PROJECT REPORT PART 1

Power Electronics and Applications

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Contents

Scope 2
System Concept – Part 1 2
Specifications 2
Circuit Design Calculations – Part 2 4
DC to Single-Phase AC Conversion – Part 3 5
Bibliography 7
Appendix 7

Project Report

Part 1

Scope

This investigation involves the integration of a photovoltaic *(PV)* battery system as denoted below in *Figure 1,* with the battery converting solar power to supply a DC link with specifications mentioned in sections below.

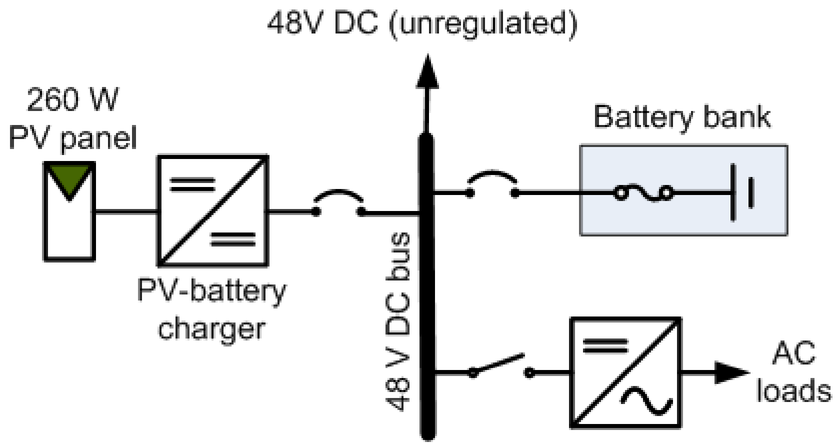

Figure 1: PV System

(Sydney, 2020)

System Concept – Part 1

- Power source is the PV panel with a nominal power rating of 260W.
- A PV-battery charger converts the solar power to supply DC link, which is rated to be 48V DC.
- The battery bank is rated as 48V nominal and 4.8kWH in capacity.
- A DC to single-phase AC converter supplies AC loads, which is rated as 230V (RMS) and 50Hz.

Specifications

Table 1: Circuit Specifications

Parameters	***Specification***
Rated Maximum Power	$260W$
Open Circuit Voltage (V_{oc})	$39.10V$
Short Circuit Current (I_{sc})	$8.56A$
Voltage (Max Power) (V_{mp})	$31.91V$
Current (Max Power) (I_{mp})	$8.15A$
Maximum Fuse Current	$15A$
Maximum System Voltage	$1000V$
Module Size	$1640 \times 992 \times 35\ (mm)$
Module Efficiency	15.98%
Types of Solar Cell	Polycrystalline

The converter topology for the PV – battery charger according to the step-up voltage conversion from $48V$ to $230V$ is a flyback converter with the following section highlighting the calculated parameters and further specifications of the converter. This decision to utilize a flyback topology with a transformer structure is attractive due to the low power application, low cost, high efficiency.

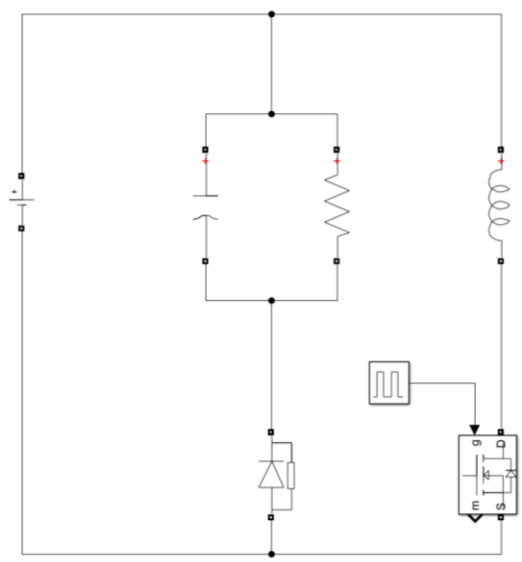

Figure 2: Flyback Configuration Section

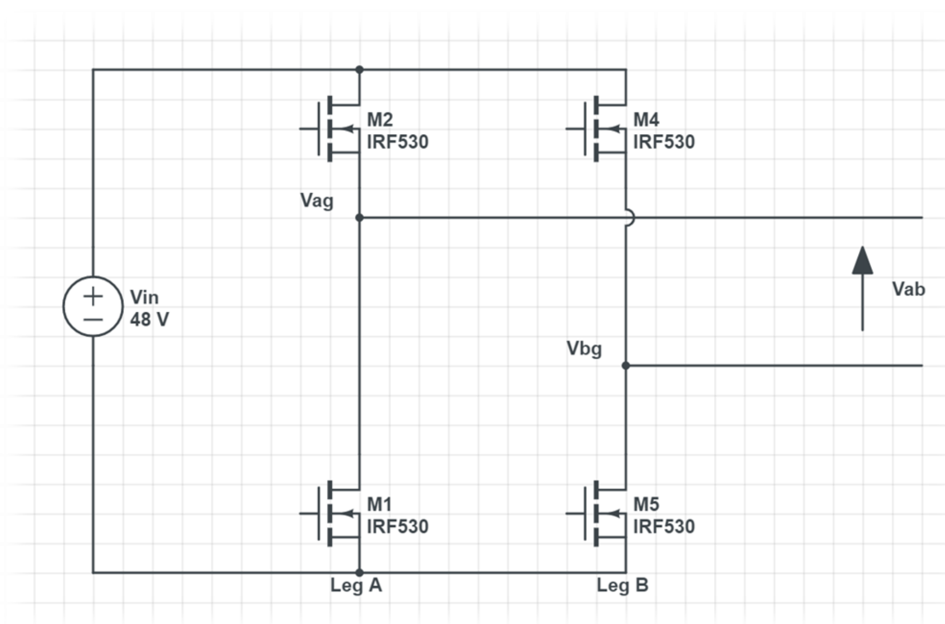

Figure 3: DC/AC Conversion Configuration

Circuit Design Calculations – Part 2

- Based on the converter for the PV-battery charger, the design is as follows:

Table 2: Design Specifications

Parameters	***Specification***
V_{in}	$31.91V$
V_o	$48V$
R	8.86Ω
f_{sw}	$100kHz$
ΔI_L	$2A$
ΔV_o	$1V$

a. Assuming the operation of the converter is in CCM, the on-state duty ratio D_{on} is determined as follows;
   - The selection of a duty cycle of $D_{ON} = 40\%$ is utilized to determine the limitation of the turns or coils n.

