EXPERIMENT 1 LAB REPORT

ECEN 5517 (Spring 2017)
Power electronics and Photovoltaic Power Systems Laboratory

1/21/2017

TEAM MUSE
Maneesh Kumar Singh
Vivek Sankaranarayanan

Objectives

The objectives of this experiment are:

- To characterize the laboratory photovoltaic panels, and find numerical parameters of the equivalent circuit model for use later in the semester.
- To test the sine wave inverter provided.
- To charge the deep-discharge lead-acid battery using the Direct Energy Transfer approach.

Experimental data

Equipments used

Power	**Measurement**
Inverter: AIMS POWER PWR130012S Panel: SQ85-P Load: Bulb 75W Battery: 12V-56Ah (PVX-560T)	Meter1: FLUKE 45 Meter2: FLUKE 45 Pyranometer: Apogee SP-110 Rheostat: 0 -15.5 Ohms Power Meter: Kill A Watt P4400

Nameplate data (PANEL Specifications)

PANEL: SQ85-P

Below specs are taken at STC: 1000W/m^2, irradiance, 25 Cell temperature

Parameter	**Value**
Maximum Power Output (W)	85
Short Circuit Current (A)	5.45
Open Circuit Voltage (V)	22.2
Rated Current (A)	4.95
Rated Voltage (V)	17.2
Maximum Open Circuit Voltage	600V (UL) / 715V (TUV)
Fire Rating	Class C
Series Fuse	20 A
Field Wiring	Copper Only, 14 AWG Min, Insulated for 90 C Min

Battery Discharging start

Time Started	14:50
Vbat (V)	12.94
Vac (V)	113.2
Iac (A)	0.62
Pout (W)	71
Frequency (Hz)	61.9
Power Factor	1.0

Pyranometer and PV Discharge

The pyranometer readings in the below table was taken at various points on the panel and an average reading obtained.

Time: 1/19/2017, 15:11

Pyranometer readings

No	mV
1	180.4
2	183.47
3	183.47
4	183.47
5	181.5
Average	182.462

Initial PV readings

PV Voltage at MPP (V)	15.605
PV Current at MPP (A)	3.906
PV Power at MPP (W)	60.95

Irradiation calculated in Step 10

I-V Curve (No Shading)

I-V Curve with no shading (Time: 1/19/2017; 15.11**)**

No	Voltage (V)	Current (A)
1	20.44	0
2	19.4	1.29
3	19.36	1.336
4	19.297	1.404
5	19.25	1.455
6	19.187	1.516
7	19.06	1.632
8	18.98	1.719
9	18.92	1.748
10	18.86	1.816
11	18.79	1.884
12	18.752	1.923
13	18.679	1.993
14	18.652	2.016
15	18.578	2.081

No	Voltage(V)	Current (A)
16	18.44	2.202
17	18.27	2.36
18	18.185	2.423
19	17.962	2.612
20	17.604	2.887
21	16.911	3.313
22	16.165	3.683
23	15.605	3.906
24	12.102	4.341
25	8.233	4.385
26	6.335	4.368
27	3.888	4.385
28	1.5802	4.417
29	0.202	4.447

Open Circuit Voltage (Voc): 20.44V
Short Circuit Current (Isc): 4.389 A[1]

Note [1]: The Isc measured is lower than the last reading in I-V curve. This is impossible and can be attributed to possible measurement or setup error. For calculations the final reading of 4.447A is considered to be short circuit current

I-V Curve (4 cell shading)

4 cells on the right side were covered.

