14-Off-Grid System Operation & Control

Off-Grid Electrical Systems in Developing Countries, 2nd Edition

Chapter 14

Preface

- These lectures slides are intended to accompany the textbook *Off-Grid Electrical Systems in Developing Countries, 2nd Edition, 2025* written by Dr. Henry Louie and published by SpringerNature
- Additional content, explanations, derivations, examples, problems, errata, and other materials are found in the book and on www.drhenrylouie.com
- To request solutions, explanations, permissions to use author-supplied images, or if you notice an error, please email the author at hlouie@ieee.org
- Inquiries about guest lectures, seminars, or trainings can be made to hlouie@ieee.org
- If you want to support work in electricity access, consider donating to KiloWatts for Humanity or IEEE Smart Village

Learning Outcomes

At the end of this lecture, you will be able to:

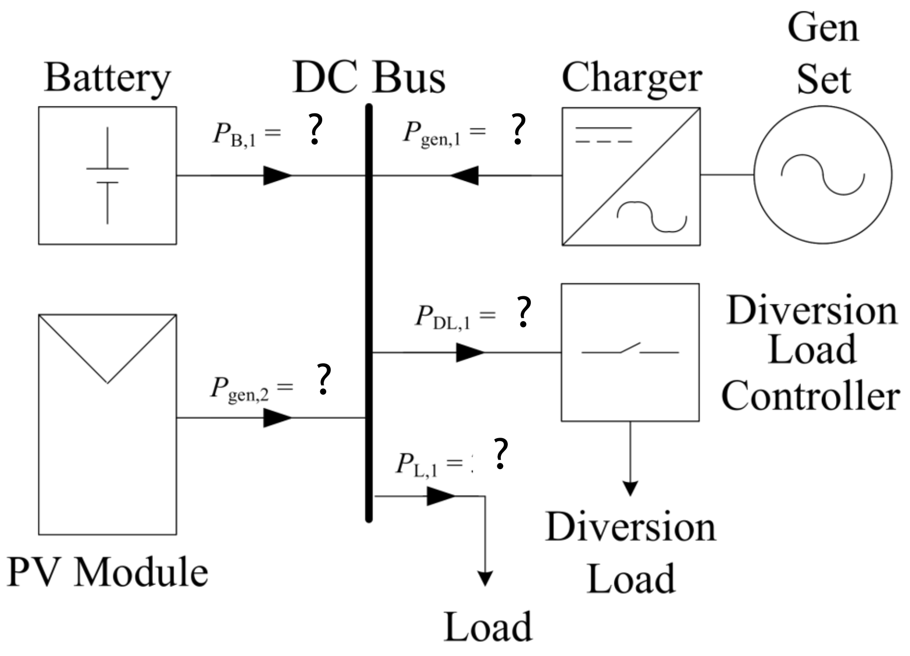
- ✓Create and apply a power flow model to a variety of off-grid system architectures to determine the power produced, consumed, or converted by various components
- ✓Describe the need for and rationale behind off-grid system priority schemes
- ✓Compare and contrast the different approaches for frequency and voltage control such as droop, isochronous, Controller–Responder, and frequency shift power control
- ✓Describe the role of remote monitoring in off-grid system operation

Introduction

- Focus on the operation of an off-grid system as a whole, with emphasis on AC bus
- Coordination of power flow required in off-grid systems with multiple generation sources and energy storage
  - Which sources are prioritized?
  - How to manage changes in generation?
- AC bus control requirements: voltage frequency and magnitude

Power Flow Model

- Goal: develop an algebraic mathematical model of the power into and out of each component in an off-grid system
- Developed model
  - reflects steady-state conditions
  - based on conservation of power
  - largely ignores losses
  - assumes no voltage drop



How do we determine the power into/out of each component?

Power Flow Model

- Conservation of power: sum of power generated equals sum of power consumed by the load (plus losses)

$$\sum_{j=1}^{J} P_j = 0$$

power of the jth component

- Separating power into generation (gen), battery (B), load (L), diversion load (DL), and ballast load (BL):

$$\sum_{g=1}^{G} P_{\mathrm{gen},g} + \sum_{b=1}^{B} P_{\mathrm{B},b} - \sum_{l=1}^{L} P_{\mathrm{L},l} - \sum_{m=1}^{M} P_{\mathrm{DL},m} - \sum_{n=1}^{N} P_{\mathrm{BL},n} = 0$$

battery power is positive when discharging

Power Flow Model

- Simplifying the notation so that all similar components share a single variable (equal to their sum) such as $\sum_{b=1}^{B} P_{\mathrm{B},b} = P_{\mathrm{B}}$
- Results in

$$P_{\mathrm{gen}} + P_{\mathrm{B}} - P_{\mathrm{L}} - P_{\mathrm{DL}} - P_{\mathrm{BL}} = 0$$

Power Balance at DC and AC Buses

- Net power of components at DC bus (P_{DC}) summed with net power at AC bus (P_{AC}) must equal zero

$$\sum P_{\text{DC}} + \sum P_{\text{AC}} = 0$$

- But, net power at each bus does not individually have to equal zero
- When net power at a bus does not equal zero, there is power through the converter connecting the buses

Power Balance at DC and AC Buses

- Converter power

$$P_{\text{con}} = \sum P_{\text{DC}} = P_{\text{DC,gen}} + P_{\text{B}} - P_{\text{DC,L}} - P_{\text{DL}}$$

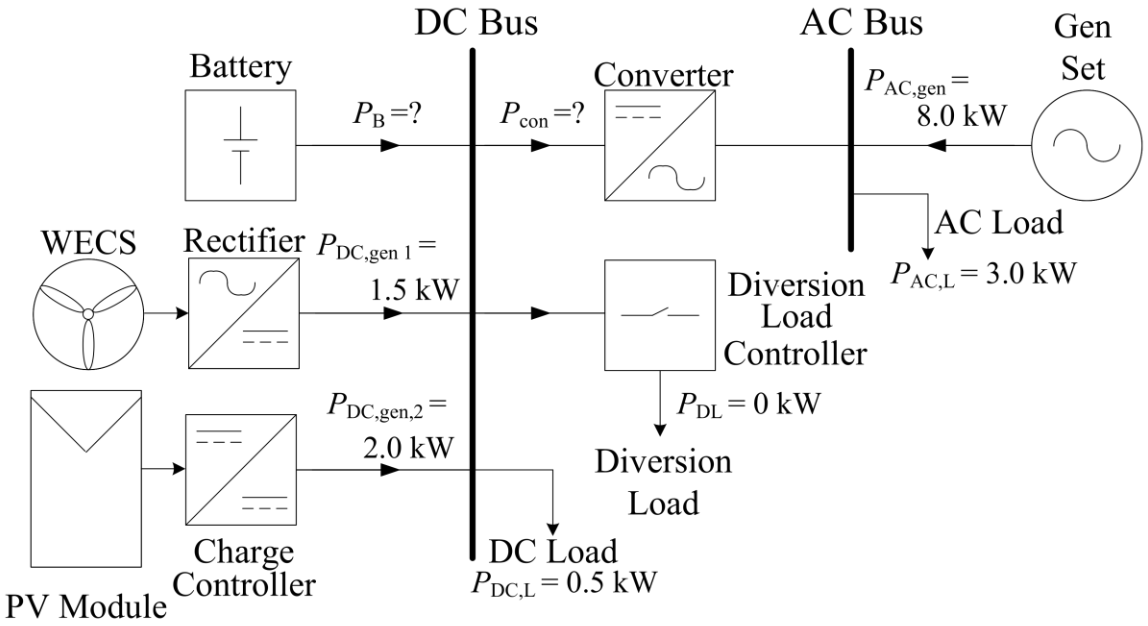
$$P_{\text{con}} = -\sum P_{\text{AC}} = -P_{\text{AC,gen}} + P_{\text{AC,L}} - P_{\text{BL}}$$

$P_{\text{con}} > 0$ means the converter is acting as an inverter

- Above equations account for which components can be connected to which bus (i.e. diversion loads are connected to DC bus, ballast loads connected to AC bus, and there can DC loads and AC loads)

Example 14.1

Compute the battery power and converter power.



Example 14.1

Compute the battery power and converter power.

$$P_B = -\sum_{g=1}^{G} P_{gen,g} + P_L + P_{DL}$$

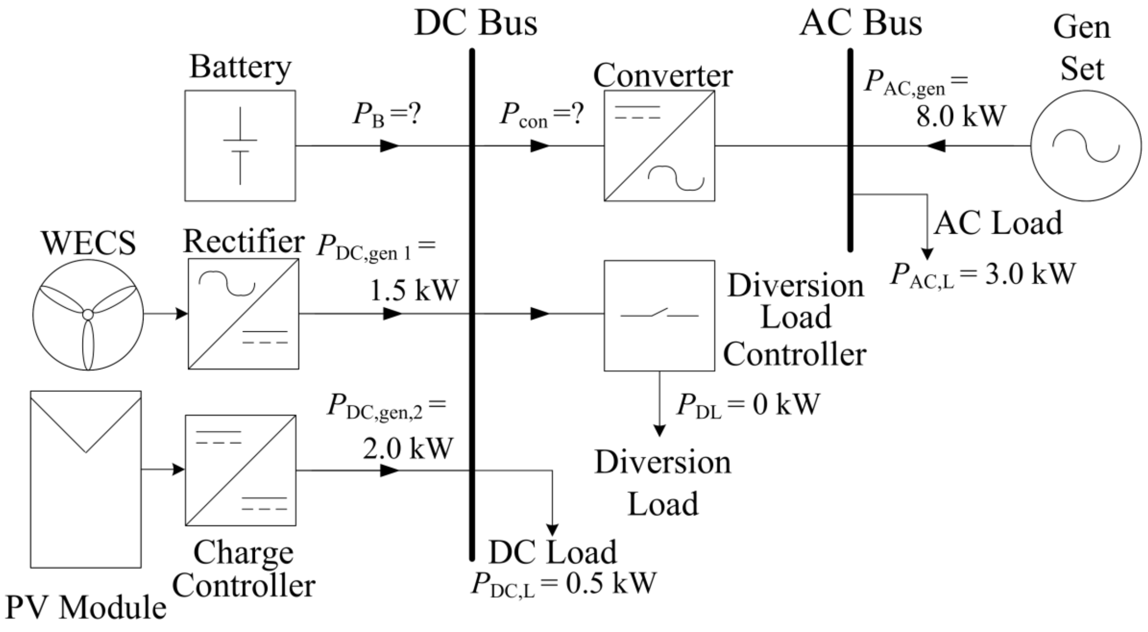
$$P_B = -1.5 - 2 - 8 + 3 + 0.5 + 0 = -8 \text{ kW}$$

negative sign means the battery is being charged

summing power at AC bus

$$P_{con} = -8 + 3 = -5 \text{ kW}$$

negative sign means the converter is acting as a rectifier (AC to DC)



