Workshop exercise: Designing dc bus hybrid system

A guesthouse owner is looking to install a dc bus hybrid system as their generator is due for replacement. They would like:

- A battery bank with 2 days of autonomy without needing to run the generator in the event of bad weather.
- A new generator that would meet the maximum demand of the loads but will also provide maximum charging current possible from the inverters and the selected battery bank

This hybrid system will therefore use the generator as a back-up.

Site information

- Site location: Vanuatu, 15°S
- Large available roof facing North
- Occupants, 4 adults full time (owners + 2 staff)
- 4 guest rooms for up to 12 guests.
- Possible locations for equipment include semi-used storage shed, building a dedicated shed, or installing equipment in a container at rear of the premises

Table 1: Site weather and solar resource, retrieved from https://power.larc.nasa.gov/data-access-viewer/ using climatology average

Month	Daily solar radiation 15° tilt (kWh/m^2/day)	Average Air temperature (°C)
JAN	6	27.68
FEB	5.29	27.89
MAR	5.5	27.8
APR	4.97	27.47
MAY	4.59	26.78
JUN	4.33	26.1
JUL	4.52	25.4
AUG	5.01	25.2
SEP	5.44	25.48
OCT	5.83	25.92
NOV	5.95	26.67
DEC	6.38	27.31
Annual average	5.32	26.64

Initial Load Assessment

A data-logger was used to measure demand and energy consumption over a typical day with full occupancy – results are shown in the chart and table below. Investigation and discussion with the customer show that there are no dc loads. Assume that this usage pattern is applicable all year round.

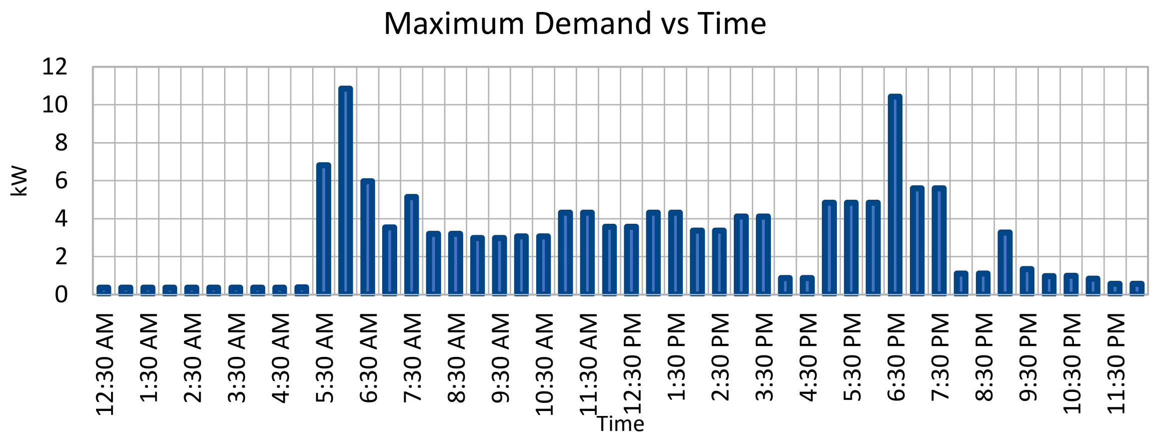

Figure 1: Initial results of monitoring Maximum Demand vs Time

Overall consumption was 55.63 kWh/day with a maximum demand of 11 kVA and surge demands (not shown) of 15 kVA during the middle of the day

Assume that:

ac daily energy load (E_{AC}) = 55,630 Wh/day
Maximum demand = 11,000 VA
Surge demand = 15,000 VA

Proposed System Architecture details

The following dc bus hybrid system has been selected:

- Three-phase system
- Nominal battery voltage: 48V
- Inverter waveform – Pure sine wave for proper operation of all electronic equipment
- Inverter type – dc bus interactive inverters from SMA's Sunny Island Range—3 single phase inverters in a 3-phase arrangement

Determine required capacity of dc Bus Interactive Inverter

1. Calculate maximum demand per phase: ____________

Assuming the loads are balanced across the system, divide the site's max demand by the number of phases to obtain this number.