   <u>Note:</u> The required $V_o = 48V$.

$$\frac{V_o}{V_{in}} = \frac{N_2}{N_1} \times \left(\frac{D}{1-D}\right)$$

   - Assume that $D = 0.4$. If this is substituted, the equation is:

$$\therefore n = \frac{N_2}{N_1} = 2.26$$

   - Let the turns ratio be rounded down to integer value $n = 2$, the duty ratio therefore, is calculated to be $D_{ON} = 0.4298$ from the equation above.

b. The computation for the on-state time T_{ON} or T_{UP} is as follows:

$$T_{ON} = \frac{D_{ON}}{f_{sw}} = \frac{0.4298}{100 \times 10^3} = 4.298 \times 10^{-6}s = 4.298\mu s$$

c. Utilizing the converter specifications, the derivation for the inductance of the converter L is as follows;

$$L = \frac{V_{in} D_{ON}}{\Delta I_L f_{sw}}$$

   <u>Note:</u> The magnetizing inductance is given by the equation about which employs the value of the magnetizing inductance current I_L which is given by the equation below:

$$I_L = \frac{V_o}{(1 - D_{ON})R} \times n$$

   - The magnetizing inductance current average is to be multiplied by a factor or percentage resulting in the value that is given within the specification.

- Since, the peak-to-peak value for the magnetizing inductance current, ΔI_L is given from the specifications, the magnetizing inductance is:

$$L = \frac{(31.91)(0.4298)}{2(100 \times 10^3)} = 68.57\mu H$$

d. The derivation of the capacitance from the converter specifications is computed as follows;

$$\frac{\Delta V_o}{V_o} = \left(\frac{D_{ON}}{RCf_{sw}}\right) \rightarrow \frac{1}{48} = \left(\frac{0.4298}{(8.86)(100 \times 10^3)(C)}\right)$$

<u>Note:</u> The output voltage ripple is limited to a percentage or factor of the output voltage.

The value with this multiplication of the factor resultant is given in the specification table above *(Table 2).*

The capacitance, C is calculated with the formula above and has resulted to be:

$$C = 23.28\mu F$$

DC to Single-Phase AC Conversion – Part 3

The converter topology for the PV-battery charger according to the voltage ratings of the input and output is the following, four-switch bridge with two legs, *A* and *B.* This topology is suitable for single-phase AC conversion from DC, since the application is of relatively low power $(< 7kW)$.

The transformer winding turns ratio is based off the operation of the flyback converter. Furthermore, this calculation is that of a non-isolated buck-boost converter. From the PV parameters in *Table 1* with the required output voltage of 230V.

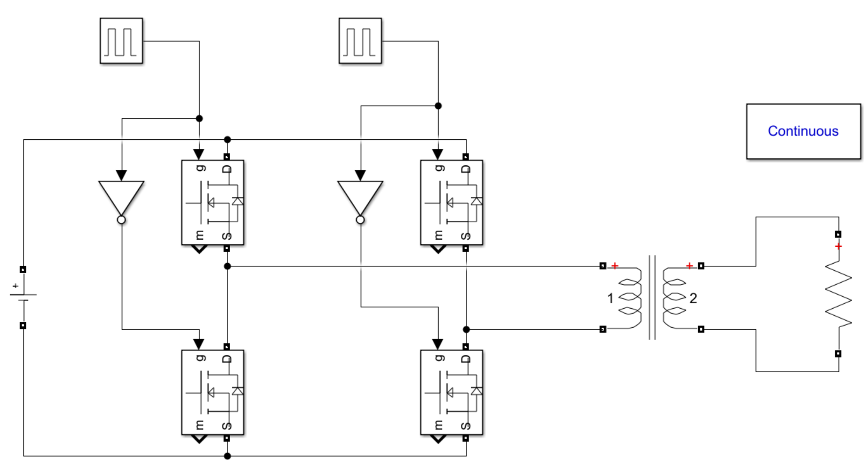

Figure 4: Converter Configuration

- If the defined phase is $\frac{\pi}{2}$ therefore, the $RMS(V_{ab})$ can be determined with the following calculation:

$$RMS(V_{ab}) = \frac{V_{in}}{\sqrt{2}} = \frac{48}{\sqrt{2}} = 33.94V \rightarrow n = \frac{V_o}{V_{ab}} = \frac{230}{33.94} = 6.78$$

$$\therefore n = 6.78$$

The values of the duty cycle for the four MOSFET's that are utilized within the system design are assumed to have a $D_{ON} = 50\%$ or 0.5.

The modulation of the index ma and mf is defined as:

$$0 < ma < 1$$

$$ma = \frac{V_r}{V_c}$$

$$ma = \frac{V_o}{V_{in}} = \frac{230}{48} = 4.79$$

$$V_{ab} = ma \times V_{in}$$

It is preferred to output a modified square wave. The following figure defines the potential filtering that can be utilized with a sine wave output in the investigation.

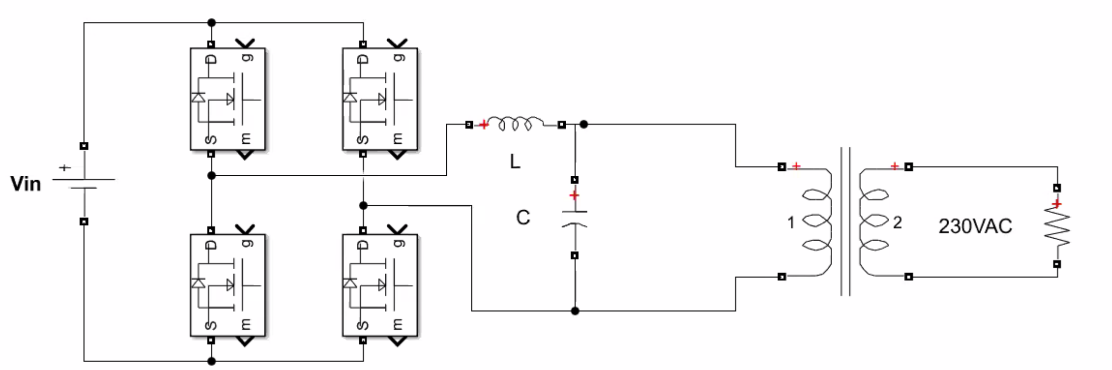

Figure 5: Potential Filter Configuration

Bibliography

Hart, D. W. (2010). *Power Electronics.* New York: Pearson Education, Inc.

Sydney, U. o. (2020). Power Electronics and Applications. *Final Project ELEC 3204/9204*, 1.

