Microgrid Components and Operation

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A Brief Overview

- ☑ **Why this is important**: What has recently changed …
- ☑ **Definition & Topology**: The big picture of a Microgrid …
- ☑ **The individual components**: The pieces - what's in there…
- ☑ **The Details**: How it all works together…
- ☑ **Difficulties**: Energy, power, and harmonics …
- ☑ **Comments**: Food for thought – scattered liberally throughout ….

Why this is important now

The new edition of NFPA-99 (*Health Care Facilities Code*) has added placeholder text that will ultimately allows microgrids to be used in lieu of emergency generators.

Definition

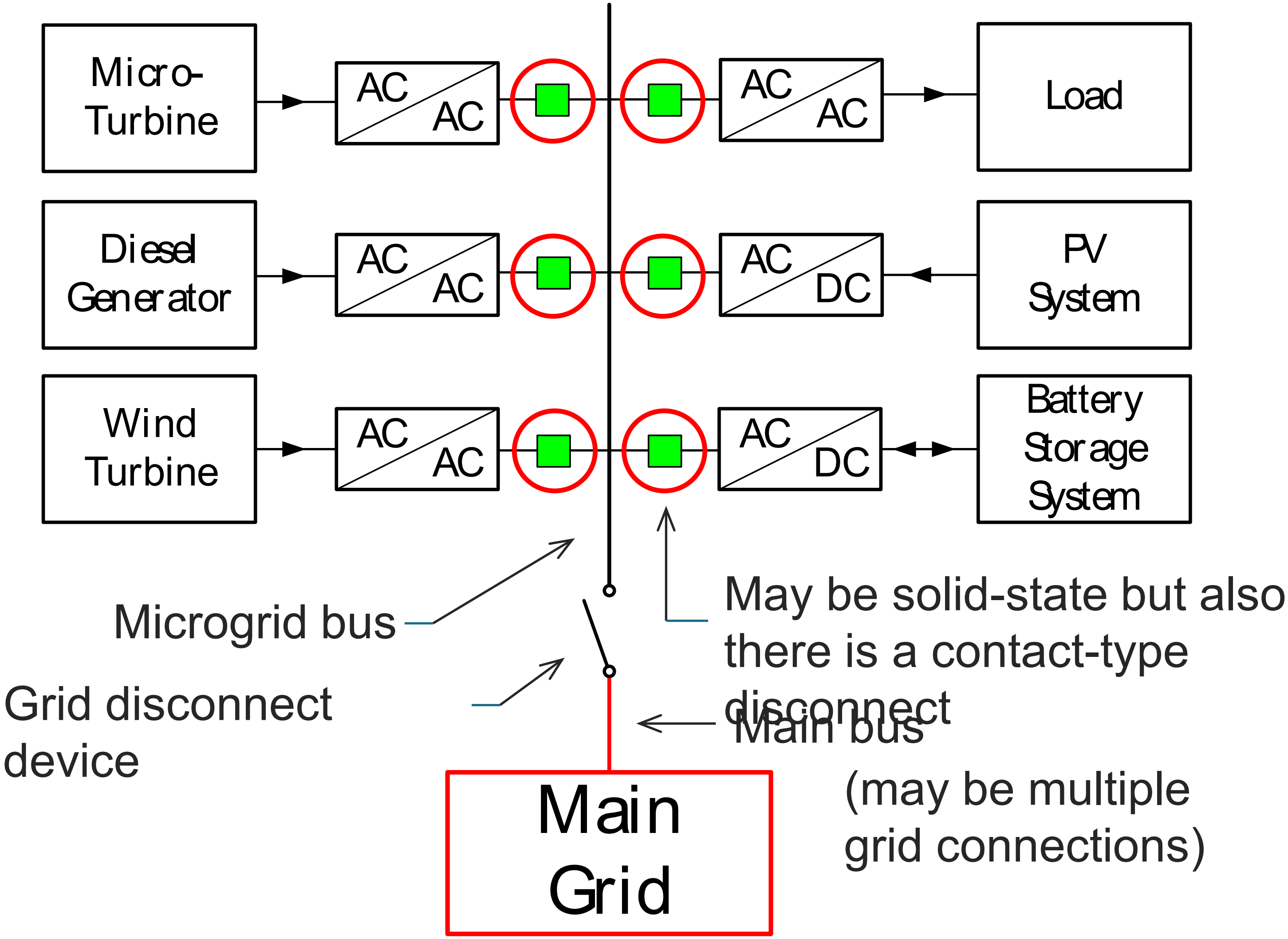
A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.

U.S. Department of Energy Microgrid Exchange Group

Comments

- Pretty broad definition – covers a lot of ground
- Doesn't say anything about size
  - Electrical size (voltages, power, energy, *etc.*)
  - Geographic area
- Doesn't say anything about quantities
  - Loads
  - Sources

In its general form a microgrid looks like this:



Comments

All microgrids will have some of these components but probably not all of them …

There may be multiple devices of each type …

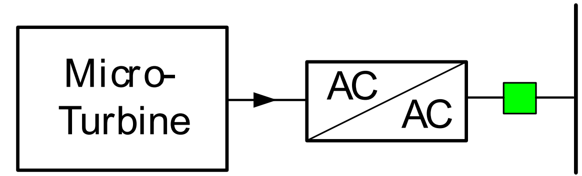
Each microgrid device will have its own disconnecting means …

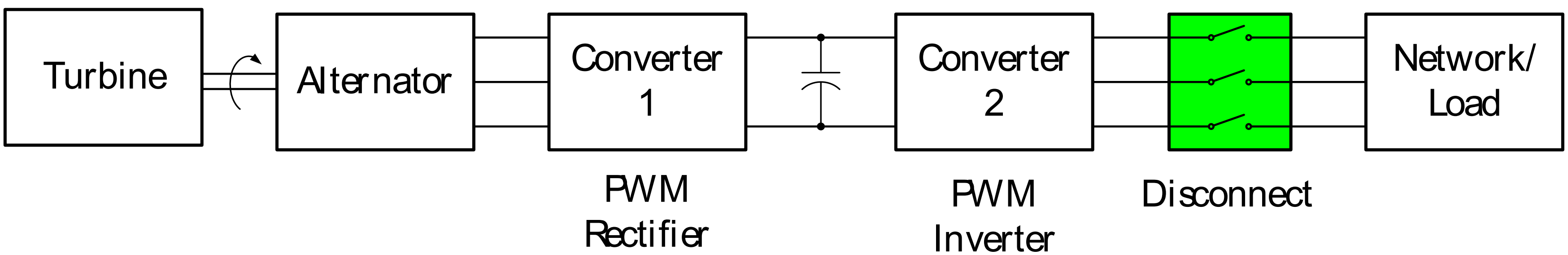
Each microgrid device will have its own characteristics

- Availability
- Size & ability to carry/support loads
- Waveforms and distortion

Look into each of the connected devices…

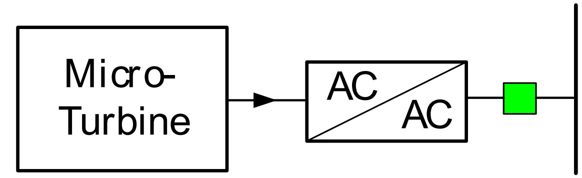
The micro-turbine component has the following elements:





Gas turbine:

- Shaft speed: 40,000 to 120,000 RPM
  - Direct drive or gear drive to alternator
- Various fuels:
  - Gasoline, natural gas, propane, diesel, kerosene…
  - Others including biogas and E85…



Alternator:
- Conventional PM synchronous machine
- Direct drive (40,000 to 120,000 RPM)
  - Alternator output frequency 667 – 2,000 Hz
- Gear drive (3,000, 3,600, 6,000, or 7,200 RPM)
  - Alternator output frequency 50 or 60 Hz