Including Losses

- Losses include those within the components and in wiring and connections
- Assume losses are included within the load (example: a 100 W load with 2% losses is modelled as a 102 W load)

Converter Losses

Converter losses are modeled as an efficiency so that

$$P_{\text{con}} = \eta_{\text{con}} \sum P_{\text{DC}} = -\sum P_{\text{AC}} : \ \sum P_{\text{AC}} < 0, \sum P_{\text{DC}} > 0$$

converter is acting as a rectifier (power from DC bus to AC bus)

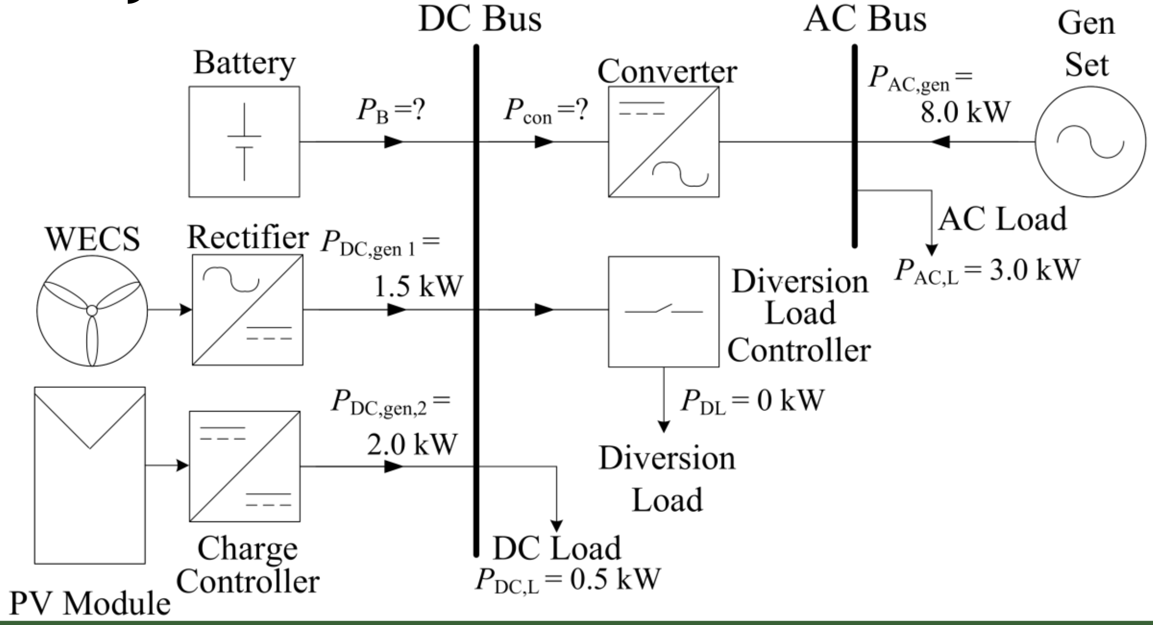
$$P_{\text{con}} = -\eta_{\text{con}} \sum P_{\text{AC}} = \sum P_{\text{DC}} : \ \sum P_{\text{AC}} \geq 0, \sum P_{\text{DC}} \leq 0$$

converter is acting as an inverter (power from AC bus to DC bus)

note: converter efficiency varies with loading

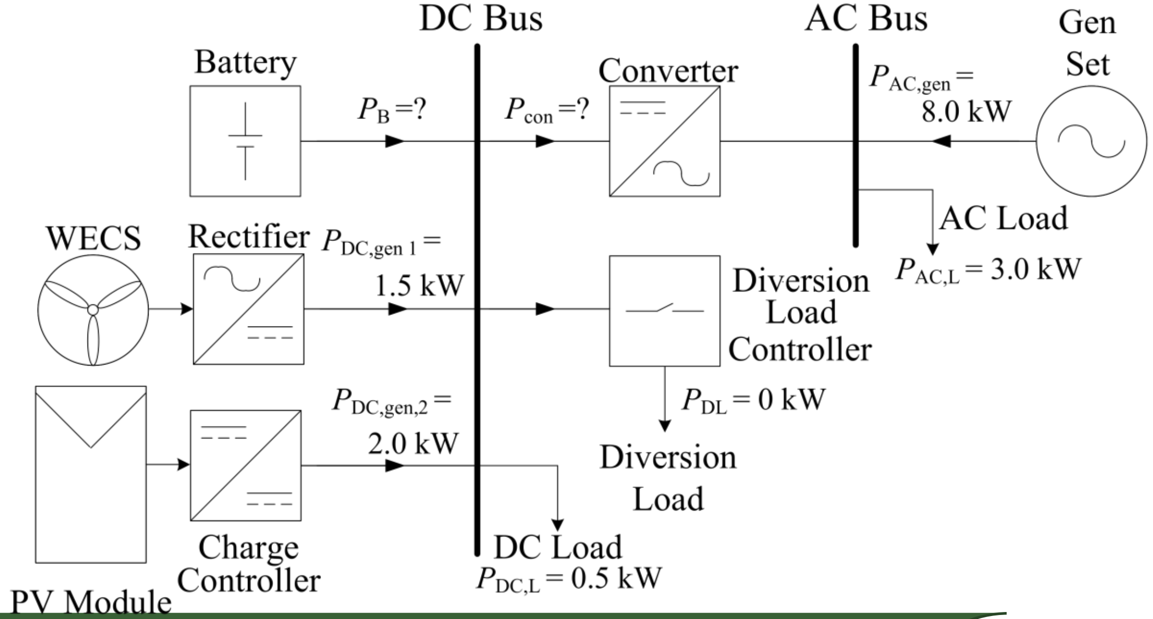
Example 14.2

Compute the battery power and converter power assuming the converter efficiency is 90%.



Example 14.2

Compute the battery power and converter power assuming the converter efficiency is 90%.



AC bus power

$$\sum P_{AC} = 8.0 - 3.0 = 5.0 \text{ kW}$$ (rectifier)

$$P_{con} = -\eta_{con}\sum P_{AC} = -0.90\times(8-3) = -4.5 \text{ kW}$$

4.5 kW is supplied from AC bus to DC bus (converter losses are 0.5 kW)

Example 14.2

Compute the battery power and converter power assuming the converter efficiency is 90%.

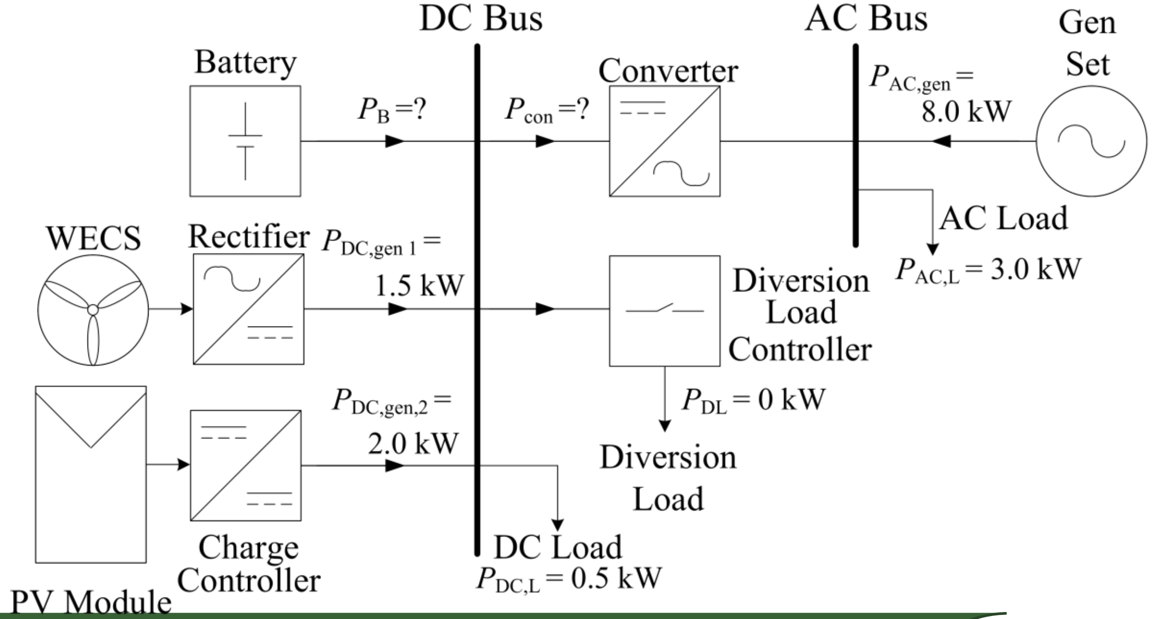
solving for battery power

$$P_{\text{con}} = \sum P_{\text{DC}} = P_{\text{DC,gen}} + P_{\text{B}} - P_{\text{DC,L}} - P_{\text{DL}}$$

$$-4.5 = (2.0 + 1.5) + P_{\text{B}} - 0.5 - 0$$

$$P_{\text{B}} = -4.5 - 3.0 = -7.5 \text{ kW}$$

battery is being charged



Including Constraints

- Constraints should reflect realistic power maximums and minimums
- Constraints modelled
  - load
  - generator
  - battery
  - converter