Appendix

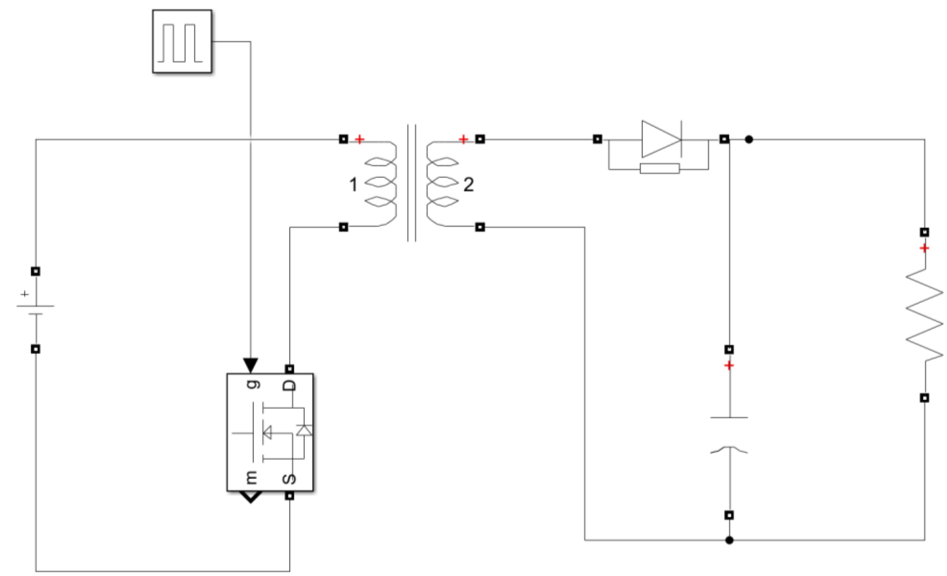

Figure 6: Flyback Component with PV

PROJECT REPORT PART 2

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Contents

Required Parameters 2
Calculations 3
STC Figures – Simulation Model 4
PV ISDM Simulation Model 5
I-V & P-V Output Curves – Solar Cell 6
Bibliography 8
Appendix 7
Iph Calculations 7
Voc Calculations 7
Is Calculations 7
Ipv Calculations 7

Project Report

Part 2

Required Parameters

The following section highlights all the required parameters to formulate a single diode model for simulation based from the Standard Test Condition *(STC)*:

Table 1: Datasheet Values

Parameter:	Specification:
Nominal Temperature (T_C)	$25°C$ or $298°K$
Boltzmann's Constant (k)	$1.38 \times 10^{-23} J/K$
Electron Charge (q)	$1.6 \times 10^{-19} C$
Short-Circuit Current of Cell at $1000W/m^2$ (k_i)	0.0006

Table 2: Simulink Rating for Modelling in Simulink

Parameter:	Specification:
Rated Power (V_{mp})	240W
Voltage at Maximum Power (V_{mp})	30.54V
Current at Maximum Power (I_{mp})	7.85A
Open Circuit Voltage (V_{ocs})	36.84V
Short Circuit Current (I_{scs})	8.38A
Total Number of Cells in Series (N_s)	60
Total Number of Cells in Parallel (N_p)	1

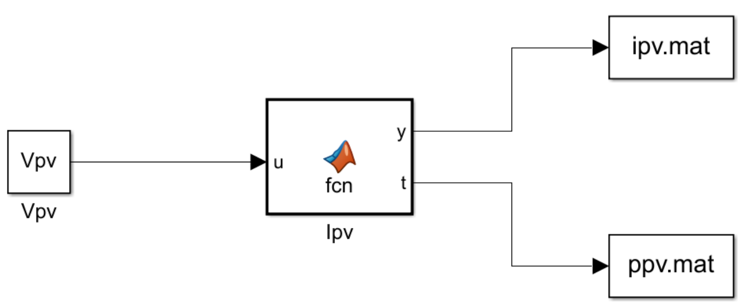

Figure 1: I-V & P-V Curve Model

Calculations

The first calculation that is required is the A_n, the diode ideality factor:

$$I_{SCS} = I_{SS}\left[e^{\frac{V_{OCS}}{V_{TCS}A_n}} - 1\right] \rightarrow I_{ss} = \frac{I_{SCS}}{e^{\frac{V_{OCS}}{V_{TCS}A_n}} - 1}$$

$$I_{MS} = I_{SCS} - I_{SS}\left[e^{\frac{V_{MS}}{V_{TCS}A_n}} - 1\right] \rightarrow I_{ss} = \frac{I_{SCS} - I_{MS}}{e^{\frac{V_{MS}}{V_{TCS}A_n}} - 1}$$

$$\therefore \frac{I_{SCS} - I_{MS}}{e^{\frac{V_{MS}}{V_{TCS}A_n}} - 1} = \frac{I_{SCS}}{e^{\frac{V_{MS}}{V_{TCS}A_n}} - 1}$$

$$\frac{\left(e^{\frac{V_{MS}}{V_{TCS}A_n}} - 1\right)}{\left(e^{\frac{V_{OCS}}{V_{TCS}A_n}} - 1\right)} = 1 - \frac{I_{MS}}{I_{SCS}}$$

$$V_{TCS} = \frac{kT_{CS}}{q} = \frac{60(1.38 \times 10^{-23})(298)}{1.6 \times 10^{-19}} = 1.542V$$

$$\frac{\left(e^{\frac{19.80}{A_n}} - 1\right)}{\left(e^{\frac{23.89}{A_n}} - 1\right)} = 1 - 0.9368 = 0.0632$$

$$C_1 = \frac{V_{MS}}{V_{TCS}}$$

$$C_2 = \frac{V_{OCS}}{V_{TCS}}$$

$$C_3 = 1 - \frac{I_{MS}}{I_{SCS}}$$

$$\therefore C_1 = 19.81, C_2 = 23.89, C_3 = 0.0632$$

$$f(A_{inv}) = e^{19.81A_{inv}} - 0.0632e^{23.89A_{inv}} = 0$$

$$A_{inv} = 1/A_n$$

$$\therefore A_n = 1.4538$$

<u>Note:</u> This value A_n, was determine using MATLAB 2018b solve function.