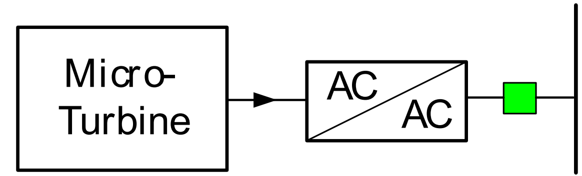
Rectifier/inverter system:
- Used when turbine drives alternator directly
- Alternator may be direct connected to grid when gear drive is used

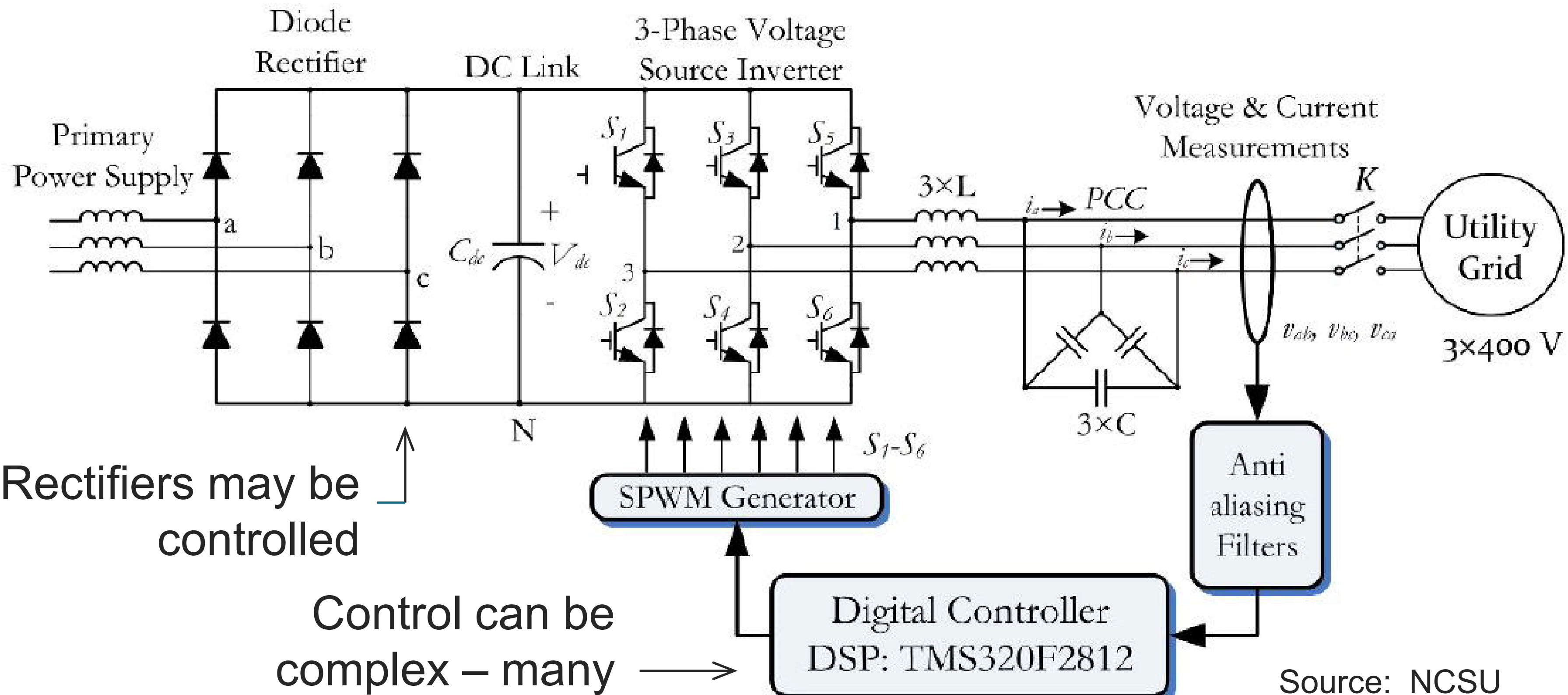
Ratings:
- 25 – 500 kW, 3Ø, 50/60 Hz at standard building delivery voltages
- Available in Medium Voltages
- Efficiency: Up to around 85%

Comments:
- Not very good with impulse loads
- Turbines don't have a lot of instantaneous torque
  - Most systems have large flywheels

Solid state electronics:

- Typical AC → DC then to a Voltage Source Inverter (VSI)…
- Electronics not needed if alternator turns at synchronous speed …



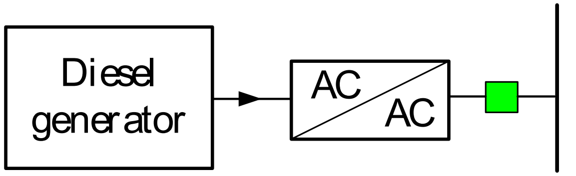


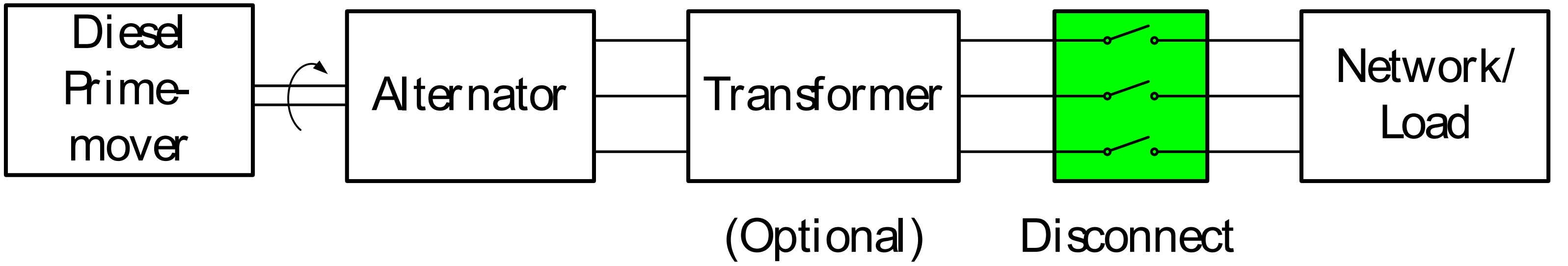
Rectifiers may be controlled

Control can be complex – many methods available

Source: NCSU FREEDM Systems Center

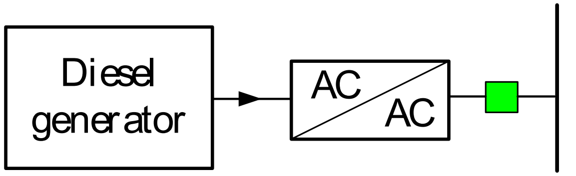
The diesel driven generator (genset) has the following elements:





Diesel prime-mover:

- Shaft speed: 900 – 3,600 RPM depending on size & frequency
  - Generally direct drive to alternator
- Various fuels:
  - Diesel
  - Natural gas, propane in smaller sizes (actually spark ignited)

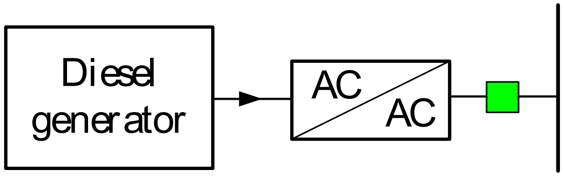


Alternator:
- Conventional PM synchronous machine
- Alternator output frequency 50 or 60 Hz

Transformer:
- May or may not be used depending on voltages involved
  - If microgrid is 'local' and no MV is involved the alternator may supply the bus directly