Initial Readings (Time: 1/19/2017; 15:30**)**

PV Voltage at MPP (V)	15.605
PV Current at MPP (A)	3.906
PV Power at MPP (W)	60.95

I-V Curve with 4 shaded cells

No	Voltage (V)	Current (A)
1	19.555	0
2	8.845	0.583
3	8.834	0.601
4	8.905	0.641
5	8.78	0.678
6	8.728	0.748
7	8.696	0.803
8	8.681	0.835
9	8.657	0.856
15	8.449	1.223

No	Voltage(V)	Current (A)
16	8.416	1.289
17	8.344	1.425
18	8.198	1.677
19	8.021	1.972
20	7.815	2.298
21	7.505	2.72
22	6.039	3.835
23	2.6635	4.018
24	0.25	4.011

Open Circuit Voltage (Voc): 19.555 V
Short Circuit Current (Isc): 3.606 A[1]

Note [1]: The Isc measured is lower than the last reading in I-V curve. This is impossible and can be attributed to possible measurement or setup error. For calculations the final reading of 4.011 A is considered to be short circuit current

Energy consumed readings

Time: 15:36
Time Elapsed: 46 min
Battery Voltage (loaded): 12.21 V
Battery voltage (no Load): 12.625 V
KwH output from inverter: 0.05 kWh

Charging the battery - direct energy transfer

Time: 15:45
PV/Battery voltage: 12.637 V
Battery charging current: 2.11 A

CALCULATIONS

Panel Efficiency calculations

Solar irradiation as per pyrometer reading in step 4
Average of all readings = 182.462 mV
Irradiation on panel = 182.462/0.2 W/m^2 = 912.31 W/m^2

Direct Normal Insolation from NREL website
Time: 15.11
DNI: 820 W/m^2

Panel Area from datasheet: 1.20m x 0.527m = 0.6324 m^2

Max watt measured for no shading: 15.605 * 3.906 = 60.953 W

Panel efficiency as per pyrometer
Max watt that can be generated = 912.31*0.6324 = 576.94 W
Panel Efficiency = (60.953/576.94)% = 10.56%

Panel efficiency as per NREL data
Max watt that can be generated = 820*0.6324 = 518.568 W
Panel Efficiency = (60.953/518.568)% = 11.75%

The above calculations are tabulated below:

PANEL Efficiency		
Peak power measured = **60.653W**; Panel Area = **0.6324m^2**		
	Pyranometer	**NREL**
Irradiation (W/m^2)	912.31	820
Efficiency (%)	10.56	11.75

