 rpm. Hence the output voltage of the generator is in the kHz range. A microturbines thus requires a rectifier (+ inverter if connected to an AC grid).
Internal combustion engines
Internal combustion engines

ICEs are widespread:

- low capital cost,
- low operation.\footnote{Fuel may nevertheless be very expensive in some parts of the world} and maintenance cost
- can be easily moved from one place to another
- Can be designed to work with a variety of fuels

Units of several kW to several MW.
Working principle of ICEs

1. Intake (induction) stroke
2. Compression stroke
3. Power stroke: combustion/expansion
4. Exhaust stroke

ICEs follow an Otto thermodynamic cycle.