University of Jordan

School of Engineering

Department of Mechatronics Engineering

Power Electronics - 0908421

Semester Project

Project Title: Design and Analysis of a DC Nano-Grid System

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Objectives

- Exploit what we have learned during the Power Electronics Course to design and analyze a DC Nano-Grid System using MATLAB Simulink.
- Research and ask to acquire information that are beyond the course to fully build the project.
- Document, explain and present the what we've learned during our work in the project.

Introduction

Power Electronics is the study of switching electronic circuits control the flow of electrical energy. It is the technology behind switching power supplies, power converters, power inverters, motor drives, and motor soft starters, power electronics play an important role in **energy conservation** and **renewable energy systems**.

Renewable Energy

Simply put, Renewable energy is any form of energy harvested by humans that has unlimited existence in nature.

According to "BP Statistical review of Global energy" [1], adoption of renewable energy sources has drastically increased in the last decade, this change is illustrated in figure (1) below.

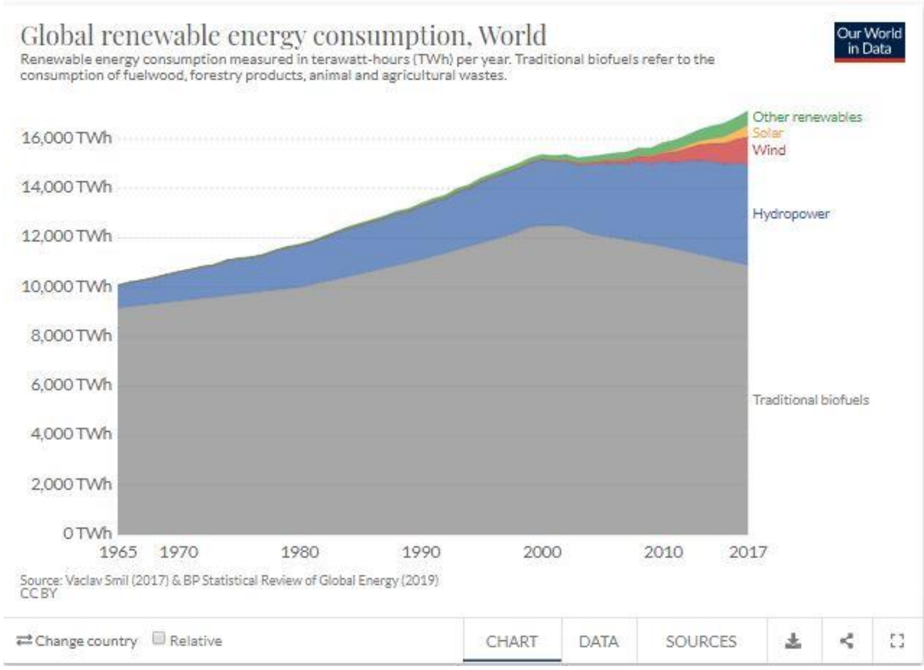

Figure 1. Consumption of Energy Since 1965

This increasing adoption of renewable energy was accompanied by increasing of investments in this field. It is estimated that in 2017, worldwide investments in renewable energy amounted to US$279.8 billion, with China accounting for 45% of global investments. [2]

The main categories of renewable energy sources are:

1- **Wind Energy**
People used to harvest the energy of wind since hundreds of years using traditional wind mills. However, today's wind energy is being harvested by turning a turbine's blades, which feeds an electric generator and produces electricity.

2- **Geothermal Energy**
Due to the slow decay of radioactive particles in rocks at the center of the planet, the earth's core is about as hot as the sun's surface. We harvest this energy by Drilling deep wells to bring very hot underground water to the surface, which is then pumped through a turbine to create electricity.

3- **Solar Energy**
Solar energy is used in many ways; Heating homes, heating water or generating electricity. In this report we'll be focusing on solar energy generated through PV (Photovoltaics) technology, which is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect, a phenomenon studied in physics, photochemistry, and electrochemistry. A photovoltaic system employs solar modules, each comprising several solar cells, which generate electrical power.
In this report, we'll be using PV modules that feeds energy to a load and to charge a battery.

Boost Converter

Boost converter circuit (also known as step-up circuit) is a power electronics circuit that classified as DC to DC converter circuit, if we apply a DC voltage to the input terminals of this circuit, we will obtain an N times of the input voltage value on the output terminals.

The boost converter is a very important component in power electronics, due to the capability of controlling the voltage supply, since the power sources in the various places and applications are fixed, so this is a way to change any DC voltage supply to a suitable one for the various applications in order to maintain it at a specific value.

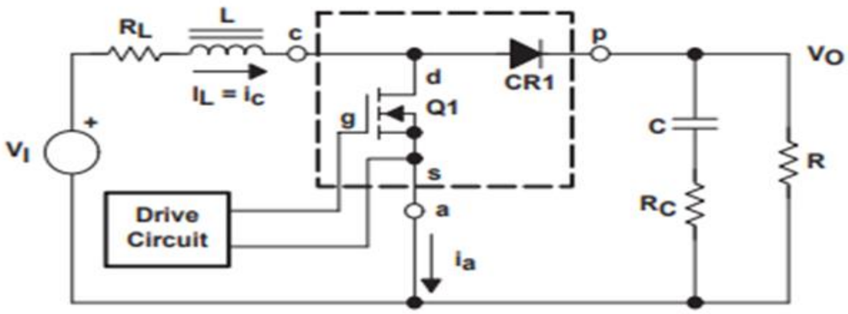

Figure 2. The Wiring Connection of A Boost Converter

Applications for Boost Converter

Boost (step up) converters have a widely used applications such as **Personal, Automotive, Industrial, Communications and Enterprise systems**, these are some applications for the mentioned fields above from Texas Instruments Company:

Personal applications:
TI offers a broad portfolio of boost (step-up) converters with low quiescent current and compact solution size for personal electronics electronic devices powered by one or two-cell alkaline, coin-cell or Li-Ion batteries.