I-V curves for measured data

Figure 1: I-V curve for uniform irradiation

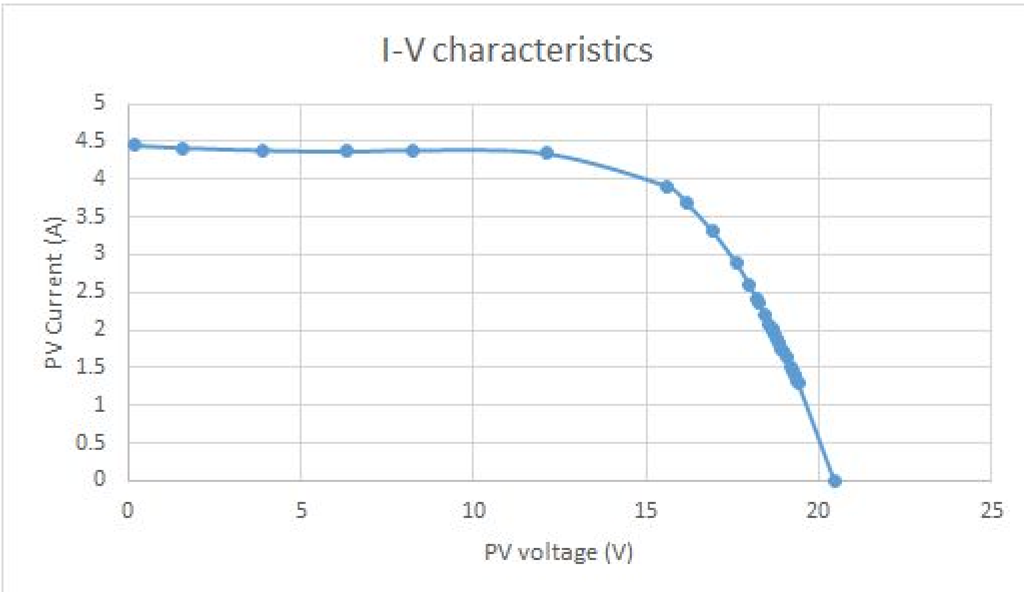
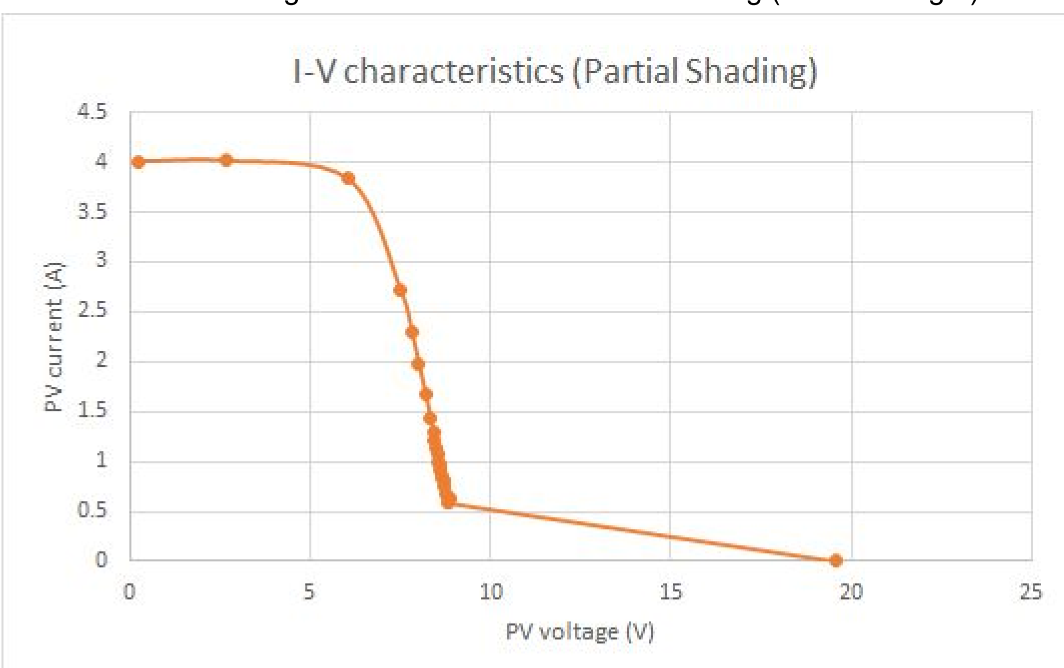


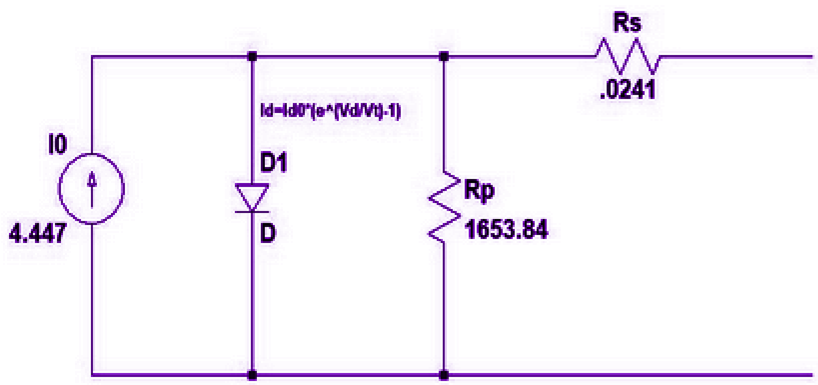
Figure 2: I-V curve with Partial shading (4 cells on right)



With partial shading, it can be seen that the panel voltage when loaded has dropped to half of the uniform irradiation case. This is because one of the backplane diode conducts bypassing half the solar cells.

