



VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

ELEKTRONIKOS FAKULTETAS

ELEKTROS INŽINERIJOS KATEDRA

Dovydas Gadliauskas

MPPT įkrovimo įrenginio mikroinverteriui kūrimas ir tyrimas
Development and Investigation of MPPT Charging Device for Microinverter

Baigiamasis magistro darbas

Elektros energetikos sistemų inžinerijos studijų programa, valstybinis kodas 6211EX049

Atsinaujinančiosios elektros energetikos inžinerijos specializacija

Elektros inžinerijos studijų kryptis

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Uždaviniai: 1. Sukurti matematinį MPPT modelį; 2. Palyginti įkroviklio efektyvumą su sinchroniniu ir asinchroniniu BUCK topologijos keitikliu 3. Palyginti MPPT veikimą taikant skirtingus valdymo metodus 4. Ištirti skirtingų baterijų panaudojimą.

Brėžiniai: Mateikti matematinio modelio principines schemas.

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Sukurti MPPT matematinį modelį. Palyginkite įkroviklio efektyvumą su sinchroniniu ir asinchroniniu BUCK topologijos keitikliu. Palyginkite MPPT veikimą taikant skirtingus keitiklio valdymo metodus. Ištirti skirtingų baterijų panaudojimą.

Introduction: Sukurti baterijų įkrovimo įrenginio matematinį modelį, ištirti jo veikimą esant skirtingiems įėjimo įtampos scenarijais.

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Design - research part.: Sukurti MPPT matematinį modelį. Palyginkite įkroviklio efektyvumą su sinchroniniu ir asinchroniniu BUCK topologijos keitikliu. Palyginkite MPPT veikimą taikant skirtingus keitiklio valdymo metodus. Ištirti skirtingų baterijų panaudojimą.

Explanatory letter. Drawings.: Pateikti matematinio modelio principines schemas

Analytical part.: Apibendrinti gautus rezultatus ir pateikti darbo rezultatų išvadas

Academic Supervisor Associated Professor Audrius Grainys

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Baigiamojo darbo tikslas yra ištirti saulės panelės MPPT įkrovimo įrenginio veikimą. Veikimo tyrimas atliekamas pasitelkiant simuliacinius modelius ir „MatLab“ ir „Qspice“ aplinkoje. Tyrimą sudaro įrenginio veikimo palyginimas, keičiant elektronikos komponentus bei kraunamos baterijos nominalią įtampą. Taip pat tiriamas įrenginio efektyvumas, naudojant skirtingus valdymo algoritmus. Tyrimo rezultatai parodė, koks MPPT algoritmas buvo optimalus, kokios talpos kondensatoriai sumažina pereinamųjų procesų trukmę, puslaidininkių poveikį išėjimo galios efektyvumui ir kokios nominalios įtampos baterija yra optimali efektyviam ir saugiai naudoti. Remiantis tiriamu modeliu galima kurti įrenginį ir pritaikyti mažos galios (1kW) saulės elektrinėje, kaip mikrokeitiklio komponentą baterijai krauti. Darbą sudaro 7 dalys: literatūros aptarimas, įvadas, analitinė dalis, tiramoji dalis, išvados ir siūlymai, literatūros sąrašas, priedai. Darbo apimtis – 57 p. teksto be priedų, 57 iliustr., 5 lent., 51 bibliografinis šaltinis. Atskirai pridedami darbo priedai.											
Prasminiai žodžiai: Saulės modulis, nuolatinės įtampos keitiklis, MPPT algoritmas, baterija, saulės intensyvumas, kondensatorius, tranzistorius, diodas.											

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Annotation

The objective of the thesis is to investigate the behavior of solar MPPT charger. The investigation is accomplished by building simulations in MatLab and qSpice environment. The research consists of behavior comparison when components as well as the nominal battery voltage is changed. Different MPPT algorithms are used in order to compare the efficiency of the device. The results show what MPPT algorithm is the most optimal, what capacitors reduce time span of transient processes, different semiconductor impact on efficiency and optimal nominal voltage of the battery for effective and safe operation of the charger. It is possible to continue the investigation by designing and building a charger prototype which could be used in small scale (1kW) solar power plant as a part of the microinverter and would charge the external battery.

The work consists of 7 parts: literature review, introduction, analytical part, research part, conclusions, bibliography, addendum.

Work size: 57 pages without bibliography and addendum, 57 images, 5 tables, 51 bibliography sources.

Keywords: Solar panel, DC/DC converter, MPPT algorithm, battery, irradiance, capacitor, transistor, diode.

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LITERATURE REVIEW

Before I began my development and investigation work I read some literature related to MPPT charging. Gained knowledge is a vital theoretical part of this work and will help to understand the usefulness of MPPT, the methodology of realizing MPPT, potential implementation fields, and obstacles that we might run into during our work.

Since the target of this work is photovoltaic systems, it is necessary to understand how solar energy is converted into electricity. Articles [1], [2], [3], [4] and [5] provide some useful general information about photovoltaic elements and arrays. These articles are focused on the mathematical modeling of solar panels and solar panel arrays — this information is especially useful when there is a need to deeply understand mathematical representations of photovoltaics. [6] and [7] provide more detailed information about alternative models of solar panels by explaining what are the specific elements in the model.

Another topic is closely related to photovoltaics as well but it is focused on the efficiency of different types of solar panels in different conditions. Some simplified general information is provided in article [8]. Other studied sources are more focused on specific types of solar panels. For example, research in articles [9], and [10] is focused on bifacial solar panels. [11] provides more general information, while the previous two are more detailed comparative pieces of research with proposed solutions. Articles [12], [13] and [14] were used in order to clear differences between different types of silicon material in photovoltaic elements and show which material-based solar panel is more effective and in which circumstances one is better than the other.

Efficiency is not only dependent on the solar panel itself but also on operation control. Constant maximum power point tracking is necessary in order to use photovoltaics efficiently. Articles [15], [16], [17] and [18] were used to understand what the MPPT is. The [16] is related to the research of PV systems with battery charging but it reveals some important reasons why MPPT and PWM are necessary for such systems. The other three articles are purely about different MPPT implemen-

tations and comparative studies of different algorithms. Sources [19] and [20] explain the main differences between PWM and MPPT. Going deeper into MPPT a new problem occurs. This problem is related to partial shading and global MPP tracking. The problem is explained in article [21]. Article [22] helps to understand why traditional MPPT methods do not work and Articles [23] and [24] briefly reveal recent innovative global MPPT control techniques.

There are also a few sources that help to understand several advanced MPPT techniques such as fuzzy logic ([25], [26], [27]) and neural networks ([28], [29], [30] and [31] where MPPT problem and possible neural network solution is described in detail).

Another topic is DC-DC converters. In order to understand what is happening in DC-DC converters a few books have been used ([32], [33]). A couple of books were also used to better understand how pulse width modulation works ([34], [35]).

A lot of attention was given to MPPT battery charging solutions. Different techniques from analog-based control to PID and P&O are introduced ([36], [37], [38], [39], [40], [41], [42], [43]). A few articles like ([44]) are more comparative.

INTRODUCTION

In recent years the power sector has experienced massive expansion in renewable energy. Countries all around the globe are competing in renewable energy production by building solar and wind power plants. Other than that, homeowners are encouraged to install small solar power plants at home to reduce electricity costs and greenhouse gas emissions from heating. As solar technology develops new ways to improve renewable energy efficiency are about to be discovered. One of the possible ways is to implement a Maximum power point tracking algorithm into the system to extract the most power from solar arrays in certain environmental conditions.

In a couple of years the energy storage sector development has begun opening new possibilities for many companies and enthusiasts to experiment and tinker with. The topic of energy storage is still relatively fresh and new solutions keep appearing as many solar product manufacturers develop their own hardware and algorithms to control the system. Many of these solutions are not private-user-oriented though. This leaves a lot of space to work with private home solar battery systems.

As the topic is not widely explored the question, of what is an optimal solution for private house small-scale solar plants with energy storage, is still open. The choice between inverters and microinverters is open as well. What configuration of switching power supply topologies is the best is also a matter of discovery yet to come.

The objective of this research is to give some insight into small-scale solar power plants with battery-charging functionality. The results can provide additional information about switching converters, different MPPT tracking techniques, and their advantages and disadvantages. Most importantly, a solution for domestic solar battery chargers could be proposed. This charger could be further developed and integrated into a small-scale DC-AC interface (the microinverter) and a new innovative, efficient, and affordable product would appear in the market.

The proposed MPPT solar charger was simulated using software such as MATLAB Simulink and QSpice. This will allow us to safely investigate how the device works under stress without damaging actual equipment. The model will allow easy implementation and comparison of different MPPT algorithms, and various environment conditions. Easy comparison between different components will be possible as well.

The Objective: Analyze the BUCK converter in the MPPT solar charging device at the hardware and firmware level.

Tasks:

1. Create a mathematical MPPT model.
2. Compare the efficiency of the charger with Synchronous and Asynchronous buck converter.
3. Compare MPPT with feedback of voltage and current and voltage only.
4. Analyze the behavior of the solar charger with batteries of different nominal voltages.

1. LITERATURE ANALYSIS

1.1. WORKING PRINCIPLES OF PHOTOVOLTAIC ELEMENT

Photovoltaic solar panels convert solar energy into electricity with the use of various semiconductor materials infused into silicon crystal [1]. When a photon reaches the surface of a panel it can give its kinetic energy to an electron and thus the electron can get separated and move along the circuit in the lower part of the solar panel [39]. In order to better understand how photovoltaic elements work it is useful to analyze the equivalent PV circuit.

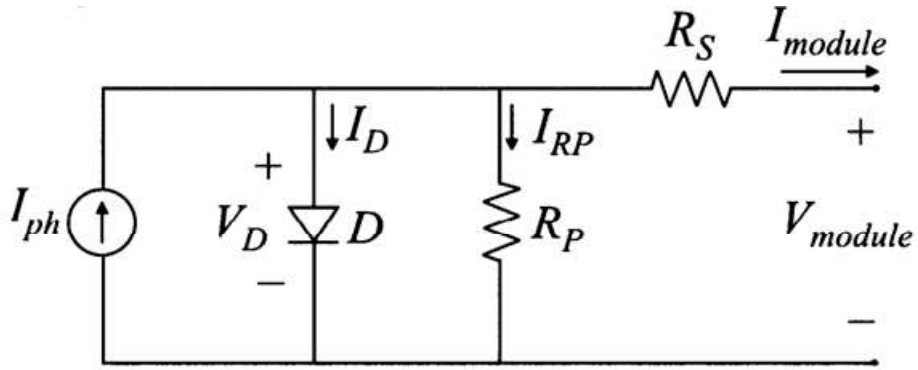


Figure 1.1: The alternative circuit for photovoltaic element [2].

In this model, a Photovoltaic element consists of four main elements: a current source I_{ph} which represents the current generated by absorbed photons, the parallel or shunt resistance R_P , metallic contact resistance R_S and a diode which represents the p-n junction effect [2]. Sometimes there are two diodes inserted in parallel as it is shown in the article [3] but for simplicity, in this work, only one will be carried.

1.1.1. Mathematical modeling

If we apply Kirchhoff's law we can find the output current (I_{module} in the equivalent circuit):

$$I_{module} = I_{ph} - I_D - I_{RP} \quad (1.1)$$

Additional parameters are:

I_{ph} — Photo-current;

I_D — Diode current;

I_{RP} — Parallel current.

In this work, it is not that important to dive deep into the mathematics behind photovoltaic elements but it is necessary to know how complex solar panel actually is. Thus it would be useful to expand the equation 1.1:

$$I_{module} = \frac{S}{S_{ref}} * \left[1 + u_I(T - T_{ref}) * I_{module}^{ref} \right] - I_0^{ref} * \left[\frac{T}{T_{ref}} \right]^3 * \left[e^{\frac{V_{module} + R_S * I_{module}}{A * V_T}} - 1 \right] * e^{\frac{n_S * E_G}{A}} \left[\frac{1}{V_T} - \frac{1}{V_T^{ref}} \right] - \frac{V_{module} + R_S * I_{module}}{R_P} \quad (1.2)$$

This equation can be slightly simplified in order to see the most important parameters and the result would look like this:

$$I = I_{ph} - I_0 * \left[e^{\frac{q(V + R_S I)}{AKT}} - 1 \right] - \frac{V + R_S I}{R_{sh}} \quad (1.3)$$

Power generation in PV panels depends on various parameters such as irradiance, temperature, semiconductor properties, etc [2]. After giving values to these parameters it is possible to plot the characteristics of solar panels.