- Automotive applications:

TI offers a broad portfolio of boost (step-up) converters with low quiescent current and compact solution size for personal electronics electronic devices powered by one or two-cell alkaline, coin-cell or Li-Ion batteries.

- Industrial applications:

TI's portfolio of step-up converters offers ultra-low quiescent current, wide input and output voltage ranges, high output current and efficiency, and excellent thermal performance, commonly found in EPOS, smart grid, medical, building automation and factory automation applications.

- Communications applications:

TI's portfolio of step-up DC/DC converters combine low-power consumption, compact solution size and excellent thermal performance for communications equipment such as telecom and wireless infrastructure.

- Enterprise systems applications:

T's portfolio of DC/DC boost converters offer wide input and output voltage ranges, low-power consumption and excellent thermal performance for server, projector, printer and high-performance computing applications.

Nano-Grid System Design

In the Nano-grid system, a basic 1.5 to 3 kW PV system is installed in a small cluster of households within a short radius of each other (ideally 230-250m) and power is distributed to the households from this system. The generation and storage of this system is 48 Volt DC. System has a DC to DC converter and its output is 220 Volt DC. This system has an option of DC (220V) to AC (220V) conversion. The payment method for the consumer is pay per unit energy (ex. Pre-paid meter).

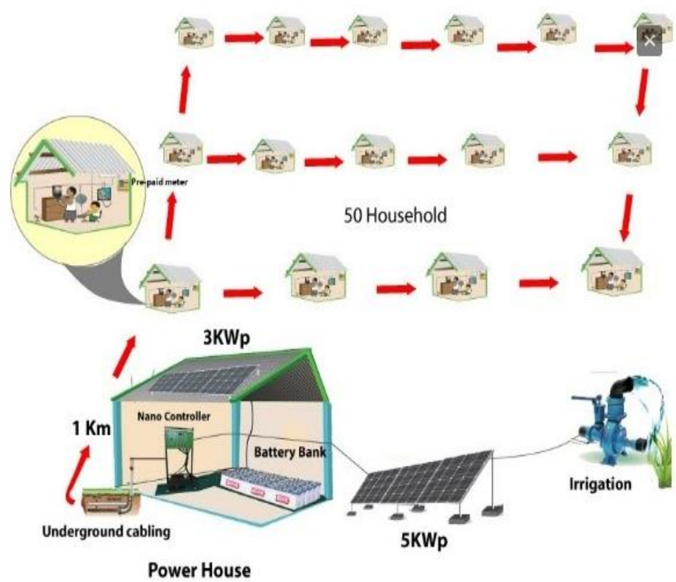

Figure 3. Illustration of a DC Nano-Grid System

Features of Nano Grid

1. Scalable at all levels (DC, High Voltage)
2. Starting load could be small to reduce the cost of installation and then scale up as the load grows
3. Unlike AC grid, Scaling up the generation is simple (just adding in parallel). No synchronization required
4. Any standard load can be used
5. No maintenance is necessary by the end customer
6. Pre-paid meter makes collection significantly easy
7. Supports irrigation pumps for farming.

Analysis and Design of A DC Nano-Grid System

Figure (4) below illustrates the design of a DC Nano-Grid System, it consists of a PV Array with an MPPT algorithm control block, the current from PV Array is then fed to a boost converter, then it feeds both a variable load and a storage battery. Incase the variable load power demand was higher than the supply of the PV Array, the storage battery will also feed the load to provide a sufficient power supply. For this dual function of the battery as a source and a load, we used a Buck-Boost converter.

We’re going explain every part in the system in detail, then we’re going to talk about control methods used to properly control the system, and finally we’ll present further documentation of the MPPT algorithm used, cost forecast of the system in addition to our observations and conclusions.

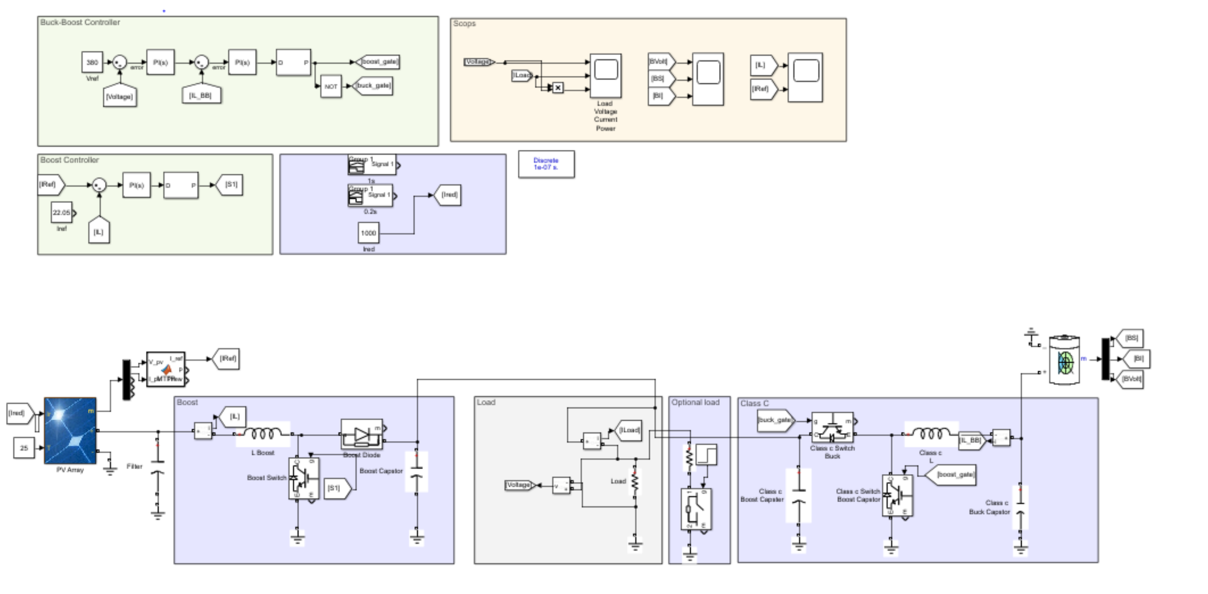

Figure 4. Nano-Grid System Used in This Report

Detailed Description of System Components:

PV Array

Figure (5) shows the PV array used in the system model, this PV array consists three strings, each string is composed of 8 PV modules connected in series.