Ratings:
- 30 kw – 2,500 kW, 3Ø, 50/60 Hz at standard building delivery voltages
  - *Usual* maximum voltage is 5 kV class
- Efficiency: Up to around 50%

Comment:
- Good 'grid forming' element
  - Can be large
  - Stable in operation
- Diesels have a lot of rotating mass and good instantaneous torque



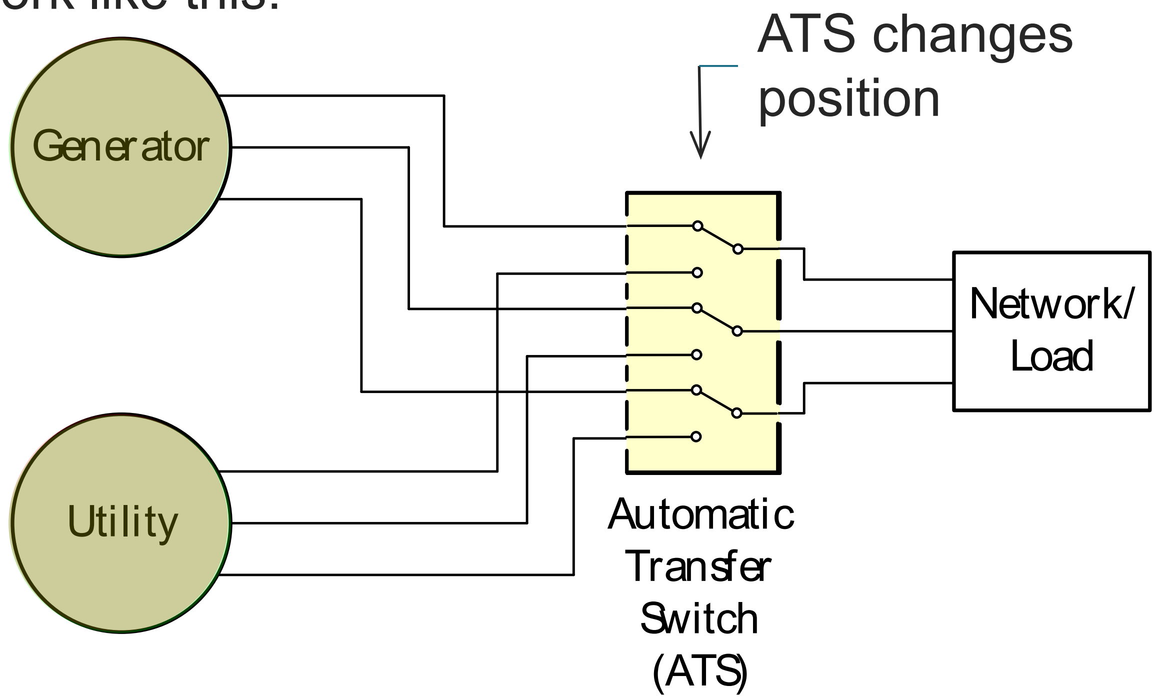
Additional switching:

- Diesel gensets can be used in non-synchronized applications
    - Emergency power with open transition or closed transition

Transitions:

- Open transition – genset and utility are never connected in parallel
    - There is an ‘off interval’ when the load is re-transferred to the utility source
- Closed transition – genset and utility are momentarily connected in parallel
    - There is no ‘off interval’ when the load is re-transferred to the utility source

Open Transition switches work like this:



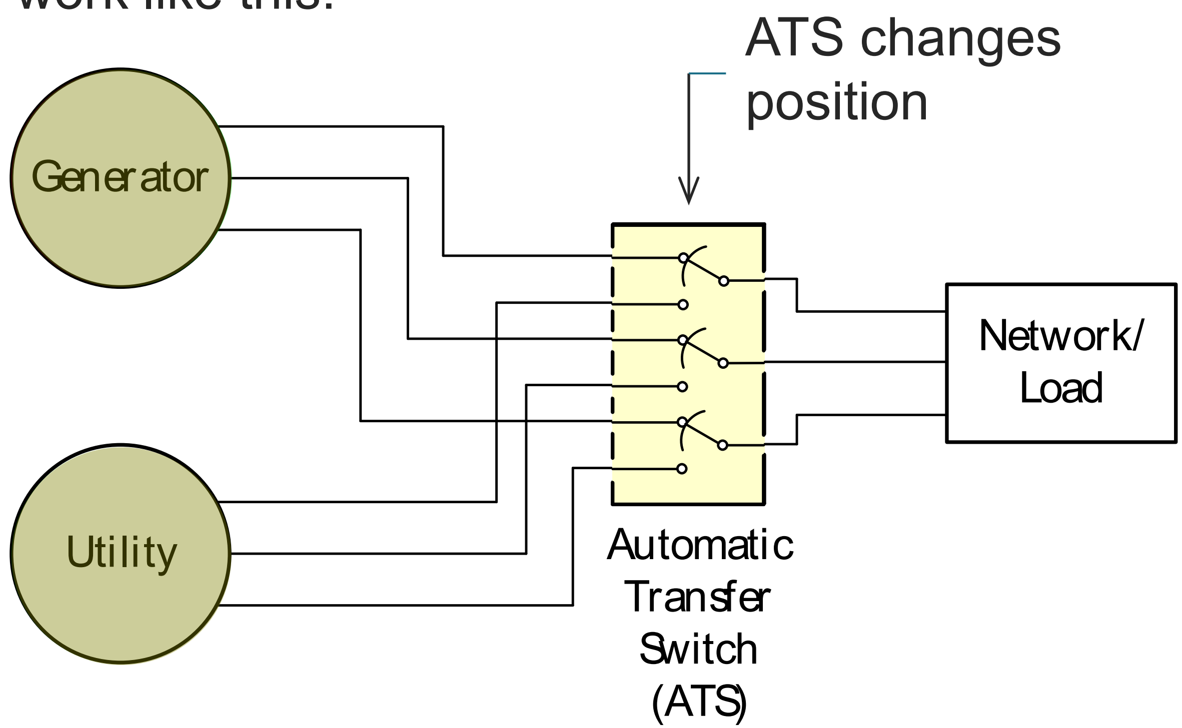
1. Normal Operation – the load is supplied by the utility source.
2. Upon a utility failure the generator starts.
3. When the ATS detects power available at the generator it switches to the generator source.
   - This is an OPEN TRANSITION
4. Eventually, utility power returns.
5. After a delay to assure utility stability the ATS switches back to the utility source.
   - This is an OPEN TRANSITION
6. After a cool-down interval the generator shuts down.
   - System is now back in the Normal Operation condition.