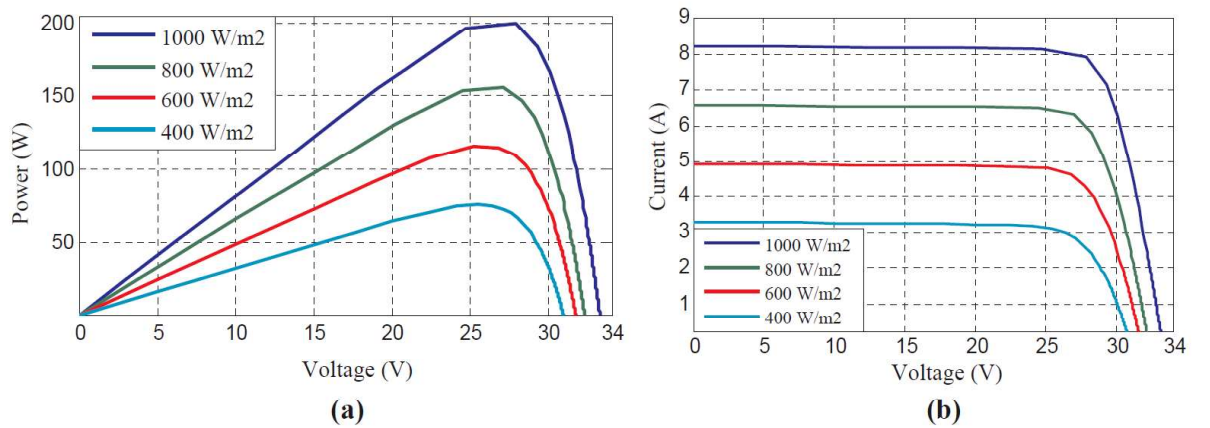


Figure 1.2: P-V curves (a) and I-V curves (b) on different solar irradiance [38].

As it is visible in **figure 1.2** after passing a voltage threshold current starts dropping and as a result, less power is delivered to the output. This phenomenon makes the task of extracting the

maximum amount of energy more complicated since it is important to find the voltage point where the current is the highest.

1.1.2. Reasons of power loss

The equation 1.3 has five most important parameters that can determine the output current of a solar cell: I_{ph} - photogenerated current; I_S - saturated current; A - diode quality factor; R_{sh} - shunt resistance; R_S - cell series resistance.

The photogenerated current is generated by light and is equal to the short circuit of the cell [4]. The saturated current is dependent on material properties and p-n junction configurations better known as diode quality factor A [4] which in this case determines the quality of the solar cell [45]. The relation between the two parameters is derived from the Shockley equation [5]:

$$I_S = Ae^{-\frac{E_g}{kT}} \quad (1.4)$$

The E_g is the semiconductors energy gap, T is temperature and k is the Boltzmann constant. The shunt resistance provides an alternative path for light-generated current. The lower the shunt resistance, the higher the energy losses [6].

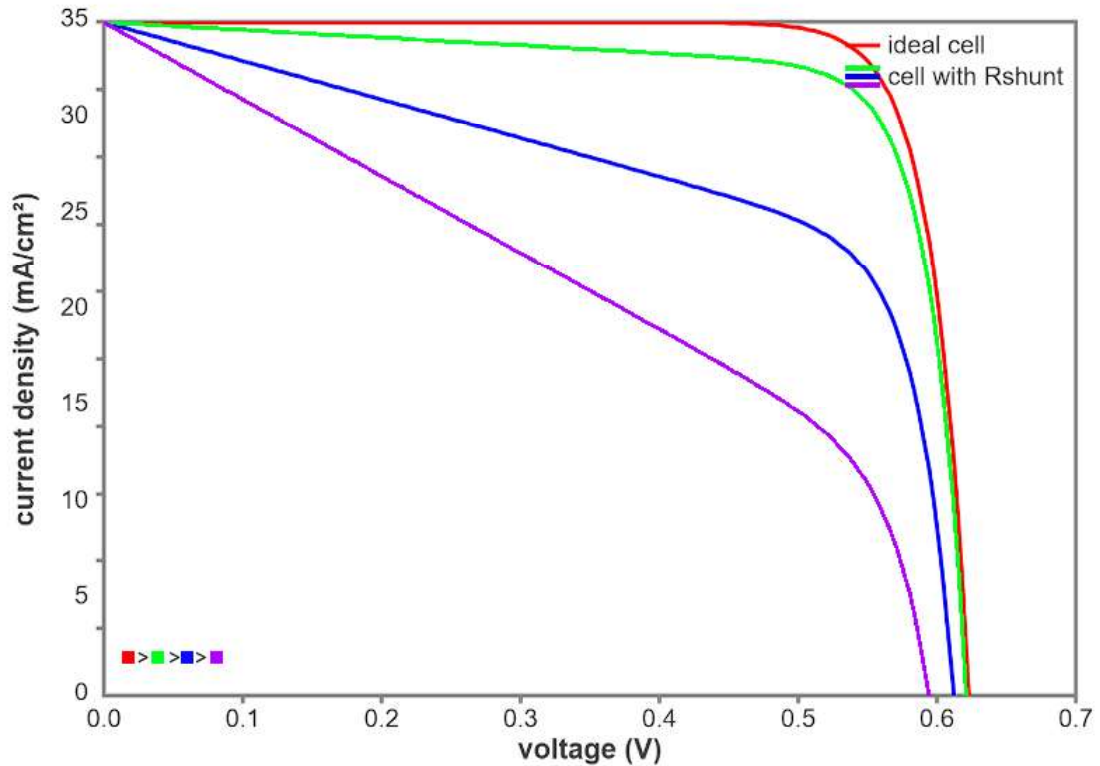


Figure 1.3: I-V curves on different shunt resistances of the solar cell [6].

The series resistance appears in contact between metal and semiconductor material as well as top and rear metal contacts. There is also some resistance generated in the emitter-base connection [7].

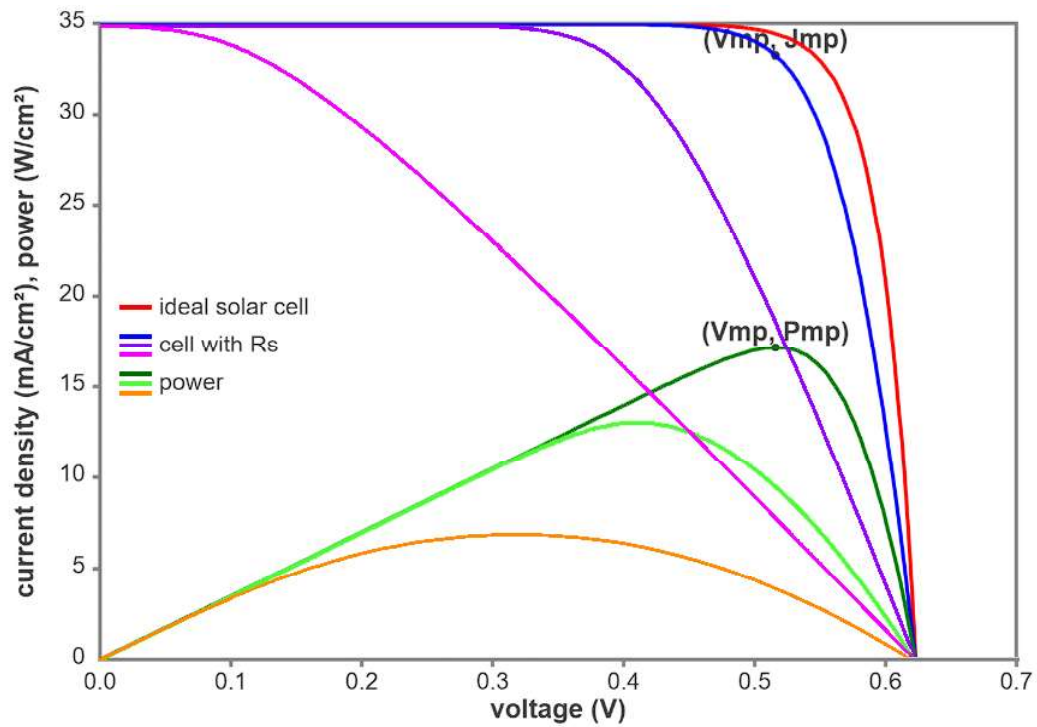


Figure 1.4: I-V and P-V curves on different series resistances of the solar cell [7].

Some of the mentioned parameters depend purely on manufacturing materials and quality. Manufacturers may not even mention them in manuals. Others as it is possible to derive from equations are dependent on two ambient conditions — temperature and irradiance [2], [3].

1.2. THE EFFICIENCY OF SOLAR PANELS

The efficiency of the solar system is heavily dependent on the control of the PV plant. However, the first thing to take into account is the solar panel itself. Solar panel efficiency is dependent on different factors such as construction, environment, placement, and others. In this section, common efficiency-related factors will be discussed and different types of solar panels will be compared.

1.2.1. *Environmental factors*

Different amounts of energy will be extracted under different environmental conditions. For example, less energy will be generated during cloudy or rainy days. The weather has a major impact on solar irradiance and as a result, on solar panel efficiency [8].

The temperature has a huge impact on solar efficiency as well. Most manufacturers usually provide information about the temperature on which generation is most efficient [8].

Panel orientation is also important as the sun angle in different regions is not the same. The placement angle usually varies between 30 and 45 degrees. Of course, the main issue is direction. The southern side is the most suitable for solar panels [8].

The last important factor is the cleanness of the solar panel. Dust and small debris as well as three leaves cover solar cells and thus regular cleaning is required since rainfall is not enough [8].

1.2.2. *Construction. Monocrystalline and Polycrystalline*

Three most known types of solar cells are Monocrystalline, Polycrystalline, and Thin-film. The first two are often found in comparative studies, for example, article [14] compares energy generation, efficiency, and performance ratio of two types of PV's in different conditions.

As we can see in **figure 1.5**, the efficiency is much better in monocrystals. The polycrystalline solar cell is performing especially poorly during cold months. However, energy generation, which depends on ambient temperatures, can be different for each type of solar cell. For example, in **figure 1.6** it is clear that monocrystalline solar cells perform better during cold months but polycrystalline is leading in summer [14].

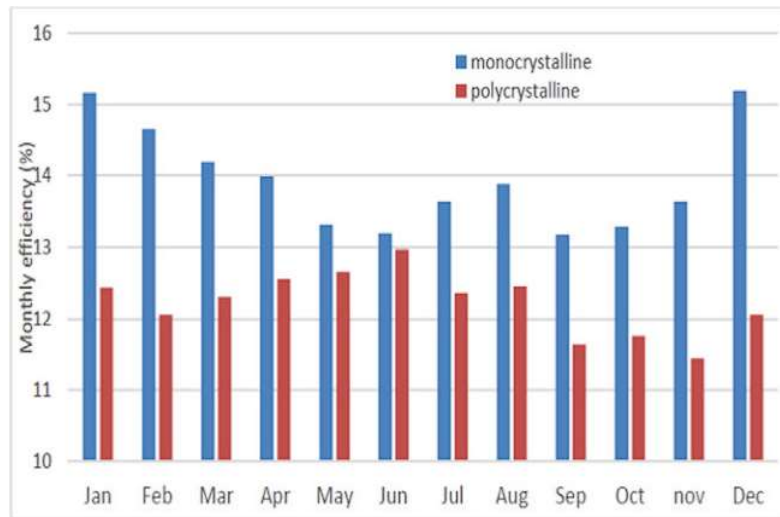


Figure 1.5: The efficiency comparison between Monocrystalline and Polycrystalline solar cells [14]

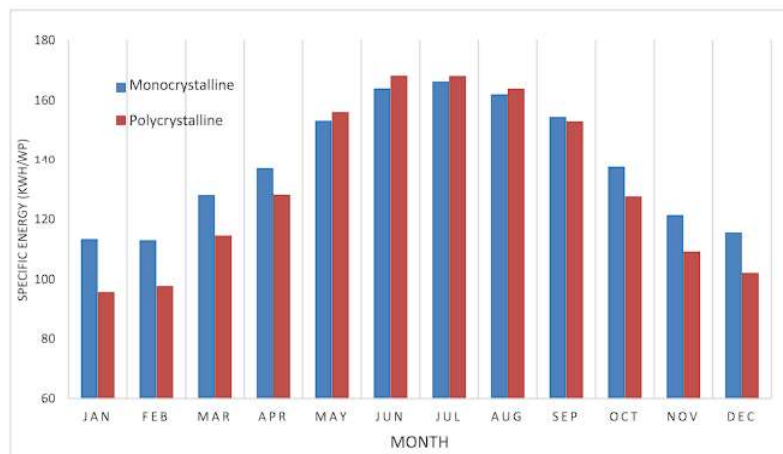


Figure 1.6: The yearly energy generation comparison between Monocrystalline and Polycrystalline solar cells [14]

The performance ratio is calculated by dividing the efficiency of the system and the efficiency of *Standart Testing Conditions*. This ratio seems to be heavily dependent on temperatures as well and follows trends of power generation [14].

This is just one example of a comparative study (more related studies are mentioned in the article). The results may depend on where they were performed (this particular was completed in Iran). But it is clear that two types of solar cells perform differently in different environmental conditions even though, the behavior of both solar cell types is nearly the same [14].

Financial comparison says that Monocrystalline solar cells are more expensive but with proper maintenance these cells can last significantly longer [8].