$$I_{SS} = \frac{I_{SC}}{e^{\frac{V_{OCS}}{V_{TCS}A_n}} - 1} \rightarrow I_{SS} = \frac{8.38}{e^{\frac{36.84}{1.542(1.4538)}} - 1}$$

$$\therefore I_{SS} = 6.1097 \times 10^{-7}A$$

$$i_d = I_{ss} \times e^{\frac{qV_{pv}}{k\times 298\times A_n N_s}} - 1$$

$$I_{PV} = I_{SCS} - i_d$$

$$D_{OC} = \sqrt{\left(\frac{\tilde{V}_{OCS}}{V_{OCS}} - 1\right)^2} \;\&\; D_{SC} = \sqrt{\left(\frac{\tilde{I}_{SCS}}{I_{SCS}} - 1\right)^2}$$

$$D_{OC} = \sqrt{\left(\frac{36.84}{36.84} - 1\right)^2} = 0 \;\&\; D_{SC} = \sqrt{\left(\frac{8.38}{8.38} - 1\right)^2} = 0$$

∴ As expected the output at STC display zero values for the deviation of the open-circuit voltage and short-circuit current, as per criteria.

$$D_{MPP} = \sqrt{\left(\frac{\tilde{P}_{MPP}}{P_{MPP}} - 1\right)^2 + \left(\frac{\tilde{V}_{MPP}}{V_{MPP}} - 1\right)^2}$$

$$D_{MPP} = \sqrt{\left(\frac{240.7}{240} - 1\right)^2 + \left(\frac{30.83}{30.54} - 1\right)^2} = 0.0099$$

In conclusion, the true distance from the true MPP normalization is calculated as above and shown to be accurate due to its small magnitude regarding the simulation model output.

STC Figures – Simulation Model

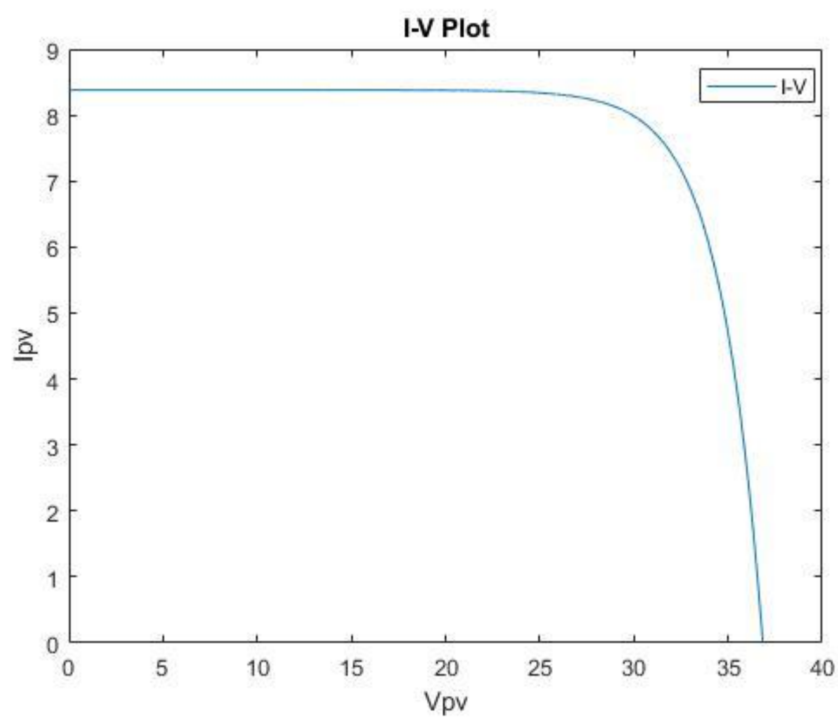

Figure 2: I-V Plot

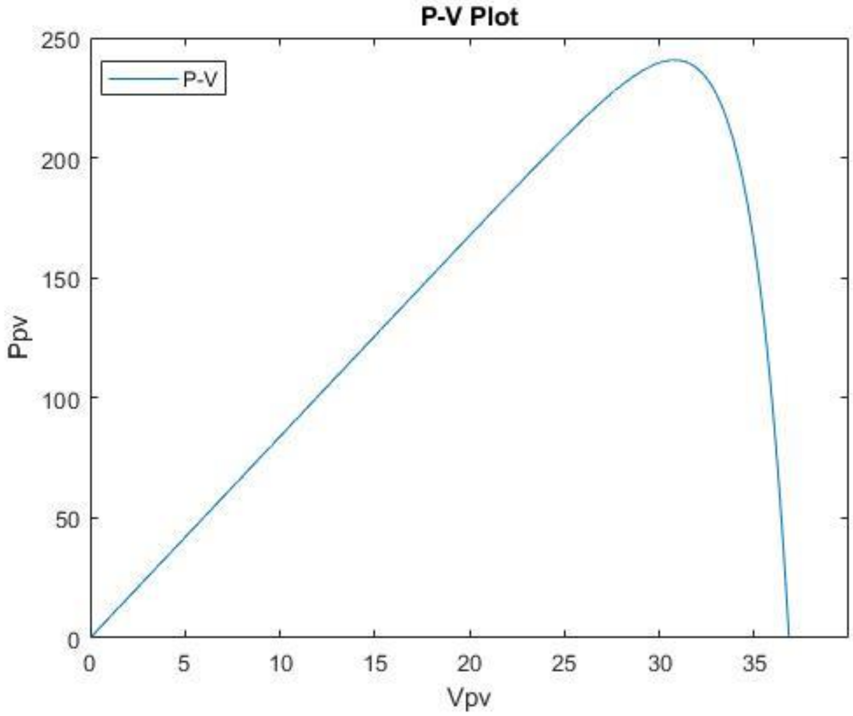

Figure 3: P-V Plot

PV ISDM Simulation Model

The following section highlights the real-world representation with appropriate solar irradiance and cell temperature of 25°C:

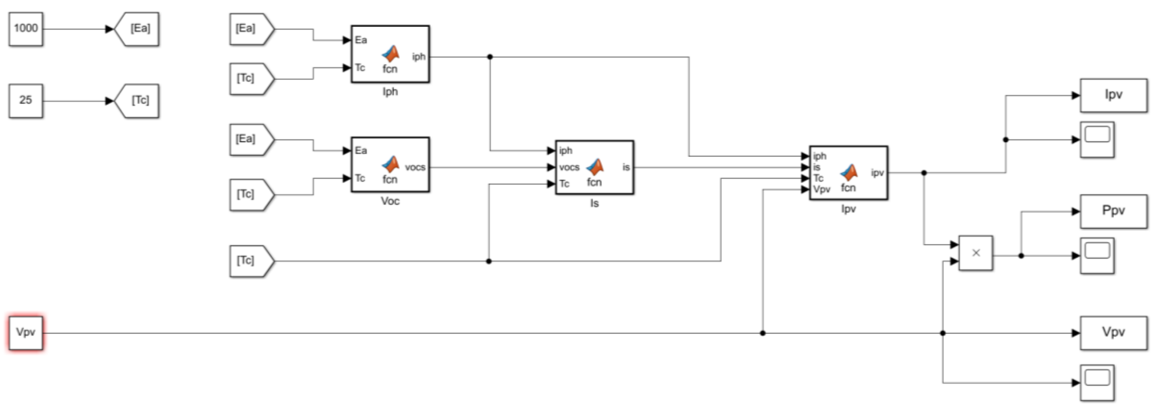

Figure 4: Simulation Model - PV ISDM

I-V & P-V Output Curves – Solar Cell

With a changing solar irradiance, the output I-V and P-V plots are as follows:

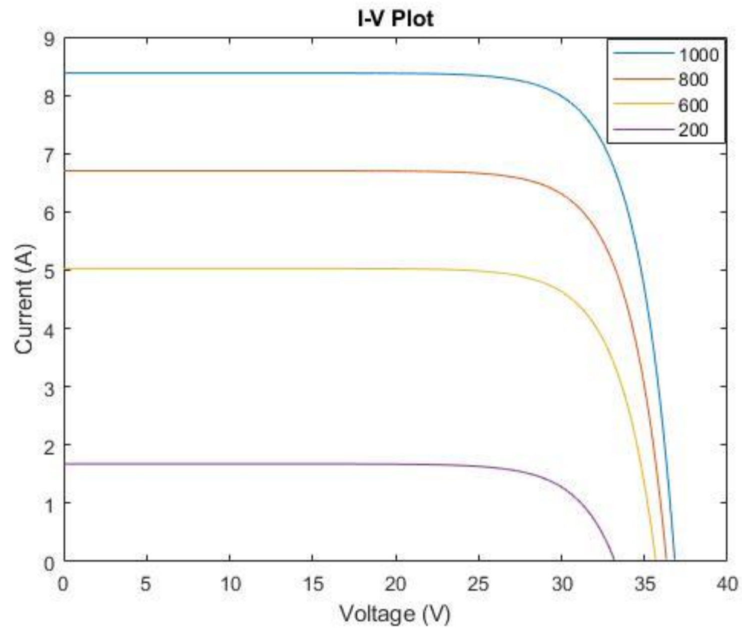

Figure 5: I-V Plot for Solar Cell

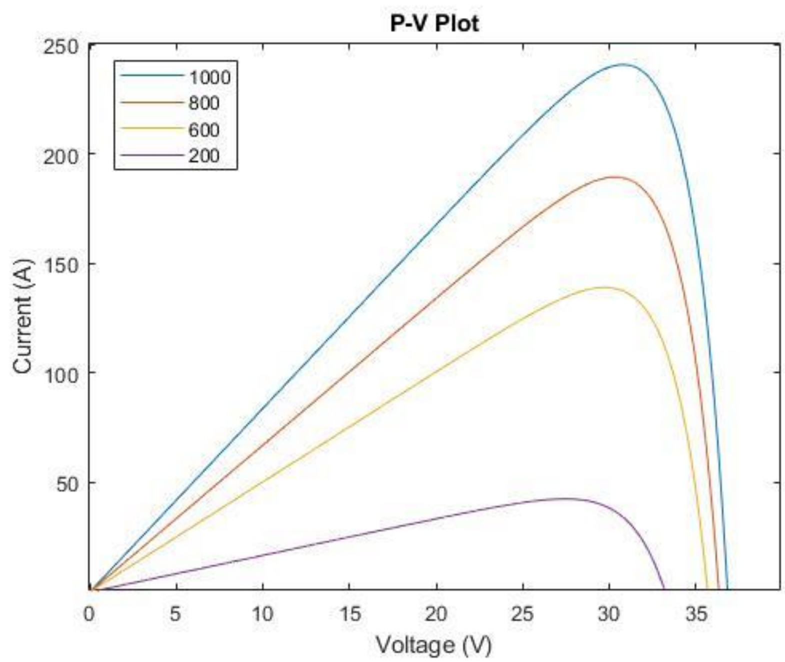

Figure 6: P-V Plot for Solar Cell

Appendix

For the calculations of the PV ISDM Simulation Model the following MATLAB functions were created in the creation of the I-V & P-V plots:

I_{ph} Calculations

```
function iph = fcn(Ea, Tc, Estc, Iscs)

    alpha = 0.06/100;
    delta_t = Tc - 298;

    iph = (Ea/Estc)*(Iscs*(1+(alpha*delta_t)));
end
```

V_{oc} Calculations

```
function vocs = fcn(Ea, Tc, Voc)

        vt = 1;
        Voc_1 = Voc/60;
        beta = -0.33/100;

        if(Ea == 1000)
            vt = 1;
        elseif(Ea == 800)
            vt = 0.989;
        elseif(Ea == 600)
            vt = 0.972;
        elseif(Ea == 200)
            vt = 0.911;
        end

        delta_t = Tc - 298;
        vocs = Voc_1*(1-beta*delta_t)*vt;
end
```

I_s Calculations

```
function is = fcn(iph, vocs, Tc, k, q, An)

    is = iph/(exp(vocs*q)/(k*Tc*An));

end
```

I_{pv} Calculations

```
function ipv = fcn(iph, is, Tc, Vpv, q, k, An)

    id = is * (exp((q*Vpv)/(k*Tc*An))-1);
    ipv = iph-id;

end
```

Bibliography

Hart, D. W. (2010). *Power Electronics.* Valparaiso, Indiana: Pearson Education, Inc.

PROJECT REPORT PART 3

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Contents

Abstract 2
Introduction 2
Specifications 2
Datasheet 3
Equations & Formulations 3
Design Requirements 4
PV System Design 5
Results & Discussion 6
Conclusion & Recommendation 7
Appendix 8
References 8

PV System – Case Study

Final Project - Report Part 3

Abstract

The following document will highlight the investigation and overall system design, performance and specifications of a *PV system*. The report will also encompass a Simulink design of the *PV system* along with an analysis of the results according to the design requirements.

Keywords – PV, photovoltaic, Simulink, solar cell, converter, inverter.

Introduction

The following investigative report will highlight the *PV system*, with reference to its simulation performance with MATLAB & Simulink. The *PV* design has been highlighted within a previous report (*Part 2)* and therefore, the system in this investigation will utilize the *PV array* function to simplify connections overall.