- Each module has an output of 29V and 7.35A.
- $Total\ Power\ of\ PV\ Array = (29 * 8) * (7.35 * 3) = 5.115\ kW$
- Thus, $V_{max} = 232V$
- We chose the value of Irradiance to be

$$1kW/_{m^2}$$

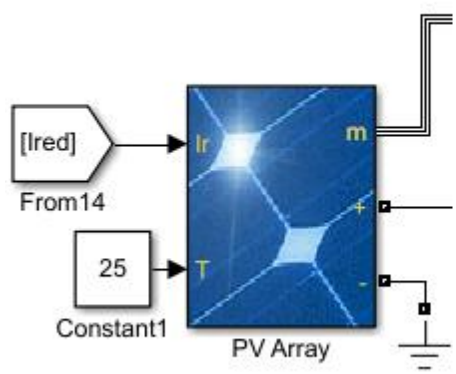

Figure 5.PV Array Used in The System

- Constant temperature of 25˚C.
- $V_{output} = 380V$

Boost Converter

Figure (6) illustrates the boost converter used in the system, its design parameters and components values are based on the following calculations:

Firstly, the Duty cycle is calculated as follows:

$$Vout = \frac{Vi}{1-D}$$

$$380 = \frac{232}{1-D}$$

$$D = 0.3895$$

Then we find $Imax$:

$$Imax = \frac{Pmax}{Vmax}$$

$$Imax = \frac{5115.6}{232}$$

$$Imax = 22.05A$$

$$\Delta iL = 0.1 * Imax$$

$$\Delta iL = 2.205A$$

We find R load:

$$Rload = \frac{P}{Vo^2}$$

$$Rload = 28.88\ \Omega$$

Given switching frequency is 20kHz, we can find the values of the capacitor and the inductor as follows:

$$\frac{\Delta Vo}{Vo} = \frac{D}{CfR} 0.005 = \frac{0.3895}{C \times 50 \times 28.88}$$

$$C = 1.34x10^{-4}$$

$$\Delta iL = \frac{D \times Vi}{f * L}$$

$$2.205 = \frac{0.3895 \times 232}{50 * L}$$

$$L = 2.05x10^{-3}$$

The transfer Function of a Boost Converter is given as:

Transfer function of $\hat{\imath}_L$ **loop** [3]

$$\frac{\hat{\imath}_L(s)}{\hat{d}(s)} = \frac{CV_O s + 2(1-D)Il}{LCs^2 + \frac{L}{R}s + (1-D)^2}$$

Transfer function of $\boldsymbol{\hat{V}_O}$ loop [3]

$$\frac{\hat{V}_O(s)}{\hat{\imath}_L(s)} = \frac{(1-D)V_O - LI_L s}{CV_O s + 2I_O}$$

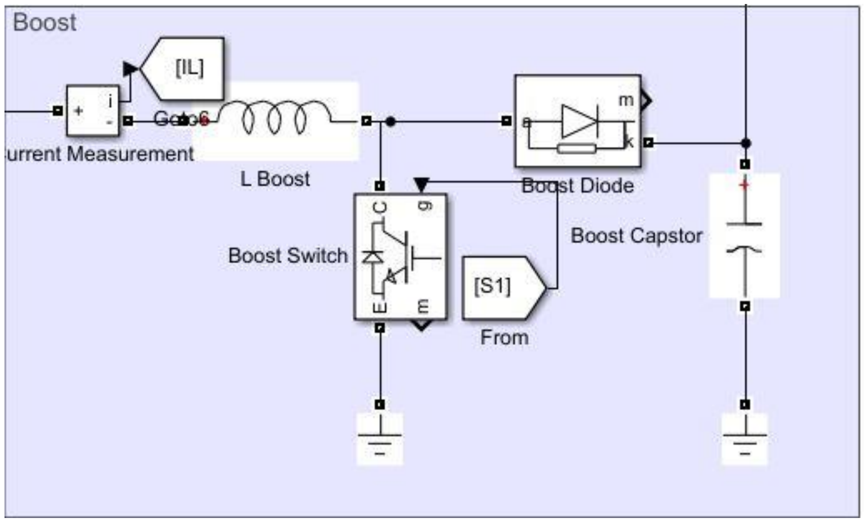

Figure 6. Boost Converter Design

Load

Figure (7) illustrates the load used in this analysis, in consists of a primary load with 4 kW, during which the PV array supplies this load and charges the battery with the excess power.

In order to test the charge/discharge characteristic of the Buck-Boost converter, an optional load of 2 kW was added in parallel, the power of the PV array was insufficient for both loads so the battery acted as a source supplying the load along the PV array.