2. Calculate the surge demand per phase: ____________

Assuming the loads are balanced across the system, divide the site's surge demand by the number of phases to obtain this number.

3. Assuming a safety factor of 10%, what is the inverter capacity required to deliver the maximum demand and surge demand?

Max demand: ____________

Surge demand: ____________

<u>Select the Inverter</u>

4: Using the calculated continuous and surge demand rating and SMA data sheet as shown below select the inverter: ____________

Technical Data	Sunny Island 4.4M	Sunny Island 6.0H	Sunny Island 8.0H
Operation on the utility grid or generator			
Rated grid voltage / AC voltage range		230 V / 172.5 V to 264.5 V	
Rated grid frequency / permitted frequency range		50 Hz / 40 Hz to 70 Hz	
Maximum AC current for increased self-consumption (grid operation)	14.5 A	20 A	26 A
Maximum AC power for increased self-consumption (grid operation)	3.3 kVA	4.6 kVA	6 kVA
Maximum AC input current	50 A	50 A	50 A
Maximum AC input power	11500 W	11500 W	11500 W
Stand-alone or emergency power operation			
Rated grid voltage / AC voltage range		230 V / 202 V to 253 V	
Rated frequency / frequency range (adjustable)		50 Hz / 45 Hz to 65 Hz	
Rated power (at Unom, fnom / 25 °C / cos φ = 1)	3300 W	4600 W	6000 W
AC power at 25 °C for 30 min / 5 min / 3 sec	4400 W / 4600 W / 5500 W	6000 W / 6800 W / 11000 W	8000 W / 9100 W / 11000 W
AC power at 45 °C continuously	3000 W	3700 W	5430 W
Rated current / maximum output current (peak)	14.5 A / 60 A	20 A / 120 A	26 A / 120 A
Total harmonic distortion output voltage / power factor at rated power	< 5% / −1 to +1	< 1.5% / −1 to +1	< 1.5% / −1 to +1
Battery DC input			
Rated input voltage / DC voltage range	48 V / 41 V to 63 V	48 V / 41 V to 63 V	48 V / 41 V to 63 V
Maximum battery charging current / rated DC charging current / DC discharging current	75 A / 63 A /75 A	110 A / 90 A / 103 A	140 A / 115 A /130 A
Battery type / battery capacity (range)		Li-Ion[1], FLA, VRLA / 100 Ah to 10000 Ah (lead-acid) 50 Ah to 10000 Ah (li-Ion)	
Charge control		IUoU charge procedure with automatic full charge and equalization charge	
Efficiency / self-consumption of the device			
Maximum efficiency	95.5%	95.8%	95.8%
No-load consumption / standby	18 W / 6.8 W	25.8 W / 6.5 W	25.8 W / 6.5 W
Protective devices (equipment)			
AC short-circuit / AC overload		● / ●	
DC reverse polarity protection / DC fuse		– / –	
Overtemperature / battery deep discharge		● / ●	
Overvoltage category as per IEC 60664-1		III	

Determine the capacity of the battery bank

Assumptions:

- Battery Inverter efficiency 94%
  (never use maximum efficiency value—assume a lesser value for calculations)
- Battery Inverter efficiency when acting as charger 94%
- Battery coulombic efficiency 90%
- Watt-hour efficiency of the battery 80%
- Maximum Depth of Discharge (DOD) 70%

The battery bank must be sized to meet the whole daily load that is being supplied by the PV array and battery bank, as there will be days where the solar irradiation is not available.

To calculate the energy required at the battery, use the equation: $E_{BATT} = E_{AC} / \eta_{INV}$

E_{BATT} = energy required from the battery bank
E_{AC} = Total daily energy (AC loads only)
η_{INV} = *inverter efficiency*

5. What is the energy required from the battery bank (E_{BATT})? __________

Use the equation: Battery Capacity (Ah) = (E_{BATT} x T_{aut})÷ (V_{dc} × DOD)

T_{aut} = *specified days of autonomy*
V_{dc} = *Battery Bank dc voltage (check inverter input voltage range)*
DOD = *depth of discharge*

6. What is the required battery bank capacity? ______ Ah

Size and select battery model

The battery bank will be selected from the Sonnenschein Solar 2V cell range of batteries using the C_{10} capacity rating. These batteries have 3000+ cycles at 50% DoD and hence will provide long life.