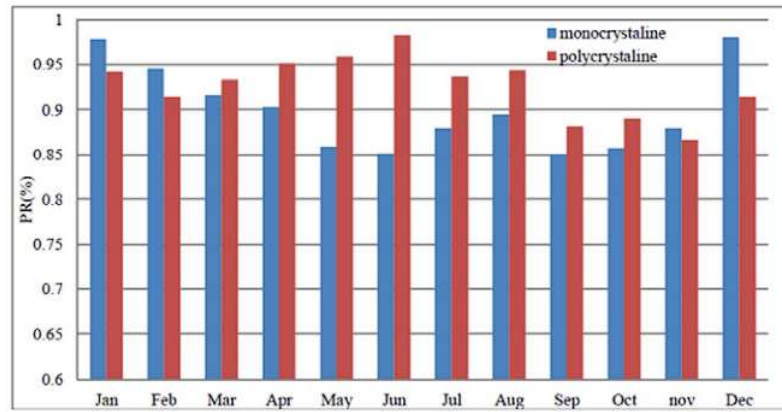


Figure 1.7: The performance ratio comparison between Monocrystalline and Polycrystalline solar cells [14]

1.2.3. Thin-Film solar cell

Silicon Thin-Film solar cells are not made of silicon crystal but from amorphous silicon. In 1981 it was considered that 15% efficiency is the maximum [13]. Compared with monocrystalline solar cells, thin-film solar cells are performing poorly — the only case where amorphous solar cell seems to outperform monocrystalline is exposure to dust [12]. These solar cells last shorter but are cheap and perfectly suitable for small-scale projects [8].

1.2.4. Bifacial solar panels

Bifacial solar cells are not the most popular products in the market but in recent years many new comparison studies have been performed [9]. The key difference of this cell is that it absorbs solar energy from both sides. The major benefit is that bifacial solar panels can be placed vertically and thus, improve generation during morning and evening as well as increase space usage efficiency. Weather conditions are not that relevant for bifacial photovoltaics, except string winds of course. Most of the bifacial solar cells are made of monocrystalline silicon but sometimes polycrystalline bifacial panels can be found as well [11]. Even placed like mono facial panels, bifacial PVs can generate more energy, since they can absorb reflected light [10].

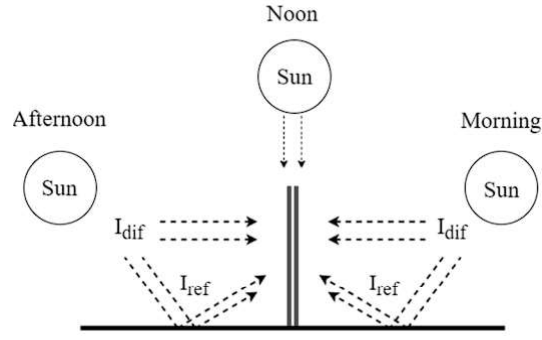


Figure 1.8: Vertical position for bifacial solar panel [10]

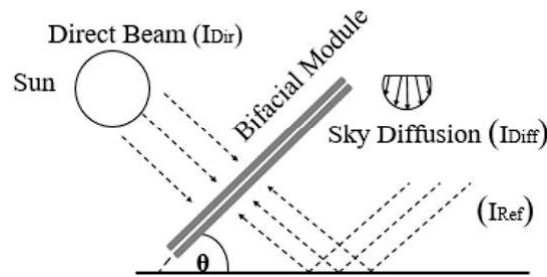


Figure 1.9: The key benefit of the bifacial solar panel is that it can absorb light from both sides [10]

The efficiency is significantly better than mono facial for previously given reasons. The solution in **article [10]** has a multilevel system that, compared to fixed mono-facial solar panels, can generate approximately 55% more energy. Despite efficiency benefits, it is not recommended to build bifacial solar panels for personal use because of additional costs for special mounting and potentially solar tracking systems [11].

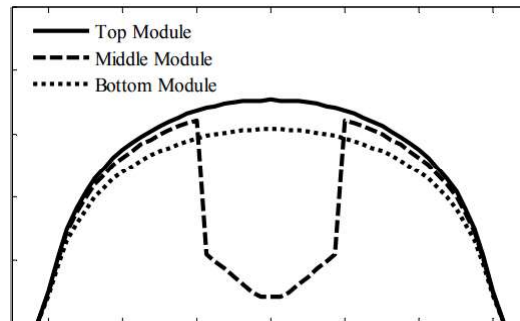


Figure 1.10: Generation of the bifacial solar panel over the day. The middle module is the one which is placed vertically [10]

1.3. MAXIMUM POWER POINT TRACKING

In this paragraph we will discuss the main features, advantages, and basics of MPPT, the differences between MPPT and PWM, and the most popular MPPT control algorithms.

1.3.1. *MPPT vs PWM*

As it was already cleared, the current and voltage taken from the photovoltaic element are dependent on various parameters of the PV. It is easy to control the amount of power extracted from the solar system. A simple *PWM* controller can be used to control average current output [19]. The *PWM* system also serves as a voltage limiter. When the photovoltaic system is generating higher voltage, the *PWM* element can reduce the duty cycle and voltage in the output [20]. This solution is perfectly suitable for controlling battery charge. However, *PWM* controlled system can operate on a limited voltage range, especially when the system has to charge batteries — the PV voltage has to be equal to or slightly higher than the battery voltage [19]. And since batteries are delicate devices they can be easily damaged with overvoltage or overcurrent, which is quite common in such unstable power generation systems as solar panels [16]. Moreover, *PWM* systems cannot increase the efficiency of PV string [19].

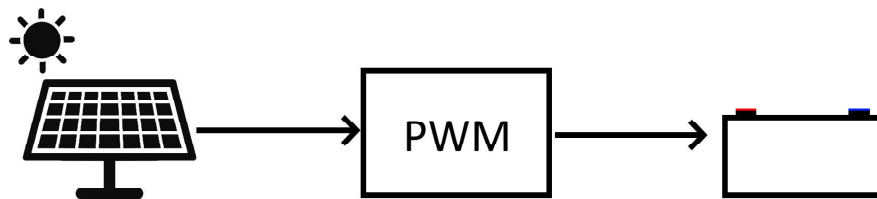


Figure 1.11: Simplified PWM system model

It was mentioned before that photovoltaic elements have voltage points where power output is the highest. These points are called *Maximum Power Points*. There are devices capable of finding these points called Maximum PowerPoint Tracking or *MPPT* controllers [19]. These devices can find the highest efficiency point and adjust photovoltaic interfaces and make sure that load matches MPP characteristics [15].

The implementation difference between PWM and MPPT is a few additional components in the circuit. Here is an example of possible MPPT implementation:

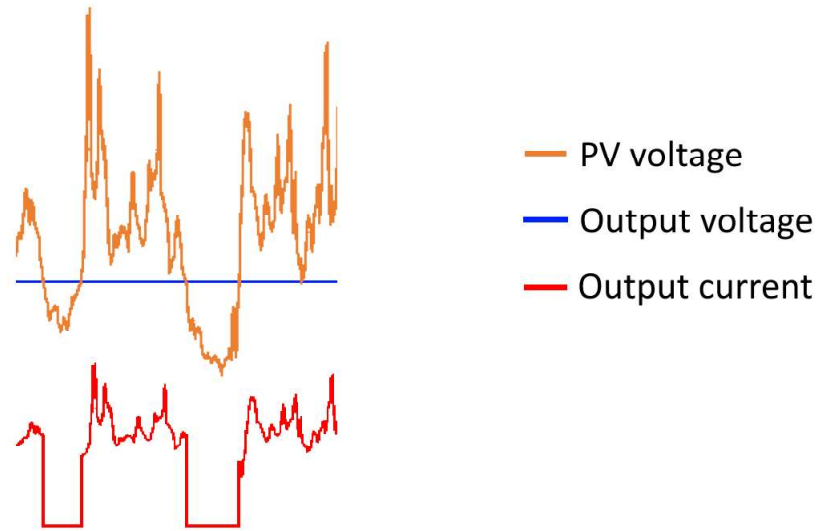


Figure 1.12: Possible relation of PV generation and PWM output

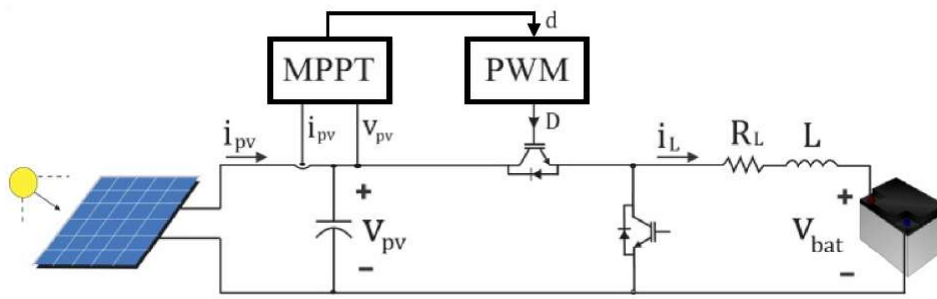


Figure 1.13: Possible MPPT implementation [44]

As we can see the system consists of a Buck converter, source, battery, and MPPT control. From this example, we can derive a simplified MPPT system, which is similar to **figure 1.13**. In addition, the MPPT system has a second PWM (left block in **figure 1.14**) controlled by the MPPT algorithm and LC filter. There could also be a capacitor between the solar panel and the MPPT part.

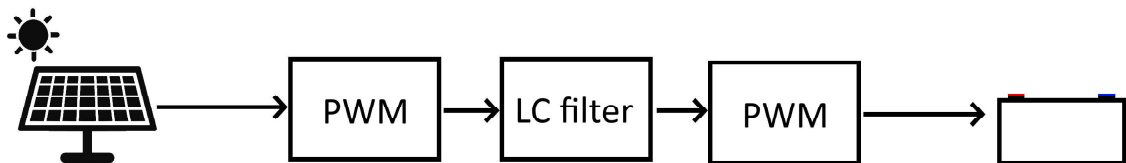


Figure 1.14: Simplified MPPT implementation

The MPPT system meets nearly the same features as the PWM system. The PWM closer to the battery is adjusting voltage and current to control charging parameters and keep the battery safe. The other PWM module is adjusted to control voltage or current input and thus extract as

much power as possible. There are many ways to find Maximum power points — some of these algorithms constantly change voltage and compare with the previous values, some are purely mathematical and some are based on artificial intelligence.

Voltage control is realized by Pulse Width Modulation or *PWM*. This method was used in radio technics first but later was implemented in power electronics as well [35]. The idea of this method is to switch voltage from high to low in a fixed time interval (switching cycle) and create an effect of average voltage in that interval [34].

1.3.2. Open Voltage algorithm

The Open Voltage algorithm is a popular algorithm for MPPT tracking [46]. In theory, open-circuit voltage has a linear relationship with MPP voltage $V_{MPP} = kV_{OC}$ (k usually is in the range of 0.7-0.78) [47]. To find open-circuit voltage it is necessary to disconnect the input source. This is a significant disadvantage since the measurement system is losing power. Another issue is that this algorithm is not tracking real MPP but instead, a reference [46].

1.3.3. Perturbation and Observation algorithm

Perturb and Observe (*P&O*) algorithm is one more popular algorithm in MPPT solutions because it is simple and requires little computational resources [44]. In this method, the solar array voltage is constantly incremented or decremented and current power is compared to the previous value. If power is increasing, voltage is changed in the same manner, and if power drops, voltage change direction is switched. Once MPP is reached, the voltage oscillates around that point [17].

As *P&O* can lead to errors during rapid changes in solar irradiance, some improvements were created. For example, it is possible to measure power change between two voltage deviations. This allows to capture power changes caused by rapidly changing environmental conditions and thus, avoid wrong voltage change directions while searching for MPP. This improved method is called *dP-P&O* algorithm [44].

Even more advanced *P&O* algorithm is *Modified P&O*. This method has two operation modes. The first one is used for the estimation of power variation due to previous voltage changes. In this mode, no voltage deviation is performed. The second mode runs the same perturbation process. The whole idea of this algorithm is to distinguish PV power fluctuations that appear during the hill-climbing process and those caused by environmental changes [18].

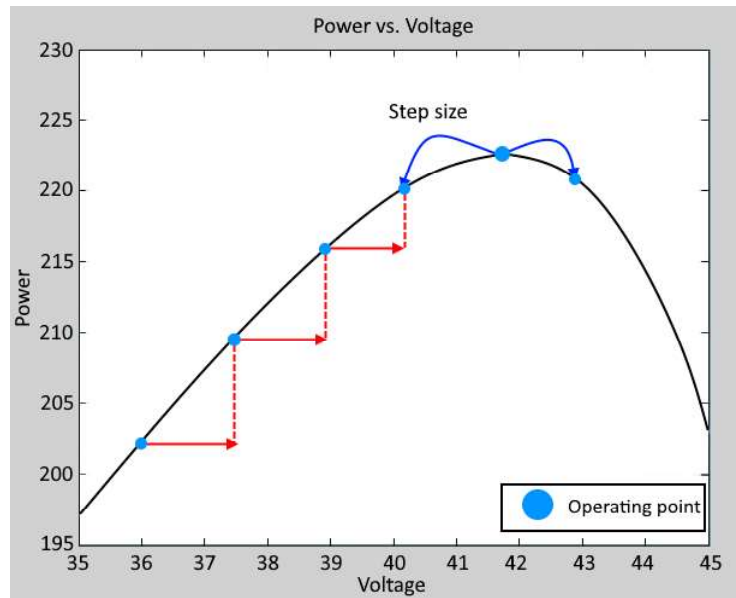


Figure 1.15: P&O algorithm working principle in PV curve [41]

1.3.4. Neural networks in MPPT

The *P&O* algorithm is simple to understand and implement. However, it requires many iterations to get close to MPP [28] and never actually stays on that point but oscillates around it [17]. It also fails during the rapid change in weather conditions, as it was mentioned in article [44]. With all these issues *P&O* becomes quite inefficient in maximum power extraction compared to artificial intelligence-based methods. Neural network and Fuzzy logic-based systems do not require additional mathematical models like a few more primitive methods and can easily do mapping of non-linear systems. These algorithms can avoid errors due to rapid changes [28].