Estimation of Panel Parameters

Figure 3: Solar Cell circuit model



- Rs is 1/slope of the I-V curve close to open circuit voltage
  - Rs_{PV} = dV/dI (closer to Voc operation)
    = (19.4-19.36)/(1.336-1.29) = 0.8695 Ohms
  - Rs = Rs_{PV} / 36 = ***0.0241* Ohms**

- Rp is 1/slope of I-V curve close to short circuit operation
  - Rp_{PV} = dV/dI (closer to Isc operation)
    = (1.5802-0.202)/(4.447-4.417) = 43.94 Ohms
  - Rp = Rp_{PV} * 36 = ***1653.84 Ohms***

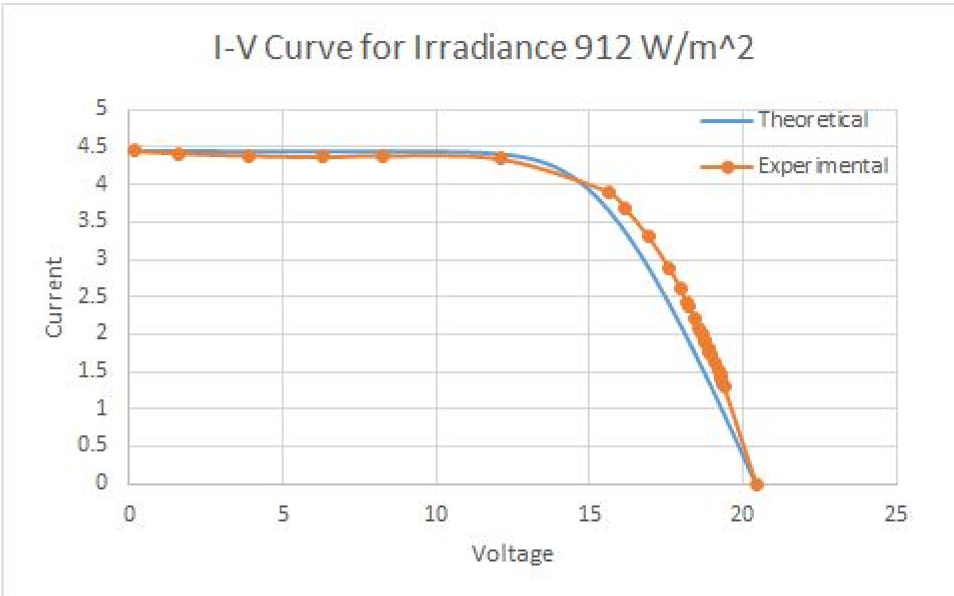
- $I_0 = I_{SC}$ = ***4.447 A***

- When panel is open circuited entire I_0 current flows into diode. Thus,
  - $I_D = I_0 = I_{D0} * (e^{Vd/Vt} - 1)$
  - $4.447 = I_{D0} * (e^{0.567/0.026} - 1)$ [V_D = Voc/36; Vt = 26mV]
  - I_{D0} = ***1.501 nA***

Summary of Circuit Parameters	
R_P	1653.84 Ohms
R_S	0.0241 Ohms
I_0	4.447 A
I_{D0}	1.501 nA

Comparison of model predicted PV parameters with measured data

Figure 4: Comparison of Model predicted and measured I-V curves (Irradiation = 912.31 W/m^2)



	Analytical	Experimental
Open circuit voltage (V)	20.5	20.44
Short Circuit current (A)	4.4469	4.4470
Maximum power point voltage (V)	14.5	15.605
Maximum power point current (A)	4.09	3.906
Maximum power (W)	59.32	60.9

The model predicted PV parameters agree well with experimental data except for Vmp and Imp points. The model predicts lower Vmp and higher Imp than the experimental data. The power predicted is very close to measured value.

I-V and P-V curves for different Irradiations

I0 for various irradiation values

Irradiation (W/m^2)	**I0 = K * Irradiation**
250	1.218
500	2.437
750	3.655
912.30	4.447
1000	4.874