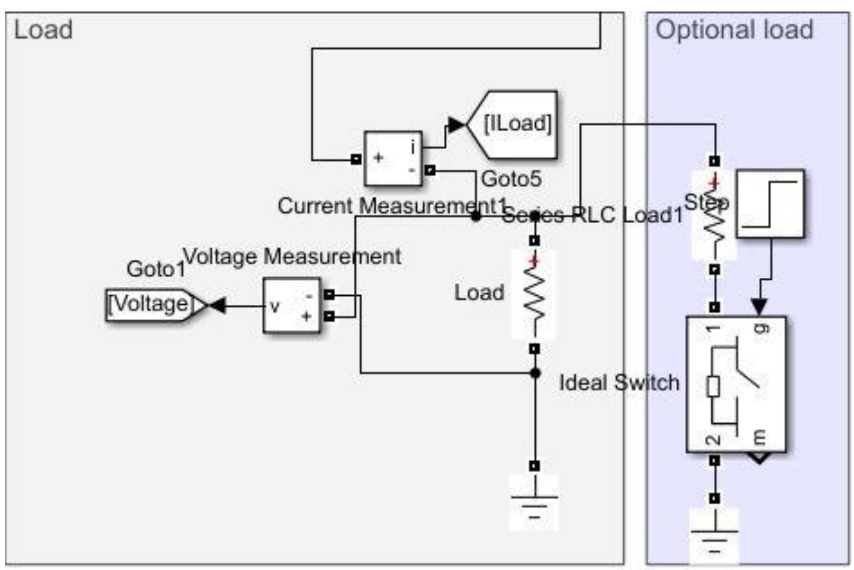

Figure 7. The primary and Secondary Loads in The Model

Buck-Boost Converter

Figure (8) illustrates the design of the Buck-Boost Converter, it’s connected in parallel to the load, and depending on the power consumption of the load, it will act as either a buck converter from the PV array to the battery or as a boost converter from the battery to the load.

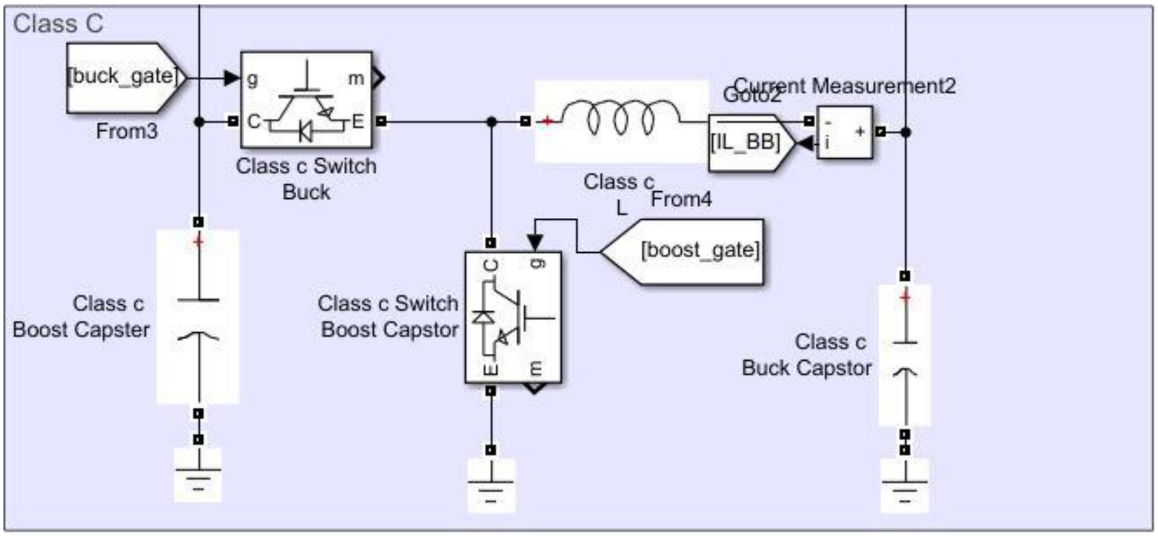

Figure 8. Buck-Boost Converter Design

Battery

Figure (9) illustrates the battery module used in the model. The battery has a nominal voltage of 232 V and 60% initially charged.

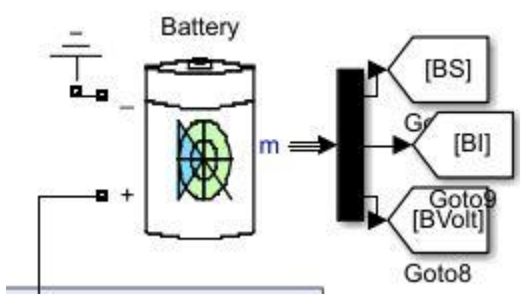

Figure 9. Battery Module Used in The Model

Design and Tuning of System Controllers:

The design of system's components was achieved, but a control system was needed to orchestrate the various components and achieve the desired behavior of the system.

In our system, we used **3PI controllers** as it can be seen in the model of the system above. two PI controller for the inductor current loops in Boost Converter and in Class-C Converter and the third one for the output voltage controlling

These controllers are needed to keep track of the output voltage generated by the circuit in and out of the Battery Bank, and the current flow in the inductor of Boost Converter and Class-C converter.

With the use of Transfer Functions of the Boost Converter stated in the section above, we used ***Auto-tuning*** functionality in MATLAB Simulink for the PI Controllers in the Frequency Domain and found that the best frequency for PI controller which controls the output voltage equals 477.5 Hz; AND the best frequency for PI controller which control **IL=2000Hz**

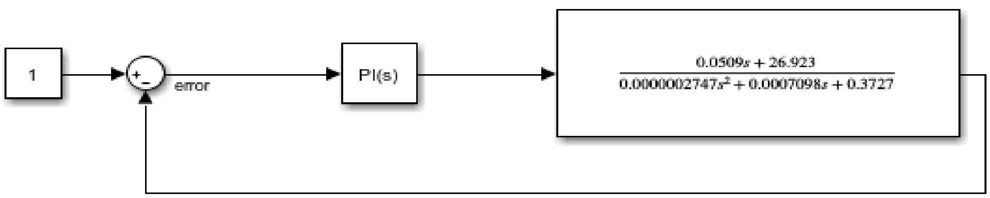

Figure 10. Transfer Function of Boost Converter to Control the Current

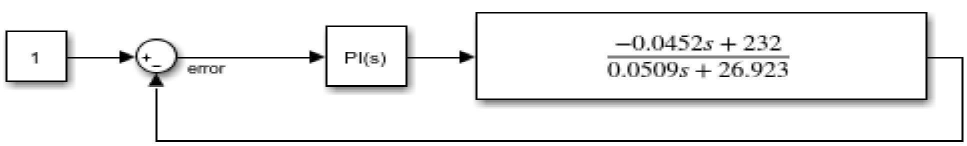

Figure 11. Transfer Function of Type C Converter to Control the Voltage Across the Load

The tuning process of the PI controllers was as follows:

- Having the switching frequency of $f_s = 20\ kHz$

Taking the $\frac{\hat{\imath}_L(s)}{\hat{d}(s)} = G_1 \rightarrow f_{x1} = 10\% f_s = 2000\ Hz$, so we Tune at the frequency of $w = 2000 * 2\pi = 12566\ rad/s$ (Bandwidth), within the 60degree phase margin.