The largest battery is the A602/3920 which has a C_{10} capacity of 3036. So the battery bank will need to consist of two parallel strings of batteries. Therefore the minimum battery capacity required in each strings would be 3523/2 Ah = 1762Ah.

7. What battery model would you select? ______________________

Capacities C_1 - C_{120} (20 °C) in Ah

Type	C_1 1.67 Vpc	C_3 1.75 Vpc	C_5 1.77 Vpc	C_{10} 1.80 Vpc	C_{24} 1.80 Vpc	C_{48} 1.80 Vpc	C_{72} 1.80 Vpc	C_{100} 1.85 Vpc	C_{120} 1.85 Vpc
A602/295 SOLAR	124	167	193	217	248	273	289	285	294
A602/370 SOLAR	155	209	241	272	310	342	362	357	367
A602/440 SOLAR	186	251	289	326	372	410	434	428	440
A602/520 SOLAR	229	307	342	379	435	471	503	505	519
A602/625 SOLAR	275	369	410	455	523	565	604	606	623
A602/750 SOLAR	321	431	479	531	610	659	705	707	727
A602/850 SOLAR	368	520	614	681	729	782	827	822	845
A602/1130 SOLAR	491	694	818	908	973	1043	1102	1096	1126
A602/1415 SOLAR	614	867	1023	1135	1216	1304	1378	1370	1408
A602/1695 SOLAR	737	1041	1228	1362	1459	1565	1654	1644	1689
A602/1960C SOLAR	867	1222	1371	1593	1803	1942	2016	1957	1994
A602/2600 SOLAR	1047	1548	1782	2024	2276	2472	2599	2547	2613
A602/3270 SOLAR	1309	1935	2227	2530	2846	3090	3249	3184	3266
A602/3920 SOLAR	1571	2322	2673	3036	3415	3708	3899	3821	3919

Figure 2: Sonnenschein A600 SOLAR 2V battery range capacity table

8: What would be the total capacity of the battery bank @ C_{10}

____

Use the equation $N_{series} = V_{dc}$ / Cell Voltage

9: Calculate the number of cells/blocks in series for each string: ____________

10: Calculate the total number of cells: ____________

Size and select PV Array - DC bus

The PV array will be sized for the month with the lowest irradiation. From Table 1 this is 4.33kWh/m^2 (PSH) with an average temperature of 26.1°C

Assume:

- Daily energy load is 55,630Wh/day
- No PV array oversizing required because there is a generator
- Month with lowest irradiation is chosen as the design month (See Table 1)
  - Average temperature of 26.1°C for the design month (June)
  - Average solar resource at 15° tilt (H_{tilt}) 4.33 PSH/day
- PV module rated capacity (P_{STC}) 300W
- V_{MP} 32.4V
- I_{MP} 9.27A
- V_{oc} 39.7V
- I_{sc} 9.7A
- Derating factor due to dirt (F_{DIRT}) 95%
- Derating factor due to manufacturer's tolerance (F_{MAN}) 95%
- Watt-hour efficiency of the battery 80%
- P_{MP} Temp Co-efficient(γ) -0.39%/°C
- V_{oc} Temp Co-efficient (β) -0.30% / °C
- Cable losses have been calculated and reflected in the figure below