Figure 5: I-V curve for various irradiation from theoretical model

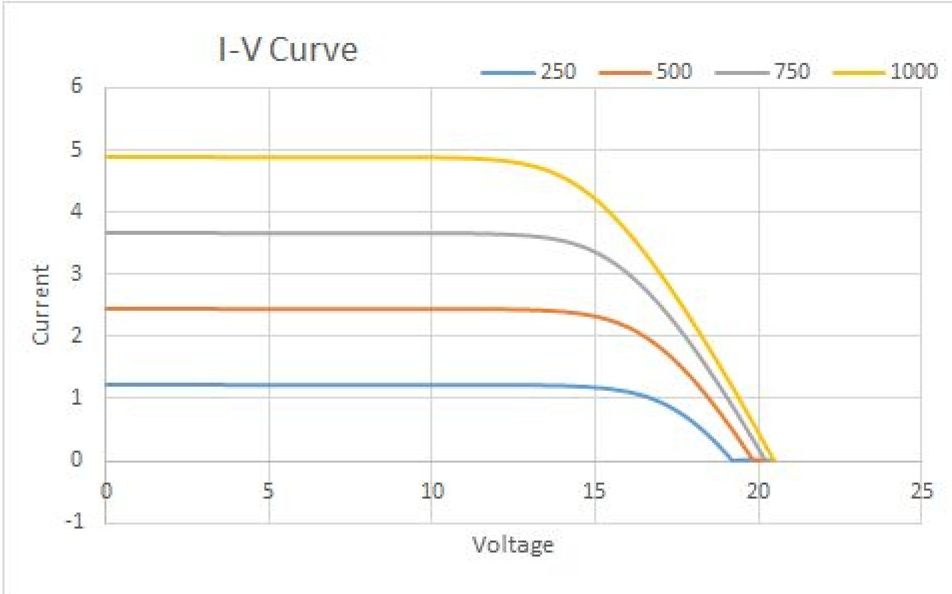
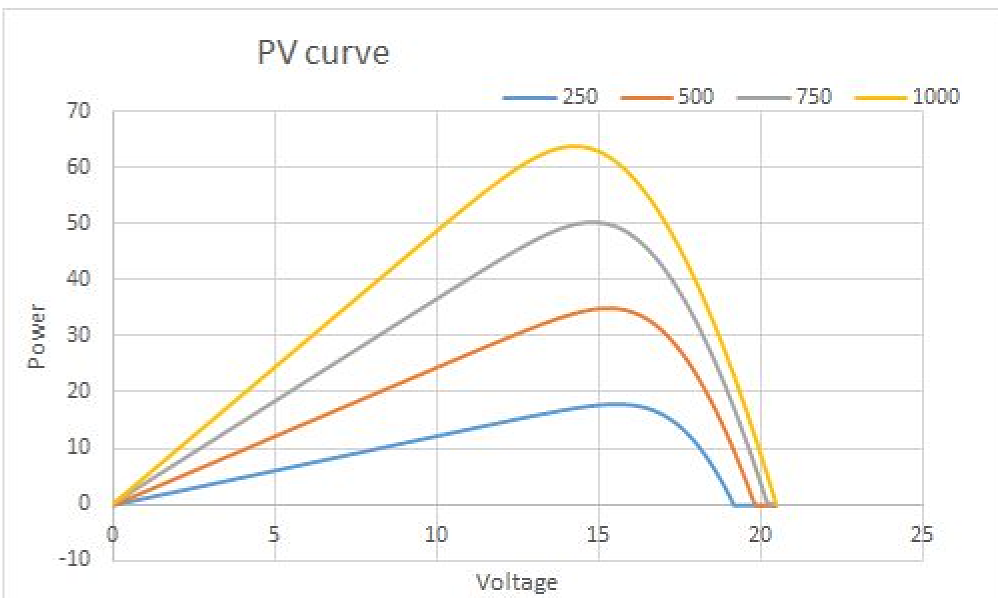
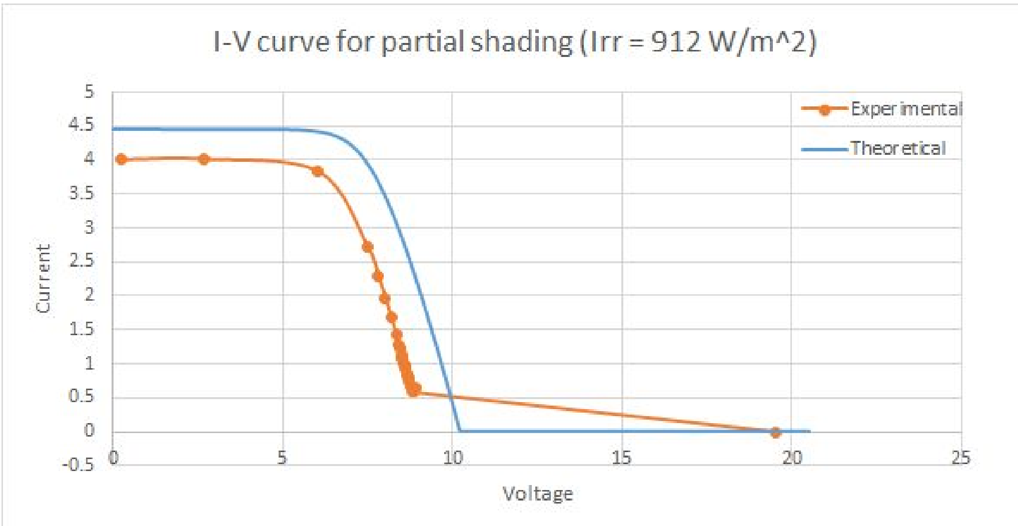