Closed-transition switches work like this:

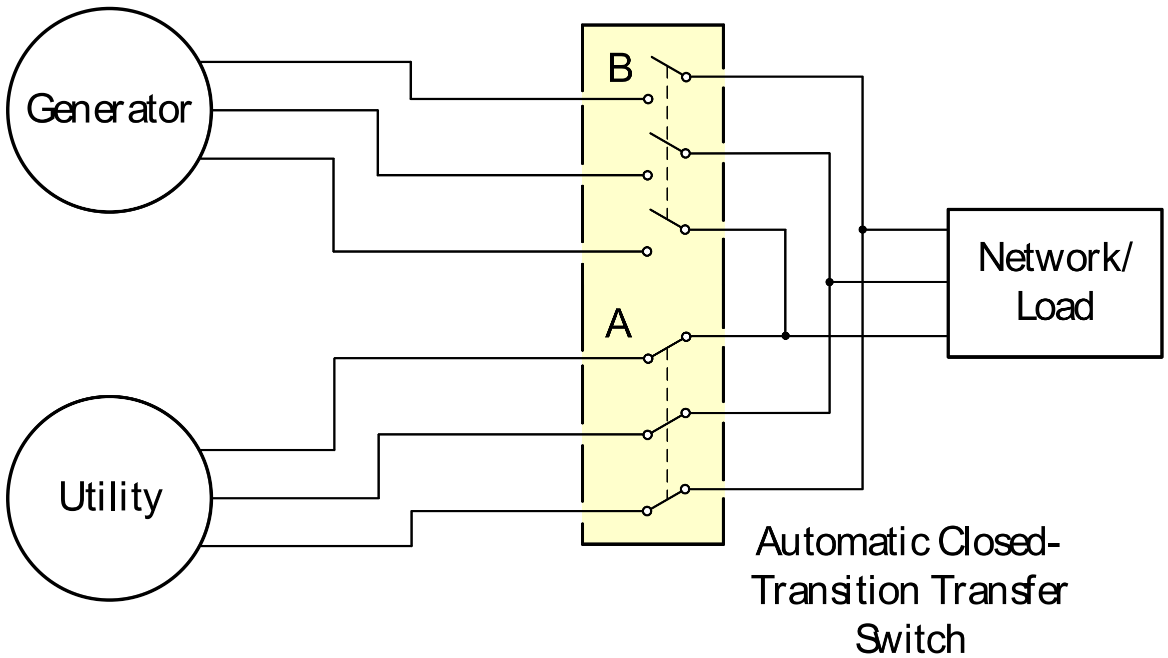
1. Normal Operation – the load is supplied by the utility source.
2. Upon a utility failure the generator starts.
3. When the ATS detects power available at the generator it switches to the generator source.
   - If the generator is not running this is an OPEN TRANSITION
4. Eventually, utility power returns.
5. After a delay to assure utility stability the ATS switches back to the utility source.
   - This is a CLOSED TRANSITION

Closed-transition *interval* $\approx$ 150 ms.

6. After a cool-down interval the generator shuts down.
7. The system is now in the Normal Operation condition.

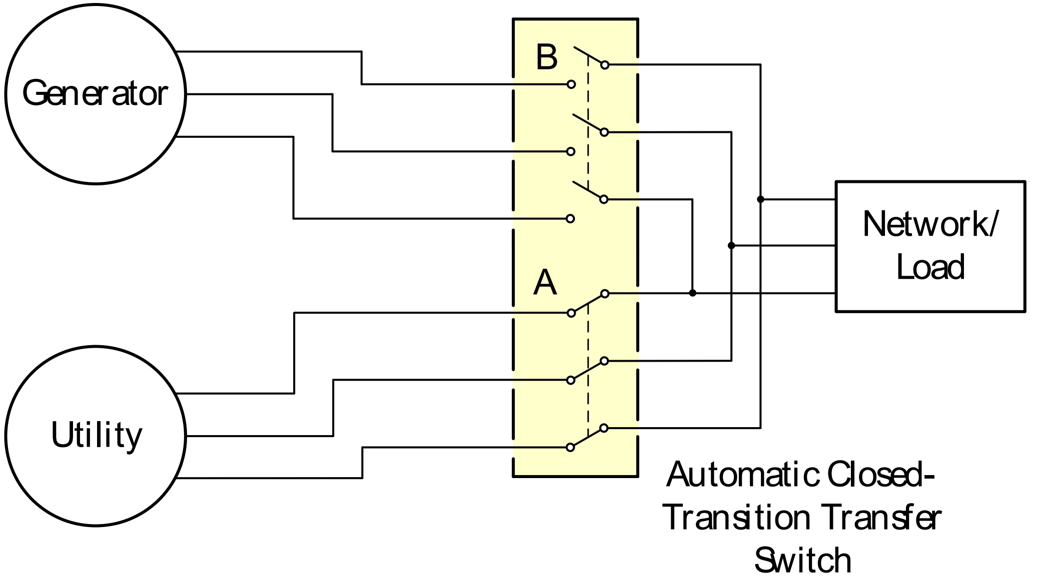


Closed-transition Comments:



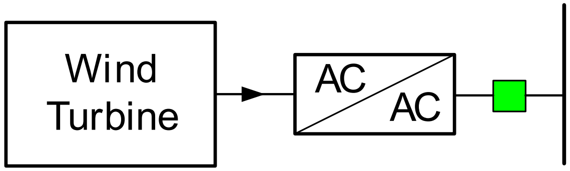
1. Diagram shows ‘overlapping’ contacts but usual arrangement is two independent sets of 3 or 4-pole contacts (Switch A & B)….
2. Contact control is independent but the contacts are carefully interlocked to prevent unintentional paralleling of the sources…
3. A closed-transition ATS can be operated in the open-transition mode.

Closed-transition Comments, con't:



4. Typical operation of a closed transition ATS:
   - Open-transition upon utility failure if genset is offline – this is the usual case…
   - Closed-transition upon utility failure if genset is online (usually a test condition)
   - Closed-transition on re-transfer to utility source
   - Open-transition on re-transfer to utility source if there are 'issues.'
5. Closed-transition ATSs are quite expensive …. More about this later ….

A wind turbine is actually *much* more complex than the simple block diagram to the right would indicate…

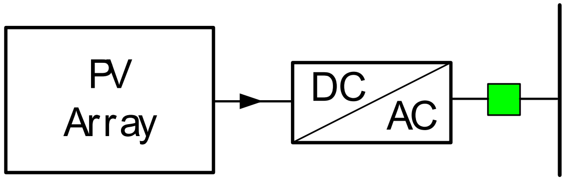


The reason is that, unlike the previous components, the energy source (*i.e.*, wind) is not constant…

But …

The interface requirements of the 'grid' are quite constant

- Frequency – generally fixed at 50 or 60 Hz
- Voltage magnitude and phase angle – source voltage/angle must be higher than grid voltage to deliver either real or reactive power.
- In general:
  - Voltage magnitude will determine delivered/absorbed *reactive* power
  - Voltage phase angle will determine delivered/absorbed *real* power



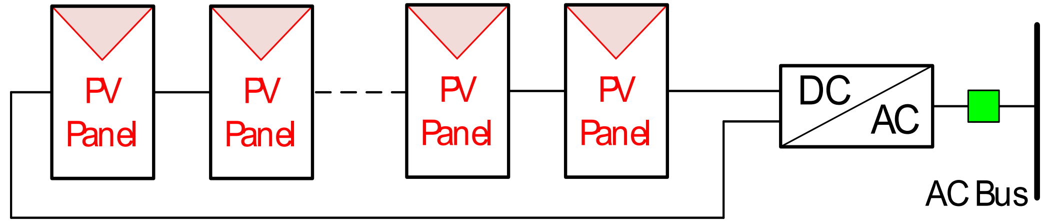
PV systems – like wind turbines – take advantage of ‘free’ energy from sunlight…

And – again like wind turbines – the available energy is quite variable

The output of individual PV solar cells is DC

- Connection to an AC grid always requires an inverter, generally a solid-state device
  - Mechanical low voltage DC → high voltage DC (or AC) converters were common up to the mid-1950s
  - Called a *dynamotor* – a DC motor and an a DC or AC generator on the same shaft…
  - Also mechanical vibrating contacts were used to chop DC to use at the input to a transformer…

The typical ‘simple’ PV system looks like this:



Individual PV solar cell panels are connected in series and supply a DC → AC inverter….