The neuron network consists of a certain number of cells called neurons which are connected. Connections have their weights. These connections are called links and they serve as paths for signals to pass. A single neuron can receive many input signals and transmit one output signal. The whole neuron network is highly capable of learning and pattern recognition. To create a neural network it is important to complete these main tasks [29]:

1. Generate data. This means obtaining as many possible operating conditions as possible.
2. Choosing independent and significant values having variables as inputs.
3. Choosing and implementing *ANN* architecture.
4. Training and testing. Training means exposing *ANN* to generated data to apply weights on each link to reduce chances of error occurrence [29].

In **figure 1.16** we can see an example of a neural network that takes PV voltage and power as inputs and spits duty cycle for a DC/DC converter [28].

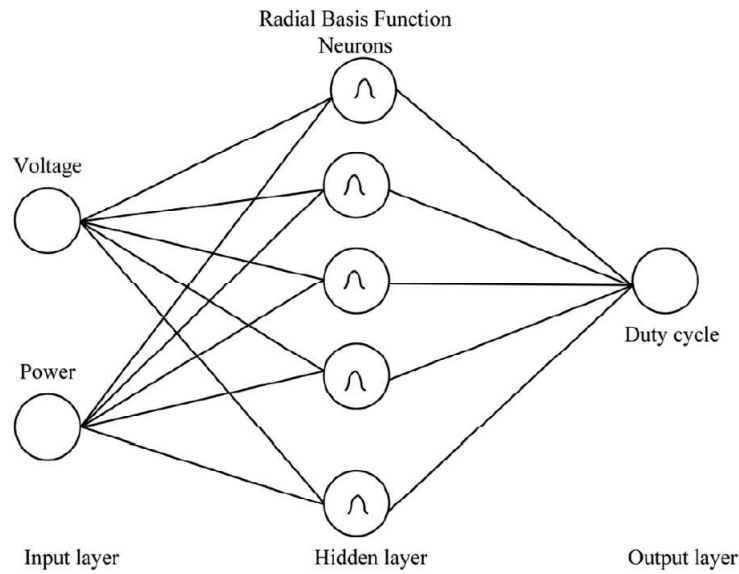


Figure 1.16: Radial basis function neural network [28]

The main advantage of a neural network-based MPPT solution is its efficiency. For example, in article [30] proposed solution was above 99% efficiency compared to P&O whose efficiency varied from 99 to 81%.

1.3.5. Fuzzy Logic

Fuzzy logic is a concept introduced in 1965 and it consists of logical true and false but true can have different levels of significance. For example, the current can be high, very high, extremely high, etc. In other words, there are still two values of logical 0 and 1 but there is also a possibility to have a value in between the extremes [25]. Technically, Fuzzy logic is one of the Artificial intelligence solutions. The goal is to derive output without a precise mathematical model of the system when inputs are not accurate. The four main steps to implement fuzzy logic are shown in **figure 1.17** [27].

As well as Neural Network systems, fuzzy logic requires a lot of information about the solar system to function correctly. Even though the possibility of error with this method is quite high [26].

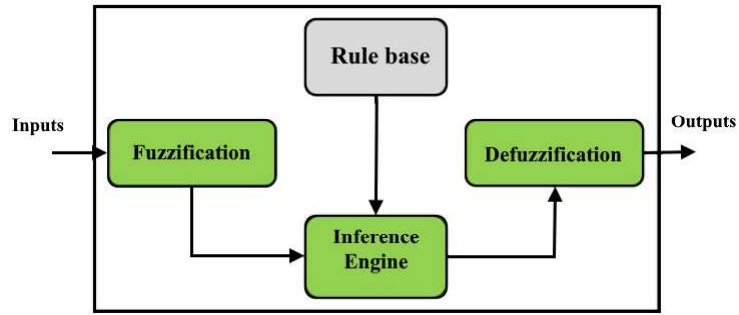


Figure 1.17: Simplified structure of fuzzy logic implementation [27]

1.3.6. MPPT in partial shading conditions

The partial shading condition occurs when not all solar panels in the array or not all cells in the solar panel are equally irradiated [24]. Partial shading can occur not only when a leaf falls on the panel or tower covers half of the array but also when panels get dirty. One of the major factors of power loss during partial shading is rising temperature. A shaded cell becomes reversely biased. Other cells respond with high resistance and thus the temperature of the area rises. As a result, a P-V curve changes and there is no more single MPP. Instead, there are many local and one global MPP [21].

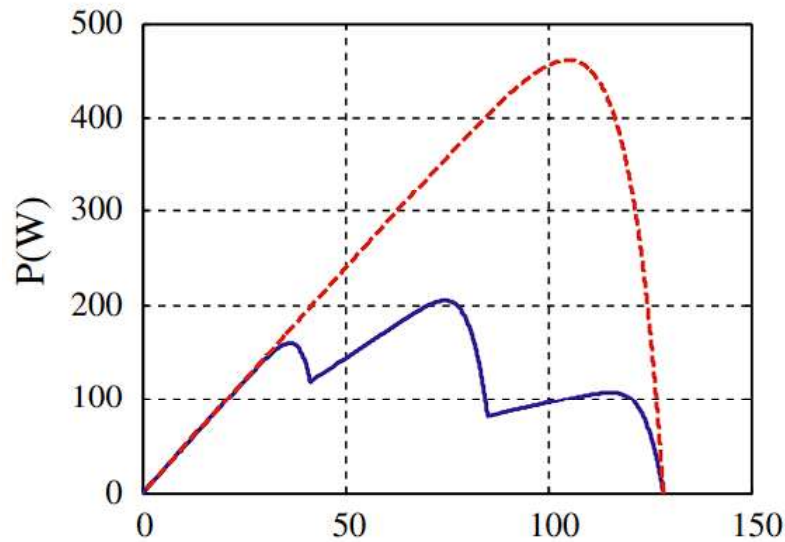


Figure 1.18: P-V curve of partially shaded solar panel [22]

Classical methods such as P&O are not suitable for such cases. P&O is capable of finding MPP when there is only one peak, but it cannot guarantee that the found peak is the global one and no losses are gained [22]. Besides AI-based solutions (one of them is in detail explained in article[31]) many biology-inspired techniques to find GMPPT were implemented. One of them is

Artificial Bee Colony. A simplified version can be put into these steps [48] [23]:

while:

1. Select areas for local search.
2. Evaluate and choose resources for the search.
3. Remaining resources are used for a random search.
4. Evaluate unused resources.
5. Update probability.

end

return best solution [48]

Other more known methods are Ant Colony Optimisation, Genetic Algorithms, Differential Evolution, and many others. In conclusion, global MPP tracking is one of the more difficult issues, which cannot be solved by traditional methods, and thus, many modern and creative methods were implemented [23].

1.4. POWER SUPPLY TOPOLOGIES

The photovoltaic element generates DC and it needs a DC-AC link to be connected to the grid. However, the DC-AC converter alone is not enough since most photovoltaic elements operate at less than 40 volts [49]. Thus an additional element is necessary between the mentioned ones — a DC-DC converter [50]. There are many different types of DC-DC converters and it is useful to analyze main topologies, especially ones that are widely used in the photovoltaic energy field.

To begin it is useful to take a look at the basics of reactive elements which together with semi-conductors play the main role in DC-DC converter circuits. Both components, the capacitor, and inductor are capable of storing energy. The charging of both components is similar and is shown in **figure 1.19** [32].

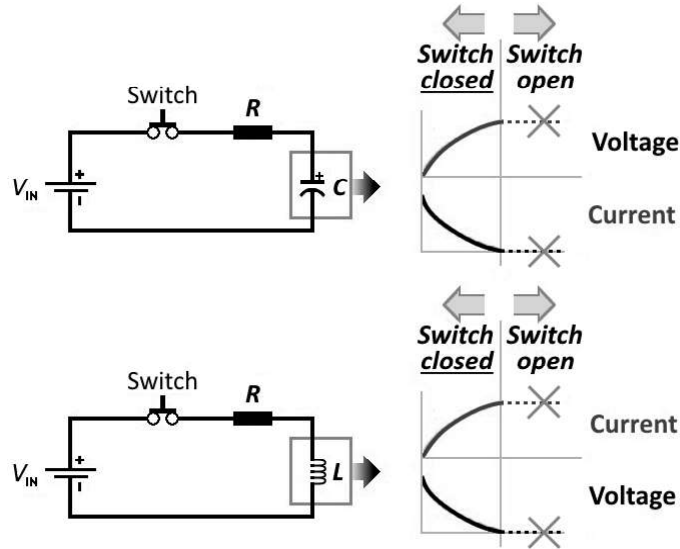


Figure 1.19: Charging phase of reactive elements.

The main difference here is that voltage and current curves mirror each other. In the capacitive elements, current begins with a very high value and then falls exponentially with time. The inductive element acts similarly but voltage and current switch roles. Breaking the circuit though will cause two different phenomena. The capacitor will keep a constant voltage and the current will be 0. But the inductor will resist sudden changes and induce an opposite voltage to keep current flow until there is no energy in the inductor [32].

If we want to mirror these two components, we have to change the voltage source in the capacitor circuit into the current source and place the switch in parallel with the capacitor. Then if the switch is off, the current in the capacitor will be high and fall exponentially (as it is with voltage in

the inductor). These voltage and current spikes can damage the circuit and the switch [32].

To prevent these spikes, it is necessary to prevent sudden changes or to keep a *Steady State*. A Steady State (or Stable State) is achieved when the current change at the beginning of the switching cycle is the same as the current at the end. If this condition is fulfilled, the circuit can be called a topology [32].

The inductor circuit in **figure 1.19** is very close to one of the topologies. However, it cannot be used as a power supply yet because every time the switch is off, the voltage in the inductor is going to rise to the point where the spark appears in the switch — in a real power supply circuit switch should be changed into a transistor which would be damaged due to reverse voltage. To solve this issue we can add a diode:

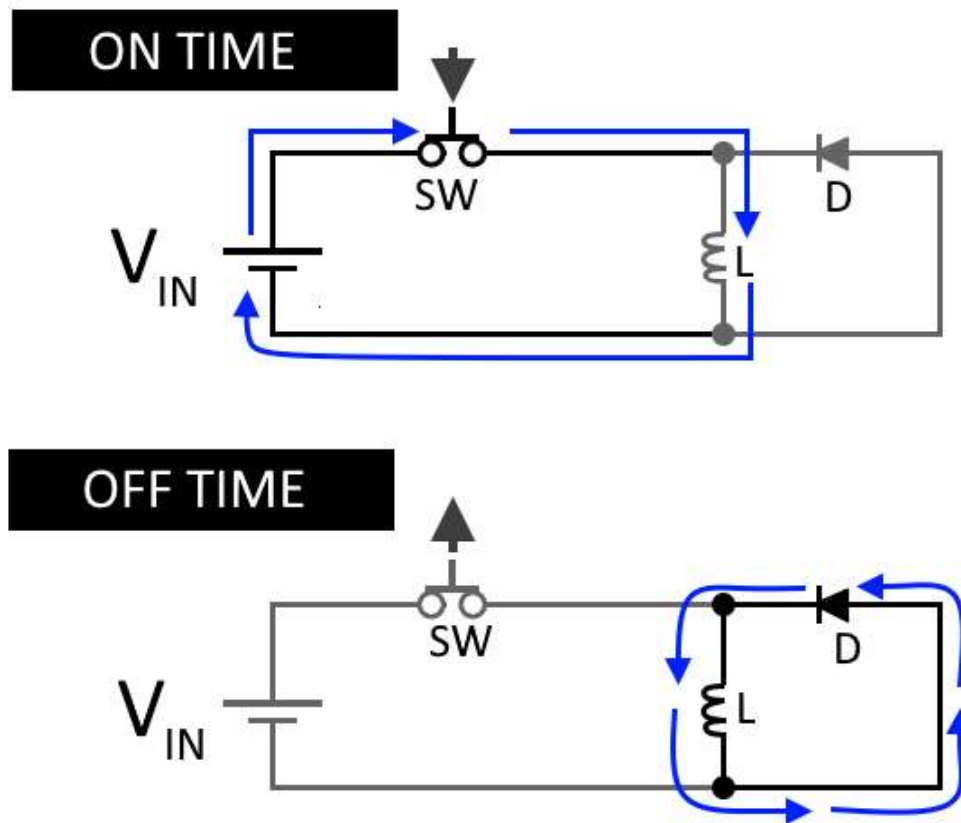


Figure 1.20: Current flow when the diode is implemented

As we can see, the current has a convenient path during the switch-off time, and the voltage spike on the switch is eliminated. However, theoretically, the current would drop very slowly during OFF time, and thus, the circuit may suffer from rising currents. This new issue requires a capacitor to be used in the circuit. As the capacitor is added in series with the diode, the voltage in this capacitor is going to increase with every cycle's OFF state. This leads to a voltage increase in the inductor during the OFF state which will help the inductor current to ramp down faster and

thus not increase indefinitely [32]. After choosing the right capacitor inductor current should look like in the **figure 1.21**

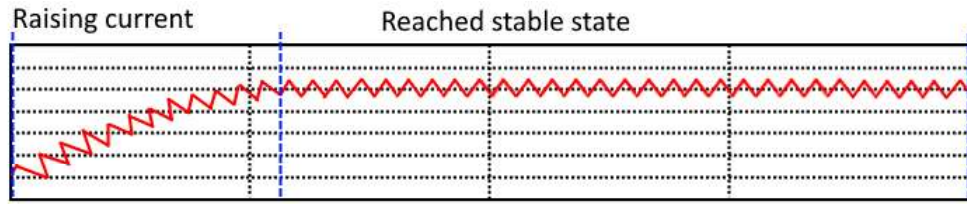


Figure 1.21: Transient process of inductor current in Buck-Boost converter

This particular example is the Buck-Boost converter. There are many other topologies however, in this work only three will be discussed — the other two are Boost and Buck. The Buck converter is part of this work because it is more popular in solar system solutions thus, more attention will be given to this particular converter topology.