Figure 6: PV curves for various irradiation



I-V curve for partial shading

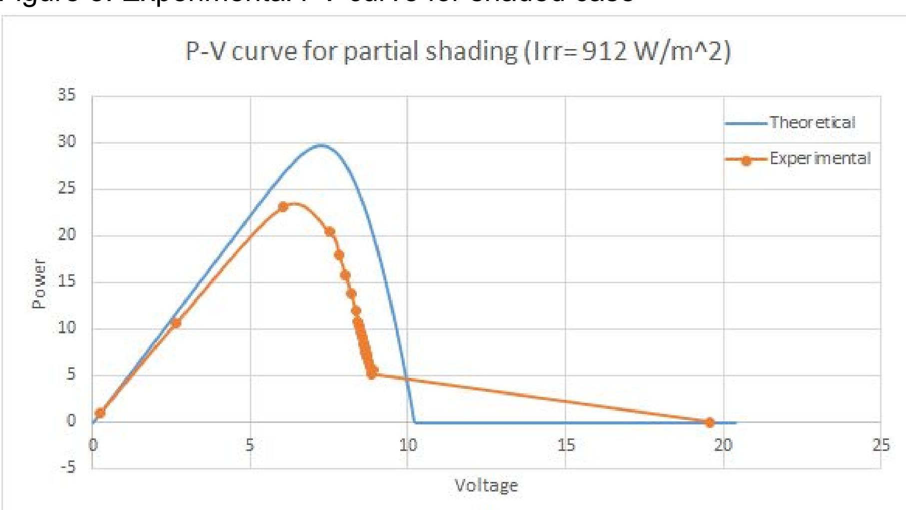
Figure 7: I-V curves for partial shading [2]



Note[2]: The experimental and theoretical curves differ significantly because of change in irradiation when the readings were taken. The theoretical plot assumes 912.31 W/m^2. The irradiation definitely reduced as it can be seen from the table of Step 6 that the short circuit current reduced to 4.011 A

The model agrees with experimental data except for the note [2] above.
The Vmp voltage has dropped to almost half that of the non shaded case because all the 18 cells on the right (shaded region) have been bypassed by the backplane diode. Thus the right backplane diode conducts.