Comments:

1. This arrangement is typically used for small PV systems, say less than around 10 kW
2. There are three basic types of PV panel
   A. Monocrystalline
   B. Polycrystalline
   C. Thin film
3. Number of panels depends on:
   A. Voltage & current output of each pa
   B. DC voltage required at the inverter

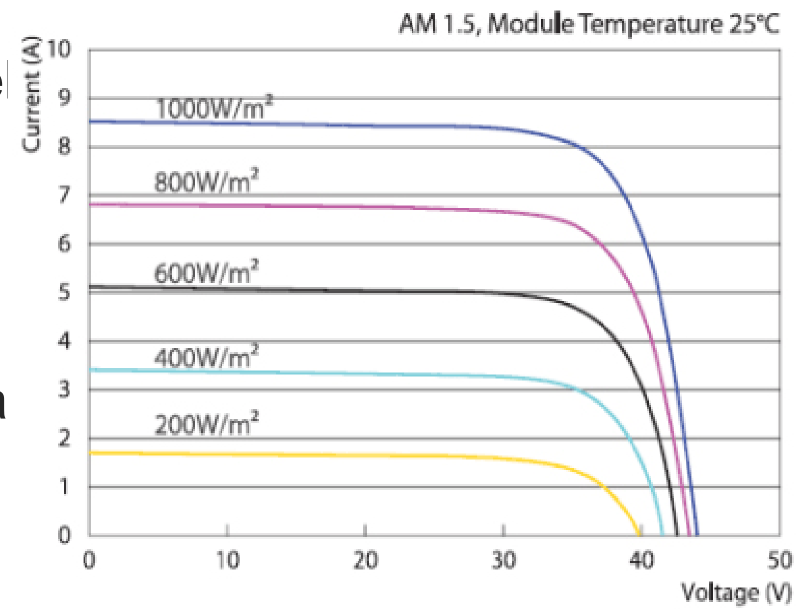
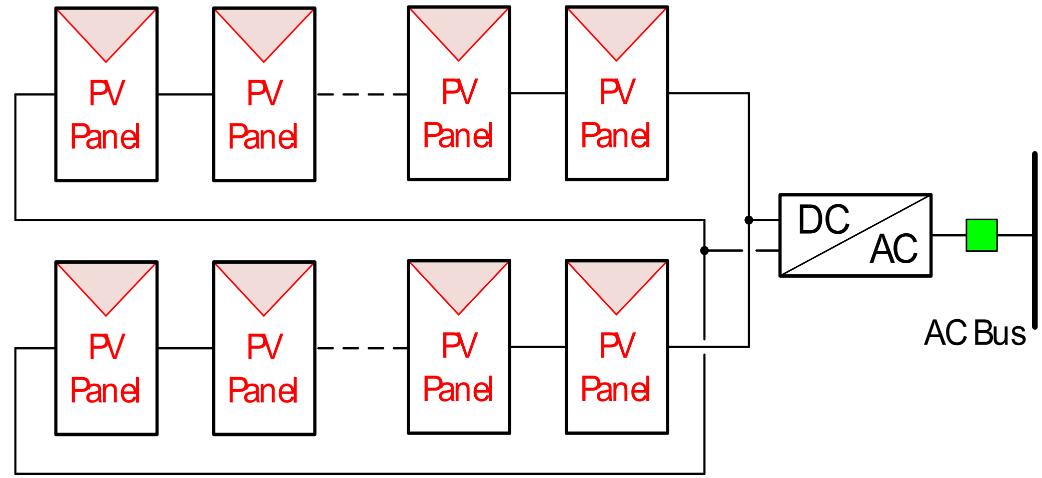
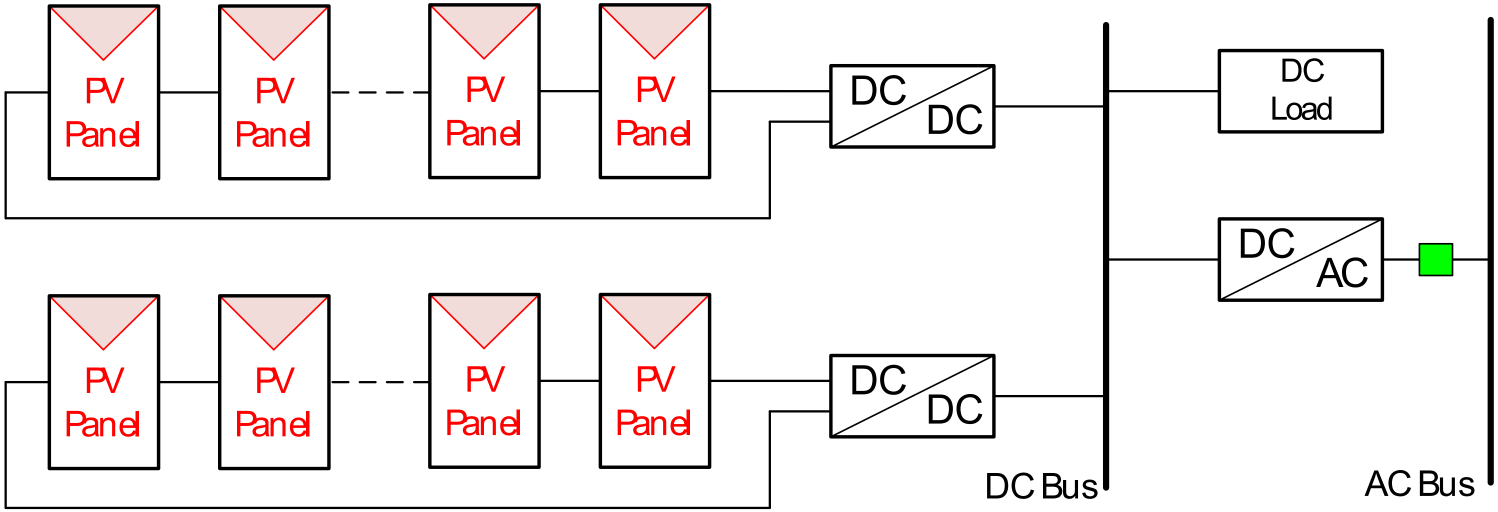


Image from *energy NP* (energynp.com)

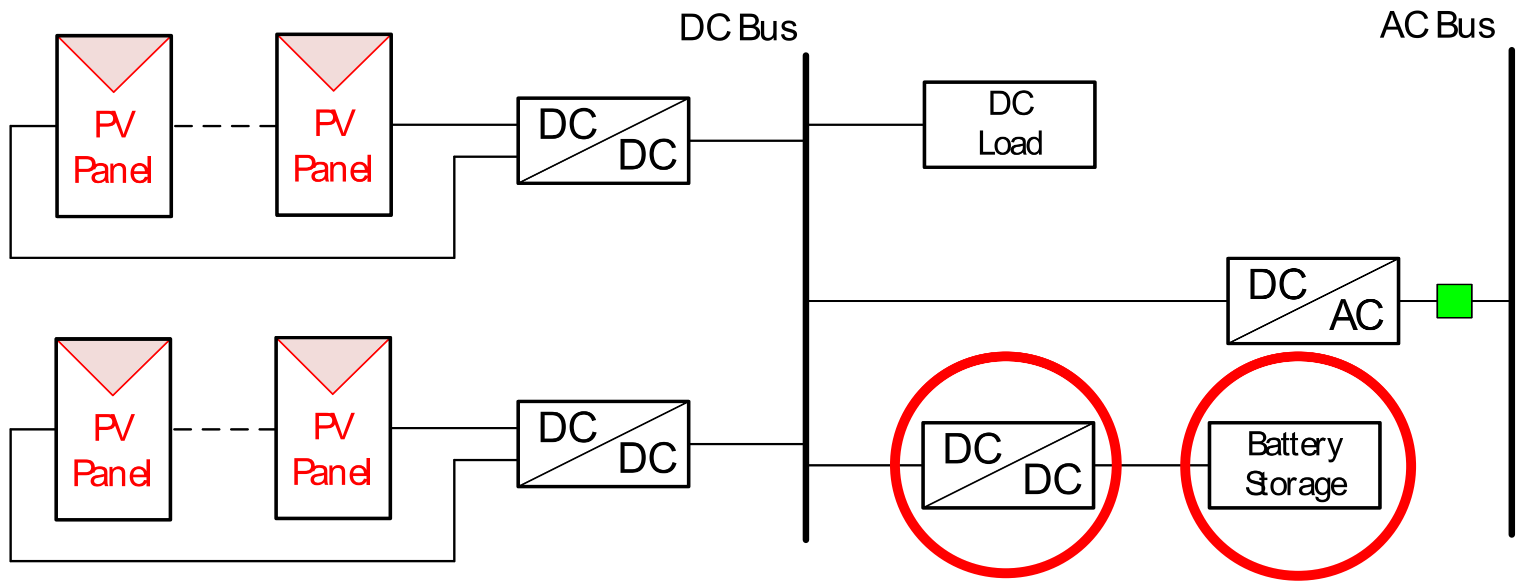
There are many possible ways to arrange PV systems.