Load Constraints

- Load cannot consume more than its rated power and cannot supply power

$$0 \leq P_{\mathrm{L},l} \leq P_{\mathrm{L},l}^{\max} \quad \forall\ l$$

- Constraints for diversion and ballast loads

$$0 \leq P_{\mathrm{DL},m} \leq P_{\mathrm{DL},m}^{\max} \quad \forall\ m$$

$$0 \leq P_{\mathrm{BL},n} \leq P_{\mathrm{BL},n}^{\max} \quad \forall\ n$$

Generator Constraints

- Generators have a maximum and minimum steady-state power
- For solar, wind, and hydro, the maximum may change over time according to the resource (e.g. windy versus calm)
- Other components (e.g. charge controller) may limit power from a generator
- Generator limits:

$$P_{\text{gen},g}^{\min} \leq P_{\text{gen},g} \leq P_{\text{gen},g}^{\max} \quad \forall\, g$$

Battery Constraints

- Power into (charging) and from (discharging) are limited by the charging stage (bulk, absorption, etc.), battery's SoC and charge controller, diversion load controller, low voltage disconnect, charger
- Battery limits:

$$P_B \leq P_B^{\max} \quad \text{(discharge limit)}$$

$$P_B \geq P_B^{\min} \quad \text{(charge limit)}$$

minimum limit will not be a positive value

Converter Constraints

- Converters are limited by their rated power
- Maximum or minimum limit can be set to zero if the converter is not bi-directional (e.g. maximum set to 0 if the converter is only a rectifier)

$$P_{\text{con}} \leq P_{\text{con}}^{\max} \quad (\text{inverter mode : DC to AC})$$

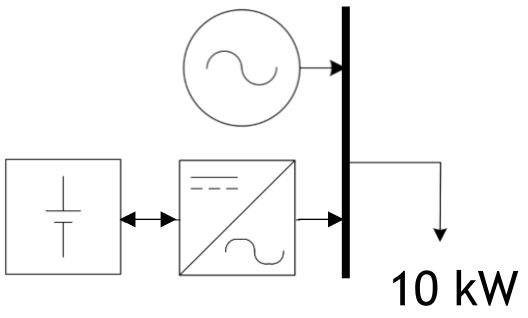
$$P_{\text{con}} \geq P_{\text{con}}^{\min} \quad (\text{rectifier mode : AC to DC})$$

Infeasible Results

- Power balance calculations can result in a “solution” where one or more of the constraints are violated
- When this happens, one or more of the assumed power values must be adjusted
- Examples include
    - load is decreased
    - generator power is increased
- Values are changed through the control of the off-grid system according to <u>an operation priority scheme</u>

Operation Priority Schemes

- Often several ways power balance can be maintained
- How much power should be supplied by each generation source and battery to serve the load?
- How should the power from each component change as the load (or generation) changes?



How much power should be supplied by the gen set and the battery to serve the load?

Operation Priority Schemes

- Controllers programmed (through their setpoints) to control an off-grid system according to an operation priority scheme
- Operation priority scheme: prioritization of actions (changes in power) taken to balance power
- General approach:
  - minimize fuel and other operational cost
  - maximize reliability
  - prolong lifespan of equipment

other considerations may also factor in to how generation sources are prioritized

Controllable vs Uncontrollable Generation Sources

- Controllable generation sources: those whose power output can be set to a certain value
  - gen sets
  - some MHP
- Uncontrollable generation sources: those whose power output cannot be set to a certain value
  - WECS
  - PV

often the power can be reduced on demand, but not increased unless there is sufficient wind or irradiance

Operation Priority Schemes: Increasing Load (Decreasing Generation)

Priority Number	Action
1	Reduce power to the diversion load and ballast load
2	Increase power from zero-energy-cost resources (WECS, MHP, PV)
3	Increase power from the battery (discharge)
4	Increase power from fossil-fuel or biomass gen sets, starting with the least expensive
5	Reduce user load, starting with least critical

Operation Priority Schemes: Decreasing Load (Increasing Generation)

Priority Number	Action
1	Decrease power from fossil-fuel or biomass gen sets, starting with the most expensive
2	Increase power to battery bank (charge)
3	Decrease power from zero-energy-cost resources (throttle)
4	Increase power to diversion load or ballast load

Example 14.3

Repeat previous example but include battery constraints

$P_{B}^{min} = -6 \text{ kW}$

$P_{B}^{max} = 25 \text{ kW}$

Example 14.3

Repeat previous example but include battery constraints

$$P_{\mathrm{B}}^{\mathrm{min}} = -6 \text{ kW}$$

$$P_{\mathrm{B}}^{\mathrm{max}} = 25 \text{ kW}$$

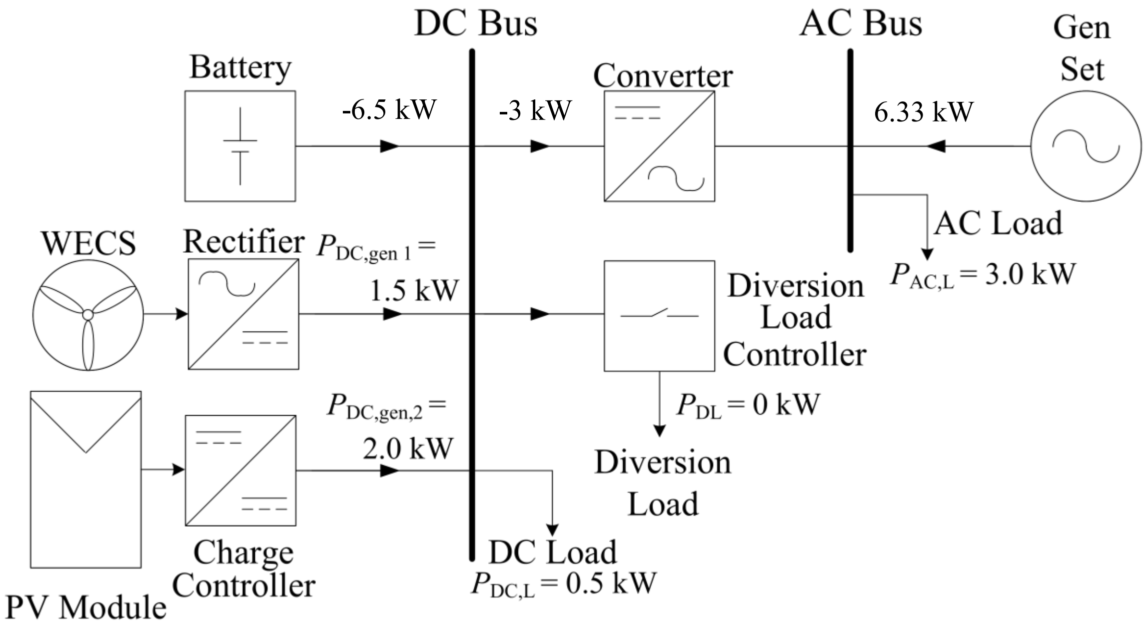
Without constraints, the battery power was -7.5 kW, which is no longer feasible due to the -6 kW charging constraint. Assumed power values must be revised according to the operation priority scheme.

Example 14.3

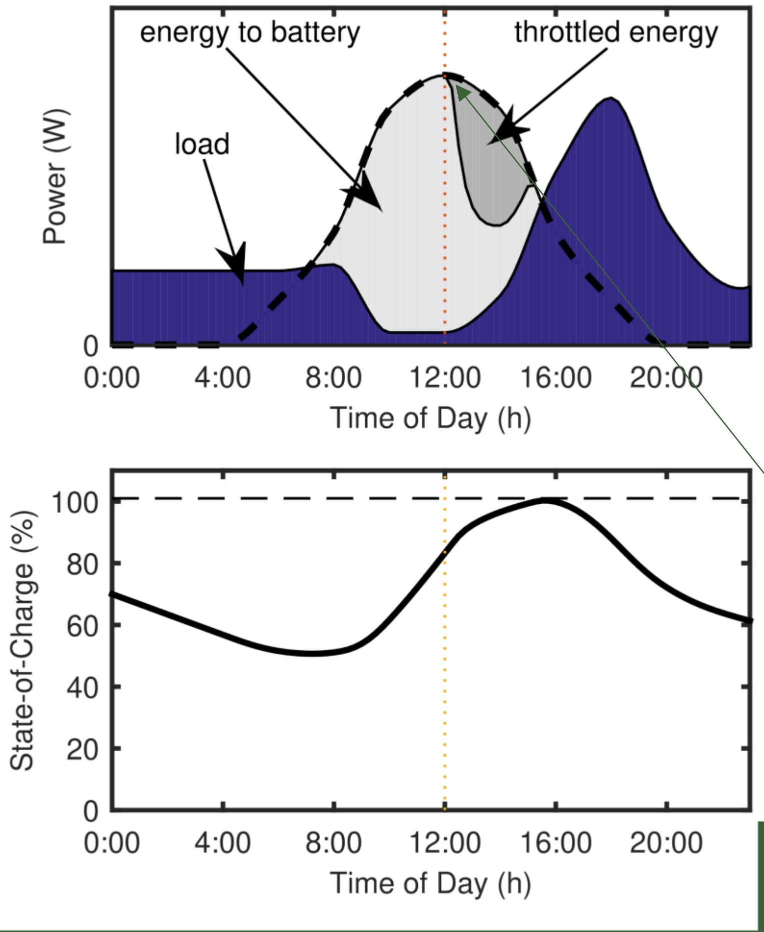
Battery power must change from -7.5 kW to its limit of -6 kW. This means less power(1.5 kw) needs to be generated. A priority scheme would likely call for the gen set power to be reduced to conserve fuel (rather than reduce power from WECS or PV array). The converter power changes by 1.5 kW to become 3 kW.

