Workshop Exercises: Designing ac bus hybrid system

A village with 250 households is being powered by a diesel generator operating 24 hours a day, with a second generator onsite for redundancy. This village is receiving funding via an aid project to build a PV and battery system to supplement its current diesel generator power plant. The aim of the PV system is to reduce generator operation to 6pm – 11pm nightly.

Customer Requirement:

- Generator to operate nightly from 6pm to 11pm
- Sealed lead-acid batteries to be used.
- Batteries to have 3000 cycles with daily depth of discharge (DoD) no greater than 50%.

Site information:

- Two 110kVA diesel generators, derated by 10% due to temperature to 99kVA.
- Site location: Vanuatu, 15°S
- Annual irradiation deficit due to shadowing (horizontal): 0%
- Irradiation for design month at optimal array tilt (15°) is 4.59kWh/m^2 or 4.59PSH
- Average temperature of design month is 26.8ºC

Table 1: load observed onsite for a day

Time	Energy Usage (Wh)	Peak Demand (VA)	Energy usage per hour as % of daily total
Midnight to 1am	9,300	26,110	1.97%
1am to 2am	9,670	24,925	2.05%
2am to 3am	9,917	24,186	2.10%
3am to 4am	11,103	25,960	2.35%
4am to 5am	11,103	25,630	2.35%
5am to 6am	14,196	27,020	3.00%
6am to 7am	18,241	27,935	3.86%
7am to 8am	18,887	34,507	4.00%
8am to 9am	20,825	36,986	4.41%
9am to 10am	24,059	39,931	5.09%
10am to 11am	25,457	42,542	5.39%
11am to noon	26,533	40,575	5.62%
Noon to 1pm	25,210	42,377	5.34%
1pm to 2pm	26,718	43,101	5.66%
2pm to 3pm	27,783	38,285	5.88%
3pm to 4pm	25,962	37,103	5.50%
4pm to 5pm	24,692	37,652	5.23%
5pm to 6pm	21,824	34,624	4.62%
6pm to 7pm	22,561	35,879	4.78%
7pm to 8pm	23,253	35,172	4.92%
8pm to 9pm	20,743	32,689	4.39%
9pm to 10pm	18,336	32,675	3.88%
10pm to 11pm	18,282	25,528	3.87%
11pm to midnight	17,795	24,624	3.77%
Total	472,450		

IT IS ASSUMED THAT THE LOAD IS THE SAME ALL YEAR

The load is the greatest in the daytime due to a number of daytime commercial operations. It then remains high during the evening peak.

<u>Determine the energy provided directly by generator, by PV array, and by battery bank</u>

1. Given that the generator is expected to run from 6pm to 11pm, work out from Table 1 the corresponding total energy usage this 5-hour period represents.

The table below is an extract from Table 1. Complete the last cells.

Time	Energy usage (Wh)
6pm to 7pm	22,561
7pm to 8pm	23,253

8pm to 9pm	20,743
9pm to 10pm	18,336
10pm to 11pm	18,282
Sum (E_{GEN})	

Determine energy provided by PV array and battery bank

Assuming the generator operates for the 5 hours each night than the remaining energy that shall be supplied via the solar array and the battery bank is determined by the following formula:

> Energy to be provided by the battery bank and PV array = Total daily energy usage – energy use supplied directly by the generator.

2. Based on the table above, what is the total daily energy that would be supplied by the battery bank/PV array (E_{BATT_DAY})? ______________

Determining the capacity of the Battery bank

Assumptions:

- Battery Inverter efficiency 94%
- Battery Inverter efficiency when acting as charger 94%
- Battery coulombic efficiency 90%
- Watt-hour efficiency of the battery 80%

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 battery capacity, use the equation E_{BATT} (Wh) = $E_{BATT\_DAY} \div (DOD \times \eta_{INV})$

E_{BATT} = *energy required from the battery bank*
η_{INV} = *inverter efficiency*
DOD = *depth of discharge*

3. Based on the requirement for maximum daily depth of discharge being 50%, what is the energy required from the battery bank? ___________

For lead-acid batteries, calculate the battery capacity with the equation $C_x = E_{BATT}/V_{dc}$

V_{dc} = system voltage

4. Assuming the battery voltage is 48V (to keep system voltage at a safe level), what is the required battery bank capacity? ______

Selecting the Inverter Capacity and type

5. What is the peak demand of the system as calculated by Table 1? Round to the nearest kVA: ______________kVA

6. Allowing for 10% oversize factor, what is the minimum required inverter capacity to meet the peak demand? Round up to the nearest KVA: __________

The system is three-phase and assume that the inverter will comprise three single phase inverters connected to provide three phase.