1.4.1. Boost converter topology

The boost topology is designed to step up voltage and not change the polarity [32].

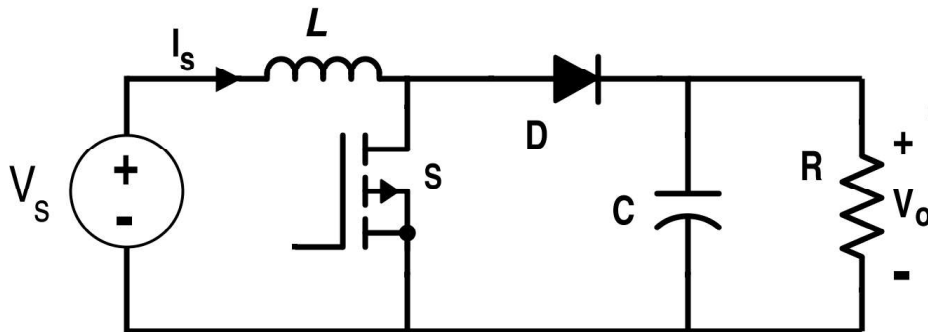


Figure 1.22: Boost converter basic design

During the ON state, the current flows through the inductor, and no energy is delivered to the output. Voltage in the inductor can be described with the simplified equation:

$$V_L = V_{in} \quad (1.5)$$

During the OFF state, the inductor pushes all energy to the output as well as the input source. Voltage in the inductor during this period can be described like this:

$$V_L = V_{in} - V_O \quad (1.6)$$

As we have voltages for both states, we can find the average inductor voltage V_L by integrating over time. The period is split into the duty cycle part D and the rest of the period D' :

$$\langle V_L \rangle = 0 = \frac{1}{T} \int_0^T ((V_{in})DT + (V_{in} - V_O)D'T = V_{in} - V_O D' \quad (1.7)$$

From the result, we can derive duty cycle D and find a simplified version of a transfer function for the boost converter:

$$D \approx \frac{V_O - V_{in}}{V_O} \quad (1.8)$$

1.4.2. Buck converter topology

As was mentioned before, the buck converter is the topology used in this work thus, it is the most interesting one and most details will be discussed. This is the topology where the average input voltage is higher than the output voltage [33].

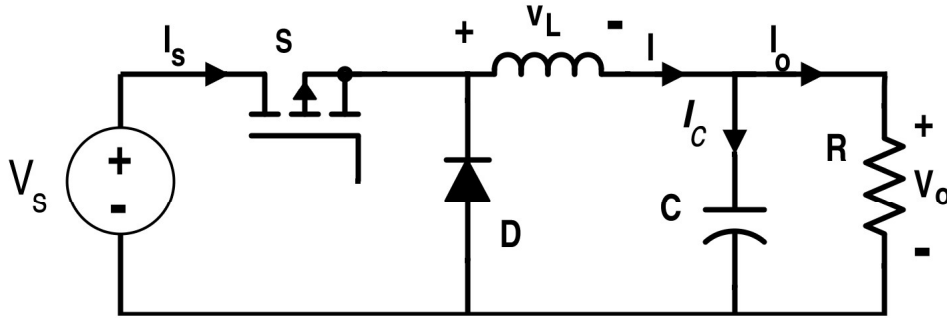


Figure 1.23: Buck converter basic design

Depending on transistor switching behavior, the buck converter (as well as Boost and Buck-Boost converters) can operate in two modes — Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM) [33].

It is important to mention that any topology can work in these two modes. In Discontinuous Conduction mode the current returns to 0 every switch cycle [32].

The Continuous conduction mode is more common in power converters and in this mode, the current returns to a non-zero value [32].

In continuous conduction mode during the ON state, the major part of the energy from the input flows to the inductor. The switch is on and the current is flowing from the input to the inductor

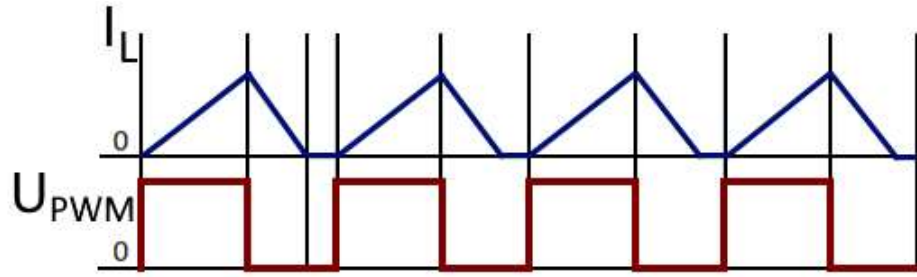


Figure 1.24: PWM voltage signal and inductor current relationship in discontinuous conduction mode

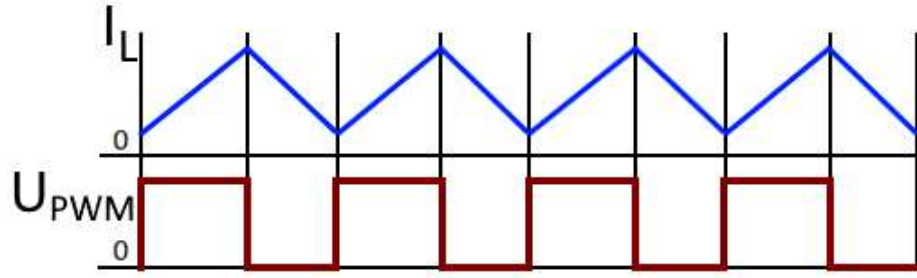


Figure 1.25: PWM voltage signal and inductor current relationship in continuous conduction mode

which generates opposite direction voltage [33]. A little portion of the current flows to the capacitor and the output [32]. As we can see in the **figure 1.26**, voltage in the inductor can be described in equation:

$$V_L = V_{in} - V_O \quad (1.9)$$

And the current in the capacitor:

$$I_C = I_L - I_O \quad (1.10)$$

During the OFF state, the switch is off and no current comes from the input, all energy from the inductor flows through the diode to the output [32]. The circuit of the buck converter in the OFF state is in **figure 1.26**. The voltage in the inductor is:

$$V_L = -V_O \quad (1.11)$$

And the current in the capacitor:

$$I_C = I_L - I_O \quad (1.12)$$

As we have voltages for both states, we can find the average inductor voltage V_L by integrating over time. The period is split into the duty cycle part D and the rest of the period D' :

$$\langle V_L \rangle = 0 = \frac{1}{T} \int_0^T ((V_{in} - V_O)DT + (-V_O)D'T) = V_{in}D - V_O \quad (1.13)$$

From the result, we can derive duty cycle D and find a simplified version of a transfer function for the buck converter:

$$D \approx \frac{V_O}{V_{in}} \quad (1.14)$$

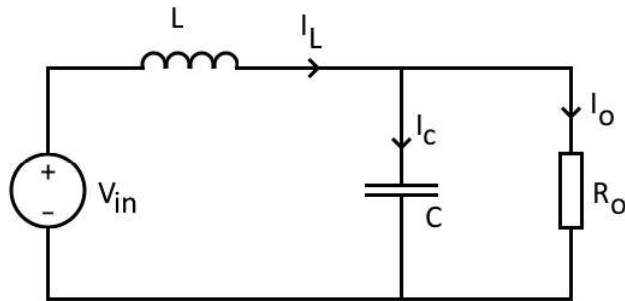


Figure 1.26: Alternative circuit for buck converter in ON state.

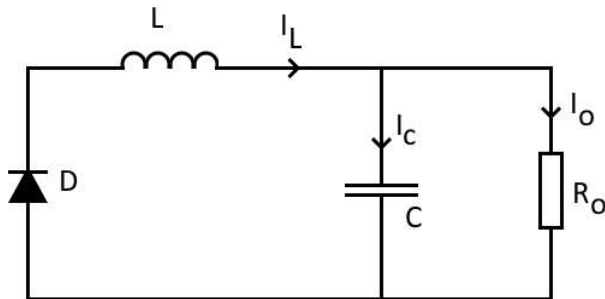


Figure 1.27: Alternative circuit for buck converter in OFF state.

2. METHODOLOGY

2.1. The proposed MPPT charge analysis

For this research the synchronous BUCK converter concept was chosen. The estimated power of the charger is 1kW. The switching frequency is 35kHz, the input voltage is 80-90 volts and the output voltage is around 50 volts. The maximum current is chosen to be up to 30 amperes. The charger is connected to a roof-top solar panel or a string of two solar panels since many roof-top photovoltaic products have a nominal power of around 500W. The voltage will fit the requirements as well.

2.2. Calculations and picking main components

The Main two components to pick are the inductor and the output capacitor. Most information is already known.

Parameter	Value
Output Voltage	50V
Input Voltage	80V
Output Current	30A
Switching frequency	35kHz
Output Voltage Ripple	1
Inductor Current Ripple	1

Table 2.1: The main parameters of the BUCK converter.

The First parameters to calculate are load and desired duty cycle.

$$R = \frac{V_{out}}{I_{out}} = \frac{50}{30} = 1,667\Omega \quad (2.1)$$

$$D = \frac{V_{out}}{V_{in}} = \frac{50}{80} = 0,63 \quad (2.2)$$

The resistance value is to be set in load for the simulation and the duty cycle is important for inductance and capacitance calculations.

$$L = \frac{V_{in} * D \frac{1}{f_s}}{2 * \Delta i_L} = \frac{80 * 0.63 * 0.000028}{1 * 2} = 706 \mu H \quad (2.3)$$

The minimum capacitance calculation is the following:

$$C_{min} = \frac{\Delta i_L}{8 * f_s * \Delta V_{out}} = \frac{1}{8 * 35000 * 1} = 706 \mu F \quad (2.4)$$

The found parameters are added to the Spice simulation (**figure 2.1**). The simulation is run several times with different inductances to find a more suitable value.

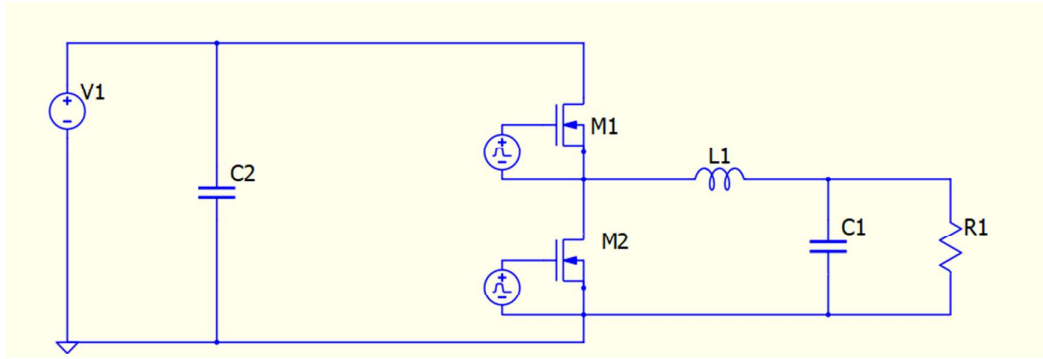


Figure 2.1: The spice model of the BUCK converter

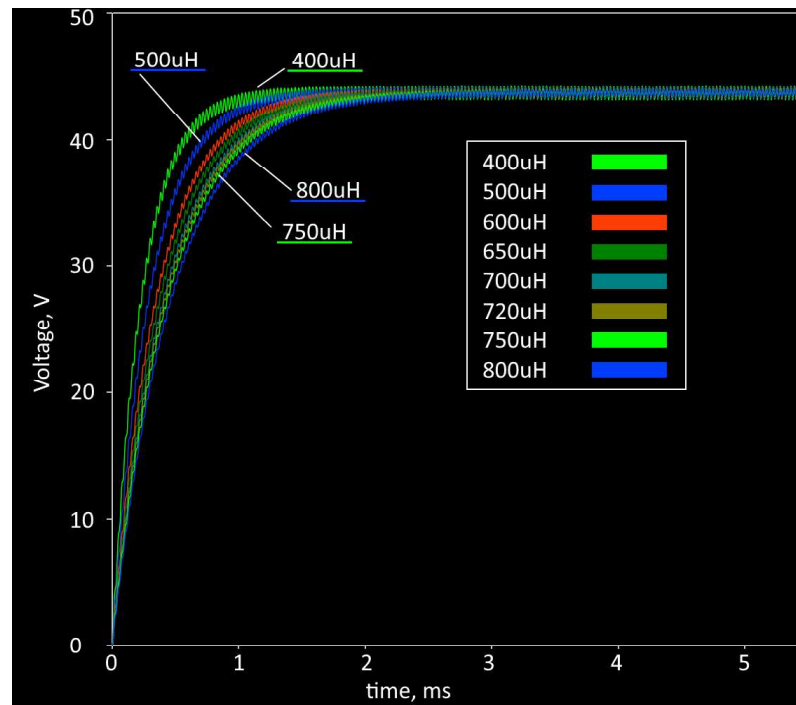


Figure 2.2: Voltage transient processes under different inductances.