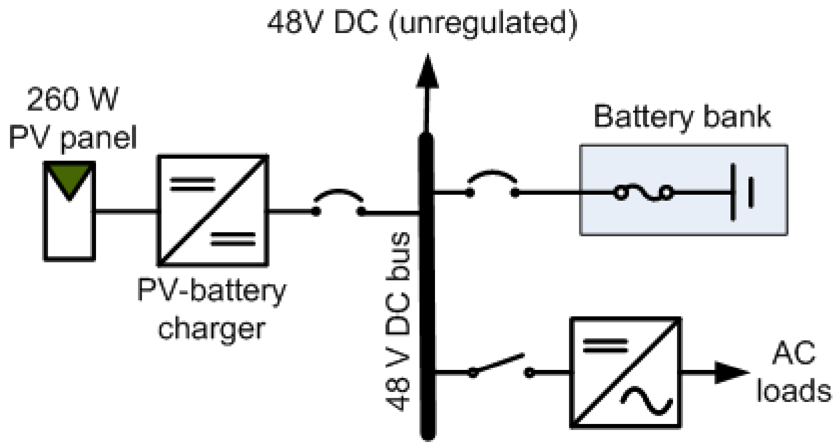

Figure 1: PV System

(Sydney, 2020)

Specifications

The power source is *PV* is rated at a nominal power $260W$. The *PV-battery charger* within this report in specific aims to covert the solar power to supply the DC link, rated at $48V$ DC. The *battery bank* is rated as $48V$ nominal and $4.8kWH$ in capacity. Finally, the *DC to single-phase AC converter* supplies AC loads, which is rated as $230V$ (RMS) and $50Hz$.

Datasheet

Table 1:Design Specifications

Parameter	Specification
Rated Maximum Power	$260W$
Open Circuit Voltage (V_{OC})	$39.10V$
Short Circuit Current (I_{SC})	$8.56A$
Voltage (Maximum Power) (V_{mp})	$31.91V$
Current (Maximum Power) (I_{mp})	$8.15A$
Maximum Fuse Current	$15A$
Maximum System Voltage	$1000V$
Module Size	$1640 \times 992 \times 35(mm)$
Module Efficiency	15.98%
Types of Solar Cell	*Polycrystalline*

Equations & Formulations

Table 2:DC - DC Boost Converter Specifications

Parameters	***Specification***
V_{in}	$31.91V$
V_o	$48V$
R	8.86Ω
f_{sw}	$100kHz$
ΔI_L	$2A$
ΔV_o	$1V$

- If the defined phase is $\frac{\pi}{2}$ therefore, the $RMS(V_{ab})$ can be determined with the following calculation:

$$RMS(V_{ab}) = \frac{V_{in}}{\sqrt{2}} = \frac{48}{\sqrt{2}} = 33.94V \rightarrow n = \frac{V_o}{V_{ab}} = \frac{230}{33.94} = 6.78$$

$$\therefore n = 6.78$$

Hence, the n can be rounded to 7 turns.

Therefore, the specifications for the transformer windings has been arranged as follows:

$$winding\ 2\ parameter:$$

$$\rightarrow voltage\ V_2(V_{RMS}) = n \times RMS(V_{ab})$$

$$\rightarrow 33.94 \times 7 = 237.58V$$

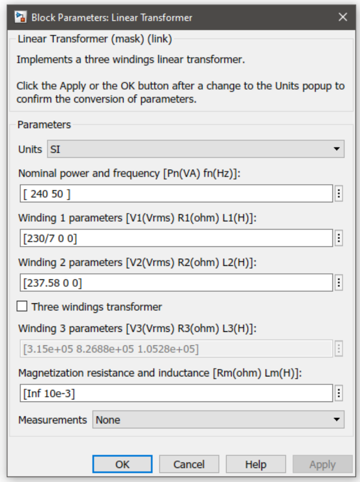

Figure 2: PV Array Specifications

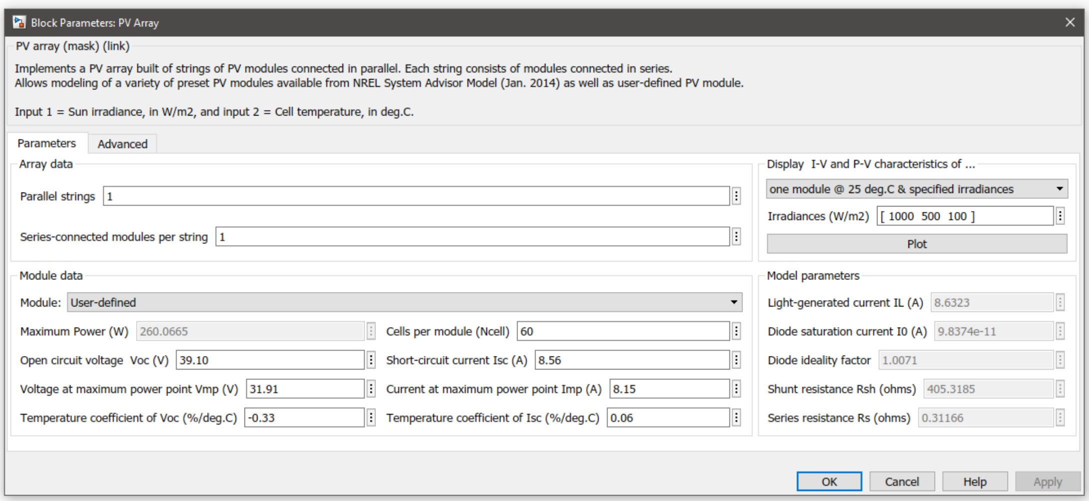

Figure 3: Transformer Specifications

Design Requirements

The following section highlights all the required parameters to formulate a single diode model for simulation based from the Standard Test Condition *(STC)*:

Table 3: Datasheet Values – PV IDSM Design

Parameter:	Specification:
Nominal Temperature (T_C)	$25°C$ or $298°K$
Boltzmann's Constant (k)	$1.38 \times 10^{-23} J/K$
Electron Charge (q)	$1.6 \times 10^{-19} C$
Short-Circuit Current of Cell at $1000 W/m^2$ (k_i)	0.0006

Table 4: Cell Count – PV IDSM Design

Parameter:	Specification:
Total Number of Cells in Series (N_s)	60
Total Number of Cells in Parallel (N_p)	1

PV System Design

The system can be broken down into an initial *PV solar cell array* function or component that is responsible for the solar panel or *PV ISDM* element representing a real-world situation with *solar irradiance* and c*ell temperature*. The *battery bank* operates in conjunction to the *DC Bus* acting as an entire unit that is the *PV – battery charger*. Prior the battery's operation within the system, the *DC-DC* boost (further discussed in the *Discussion* and *Conclusion* section of this investigative report) is designed to operate to the design requirements for the voltage input and output ratings. The integration of the simulated *DC/AC inverter* allows for the appropriate connection from the battery to the *step-up transformer*. This allows for connection to grid or for further filtering to occur (discussed further in the *Discussion* and *Conclusion* section of this report).