Figure 8: Experimental PV curve for shaded case



Vmp = 6.039 V, Imp = 3.834 A

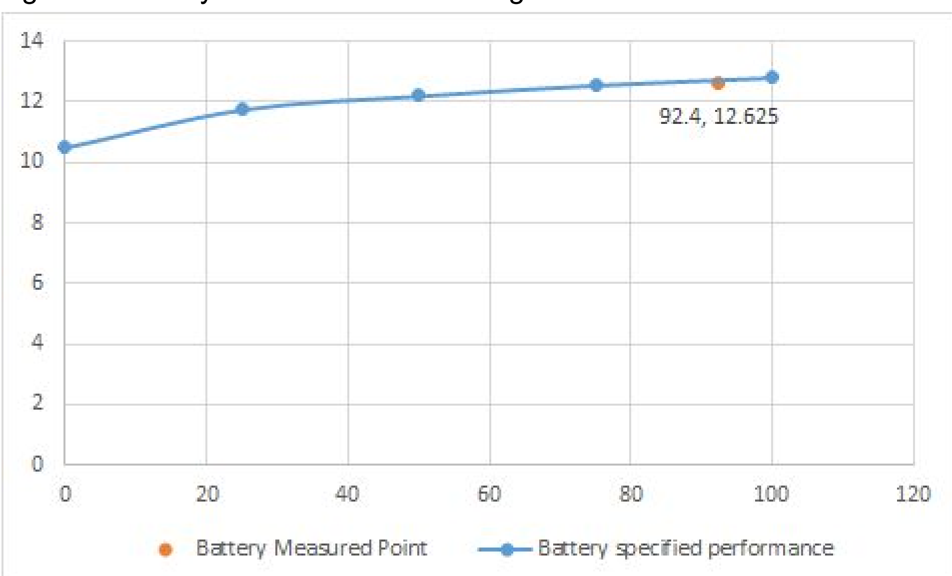
Battery Energy Calculations

Ah Consumed from battery = (Wh supplied by Inverter/Inverter_efficiency)/nominal_battery_voltage
= (0.05*1000/0.95)/12
= 4.25 Ah

SOC of battery at end of discharge = (Batt. rated Ah - Ah Consumed)*100/Batt. Rated Ah
= (56 - 4.25)* 100 /56
= 92.4 %

Battery terminal Voltage at end of discharge: 12.625 V
Comparing with battery SOC vs Terminal Voltage, it can be seen that SOC must fall between 75 to 100% which was what observed experimentally.

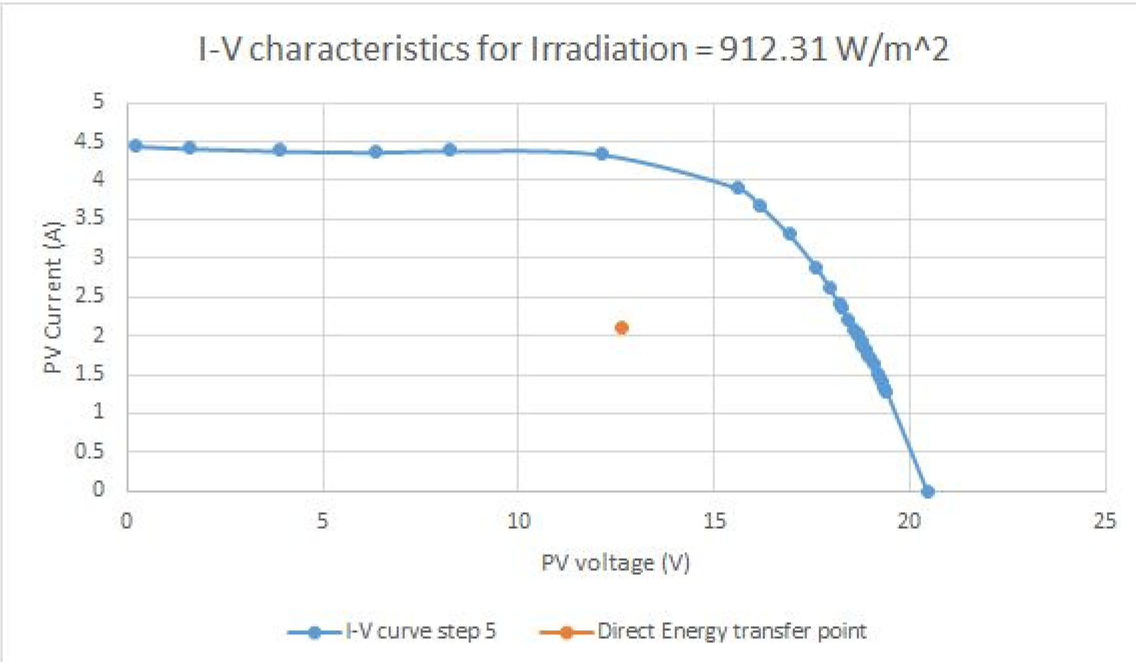
Figure 9: Battery SoC vs Terminal voltage