The simulation shows that transient processes can be shortened by using lower inductance. However, it is important to evaluate ripple voltage as it becomes bigger with lower inductance (visible in **figure 2.3**). In **figure 2.3** it is visible that 400uH and 500uH increase quite significantly. But ripple voltage under 600uH inductance is quite close to the calculated. As transient processes slightly improve, the 600uH inductance is chosen for further research.

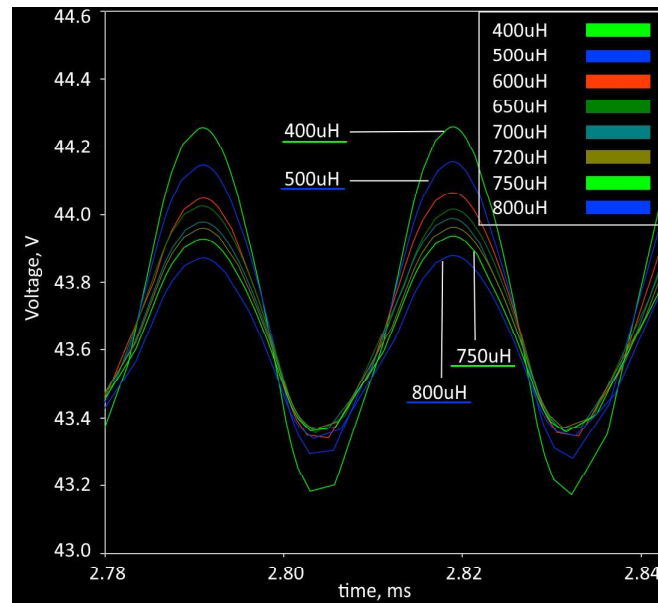


Figure 2.3: The ripple voltage under different inductances.

The Second simulation is run under different capacitances. The calculated capacitance is the minimum value thus, it is possible to find a value under which transient processes would improve.

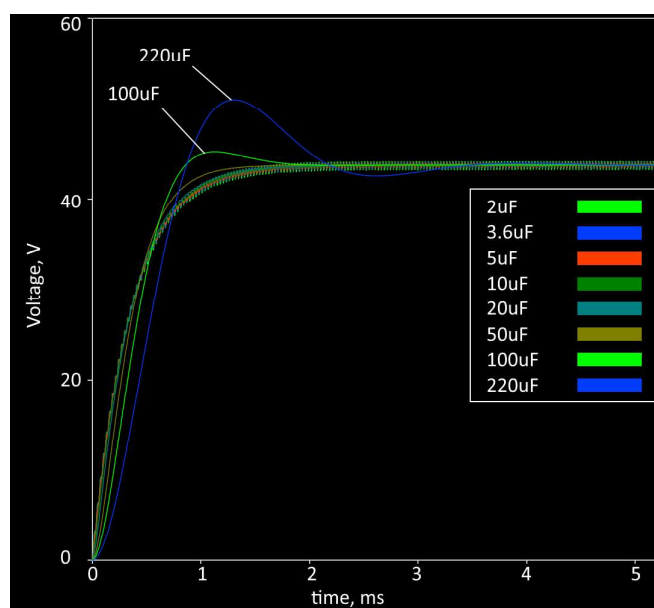


Figure 2.4: Voltage transient processes under different capacitances.

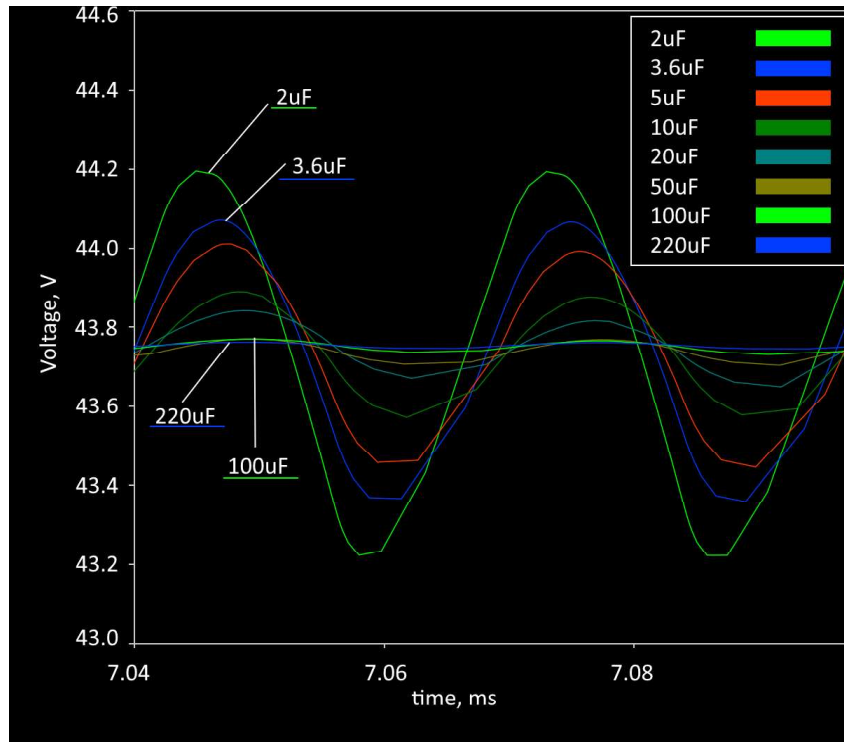


Figure 2.5: The ripple voltage under different capacitances.

Results in **figure 2.4** show that higher capacitances reduce ripple voltage but 100uF and 220uF capacitances cause voltage overshoot which is not a desirable result. More desirable results are seen with 50uF capacitance as it significantly reduces ripple voltage, does not cause a voltage overshoot, and slightly reduces transient processes (**figure 2.5**).

In conclusion, chosen inductance is 600uH and capacitance is 50uF. These parameters are used in further investigations.

2.3. Semiconductor analysis

The proposed charger is based on a synchronous buck converter. The *Synchronous* means that the diode is replaced with a transistor. The objective of the second simulation was to find out the efficiency difference between synchronous and asynchronous buck converters. For this purpose, two models are built in a *MatLab Simulink* environment. The transistor was unchanged and taken from the proposed MPPT charger circuit (from datasheet [51]).

The main model consists of the synchronous buck converter, connected to a solar array in the input and resistive load in the output. In this particular simulation, the *mpptFind* function returns

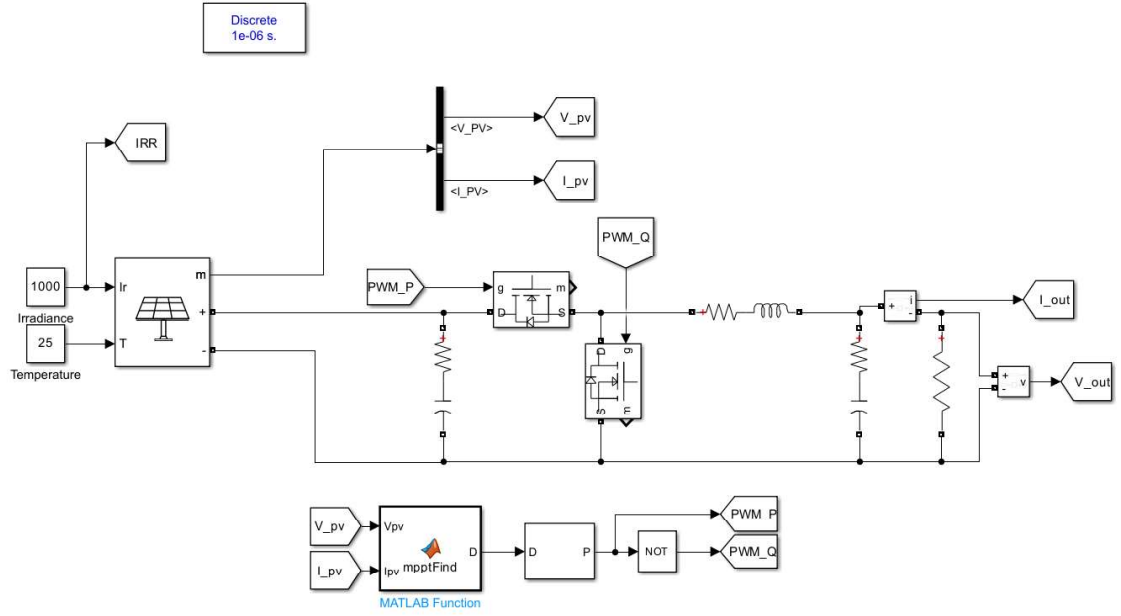


Figure 2.6: Mathematical model of a synchronous MPPT buck converter.

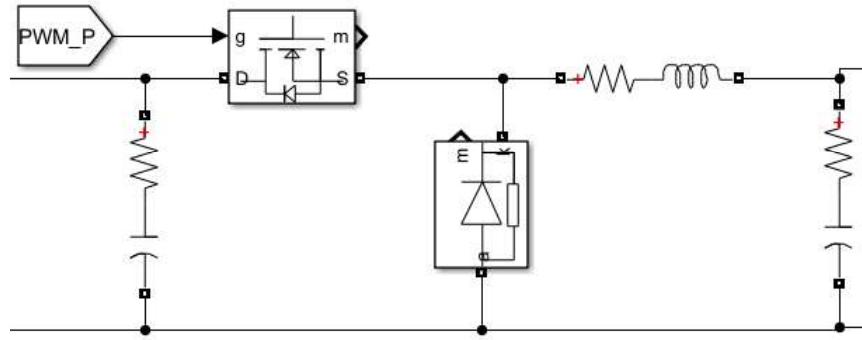


Figure 2.7: The model shown in **figure 2.6** modified by replacing MOSFET with the diode.

a constant duty cycle value despite input values. Input and output voltages and currents are used to calculate power. The first five milliseconds are ignored to skip transient processes. During the next five-second period, measurements are sampled and used to find the average input and output power.

$$P_{avg_{in(out)}} = V_{in(out)} * I_{in(out)} \quad (2.5)$$

The efficiency is calculated by dividing the average output power and input power.

$$eff = \frac{P_{avg_{out}}}{P_{avg_{in}}} \quad (2.6)$$

The simulation was run three times, each time with different duty cycle values. and results are shown in **table 2.2**.

duty cycle	Synchronous	Asynchronous
0.3	0.953	0.848
0.6	0.962	0.911
0.9	0.966	0.954

Table 2.2: Synchronous and Asynchronous buck converter efficiency comparison with three duty cycle values

Results show that efficiency can differ from 1 to 10% percent. This is a significant difference and should be taken into account. Differences are lower when the duty cycle is closer to 1. This is because the higher the duty cycle, the less current flows through the diode. However, knowing the nature of the MPPT curve duty cycle range close to 1 will not be the range to reach the maximum power point. Thus, power efficiency differences most of the time would not be negligible.

2.4. Open Voltage and P&O algorithm analysis

For this research two simple algorithms were chosen to be implemented and compared — Open Voltage and Perturb and Observe. These two algorithms are easy to implement and they both use feedback from the circuit to track MPP. The observation was completed under several different irradiance values. Results were evaluated by mean square error and standard deviation. During the analysis, simulations of each MPPT algorithm were tested with different input capacitance and measurement improvements. Simulations were completed at room temperature (298K).

2.4.1. Open Voltage algorithm

The Open Voltage (further OV) is a voltage-feedback-based algorithm. The objective is to measure the open circuit voltage (V_{OC}) of the solar array and calculate the MPPT voltage.