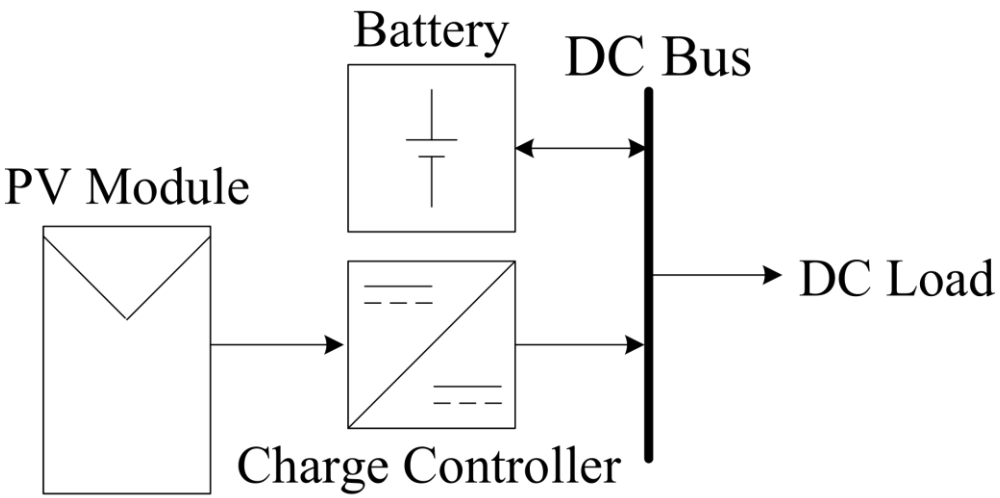
Accounting for the converter efficiency of 90%, the new gen set power is

$$P_{\text{gen}} = \frac{-P_{\text{con}}}{\eta_{\text{con}}} + P_{\text{AC,L}} = \frac{3}{0.9} + 3 = 6.33 \text{ kW}$$



Priority Scheme Example





At 12:00, absorption stage starts and power to the battery is limited. Decrease power from zero-energy-cost resources (throttle) to maintain power balance and avoid over-charging the battery

Gen Set Control Schemes

- Hybrid architectures require a gen set control scheme
- Typically automated (programmed by operator into inverter, charger, etc.), but can be approximated by manual operation or in an ad hoc manner (i.e. run it for two hours every night)
- Requires gen sets have auto-start capability
- Common schemes
  - load following
  - cycle charging

Load Following

- Load following: gen set produces power only when other generation sources are unable to satisfy load
- Gen set automatically turns on when it receives signal that load is high and it may be needed
  - Example: inverter may send “start” signal to gen set when load is 90% of inverter rating
- Power is shared among generation sources with the gen set only producing the minimum required power
- Load following can result in inefficient operation of gen set (due to low loading) and extended run times (increasing maintenance needs and nuisance due to noise)

power sharing methods discussed later in this lecture

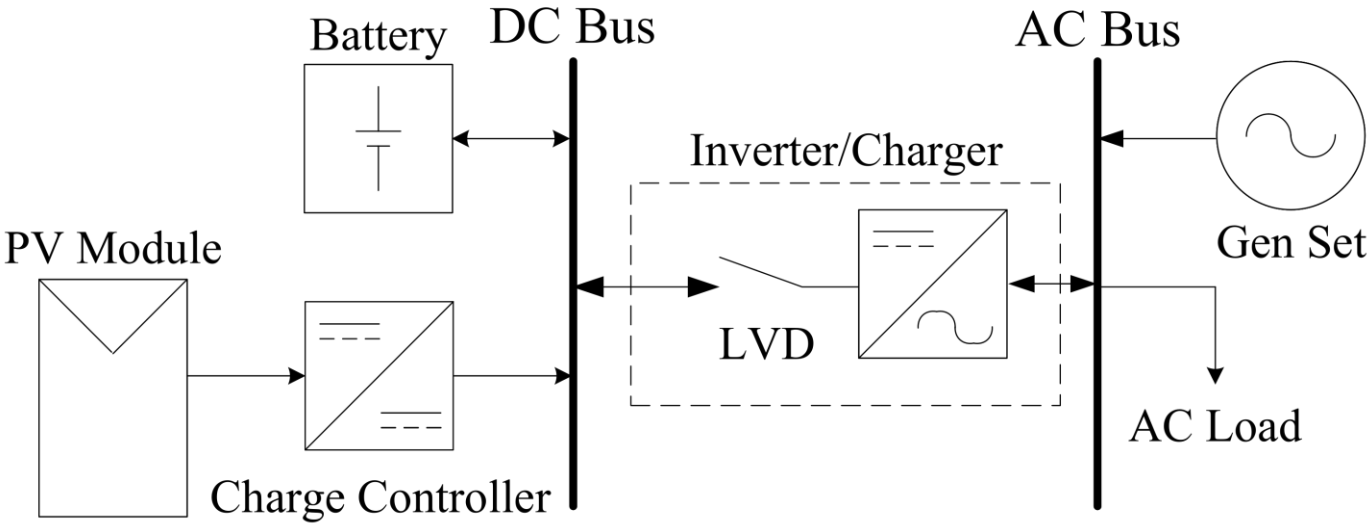
Cycle Charging

- Cycle charging: gen set operates based on battery SoC. When it operates, it operates at full capacity (or as high as possible) to recharge battery and serve load
- Battery voltage is monitored by a controller (such as an inverter/charger) and when it falls below as setpoint a start signal is set to the gen set
- Gen set operates until the battery voltage corresponding to high SoC is reached
- More efficient loading of gen set (less fuel use), reduced run time

Complex Control

- Gen set to operate with some elements of each scheme
  - gen set starts when other generation sources are not able to satisfy load OR when battery SoC is low
  - gen set operates at full (or maximum possible) capacity to recharge battery and serve load

Gen Set Control Examples

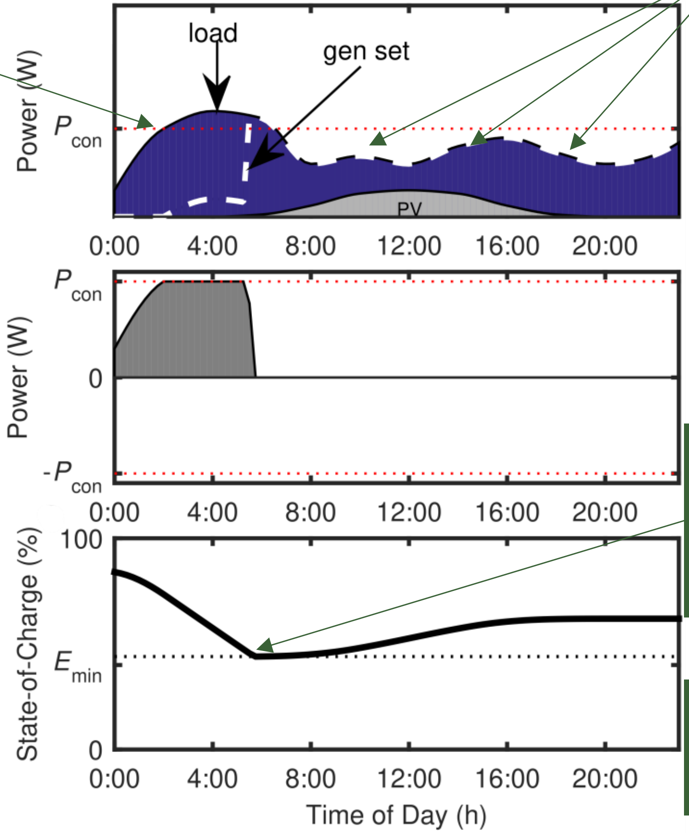


Load Following Control

battery supplies load through inverter entirely until load exceeds inverter limit (around 2:00)

gen set then turns on to supplement battery (inverter) power output

gen set "follows" load



battery stops supplying power when minimum SoC is reached and LVD actuates (6:00)

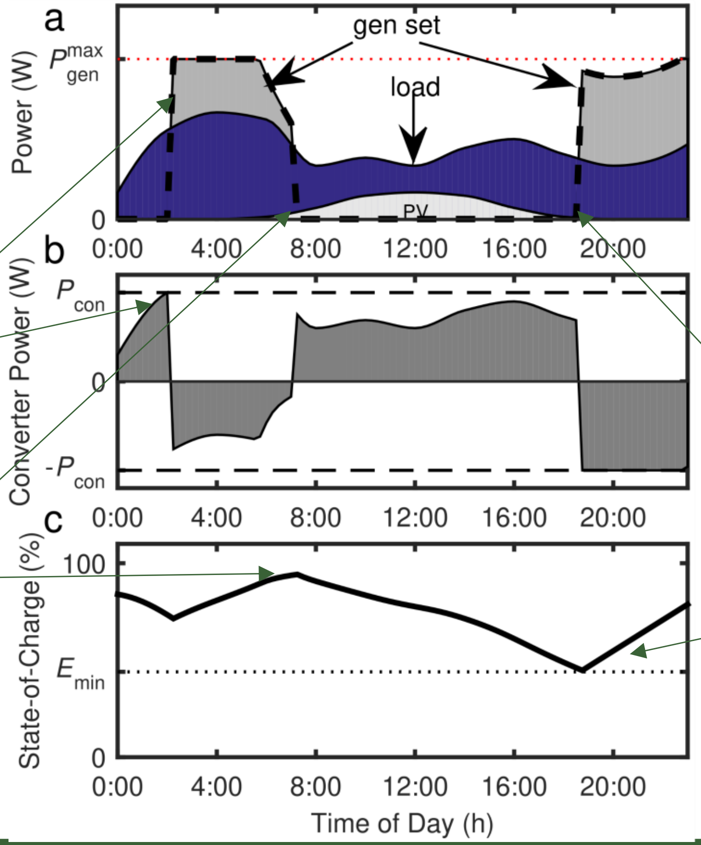
battery is recharged by PV (LVD reconnect setpoint is not reached)