Note: The Design for the *single diode model* for simulation is assumed to operate in *Standard Test Condition (STC)*.

The following section highlights the final *PV system* design utilized for the simulations and analysis:

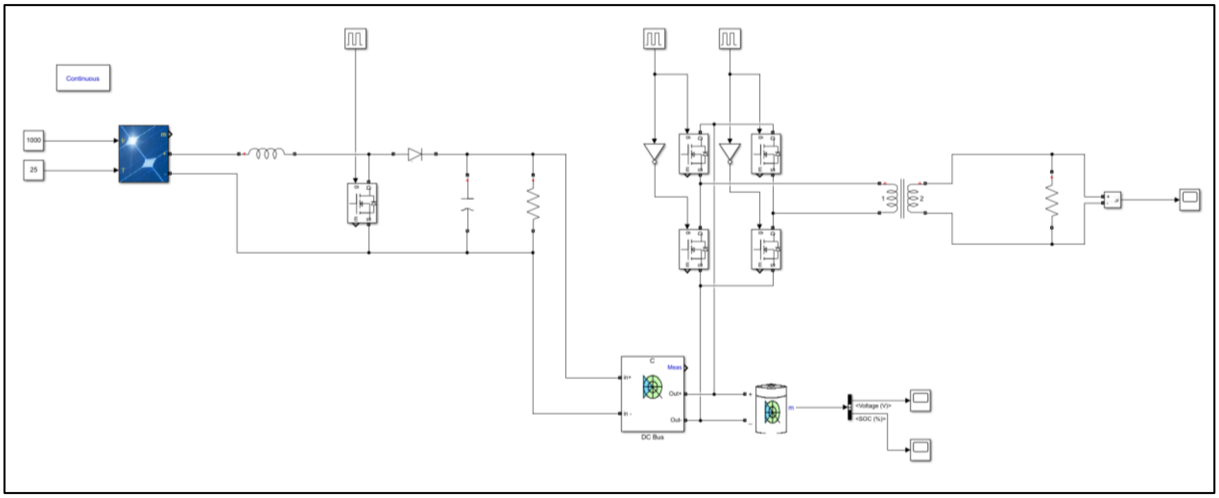

Figure 4: PV System

Note: The following displays the overall parameters utilized in designing the *PV-battery*:

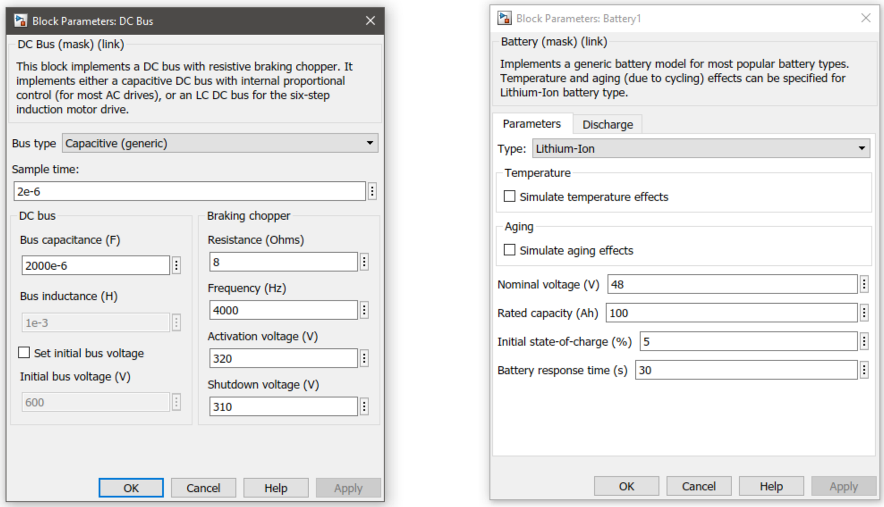

Figure 5: DC Bus & Battery Parameters

Results & Discussion

The battery charge is noted to have reached approximately $47.24V$ as an *RMS* value relatively close to the requirement of $48V$ however, falls short due to the calculation within Simulink outputs and measurement restrictions using tools within the *scope function*. The losses are caused primarily from active components such as the MOSFETS.

The following plot highlights the simulation of the charge from the *PV* generator to the battery:

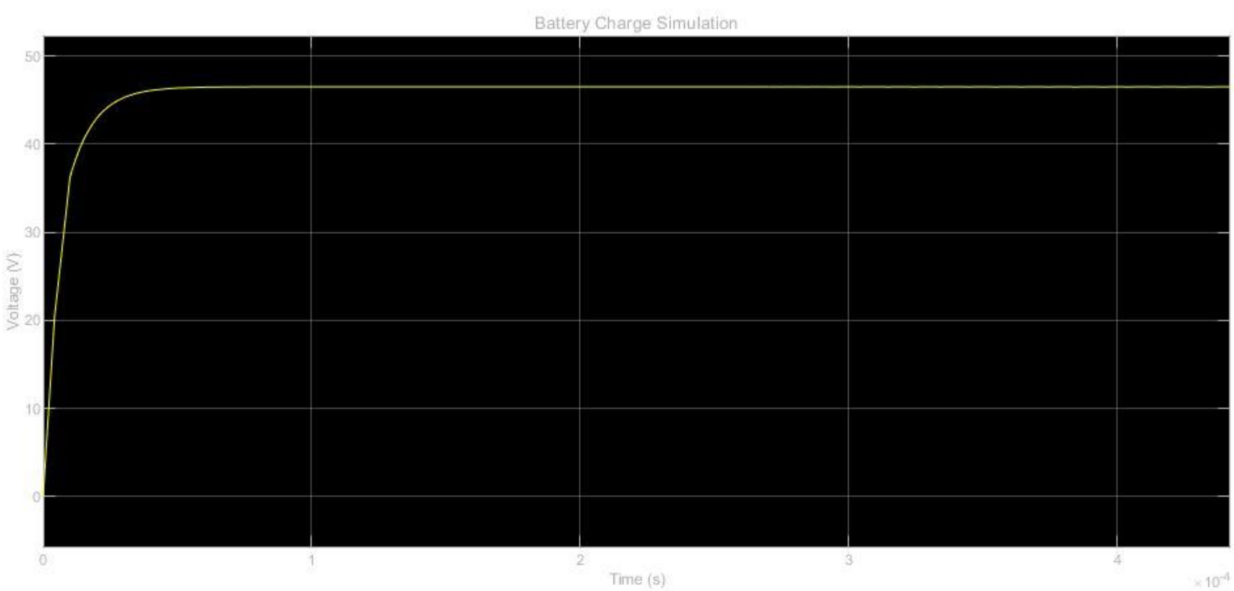

Figure: Battery Charge - PV Generator

The output voltage is measured to be close to the design requirement, highlighted at $221V$ in comparison with the expected $230V$. Possible reasons for the difference in the output voltage not matching the requirement or expected voltage is due to the chosen *duty cycle* and hence, following calculations for the *transformer* specifications (as highlighted for *Final Project Report 1* and in the *Equations and Formulations* section).