7. What is the minimum capacity rating required of each phase/inverter _____________ kVA

8: Based on the 16kVA requirement for each of 3 phases and SMA data sheet as shown below, select the inverter: ____________

9. How many inverters are needed per phase? ____________ How many clusters of three SMA sunny islands are needed? ____________

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		

Figure 1: SMA Sunny Island Inverter Technical Data

Selecting the Battery Model

The battery bank will be selected from the Sonnenschein Solar range of batteries due to it meeting the 3000+ cycle at 50% DoD requirement.

From earlier section, the required battery capacity is 16,368 Ah. The battery capacity should be divided between each cluster of inverter.

10. Assume there are three clusters. What is the battery capacity required for each 3-phase cluster?

____

11. Battery capacity should be selected at C_{10} rating.

How many parallel strings will there be? ______________________

What is a suitable model? ______________________

12. What is its overall C_{10} capacity of the battery bank for each cluster? ______________________
What is the overall capacity for the whole battery system? ______________________

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 battery range capacity table

Determining the portion of generator capacity which will be used to charge battery banks

Each night the generator will operate for 5 hours. The generator is derated to 99kVA (see page 1) while the maximum (peak demand) during the hours that the generator operates is 35.9kVA (see Table 1). This means that every night there is extra capacity for the generator to charge the battery

13. What is the minimum available capacity available for charging the batteries? _________

From Figure 1, each SMA Sunny Island 8.0H has a maximum charge current of 140A at full rating of 8 kW.

14. Three Sunny Islands are connected to provide three phase in each cluster, what is the maximum charge current at each cluster? ____________

The maximum charging current for a battery is 0.1x C_{10} capacity rating.

15. At each cluster, the battery bank capacity is 6072Ah at C_{10}. What is the maximum charge current for the battery that is installed in each inverter cluster? __________

16. Can the battery bank accept the maximum charging current from the inverters (yes or no)? __________

<u>What will be the actual effective charging current?</u>

From one inverter 125A of charging at 48V is 6kVA however as the battery voltage rises the current will decrease, for example with battery voltage of 57.6V (2.4V per cell) the maximum current would be 104A. To be conservative we assume that the average charging current while the genset is operating is 110A per inverter.

Charge capacity = charge current x charging duration

17. There are nine inverters in this system. What is the charge capacity of the whole system's battery banks if they are charged for 5 hours? ___________

18. With a battery columbic efficiency of 90%, ac interactive inverter efficiency of 94% and battery system voltage of 48V, what is the daily energy that will be supplied by the batteries being charged by the generator? ______________

<u>Determine the portion of energy that is to be supplied by the PV array</u>

For a hybrid system where the generator is operating daily, the total daily energy requirement is determined as follows:

$$E_{LOAD} = E_{GEN} + E_{GEN\text{-}BATT} + E_{PV} + E_{PV\text{-}BATT}$$

E_{LOAD} = *Total daily energy*
E_{GEN} = *Portion of daily energy being supplied directly by generator*
E_{BATT_GEN} = *Portion of daily energy being provided by battery bank being charged by generator.*
E_{PV_DIR} = *Portion of daily energy that will be provided by the PV array*
E_{PV_BATT} = *Portion of daily energy being provided by battery bank being charged by PV array*

The portion of daily energy that will be provided by the PV array for both direct loads and battery charging is therefore:

$$E_{PV} = E_{PV\text{-}DIR} + E_{PV\_BATT} = E_{LOAD} - E_{GEN} - E_{GEN\_BATT}$$

19. Applying the above formula, calculate the portion of daily energy that will be provided by the PV array E_{PV}: ______________kWh (round to nearest)

Determining Size of PV Array

The AC load to be supplied by the PV array is 168.266kWh while the irradiation is 4.59 kWh/m^2/day.

Note many principles in this section are covered in grid-connect and off-grid PV systems.