These are two possible ways:





Batteries can be added for energy storage. This is becoming more common…



This is actually the same topology as shown before with the addition of:

1. A DC → DC interface and controller
2. A set of storage batteries

Comments:

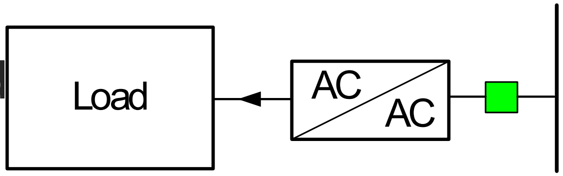
1. This looks pretty much the same as before but *now* the energy can flow two ways…
   And that introduces 'complications' ….

2. The ‘complications’ involve:
   A. How to manage the battery system…
   B. When to charge, when to discharge …
   C. How to control the reserve energy stored in the battery
   D. How to manage the condition of the battery to optimize a desired goal…
3. And, now that we come to mention it, just what does ‘optimize’ mean in the first place?
   A. Minimize energy taken from the grid?
   B. Minimize power taken from the grid?
   C. Minimize *cost* of energy taken from the gird?
   D. Minimize *cost* of power taken from the grid?
   E. Maximize battery life?
   F. Many other things that can be ‘optimized’ ….

Aside: ‘parameters’ may actually turn out to be ‘variables’ ….

The bottom line is that the control of a Battery Energy Storage System (BESS) is actually a fairly complicated exercise that is dependent on many parameters and variables.

Loads look like the simplest and most straightforward component of the Microgrid …



That is not necessarily true in that there are many considerations concerning microgrid loads. For example:

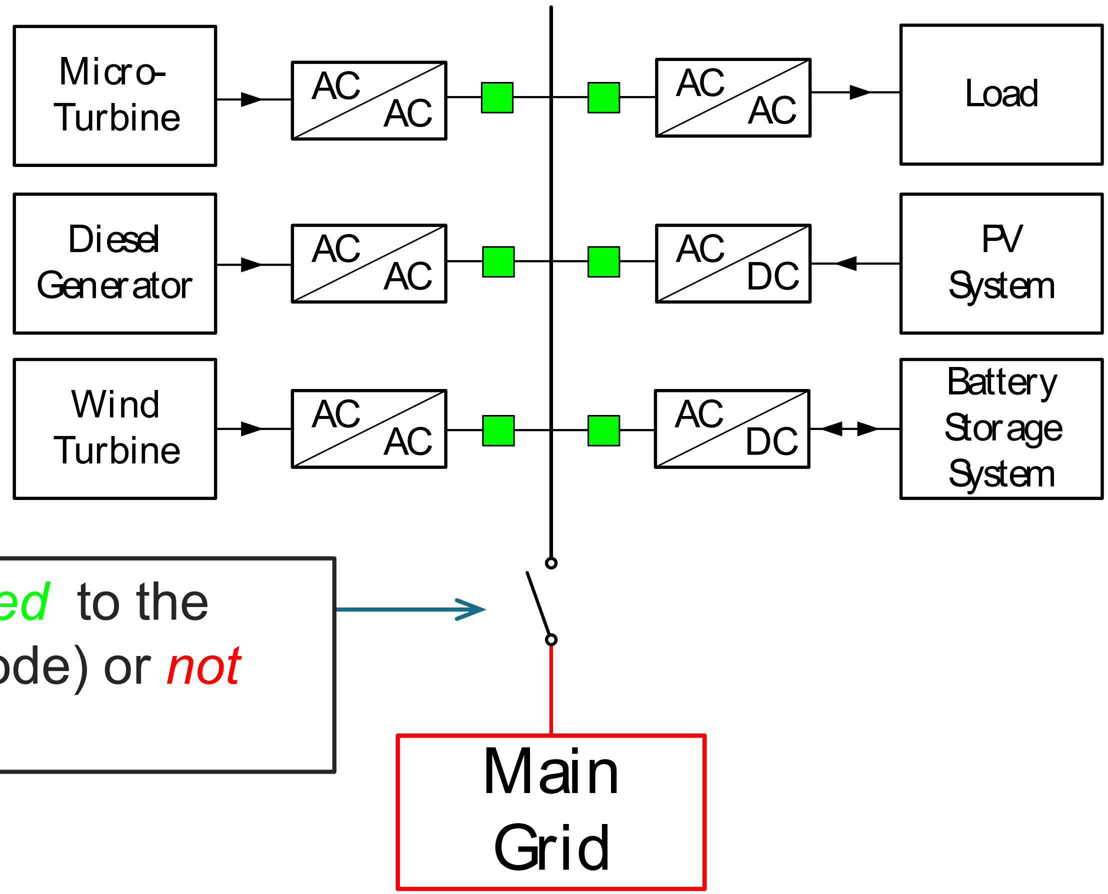
1. The size of the load, *i.e.*, kW, kVA, voltage….
2. The inrush needs of the load…
3. The harmonic content of the load’s current…
4. The sensitivity of the load to the harmonic content of the voltage source…
5. The criticalness of the load – how important is it that a load stay on in the event of certain reasonably foreseeable events ?
6. The number of loads and the interrelationship of the load with other loads…

There can be other components connected to a microgrid but this list covers all the *types* of connected elements…

Wave action, thermal, water storage, ice storage, fuel cell, *etc*.

There are really only *two* ways that a microgrid can be operated….