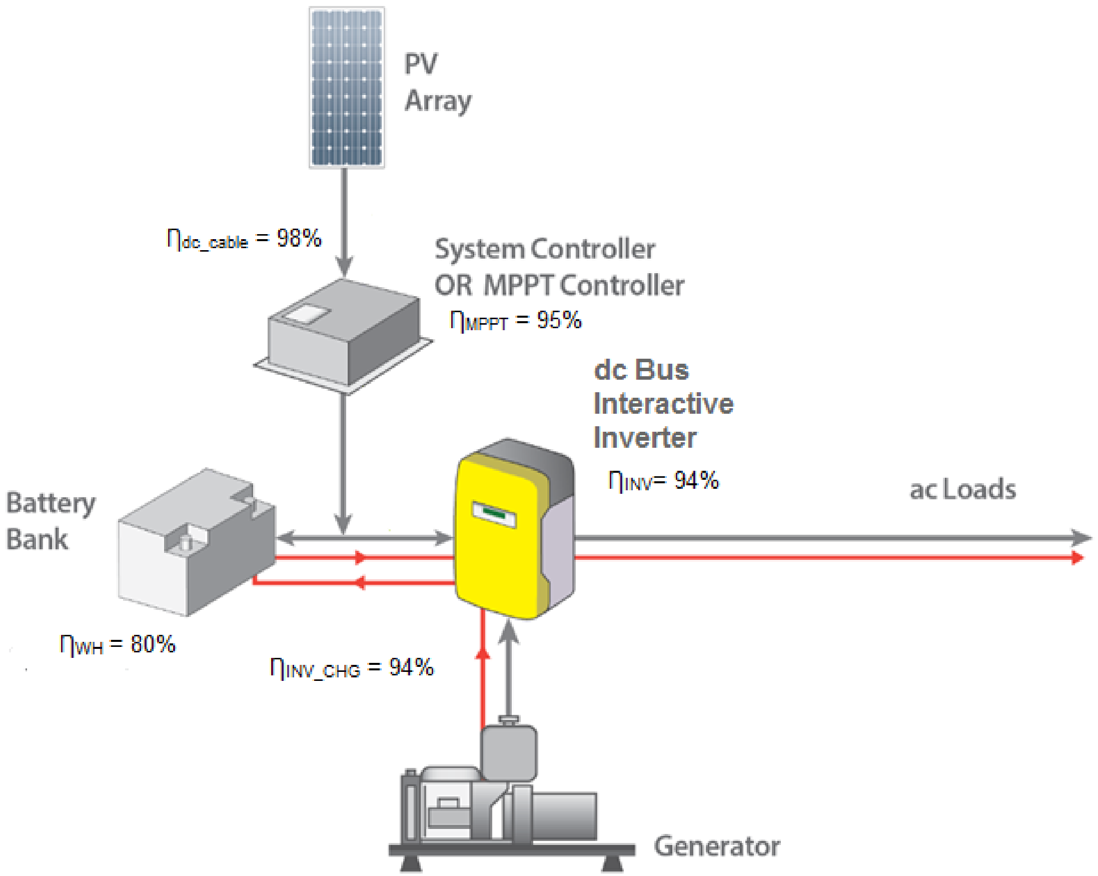

Figure 3 System block diagram showing component losses

PV module temperature derating is calculated by the formula: $F_{TEMP} = 1 + [\gamma \times (T_{CELL\text{-}EFF} - T_{STC})]$

Note: T_{CELL_EFF} *= ambient temperature + 25℃.*

11: Calculate derating factor due to temperature (F_{TEMP}): ______________________________

Use the formula: $P_{MOD} = P_{STC} \times F_{MAN} \times F_{TEMP} \times F_{DIRT}$

12: Calculate the derated power of the selected module (P_{MOD}): __________

As the system is only providing ac loads, use the equation:

$\eta_{batt\_subsys} = \eta_{INV} \times \eta_{WH} \times \eta_{MPPT} \times \eta_{dc\_cable}$

13: Calculate the System Efficiency for loads supplied from the PV array charging the battery bank: ____________

Use the equation $N_{total} = (E_{AC} \times f_o) / (P_{mod} \times H_{tilt} \times \eta_{batt\_subsys})$

14: Calculate the number of PV modules required to meet the energy requirements from the battery bank: ____________

15: What is the minimum array capacity required?

The array capacity required: ____________ kW_p

Multiply N_{total} by the module capacity and divide by 1000 to get array capacity in kW_p

Either a 3-phase inverter or three single PV inverters could be selected. Grid Connected workshops covers how to match the array to the PV inverter and hence is not covered in this workshop exercise.