Complex Control

(same load as last example)

gen set start triggered like in load following control (load exceeds inverter rating)

gen set stop triggered by battery SoC

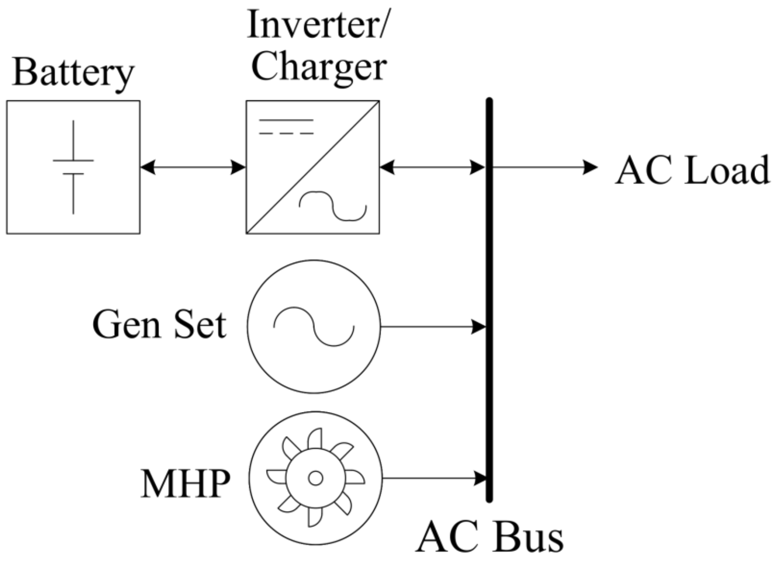


gen set operates at highest power output possible, serving load and charging battery

gen set start triggered by low battery SoC (standard cycle-charging scheme)

Frequency and Voltage Control

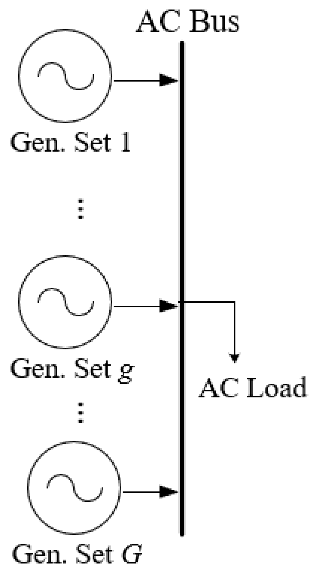
- AC bus requires consistent voltage frequency and voltage magnitude
- At least one generation source must be capable of regulating AC bus voltage
- Architectures with multiple AC-coupled generation sources and inverters require coordinated control



generation sources connected to the same AC bus is known as “paralleling”

Gen Set Paralleling

- Gen sets can be connected to the same AC bus (“paralleling”)
- More common in larger off-grid systems (>100 kW) and those with higher reliability requirements



Paralleling

Reasons for paralleling gen sets:

- Reliability—paralleling adds redundancy to the system so that if one gen set fails, a portion of or even the entire load can be served
- Scalability—gen sets can be added or removed from the mini-grid as needed
- Serviceability—maintenance can be done on one gen set at a time while the other(s) continue to serve the load

Paralleling Considerations

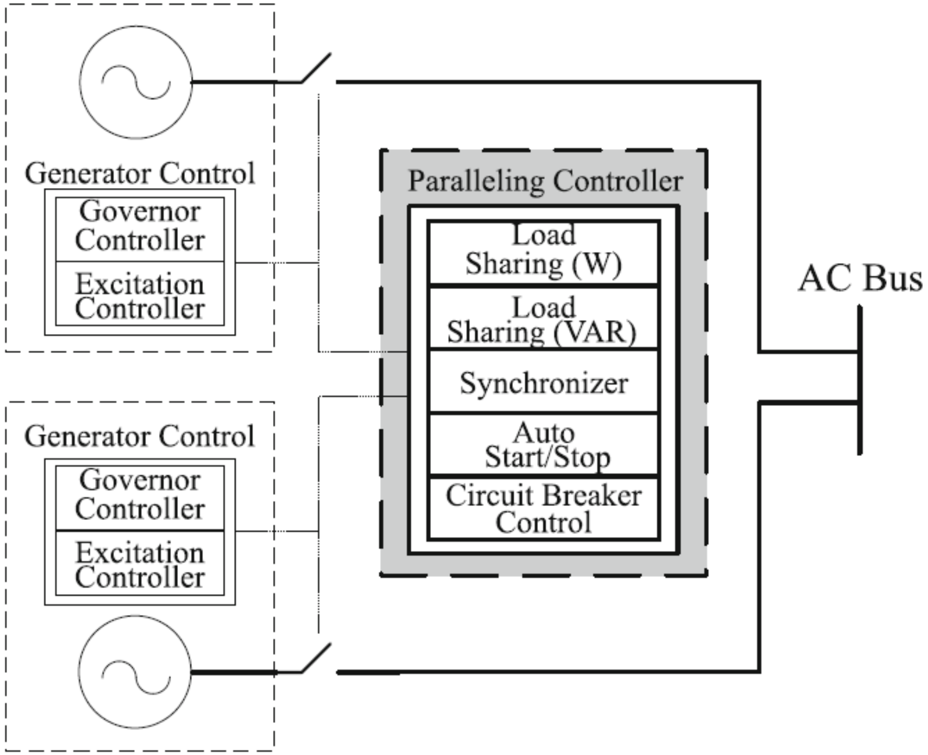
The generators should have:

1. the same number of phases
2. the same phase rotation
3. have the same open-circuit terminal voltage at a given speed
4. each have voltage and speed control, for example, through an AVR and a governor

consider using the same model generator by the same manufacturer

Parallel Operation

- Ensure that paralleled generators are operated to have the same voltage frequency, and same/nearly the same magnitude, and phase
- Manual synchronization is possible, but external controllers can be used
- One gen set is connected to the AC bus, the rest are synchronized to it and then connected



Gen Set Control Mechanisms

- Voltage magnitude control: accomplished through Automatic Voltage Regulator (AVR, see Chap. 11)
- Frequency control: fuel/air adjusted to increase or decrease mechanical power to ICE, increasing or decreasing its frequency as needed (see Chap. 6)

Inverter Control Mechanisms

- Inverter output voltage frequency and magnitude controlled by internally adjusting the modulating signal in SPWM (see Chap. 12)
- Two general categories of control
  - grid forming (GFM)
  - grid following (GFL)

often the same inverter can be programmed to operate in either GFM or GFL mode (but not at the same time)

Grid Forming Inverters

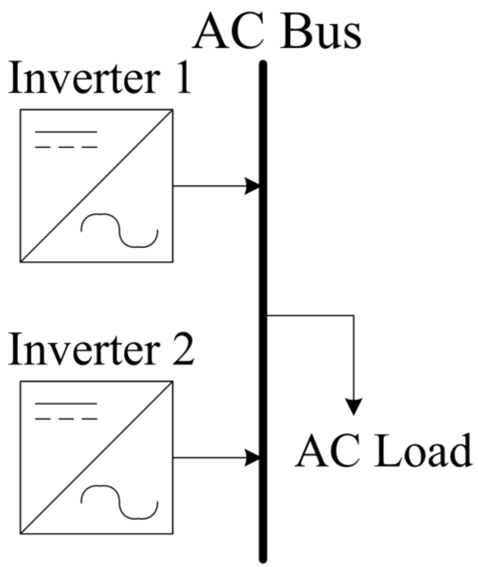
- Act as a controllable AC voltage source
- Controls voltage frequency, magnitude, phase
- Provides real and reactive power as necessary to maintain the desired AC bus voltage
- Requires a reliable power source to function (usually a battery)
  - Example: micro-inverter connected to a PV module cannot maintain AC bus voltage at night and so cannot be grid forming

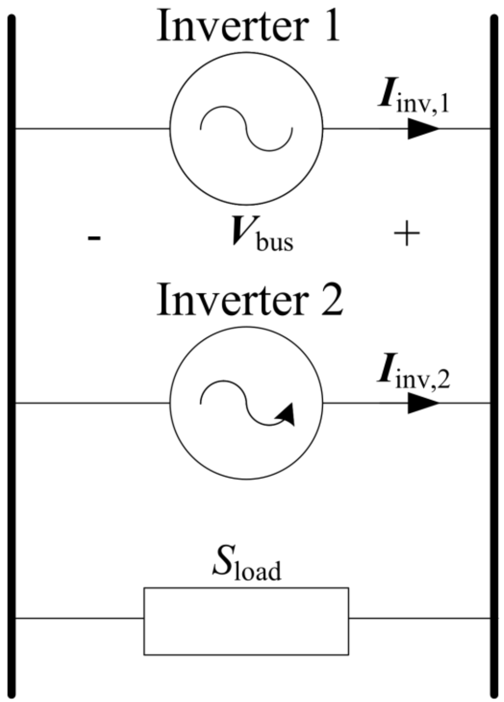
Grid Following Inverters

- Act as a controllable AC current source
- Synchronizes to (“follows”) the AC bus voltage (formed by a GFM inverter)
- GFL inverter injects current at required voltage phase and magnitude to achieve desired real and reactive power output
- Micro-inverters and wind inverters must operate in GFL mode