In Boost controller P= **0.0530850962948881** **I= 546.139318598966**

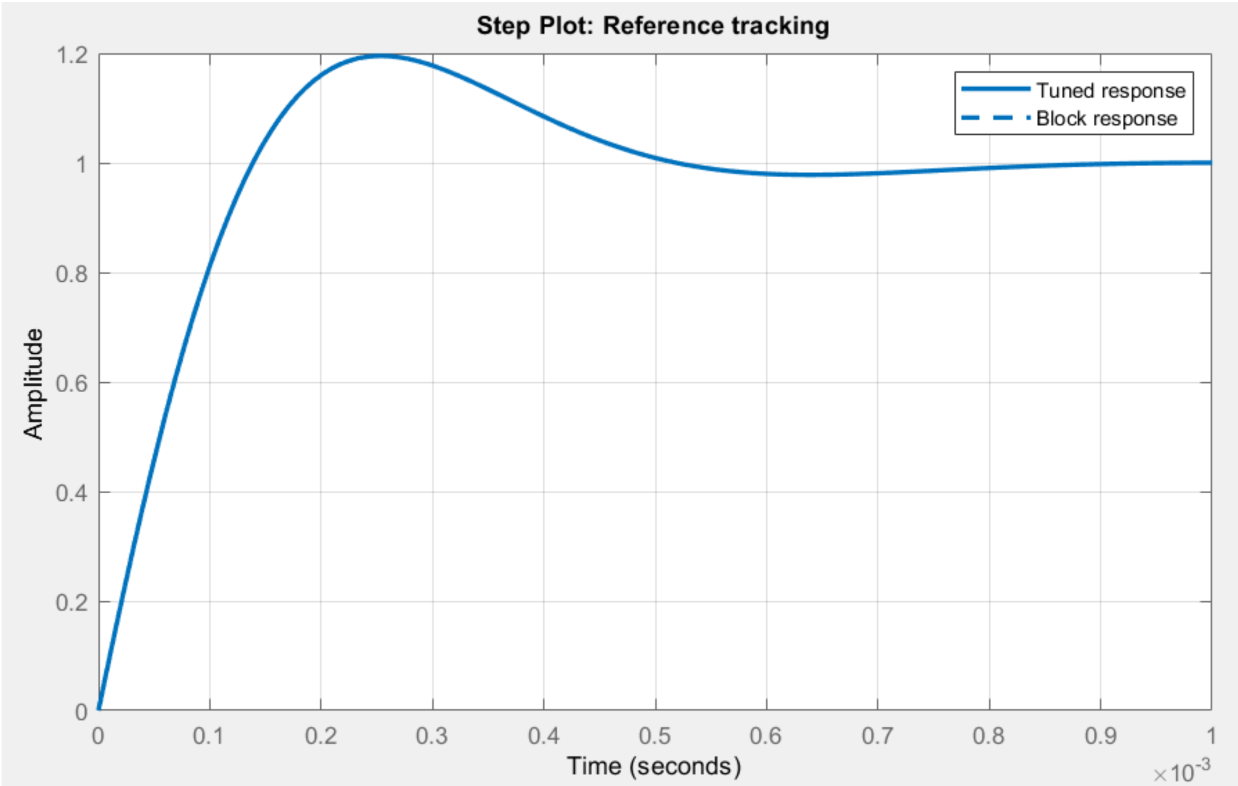

Figure 12.Tuning the PI controller for Inductor Current Loop

- In Class C Controller **P= 0.551235502483614** **I= 309.576888395126**
  - Having the switching frequency of $f_s = 20\ kHz$

Taking the $\frac{dv(s)}{\hat{d}(s)} = G_2 \rightarrow f_{x2} = 2.3\% f_S = 477.5\ Hz$, so we Tune at the frequency of $w = 2889 rad/s$ (Bandwidth), within the 60degree phase margin.

Figure 13.Tuning the PI controller for Inductor Voltage Loop

The tuned Boost Controller was used to eliminate the difference between the reference current obtained from the MPPT controller (explained later in the report) and the current drawn from the PV array, the signal from the controller is then fed to the PWM module to change the duty ratio accordingly.

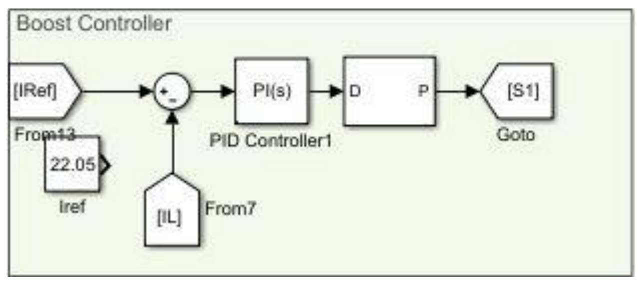

Figure 14. Boost Controller Block Diagram

The tuned Type C Controller was used to maintain the voltage across the load at 380V while also controlling the current going through the inductor. In order to achieve this, we used a tuning method referred to as ***Cascaded Controllers*** as shown in Figure (15).