Sizing the PVarray using an MPPT

Technical data	Sunny Island Charger 40		
	12 V	24 V	48 V
Input (PV generator)			
Max. PV power	630 W	1250 W	2100 W
Max. DC voltage	140 V DC	140 V DC	140 V DC
Optimal MPPT voltage range	25 V - 60 V	40 V - 80 V	70 V - 100 V
Number of MPP trackers	1	1	1
Max. PV current	40 A	40 A	30 A
Output (battery)			
Nominal DC power up to 40 °C	600 W	1200 W	2000 W
Nominal battery voltage	12 V	24 V	48 V
Nominal voltage range	8 V - 15.6 V	16 V - 31.5 V	36 V - 65 V
Battery type	flooded and sealed lead acid batteries		
Max. charging current / continuous charging current	50 A / 50 A	50 A / 50 A	40 A / 40 A
Charge control	IUoU	IUoU	IUoU
Efficiency			
Max. efficiency	98 %	98 %	98 %
Euro ETA	97.3 %	97.3 %	97.3 %
Device protection			
DC reverse polarity	●	●	●
Short-circuit proof	●	●	●
Overload protection	●	●	●
Over- and undervoltage protection	●	●	●
Over- and undertemperture protection	●	●	●
General data			
Dimensions (W / H / D) in mm	421 / 310 / 143	421 / 310 / 143	421 / 310 / 143
Weight	10 kg	10 kg	10 kg
Protection class (according IEC 60529)	IP65	IP65	IP65
Operating temperature range	-25 °C ... +60 °C	-25 °C ... +60 °C	-25 °C ... +60 °C
Air humidity	0 % - 100 %	0 % - 100 %	0 % - 100 %
Daytime operating consumption	< 5 W	< 5 W	< 5 W
Internal consumption at night	< 3 W	< 3 W	< 3 W
Features and functions			
Display	multicolored LED	multicolored LED	multicolored LED
Setting parameters	plug and play in combination with SI 5048, SI2224, SI2012 (Sync Bus Piggy Back required) DIL switch with stand-alone applications		
Parallel operation	Up to 4 devices	Up to 4 devices	Up to 4 devices
Interface: Sync Bus Piggy-Back	○	○	○
External temperature sensor (KTY type)	○	○	○
Warranty: 5 / 10 / 15 / 20 / 25 years	●/○/○/○/○	●/○/○/○/○	●/○/○/○/○
Certificates and permits	CE	CE	CE
● Standard features ○ Optional features – not available			
Last revision: May 2010			
Type designation	SIC40-MPT	SIC40-MPT	SIC40-MPT

Since the battery bank is 48V dc then the last column should be referenced:

Assume lowest temperature for the site is 10 °C and maximum cell temperature is 75 °C.

Maximum Number of Modules in String

The maximum V_{oc} of the module at coldest temperature is:

$$V_{MAX\_OC} = V_{OC\_STC} \times \{1 + [\beta \times (T_{MIN} - T_{STC})]\}$$

16: Calculate Open circuit voltage at coldest temperature: ______________________V

Maximum number of modules in the string is

$$N_{MAX\_OC} = \frac{V_{MPPT\_MAX}}{V_{MAX\_OC}}$$

17: Refer to the maximum MPPT input voltage. Calculate maximum number of modules in a string: ______________________

Minimum Number of Modules in String

The minimum V_{mp} of the module at hottest temperature is:

$$V_{\text{MIN\_MP}} = V_{\text{MP\_STC}} \times \{1 + [\gamma \times (\text{T}_{\text{MAX}} - T_{\text{STC}})]\}$$

18: Calculate V_{mp} at hottest temperature: ____V

The PV array's minimum voltage at the MPPT is de-rated by the voltage drop and is calculated as follows:

$$V_{\text{MIN\_MP\_MMPT}} = V_{\text{MIN\_MP}} \times [1 - \text{voltage drop}]$$

Note: effect of voltage drop has already been calculated and presented as a percentage in this exercise (See η_{dc_cable} on page 6)

19: Calculate V_{mp} at the MPPT: ____V

The minimum voltage of the MPPT is theoretically the battery voltage—however the battery voltage rises as the battery is charged. For instance, a 48V battery bank would be about 56V to 60V when fully charged. temperature. For the MPPT to work effectively the V_{mp} of the array should also be greater than the battery voltage.