Equivalent Circuit

Inverter 1: GFM
Inverter 2: GFL





at least one inverter must be operating in GFM mode

Load Sharing

- Control scheme is needed to determine how real and reactive power is allocated among AC-coupled sources
  - considering shorter time scales than operation priority schemes
- Recall that real and reactive power generated and consumed must balance
- Considerations for load sharing
  - all generation sources equally-loaded
  - generation sources loaded according to their rating (same loading %)
  - generators loading optimized to minimize fuel use

Load Sharing

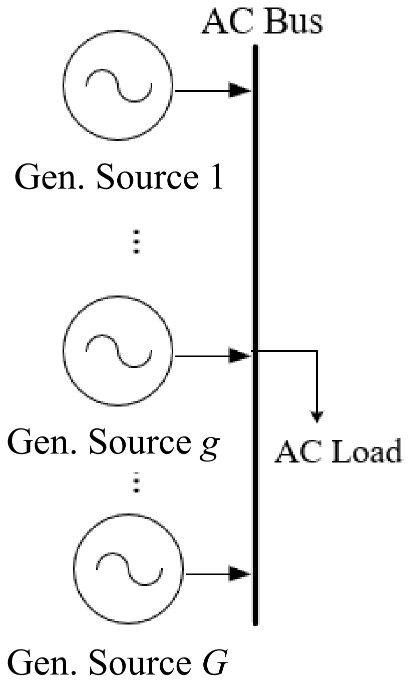
- Ignoring losses the power to the load P_L is related to the power from each generation source as:

$$P_L = P_{gen,1} + \cdots + P_{gen,g} + \cdots + P_{gen,G}$$

- Similarly for reactive power

$$Q_L = Q_{gen,1} + \cdots + Q_{gen,g} + \cdots + Q_{gen,G}$$

our focus will be on real power, but the same concepts apply to reactive power

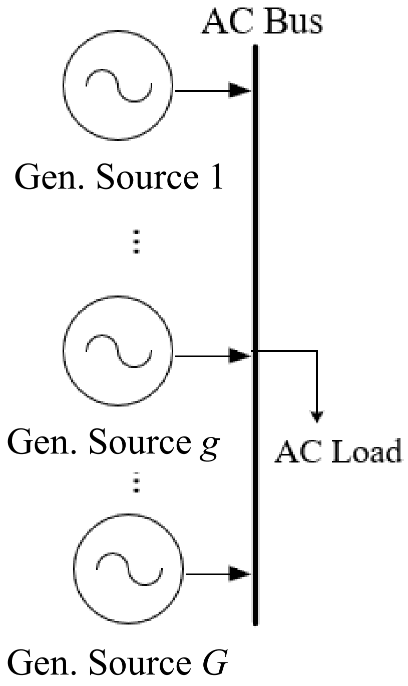


Load Sharing

If the load is shared equally, then

$$P_{\text{gen},1} = \cdots = P_{\text{gen},G} = \frac{P_{\text{L}}}{G}$$

Example: Gen 1 rated at 100 kW, Gen 2 rated at 200 kW, then for a 150 kW load, Gen 1 supplies 75 kW and Gen 2 supplies 75 kW



Load Sharing

If load is shared so that each generator is producing the same percentage of their rated power

$$P_{\text{gen},g} = P_{\text{L}} \times \frac{P_{\text{rated},g}}{\sum_{k=1}^{G} P_{\text{rated},k}}$$

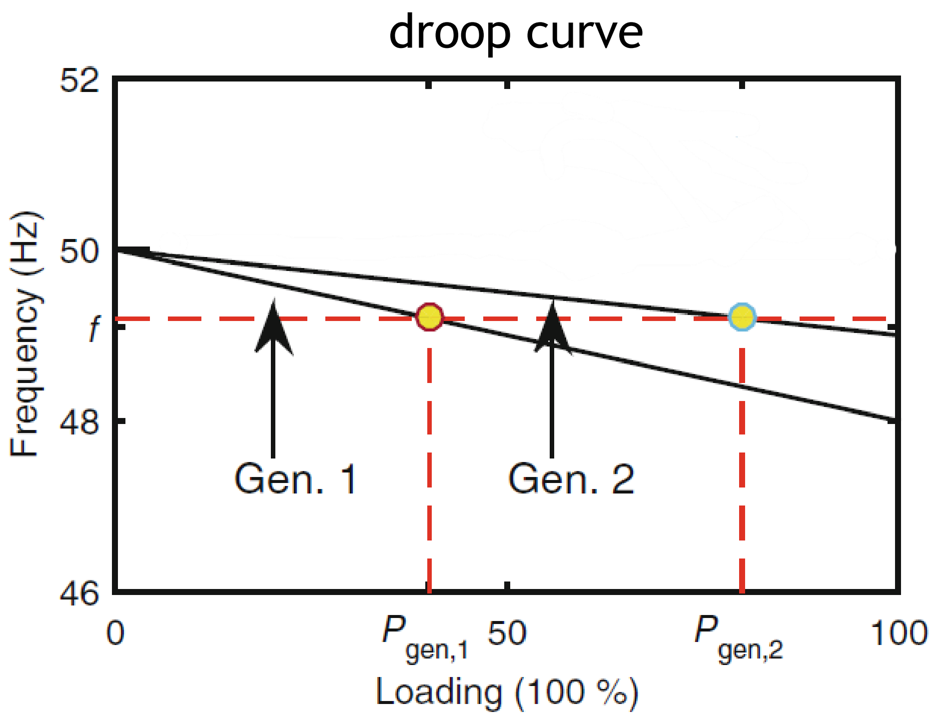
Example: Gen 1 rated at 100 kW, Gen rated at 200 kW, then for a 150 kW load, Gen 1 supplies 50 kW and Gen 2 supplies 100 kW (each loaded at 50%)

Load Sharing Approaches

- Different methods for achieving desired load shedding possible
- Considerations
  - hardware requirements
  - communication requirements
- Common approaches
  - droop
  - isochronous
  - controller-responder
  - Frequency Shift Power Control (FSPC)

Droop Control

- Basic idea: generators slightly reduce frequency as their load increases until as stable operating point reached
  - stable when power balanced between generation and load is achieved
- Can be used by GFM inverters, gen sets, some MHP (with droop-capable governing systems)
- De-centralized control method (no gen set communication needed)



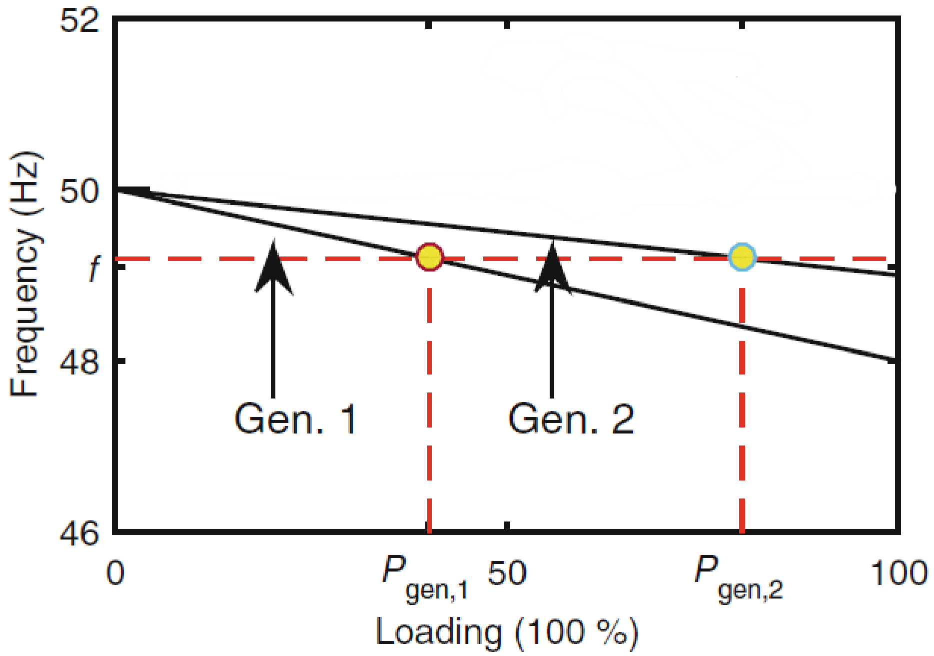
Droop

Frequency that generator g operates at is determined by

$$f_g = f_{g,0} - d_g \frac{P_g}{P_{\text{rated},g}}$$

f_g: operating frequency (Hz)
$f_{g,0}$: no-load operating frequency (Hz)
d_g: droop sloop (Hz/%)

droop curve



Example 14.5

Consider a mini-grid with two gen sets operated in parallel. Gen set 1 is rated at 75 kW with droop slope of 0.6, and Gen set 2 is rated at 37.5 kW with a droop slope of 0.3. Both have a no-load frequency of 50 Hz. Determine the operating frequency and the power output by each gen set if the load increases to 60 kW.

Example 14.5

Consider a mini-grid with two gen sets operated in parallel. Gen set 1 is rated at 75 kW with droop slope of 0.6, and Gen set 2 is rated at 37.5 kW with a droop slope of 0.3. Both have a no-load frequency of 50 Hz. Determine the operating frequency and the power output by each gen set if the load increases to 60 kW.

substitute the known values:

$$f_1 = f_{1,0} - d_1 \frac{P_1}{P_{\text{rated},1}} = 50 - 0.6\frac{P_1}{75}$$

$$f_2 = f_{2,0} - d_2 \frac{P_2}{P_{\text{rated},2}} = 50 - 0.3\frac{P_2}{37.5}$$

Two equations, four unknowns.
What other equations are relevant?