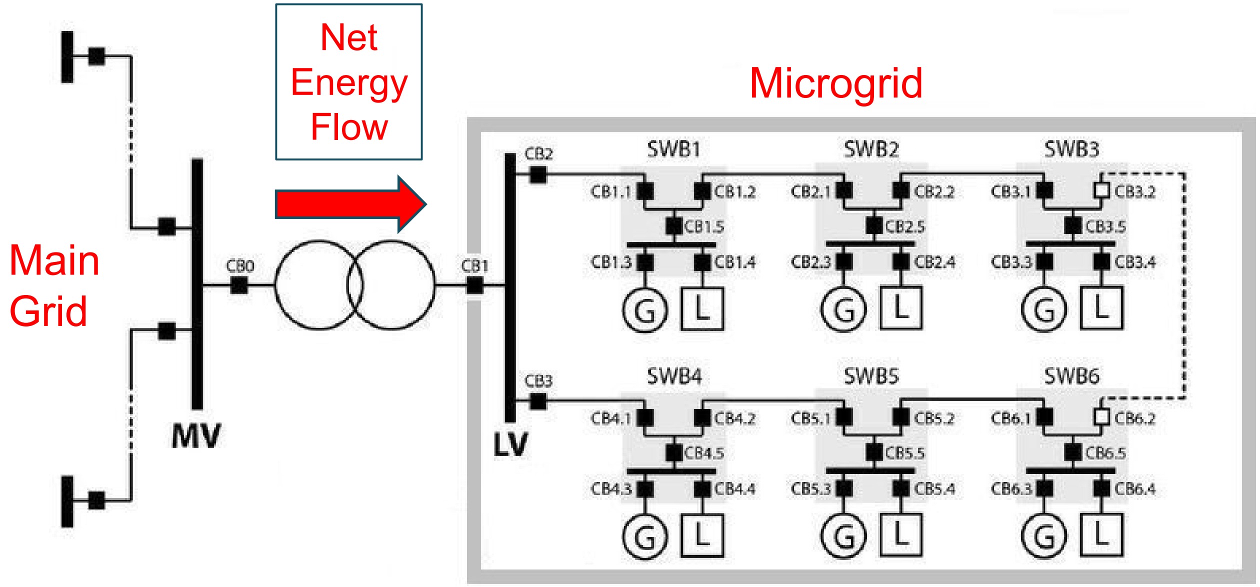
…but there are *many* variations in the ways the overall operation can be achieved…



A microgrid is either *connected* to the main grid (grid-connected mode) or *not connected* (islanded mode)

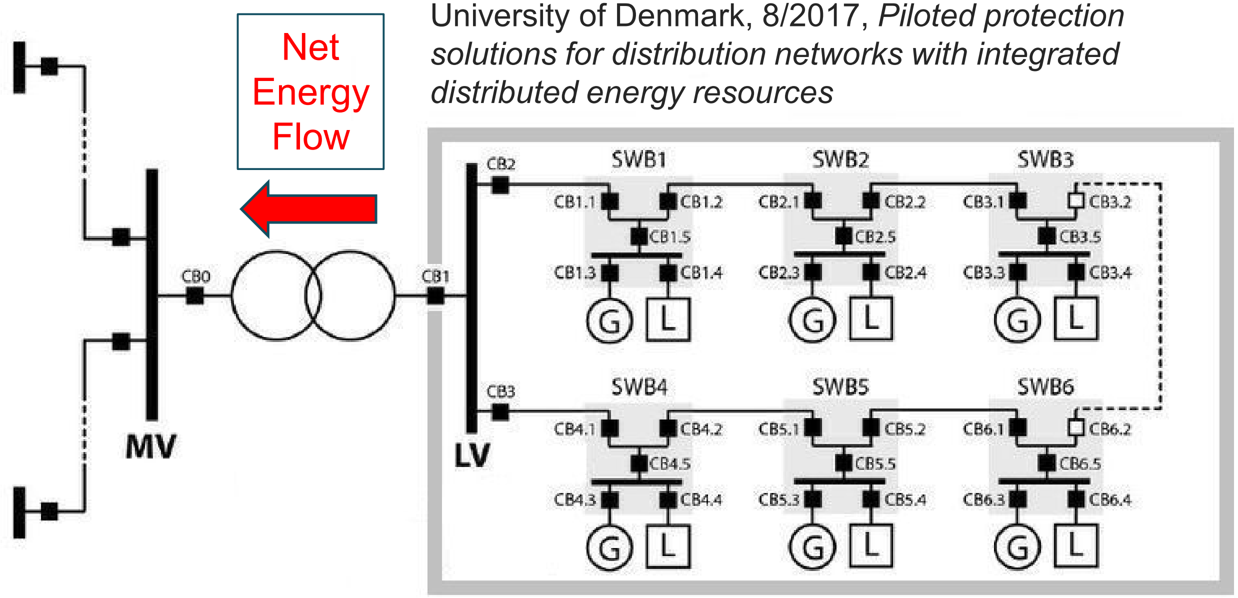
Take a detailed look at the connected mode …

For grid-connected operation where the overall energy flow is into the microgrid…

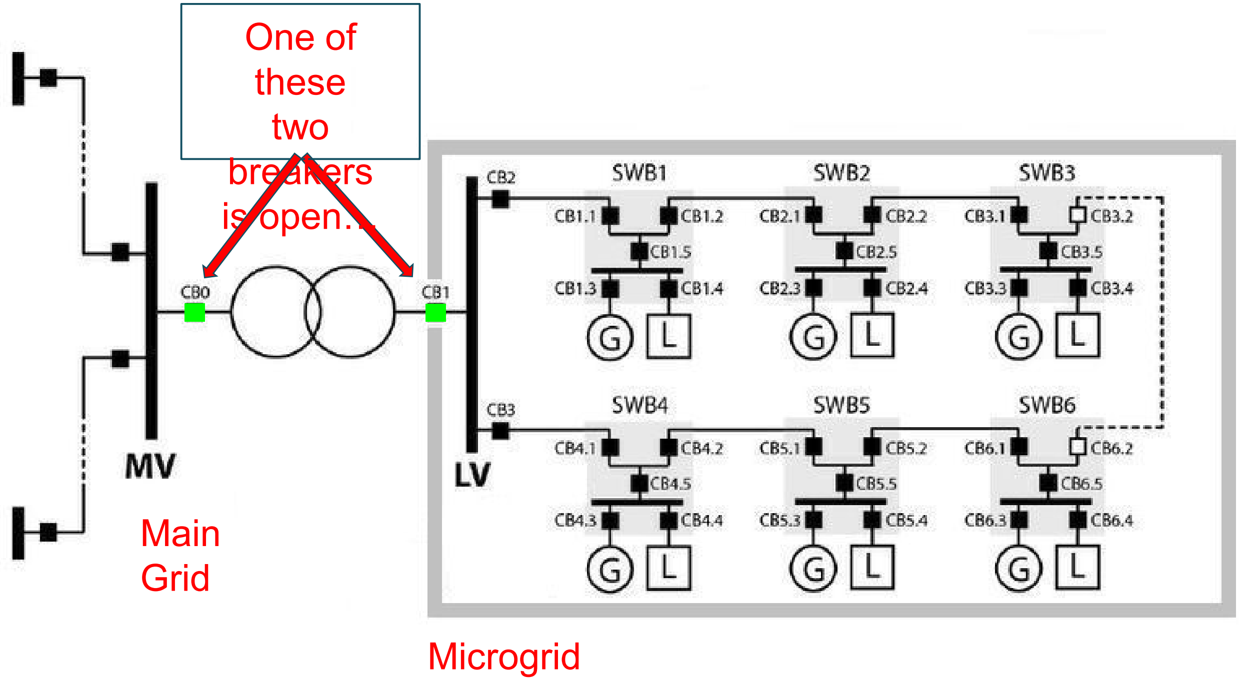


Images from MS thesis of Syed H. Kazmi, Technical University of Denmark, 8/2017, *Piloted protection solutions for distribution networks with integrated distributed energy resources*

For grid-connected operation where the overall energy flow is out of the microgrid…



For islanded operation the situation is ‘somewhat’ different….



In islanded operation:

1. The microgrid is completely disconnected from the main grid
2. Microgrid-generated power must be equal to or greater than connected load
3. Source impedance seen by the microgrid loads is *higher* than any of the grid-connected configurations
4. At least one component in the microgrid must be a ‘grid forming’ component.
   - There are many Codes and Standards that require PV to automatically shut down in the event of grid power loss

Creating a microgrid ‘island’ upon a main grid failure is relatively easy *if* the conditions for sustained operation exist at the moment of failure ….

Re-joining the microgrid to the main grid is not so easy … (*Without* a transient ….)