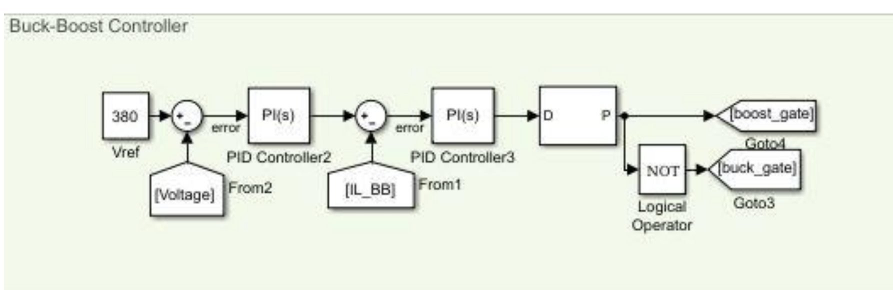

Figure 15. Block Diagram of a Type C Controller

The input Voltage to the Boost Converter, as required by the user is supposed to be 232V DC. Since we are working with Power Systems, the response has a little ripple around the value of 232 V equal to 0.002.

The output Voltage of the Boost converter is to be maintained at **380 V** DC with the use of Class-C converter, which contains a battery bank for storing and then generating power to the circuit in case of power shortage (less than 5kW). The response is shown in **Figure (16)** below.

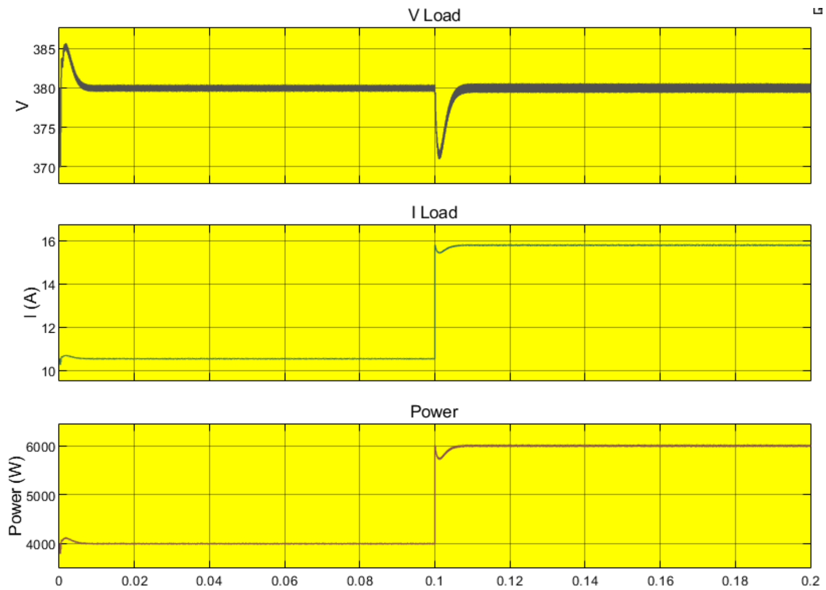

Figure 16 – load Voltage, Load Current & Output Power

Figure (17) shows the behavior of the battery during both cases charge and discharge, in the first half, the load consumes 4kW and the battery is being charged by the PV array. In the second half the load consumes 6kW and the battery discharges to supply the additional power.

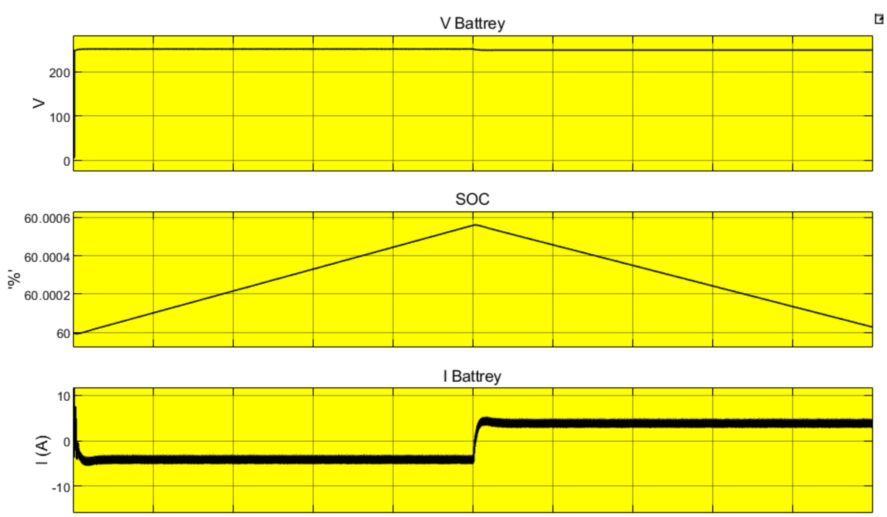

Figure 17. Battery Behavior During Charge and Discharge States

MPPT CONTROLLER

In order to optimize the system and obtain the best efficiency, an MPPT controller was used. MPPT stands for Maximum Power Point Tracker. It is typically a DC to DC converter circuit used in most modern PV inverters. Its functionality is to max-out the available energy from the strings of solar panels at any time while in use.