Example 14.5

Consider a mini-grid with two gen sets operated in parallel. Gen set 1 is rated at 75 kW with droop slope of 0.6, and Gen set 2 is rated at 37.5 kW with a droop slope of 0.3. Both have a no-load frequency of 50 Hz. Determine the operating frequency and the power output by each gen set if the load increases to 60 kW.

$$f_1 = f_2$$

$$60 = P_1 + P_2$$

Each generator must operate at the same frequency.
Conservation of power

Example 14.5

Consider a mini-grid with two gen sets operated in parallel. Gen set 1 is rated at 75 kW with droop slope of 0.6, and Gen set 2 is rated at 37.5 kW with a droop slope of 0.3. Both have a no-load frequency of 50 Hz. Determine the operating frequency and the power output by each gen set if the load increases to 60 kW.

$$f_1 = f_2$$

$$50 - 0.6\frac{P_1}{75} = 50 - 0.3\frac{P_2}{37.5}$$

$$P_1 = \frac{75}{0.6} \times 0.3\frac{P_2}{37.5}$$

$$P_1 = P_2$$

The power is evenly shared, and so apply the conservation of power. Each gen set supplies 30 kW.

Example 14.5

Consider a mini-grid with two gen sets operated in parallel. Gen set 1 is rated at 75 kW with droop slope of 0.6, and Gen set 2 is rated at 37.5 kW with a droop slope of 0.3. Both have a no-load frequency of 50 Hz. Determine the operating frequency and the power output by each gen set if the load increases to 60 kW.

$$f_1 = f_2 = 50 - 0.6\frac{30}{75} = 49.76 \text{ Hz}$$

Frequency has decreased somewhat from 50 Hz

Droop Control: Reactive Power

- Reactive power sharing can also be accomplished via droop control
  - exploit the strong voltage magnitude—reactive power relationship
- Voltage magnitude decreases as the reactive power output increases

$$|\boldsymbol{V}| = \boldsymbol{V}_{g,0} - d_{\mathrm{Q,g}} \frac{Q_g}{Q_{\mathrm{rated},g}}$$

Droop Control

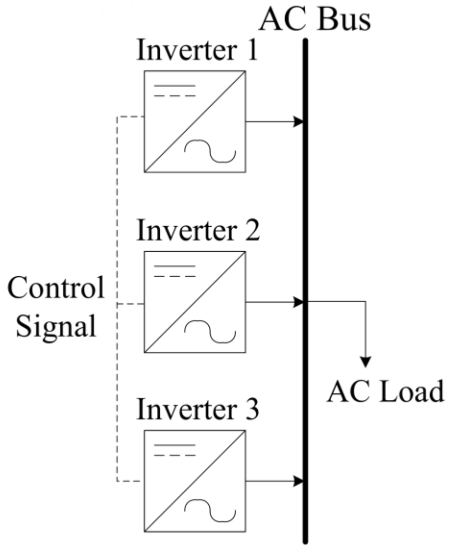
- ✓Simple to implement
- ✓No communication between generation sets is needed (measurements of bus frequency and magnitude only)
- ✓Droop slopes can be adjusted to achieve desired power sharing (equal, proportional, etc.)

Isochronous Control

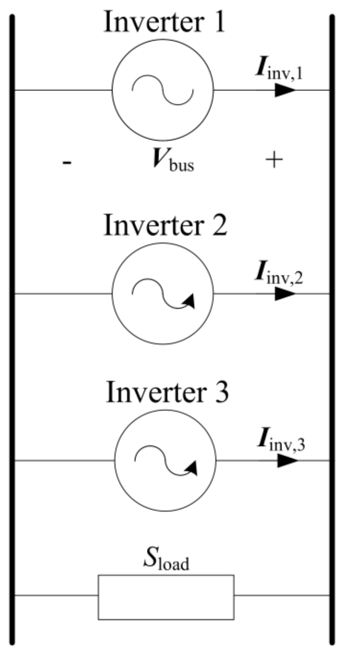
- Gen set governor or inverter automatically controlled to keep frequency constant as load changes
- Requires external communication among generation sources to coordinate load sharing
  - reverts to droop control if communication is lost
- Only available on some gen sets
- More complex than droop-based control

Controller-Responder Control

- Used in off-grid systems with multiple inverters
- One inverter operates in GFM mode (Controller), all others in GFL mode (Responders)
- Controller coordinates load sharing among the Responders
- External communication required

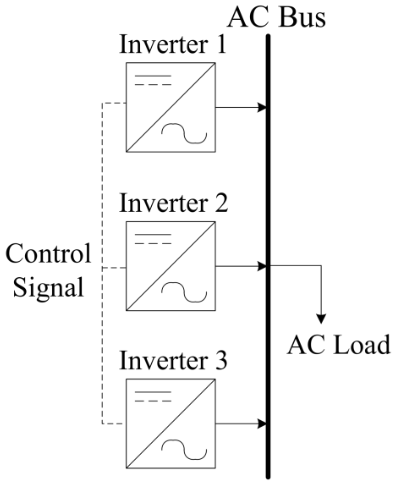


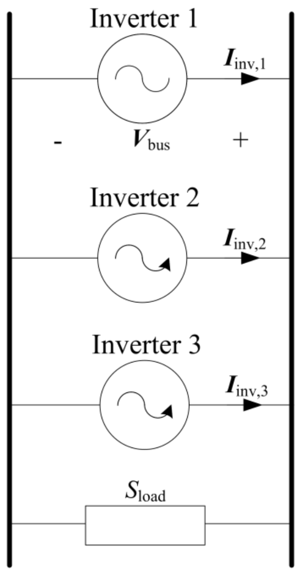
equivalent circuit



Example 14.6

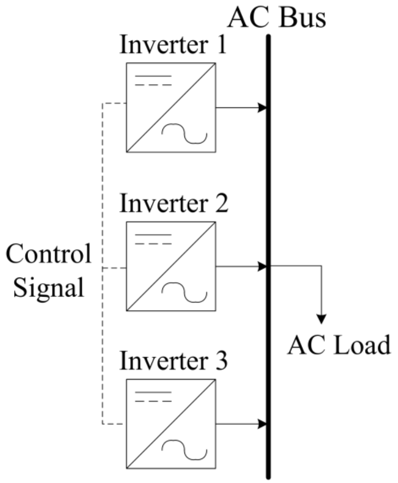
Consider the three grid-tied single-phase inverters connected to the AC bus in the off-grid system. Inverter 1 is the Controller. Inverter 2 and 3 are the Responders. The AC bus voltage is $\boldsymbol{V}_{bus}$ = 225∠0° V and the load is S_L= 3+ j0.5 kVA. The Controller commands the Responders to each inject current of $\boldsymbol{I}_{inv,2}$=$\boldsymbol{I}_{inv,3}$ = 5∠-10° A into the AC bus. Calculate the real and reactive power supplied by Inverter 1.

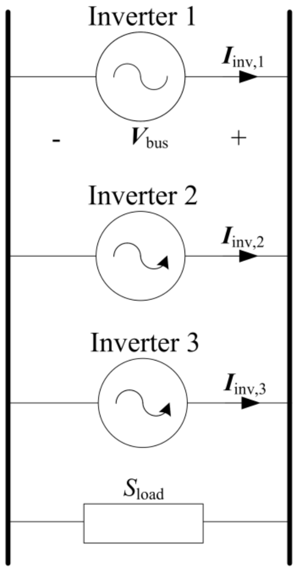




Example 14.6

Consider the three grid-tied single-phase inverters connected to the AC bus in the off-grid system. Inverter 1 is the Controller. Inverter 2 and 3 are the Responders. The AC bus voltage is $\boldsymbol{V}_{bus}$ = 225∠0° V and the load is S_L= 3+ j0.5 kVA. The Controller commands the Responders to each inject current of $\boldsymbol{I}_{inv,2}$=$\boldsymbol{I}_{inv,3}$ = 5∠-10° A into the AC bus. Calculate the real and reactive power supplied by Inverter 1.



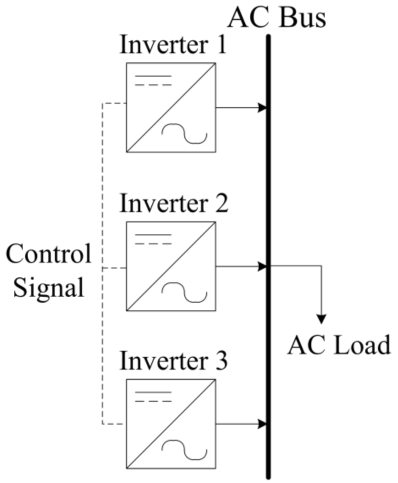


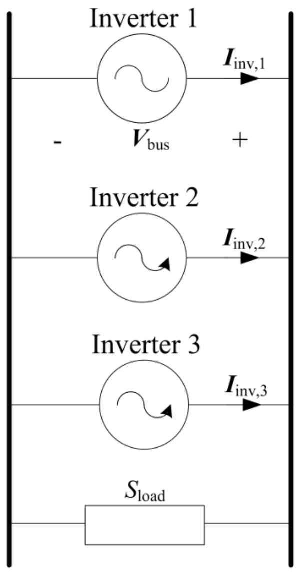
The power from the Responders is the same and equal to

$$S_{inv,2} = S_{inv,3} = \boldsymbol{V}_{bus}\boldsymbol{I}^{*}_{inv,2} = 225\angle 0^{\circ} \times 5\angle 10^{\circ} = 1.11 + 0.20\ \text{kVA}$$

Example 14.6

Consider the three grid-tied single-phase inverters connected to the AC bus in the off-grid system. Inverter 1 is the Controller. Inverter 2 and 3 are the Responders. The AC bus voltage is $\boldsymbol{V}_{\text{bus}} = 225\angle 0^\circ$ V and the load is $S_L = 3 + j0.5$ kVA. The Controller commands the Responders to each inject current of $\boldsymbol{I}_{\text{inv},2} = \boldsymbol{I}_{\text{inv},3} = 5\angle -10^\circ$ A into the AC bus. Calculate the real and reactive power supplied by Inverter 1.