Assumptions:

- No PV array oversizing required because there is a generator i.e. Oversize coefficient (f_o) 1
- Average temperature 26.8°C
- Average solar resource at 15° tilt (H_{tilt}) 4.59 PSH/day
- Battery coulombic efficiency (η_{COUL}) 90%
- PV inverter efficiency (η_{PV}) 97%
- Inverter efficiency(η_{INV}) 94%
- Inverter efficiency when acting as charger (η_{INV_CHG}) 94%
- Dirt de-rating (F_{DIRT}) 95%
- Cable losses have been calculated and reflected in the figure below:

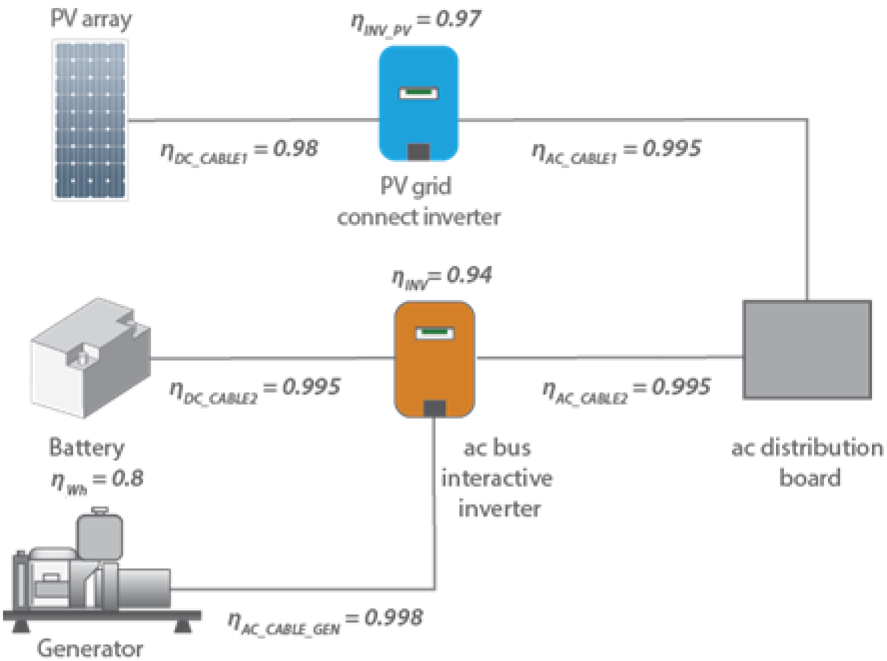

Figure 3: System Losses for ac Bus System

Solar Module has following data:

- Nominal power rating (P_{STC}) 290W_p
- Power tolerance +0W to 5W
  i.e. F_{MAN} 1
- P_{max} Temp Co-efficient(γ) -0.39% / °C
  (This is also used for V_{mp} Temp coefficient)

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℃.*

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

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

21. Calculate the derated power of the selected module (P_{MOD}): __________ (round to nearest W)

Determining Array Size for Load Energy (ac) directly supplied by PV array

In this case, it may be possible for the shortfall energy to come directly from PV during daytime

The energy directly supplied by the PV array is calculated by

$$E_{PV} = E_{ac5} = P_{MOD} \times N \times H_{TILT} \times \eta_{PV} \times \eta_{PV\text{-}Load}$$

$$N = (E_{PV})/(P_{MOD} \times N \times H_{TILT} \times \eta_{PV} \times \eta_{PV\text{-}Load})$$

In this case, $\eta_{PV\text{-}Load}$, the cable loss in the PV is: η_{dc_cable1} x η_{ac_cable1} = 0.9751 (refer to Figure 3)

22. If 100% of the required PV load can be provided directly supplied by the PV array, what is the number of modules required? __________________

What is the array capacity? __________________kWp

Determining Array Size for Load Energy (ac) indirectly supplied by PV array

The energy directly supplied by the PV array is calculated by

$$E_{PV\_BATT} = E_{ac6} = P_{MOD} \times N \times H_{TILT} \times \eta_{PVINV} \times \eta_{INV\text{-}CHG} \times \eta_{WH} \times \eta_{INV} \times \eta_{PV\text{-}Load}$$

$$N = E_{PV\_BATT}/ (P_{MOD} \times H_{TILT} \times \eta_{PVINV} \times \eta_{INV\text{-}CHG} \times \eta_{WH} \times \eta_{INV} \times \eta_{PV\text{-}Load})$$

In this case, $\eta_{PV\text{-}Load}$, the cable loss in the PV is: $\eta_{dc\_cable1} \times \eta_{ac\_cable1} \times \eta_{ac\_cable2} \times \eta_{dc\_cable2} \times \eta_{dc\_cable2} \times \eta_{ac\_cable2}$ (refer to Figure 3 and trace the cable path PV energy flows)

i.e. $\eta_{PV\text{-}Load}$ = 0.98 × 0.995 × 0.995 × 0.995 × 0.995 × 0.995 = 0.9557

23. If 100% of the required PV load is provided by the PV array via the battery bank, what is the number of modules required? __________________

What is the array capacity? __________________kWp