In order to rejoin the main grid the following things must happen:

1. The rotation and the phase-to-phase connections between the main grid and the microgrid must be the same.
   - Easy … they were previously connected before the microgrid was islanded and nothing (usually) has changed.
   - *Perhaps* … What if line work is being done in the main grid?
2. The voltages (at all phases) must match
3. The phase relationship (at all phases) must match

This is a very difficult task in the 'real world' where:

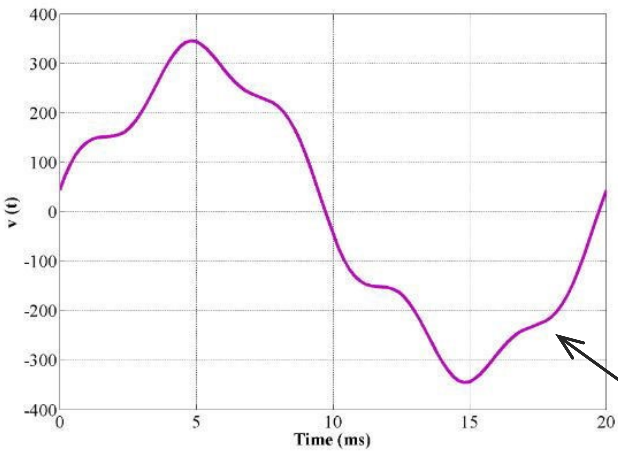
1. There are multiple energy sources involved
   - It's *bad* even when there is only a single generator and a closed-transition Automatic Transfer Switch
2. The loads draw nonlinear currents
   - Nonlinear currents $\rightarrow$ nonlinear voltages…

Consider what will happen with rejoining a microgrid to a main grid when there is a voltage mismatch.

We're not concerned about *why* there is a mismatch only that it's present. There may be many reasons it happens…

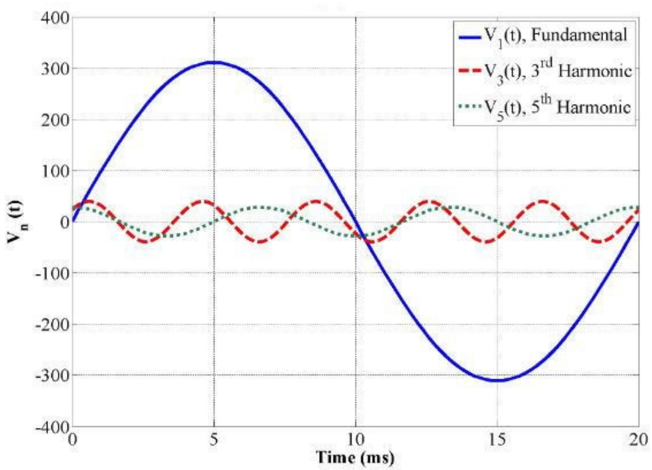
Assume, for the moment, that the difference is due to voltage waveform distortion…

The *islanded* microgrid voltage waveform might look like this:



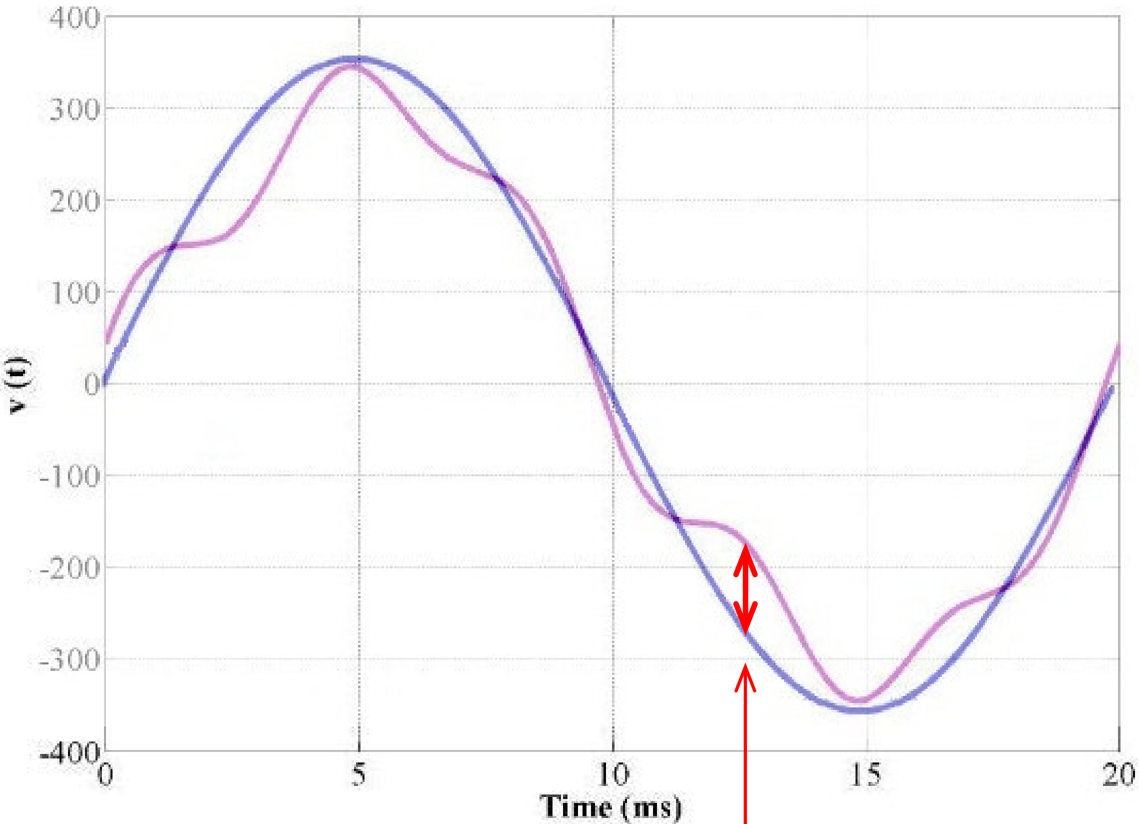
Well, probably not really….
This is fairly exaggerated to illustrate the principle…

The composite waveform look like this



The individual harmonic components look like this

Source: https://www.intechopen.com/books/power-quality-issues/harmonic-effects-of-power-system-loads-an-experimental-study



Now, the main grid voltage waveform is *more-or-less* a pure sine wave.

There is no way* to duplicate the exact main grid voltage on the microgrid before the re-connection….

So, at the instant before re-connection you have this:

There is a voltage *difference* between the two waveforms

….

* Actually, there are several ways to do this – they're just not easy …

In general, the voltage at any point in time is relatively small in relation to the total voltage….

The RMS voltage difference is even smaller….

So, what would be the current flow through this ‘small’ voltage difference? That will depend on two things:

- The impedance between the two voltages …
- The amount of time it takes the grid voltage and the microgrid voltages to stabilize, that is, the length of the transient…

Here’s the bad news: The impedance between the voltages is typically low. Actually, *very* low ….

This is especially True:

- In the grounding path…
- In low voltage systems…

The resulting current, can be thousands of Amps, enough to trip the instantaneous element of the normal side circuit breaker on the retransfer to the normal source….

Summary:

- Microgrids come in all sizes and ratings from very small in-building systems to systems that encompass many square miles
- Voltage and power levels vary over a large range too
- There are many different types of distributed generating resources, each with advantages and disadvantages
- For a microgrid to operate in island mode:
  - The total microgrid load must be less than the available generating resources
  - There must be at least one grid forming generating resource connected to the microgrid that can carry the full load of the microgrid
    - Unless loads are shed during the initial stage of islanded operation
- There can be retransfer problems when an islanded microgrid rejoins the main grid
  - In either closed-transition or open-transition mode

Questions ?