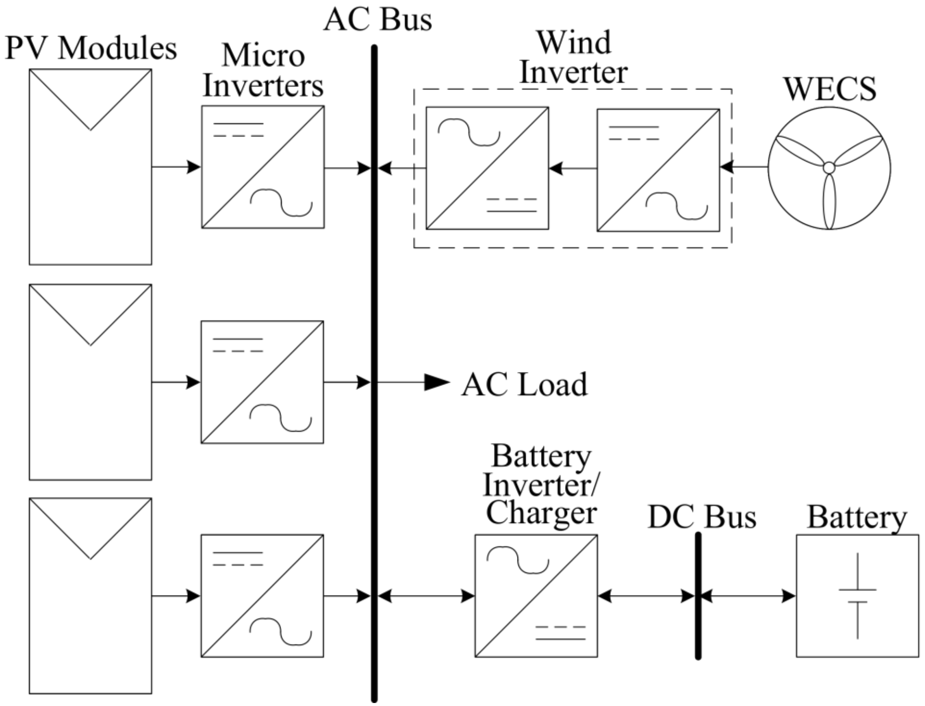
The real and reactive power at the AC bus must each be balanced. Inverter 1 supplies the portion of the load not supplied by Inverter 2 and Inverter 3

$$P_{\text{inv},1} = 3 - (2 \times 1.11) = 0.78 \text{ kW}$$

$$Q_{\text{inv},1} = 0.5 - (2 \times 0.20) = 0.11 \text{ kVAR}$$

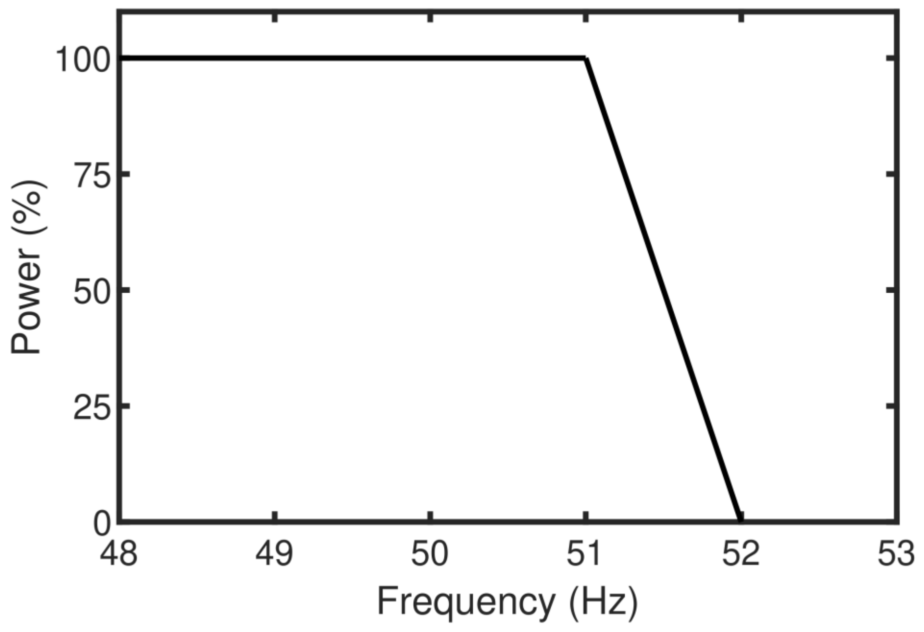
Frequency Shift Power Control

- Alternative to Controller-Responder control when external communication is not available
  - Example: system with micro inverters and/or wind inverter in GFL mode and battery inverter in GFM mode
- GFL inverters controlled to maximize power production from their sources, battery inverter supplements power as needed (charge battery) or absorbs excess power (charge battery)
- Method needed to throttle power from GFL when battery approaches full (enters absorption stage)



Frequency Shift Power Control

- GFM inverter increases AC bus frequency as battery reaches full SoC
  - GFL inverters reduce power as frequency increases
- No external communication required
- Applies to real power only



Remote Monitoring and Control

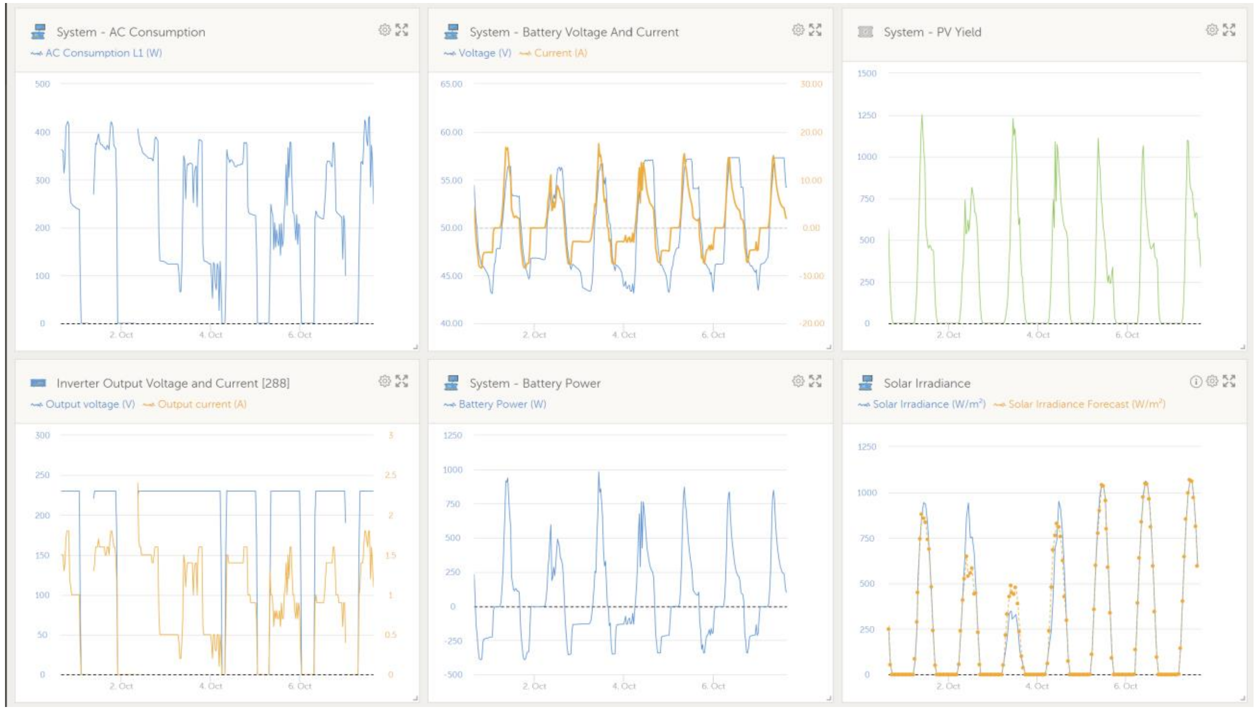
- Many components (inverters, charge controllers, BMS, meters, etc.) offer integrated data acquisition and control
  - voltage, current, power, SoC, etc. periodically measured and stored
- External sensors also used
  - irradiance, wind speed, temperature etc.
- Data can be sent via cell network (often 2G) to cloud platform

(*courtesy D. Sims*)

Remote Monitoring and Control

Uses of off-grid system data

- track real-time performance
- signal alerts/alarms
- asset management
- troubleshooting faults
- financial projections
- transparency (for donors, investors)



Remote Monitoring and Control

Remote control uses

- adjust setpoints of components
- starting gen sets
- connect/disconnect users (e.g. for non-payment)
- more

Remote Monitoring and Control

- Remote monitoring and control can save travel costs, reduce outage time, and generally improve operations
- Added cost for the ITC layer
  - hardware
  - software
  - management
  - analysis
  - expertise

Summary

- Steady-state algebraic model for off-grid systems based on power balance
- Operation schemes describe how generation and loads are adjusted to minimize fuel cost, improve reliability among other objectives
- AC bus frequency and voltage control accomplished through
  - droop
  - isochronous
  - Controller-Responder
  - Frequency Shift Power Control
- Remote monitoring and control offers a way to manage an off-grid systems across great distances but may increase cost