The MPPT voltage dependence from V_{OC} is not linear thus, the MPPT voltage curve had to be matched by connecting MPPT points from 0 to $1000W/m^2$. The step is chosen $100W/m^2$. To measure V_{OC} the duty cycle has to be dropped to 0. The period between these drops is chosen to be 5 seconds but it is a matter of tuning to find out the most optimal time and this particular task was not included in this analysis. The duty cycle is increased and decreased every 15 milliseconds

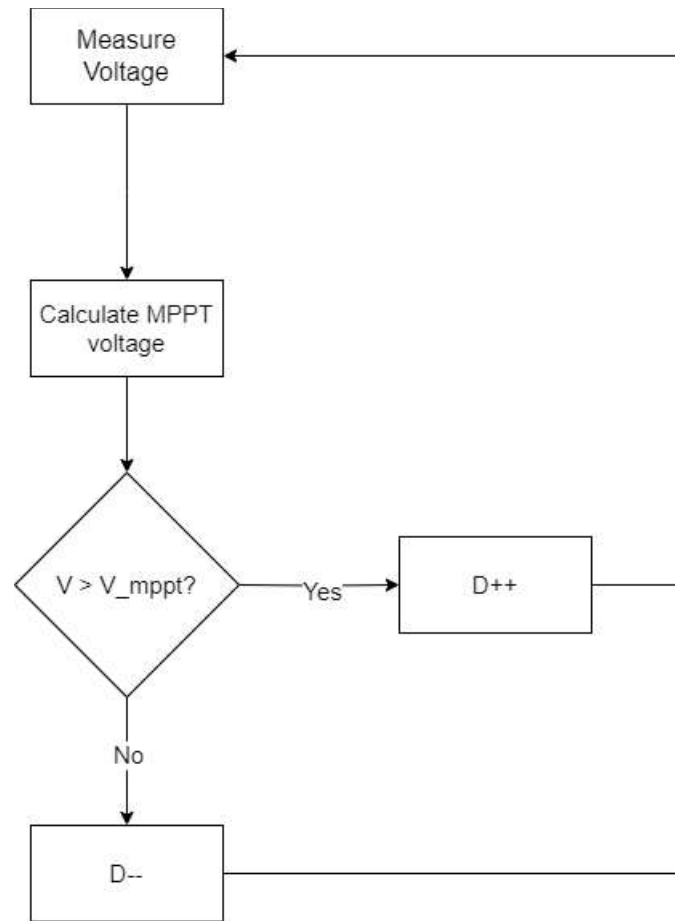


Figure 2.8: The block diagram of the Open Voltage algorithm

but this time could be tuned more to achieve higher efficiency. Results can be observed in the following graph. Blue-colored dots show the solar array input voltage and power distribution on the MPPT curve. Tails on the left side of the curve appear due to periodical duty cycle drop during the MPPT voltage measurement. The important part is marked with a red square where blue dots are close to MPP (the red point).

This first simulation shows that the duty cycle fluctuates around MPP. Higher fluctuations are observed when irradiance is lower. A couple of improvements could be made to try to reduce these fluctuations. The first method is to use the average of several voltage measurements for comparison. For the second simulation, the voltage was measured five times in 15 milliseconds, and a mean value was found and used for comparison.

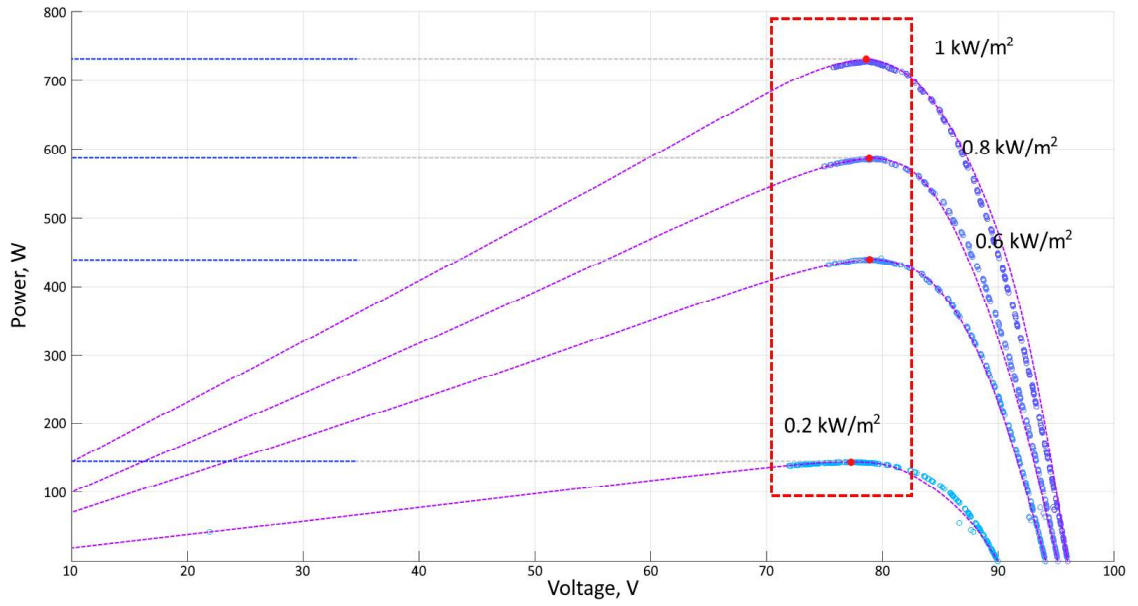


Figure 2.9: The MPPT curve and power points distribution around MPP with OV algorithm (first simulation)

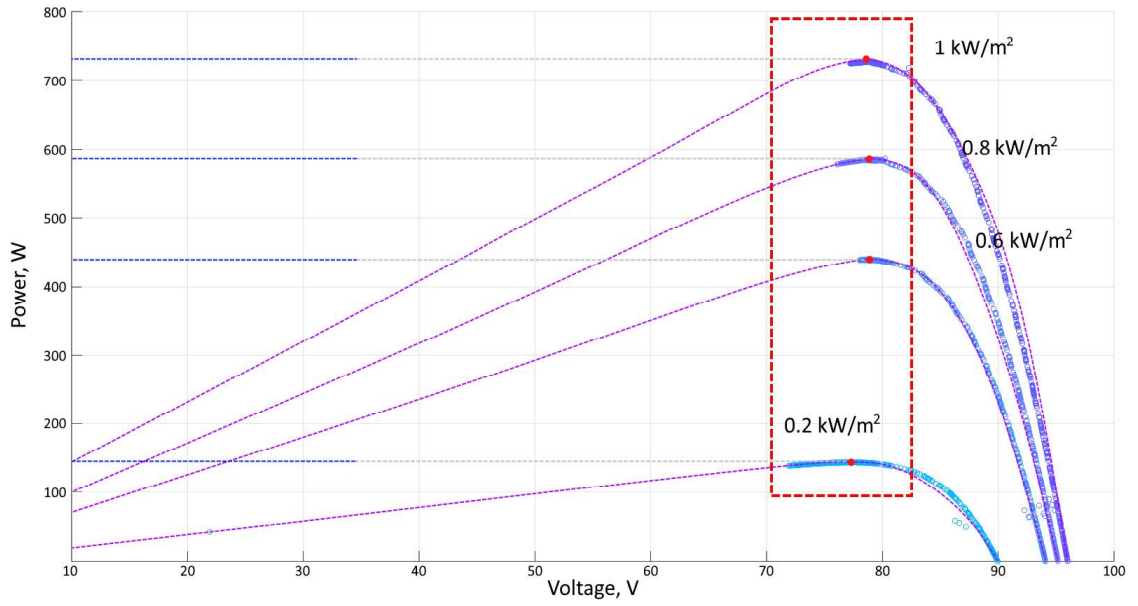


Figure 2.10: The MPPT curve and power points distribution around MPP with OV algorithm (average voltage simulation)

Results show that voltage dispersion is smaller, especially when irradiance is higher. Thus the average voltage solution seems to be effective. However, this method does not reduce noise in the measurement. The previous two simulations were completed with a capacitor in the input of the charger of 220uF. This capacitance is increased to 470uF to reduce noise in the input.

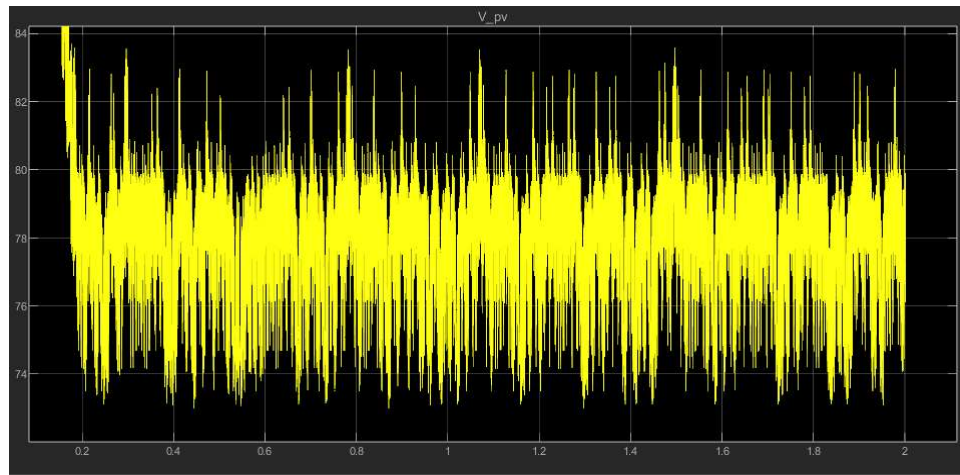


Figure 2.11: Voltage at the input when the input capacitor is 220uF.

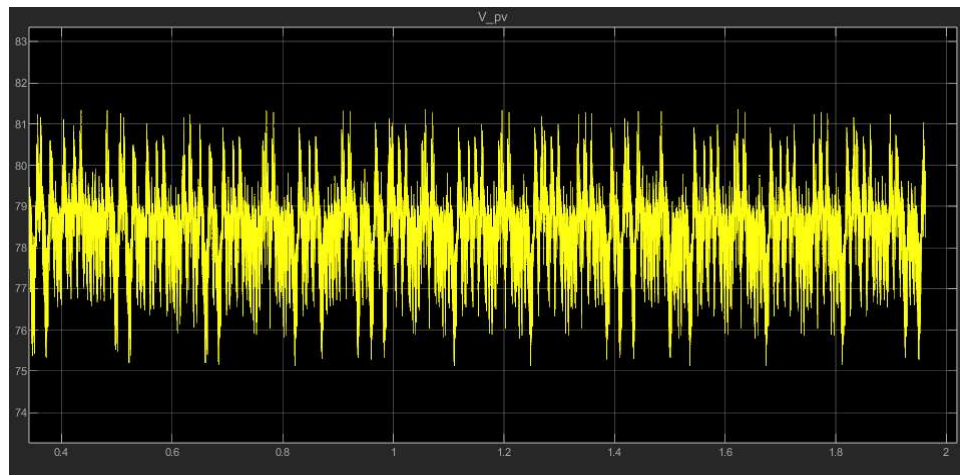


Figure 2.12: Voltage at the input when input capacitor is 470uF.

The simulation showed that voltage fluctuations reduced from 4-4.5V to 2.5V up and down. The duty cycle fluctuation range was reduced from 0.05 to 0.03. These findings explain a significant improvement in MPPT performance in the third simulation.

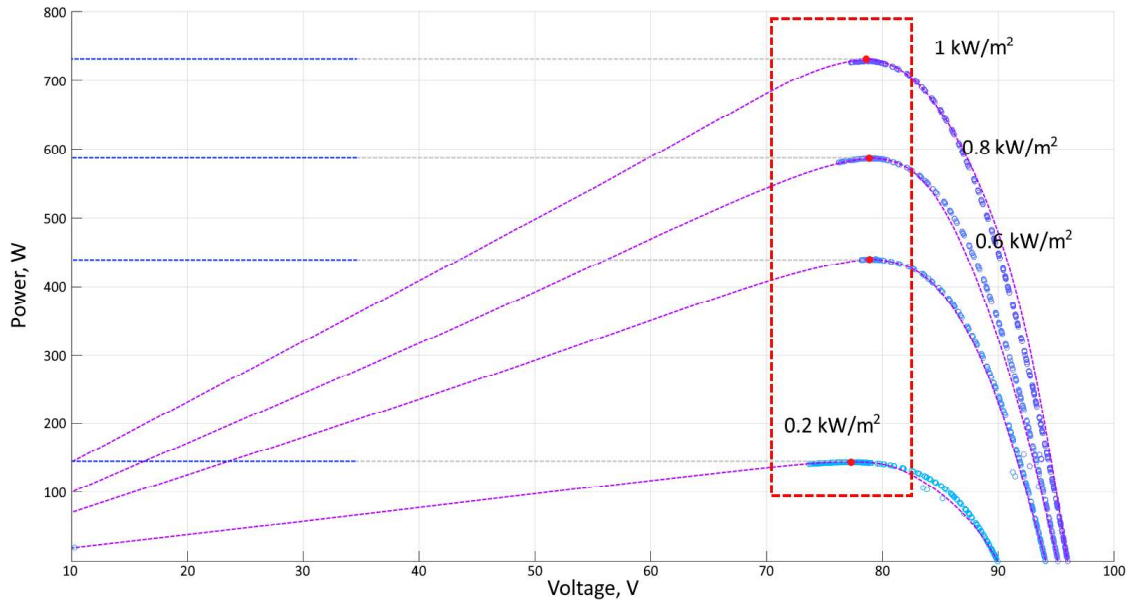


Figure 2.13: The MPPT curve and power points distribution around MPP with OV algorithm (470uF capacitor simulation)

The last simulation was run with both improvements combined and showed the most accurate MPPT performance.