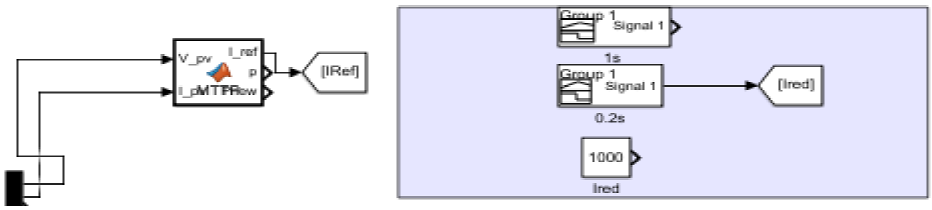

Figure 18. MPPT Block Diagram

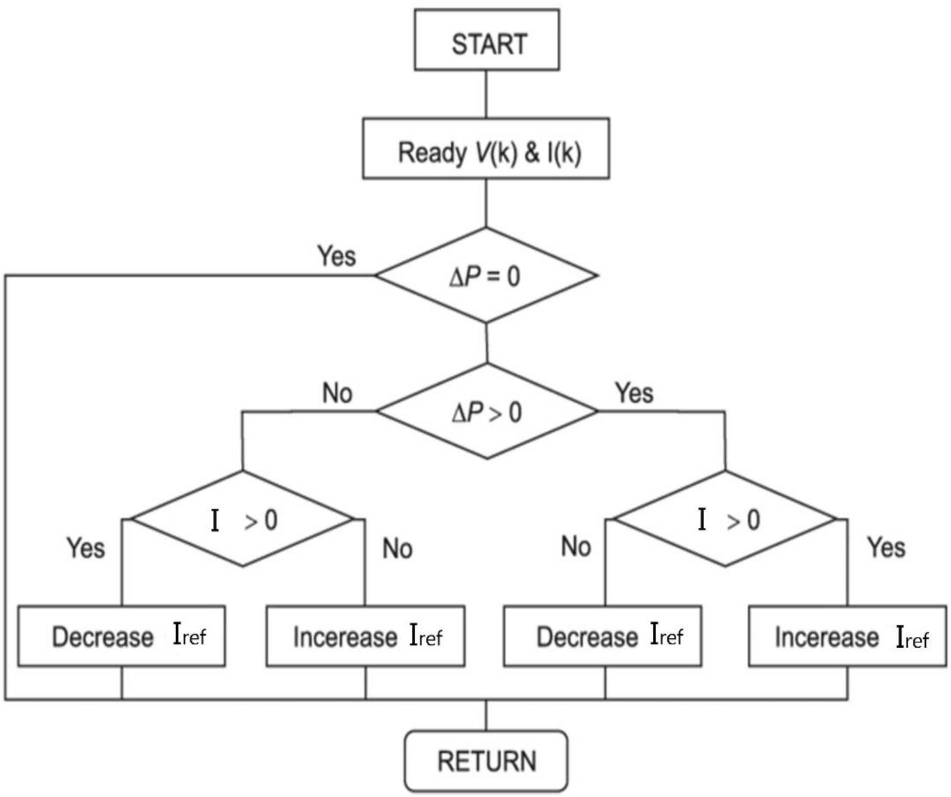

Figure 19. Flow Chart Illustrating the MPPT Algorithm [4]

```
function [I_ref,p,Pnew] =MTTP(V_pv,I_pv)
persistent P_max Ir
d=0.1;
if isempty(P_max)
P_max=1000;
Ir=3;
end
Pnew=V_pv*I_pv;
if ( Pnew==P_max)
    I_ref=Ir;

else
    if(P_max<Pnew)
        P_max=Pnew;
        if (I_pv>Ir)
            Ir=Ir-d;
        else
            Ir=Ir+d;
        end
    else
        if (I_pv>Ir)
            Ir=Ir+d;
        else
            Ir=Ir-d;
        end
    end
I_ref=Ir;
end
p=P_max;
```

Figure 20. MPPT Algorithm Used [4]

We assumed Constant value of irradiance, Ired =1kW/m^2 ,The Optimal value for the current and the actual output current are shown in figure (21). It's observed that the optimal current equals 22.05A

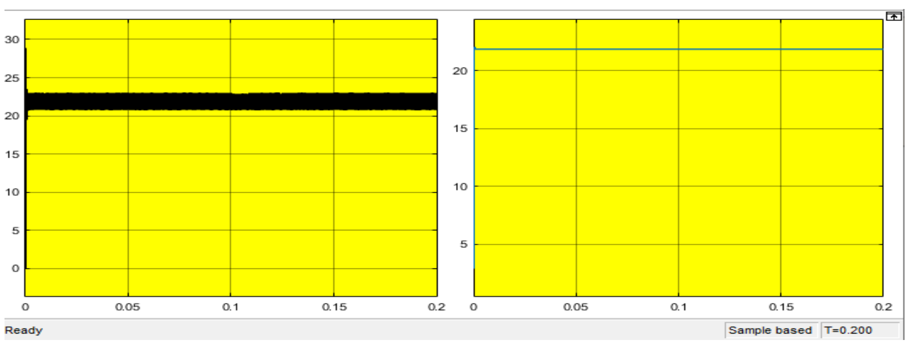

Figure 21. Desired Value of Current (right) and the Actual Output Current (left)

Then a step input was applied in order to test the behaviour of the MPPT controller; as shown in figure (22-25), the current is manipulated in order to achieve the maximum power.