The blue curve represents the specified performance of the battery. It can be seen that the terminal voltage (12.625 V) measured at the end of discharge cycle lies on this curve and matches with the measured SoC value of 92.4%

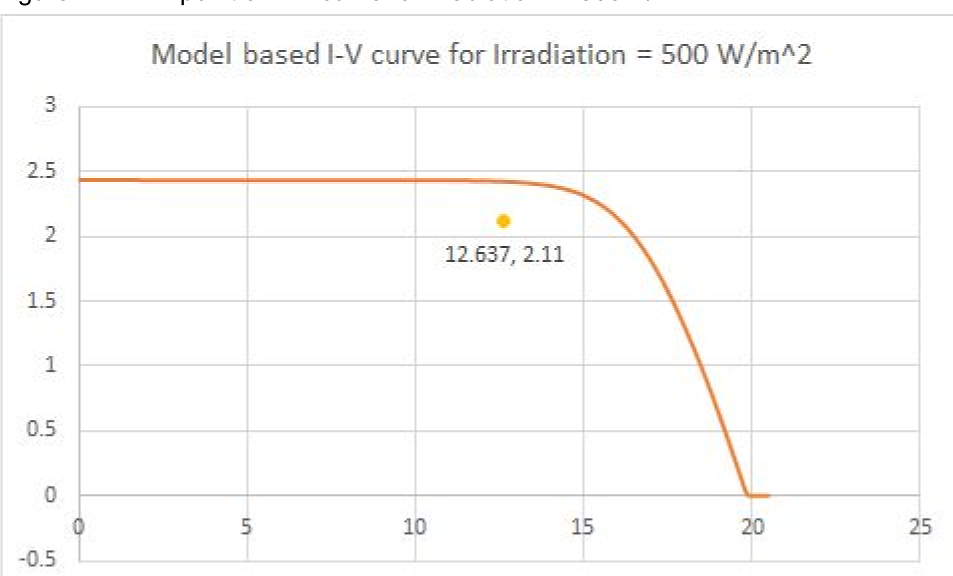
Direct Energy Transfer

Figure 10: Direct energy transfer point of the I-V curve for Irradiation = 912.31 W/m^2 (Note 3)



Note 3: The Direct Energy Transfer (DET) point does not lie on the I-V curve step 5 because the irradiation changed significantly when this step of the experiment was conducted. A measurement with Pyranometer showed that the Irradiation had become 492 W/m^2

Figure 11: DET point on I-V curve for irradiation = 500W/m^2



The DET point is much closer to the IV curve. The DET power is 12.637 V * 2.11 A = 26.66 W. The actual MPPT for this curve is 34.9 W. Thus it can be seen that DET does not operate at Max power point

MPPT strategy to increase panel power

If a buck converter is placed between battery and panel, the charging current from the buck could be controlled to get a desired output power from panel. This power point then using any suitable MPPT algorithms (Perturb and Observe) could be maximised for given irradiation.

MPPT strategy for partial shading conditions

When using multiple modules, multiple peaks can be observed for PV curves. The MPPT strategy used must ensure that, operating point is not at any of the lower peaks.
One strategy would be to periodically open circuit the panel and restart the MPPT algorithm. This would enable the algorithm to scale a new MPPT peak, if available.

Conclusion

- Under conditions on uniform irradiation, a PV panel has a single point of operation at maximum power can be extracted from the panel
- When partially shaded, the corresponding backplane diode of the panel begin to conduct bypassing half the cells. The maximum power points falls by 50%
- Direct energy transfer is an inefficient way of drawing power from a PV panel. A converter should be placed between the panel and the load, and an MPPT algorithm must be utilized to maximize energy harvested from panel.
- Under cases of partial shading, normal MPPT algorithms tend to fail in extracting maximum power from panel and more sophisticated algorithms must be used