The data sheet above states MPPT voltage is to be 70V to 100V.

In this case the lower MPPT value is also the minimum array MP voltage.

$$V_{\text{ARRAY\_MIN\_MP}} = V_{\text{MIN\_MPPT}}$$

The minimum number of modules per string is then determined by the following equation (round up):

$$N_{\text{MIN\_MP}} = \frac{V_{\text{ARRAY\_MIN\_MP}}}{V_{\text{MIN\_MP\_MPPT}}}$$

20: Calculate the minimum number of modules in a string: ______________________

What is the number of modules required per string? ________

21: Calculate power rating of each string: ______________________

Use the power rating of the MPPT to calculate the number of strings required

22: Calculate the number of strings per MPPT: ______________________

23: Calculate number of modules and array power rating per MPPT.

Number of modules per MPPT: ______________________

Array power rating per MPPT: ______________________

24: Calculate number MPPTs: ______________________

25: Calculate total number of modules and total array power: ______________________

Calculate maximum power used for battery charging

Each SMA Sunny island inverter has a maximum charge current of 110A but a rated current of 90A.

The maximum charge current from the battery charger is the sum of maximum current that can be provided by the battery charger on each phase

26: Calculate the maximum charge current the battery chargers can provide to the battery bank I_{bc} : ____________A

The selected battery bank comprises two parallel banks of A602/2600 SOLAR with a combined C_{10} capacity of 4048Ah

27: If the maximum charging current for the battery is 0.1 x C_{10} capacity rating, what is the battery's maximum charge current? ____________A

28: Can the battery bank accept the maximum charging current from the inverters? Circle: (Yes/No)

Assume the maximum charge voltage per cell is 2.4V

Use the equation V_{bc} = cell volt x N_{series} (From question 9)

29: Calculate the maximum charge voltage (V_{bc}) of the selected battery bank: ____________V

Assume that:

- *Battery charger nominal efficiency (η_{INV_CHG}) is 0.94*
- *Battery charger nominal power factor (pf_{bc}) is 1*

Use the equation $S_{bc} = (I_{bc} \times V_{bc}) / (\eta_{INV\_CHG} \times pf_{bc})$

30: Calculate Battery charger max. apparent power S_{bc} : ____________VA

Size and select backup generator

The backup generator's minimum capacity is calculated by the equation:

$$S_{GEN} = \left(S_{BC} + S_{MAX\_CHG}\right) \times F_{GO}$$

Where:
S_{GEN} = *Minimum apparent power rating of the generator (kVA)*
S_{BC} = *Maximum apparent power consumed by the battery charger under conditions of maximum output current and typically maximum charge voltage (kVA)*
S_{MAX_CHG} = *Maximum ac demand from ac loads during battery charging (kVA), i.e. the site's max demand*
F_{GO} = *Generator oversize factor (dimensionless)*

Assume $F_{GO} = 1.1$

31: What is the minimum capacity of the generator required so that it can meet the battery charging load and maximum demand at the same time? ____________kVA

<u>Calculate the Generators derating factor</u>

32: The guesthouse is located at 35m altitude, with maximum air temperature is 27°C and humidity is 82%. Calculate the site-specific temperature, humidity and altitude, and the total general derating factor using values are shown in Table 2.

Table 2: Generator derating factors

Site factor		Derating
Air Temperature		Derate 2.5% for every 5°C above 25°C
Altitude		Derate 3% for every additional 300 m above 300 m altitude
Humidity	Air Temperature between 30ºC and 40ºC	Derate 0.5% for every 10% above 60% humidity
	Air Temperature between 40ºC and 50ºC	Derate 1.0% for every 10% above 60% humidity
	Air Temperature between 50ºC and 60ºC	Derate 1.5% for every 10% above 60% humidity

Altitude derating: ____________

Temperature derating: ____________

Humidity derating: ____________

Total derating: ____________

33: Apply the generator derating factor, what is the minimum generator size required? ____________ kVA