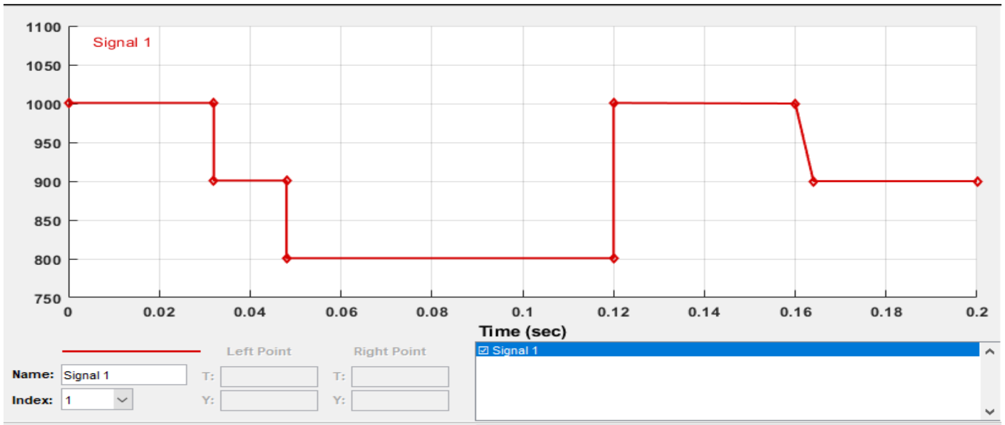

Figure 22. Manually Change the Irradiance to Test the MPPT Algorithm

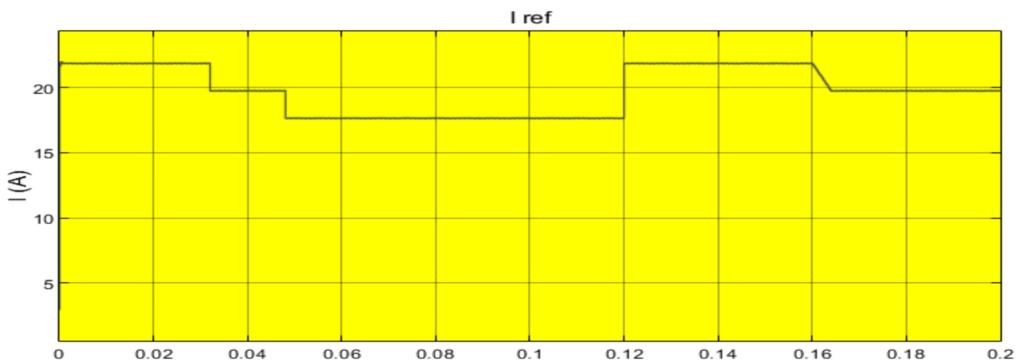

Figure 23. The Reference Current Changes to Achieve Maximum Power

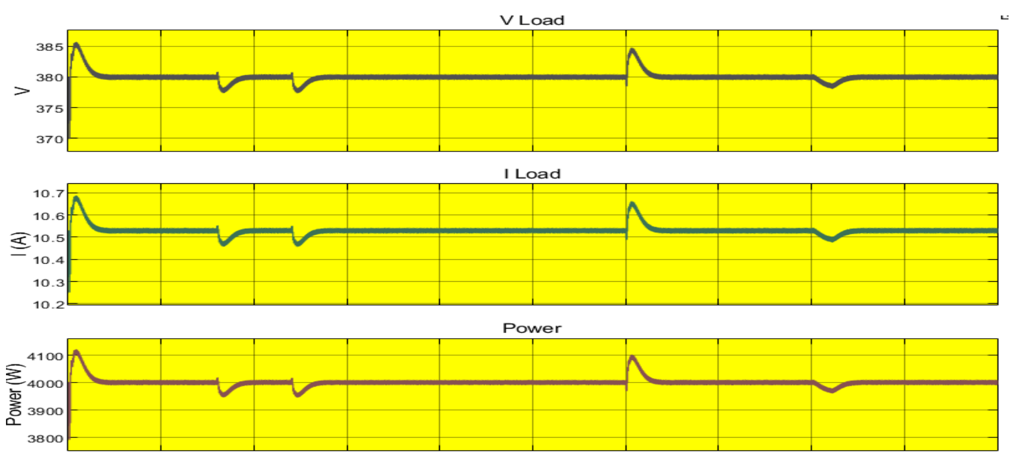

Figure 24. Load Response to the Change in Irradiance Value

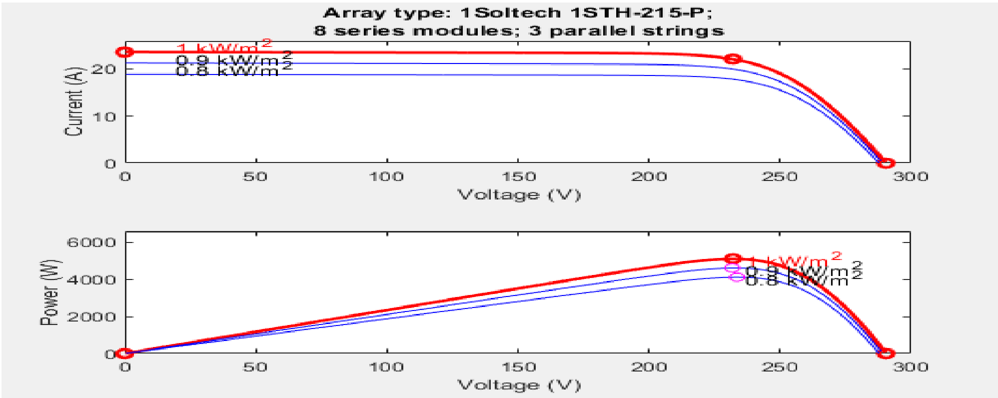

Figure 25. I-V and P-V Characteristics Curves for the PV Array

Conclusion:

In this report, renewable energy types and adoption rates over time were introduced. Then a DC Nano-Grid System fed by PV Array of cells was designed and simulated using MATLAB, PID controllers were used to get the desired behavior of the system. In addition to applying MPPT algorithm to increase the efficiency of the system.

The following are conclusive points of our observations and future development of this project:

- The field of renewable energy is on the rise, and the investments in this field are drastically increasing.
- There are multitude of ways to control and optimize power electronics systems, each with their own set of advantages and disadvantages.
- Using MPPT algorithm control can drastically improve the efficiency of the system.

References

[1] B. Dudley, "BP Magazine," 2019. [Online]. Available: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

[2] E. Union, "Frankfurt School – UNEP Collaborating Centre for Climate & Sustainable Energy Finance (2018).," 2018. [Online]. Available: https://europa.eu/capacity4dev/unep/documents/global-trends-renewable-energy-investment-2018.

[3] D. A. Kumar, "Small Signal Modelling of Boost Converter," [Online]. Available: https://www.slideshare.net/divyasri0008/ssmboost?fbclid=IwAR0FcNOGNOK-COD-AoMvSYXEyu5DCGWhfSsKFcR1waXmAD_JqIgv5rQLtXo.

[4] I. The MathWorks, "mathworks," [Online]. Available: https://www.mathworks.com/solutions/power-electronics-control/mppt-algorithm.html. [Accessed December 2019].