The output voltage delivered to the grid is highlighted below:

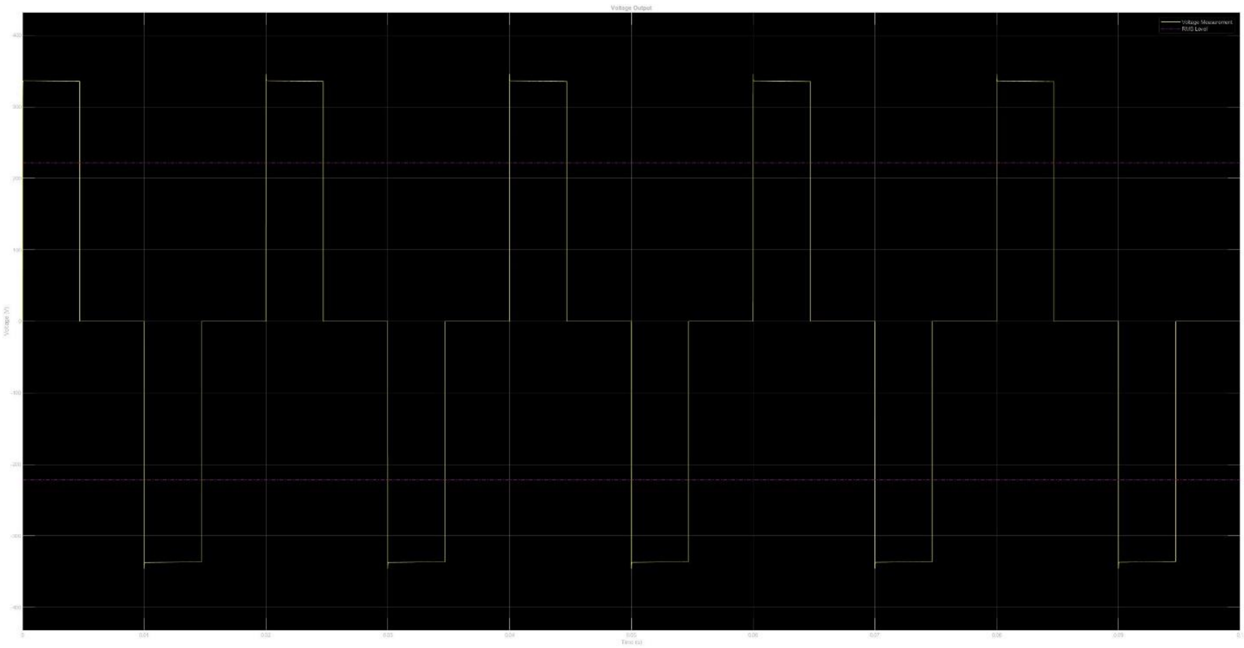

Figure 6: Voltage Output

Conclusion & Recommendation

In summation, the overall system operates in close specification to the design requirements with the appropriate output voltage, SOC (denoted in *Appendix Figure 8)* and battery charge as mentioned. Furthermore, within this project as an overall overview, the buck converter design within the *Final Project Report Part 1*, was replaced with a boost converter due to a simpler design, calculations and furthermore, realistically allows for a more efficient performance.

For future investigations, it is recommended that a capacitor and inductor is utilized at the *AC Loads* section of the system design acting as a filter to create a more consistent voltage output for realistic applications. This was not explored due to its mention being not included from the design requirements.

Appendix

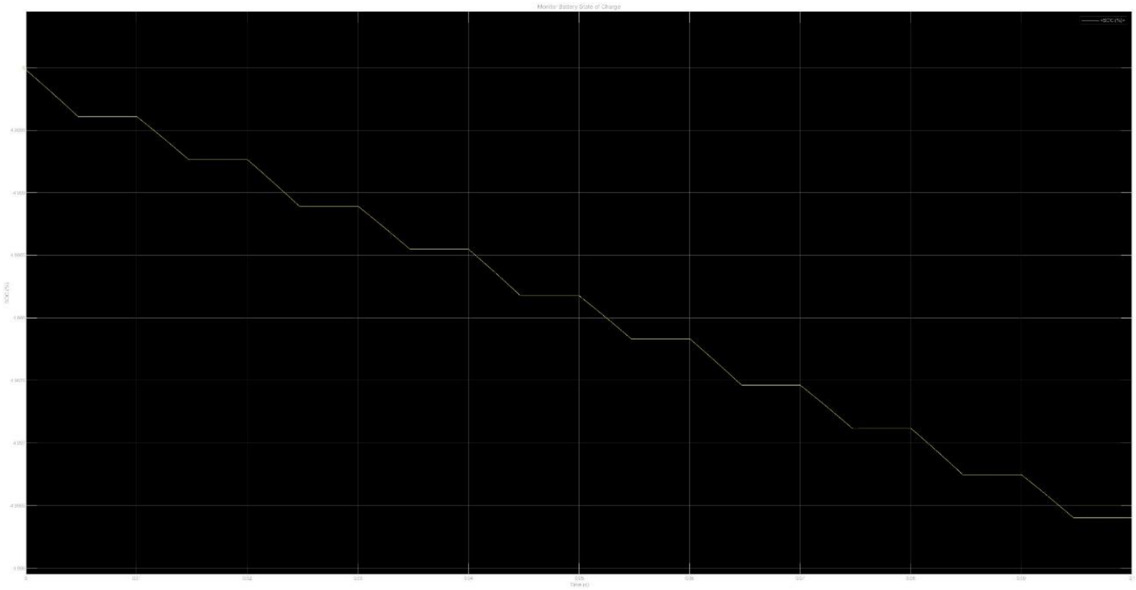

Figure 7: SOC Trace - PV Battery

References

[1] Hart, D. W. (2010). *Power Electronics.* New York: Pearson Education, Inc.

[2] Sydney, U. o. (2020). Power Electronics and Applications. *Final Project ELEC 3204/9204*, 1.