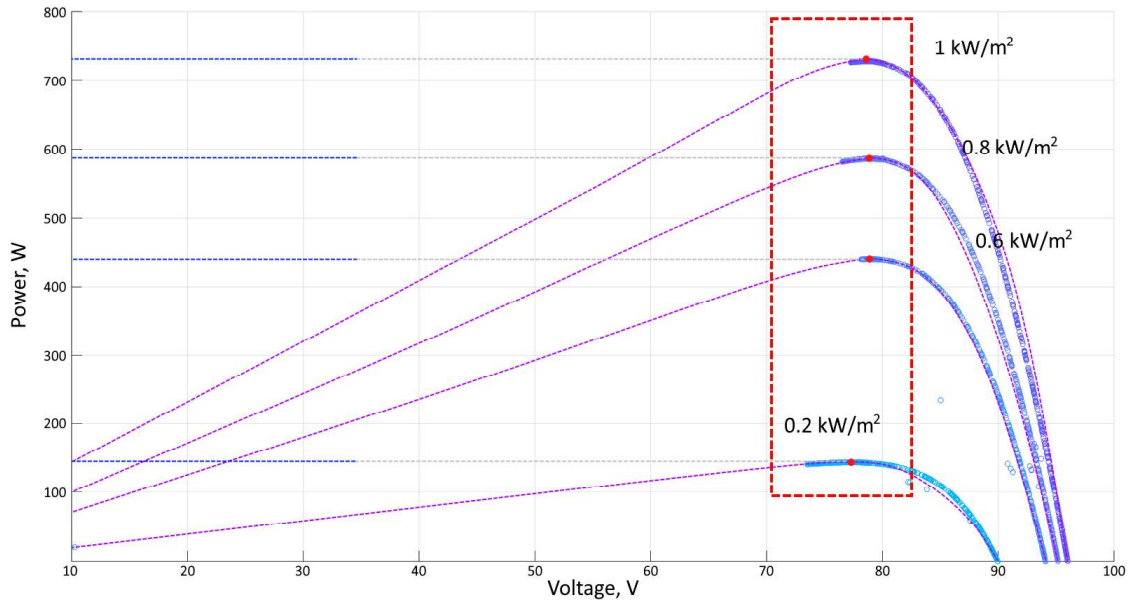


Figure 2.14: The MPPT curve and power points distribution around MPP with OV algorithm (470uF capacitor and average voltage simulation)

The simulation results show that the Open Voltage algorithm has some disadvantages. The first issue is constant open circuit voltage measurement which leads to power loss. Another important problem is sensitivity to voltage fluctuations and noise. Of course, it is possible to improve the algorithm by tuning duty cycle change speed and delays between open circuit voltage mea-

surements. But more importantly, the simulation showed that the capacitor in the input side of the charger has to be chosen by taking into account both — transient processes and input fluctuations. Simulation results show that higher capacitance in the input significantly improves the accuracy of a simple MPPT algorithm.

2.4.2. *Perturb and Observe algorithm*

Perturb and Observe (P&O) is a voltage and current feedback-based algorithm that compares current measurements with previous ones and changes the duty cycle accordingly.

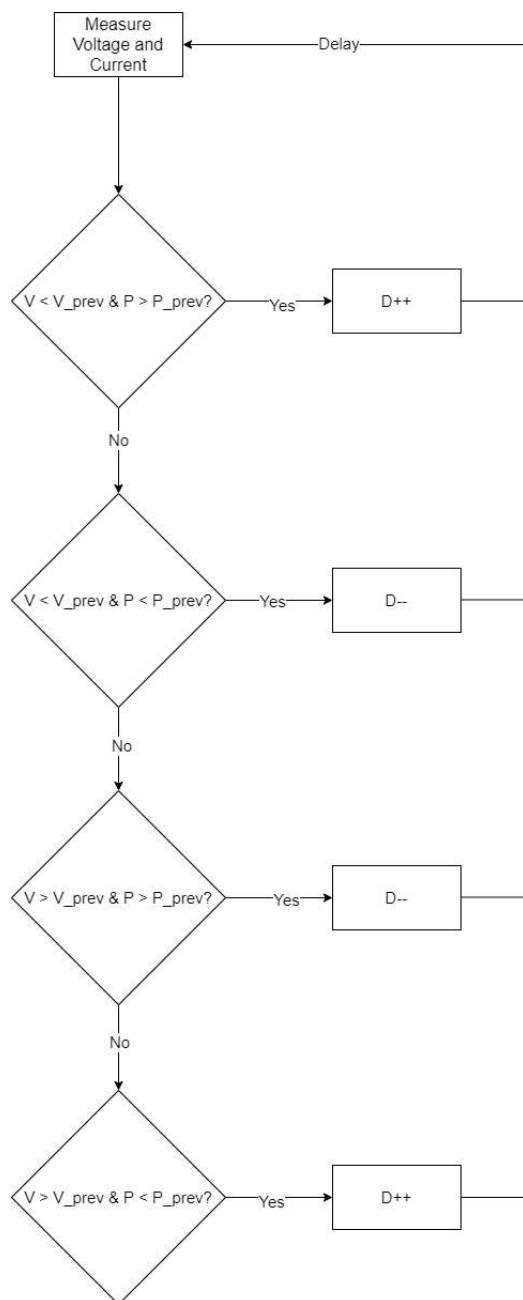


Figure 2.15: The block diagram of the Perturb and Observe algorithm

Measurement and adjustment were set to occur every 10 milliseconds. This algorithm was tested in the same series of four simulations. The first simulation ran simple P&O with a 220uF capacitor in the input.

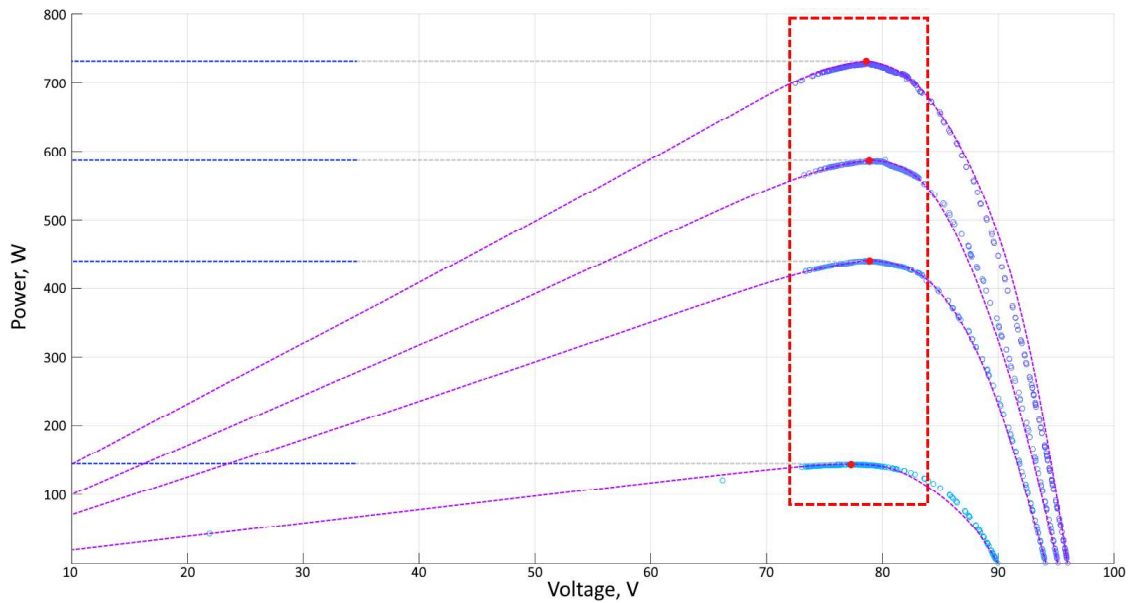


Figure 2.16: The MPPT curve and power points distribution around MPP with P&O algorithm (220uF capacitor)

Comparing with the OV algorithm P&O algorithm reached significantly lower accuracy. The average measurement did show slightly better performance in higher radiance but MPPT at lower irradiance did not show any improvement.

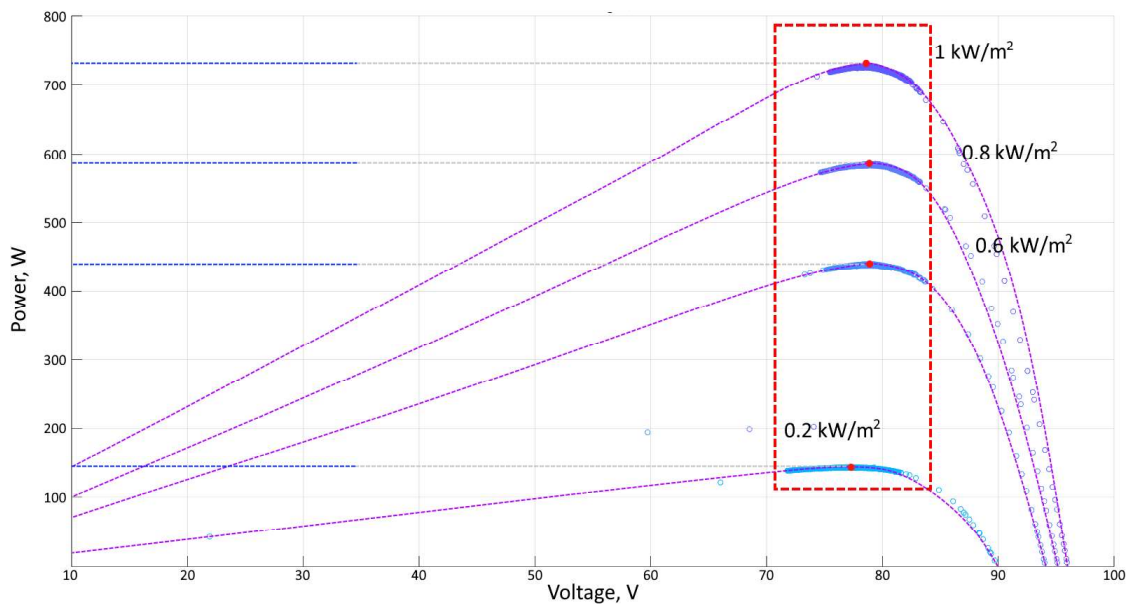


Figure 2.17: The MPPT curve and power points distribution around MPP with P&O algorithm (average measurement)

Increasing capacitance in the input improves accuracy at lower irradiance but changes seem to be insignificant. Combining both improvements did result in more significant improvement however, the OV algorithm fluctuation range is approximately three times smaller.

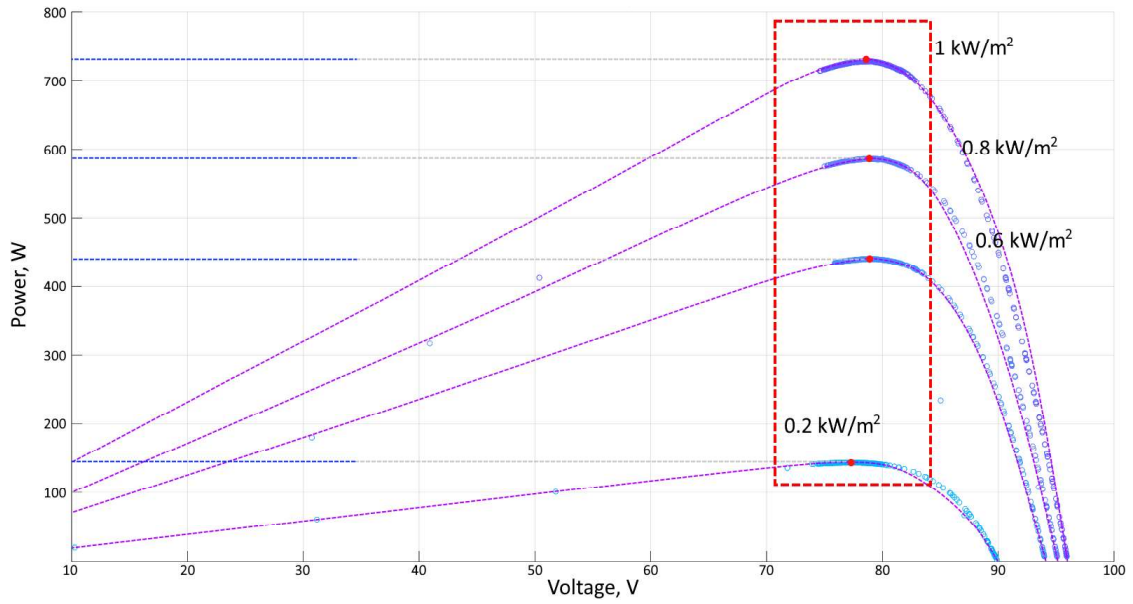


Figure 2.18: The MPPT curve and power points distribution around MPP with P&O algorithm (470uF capacitor)

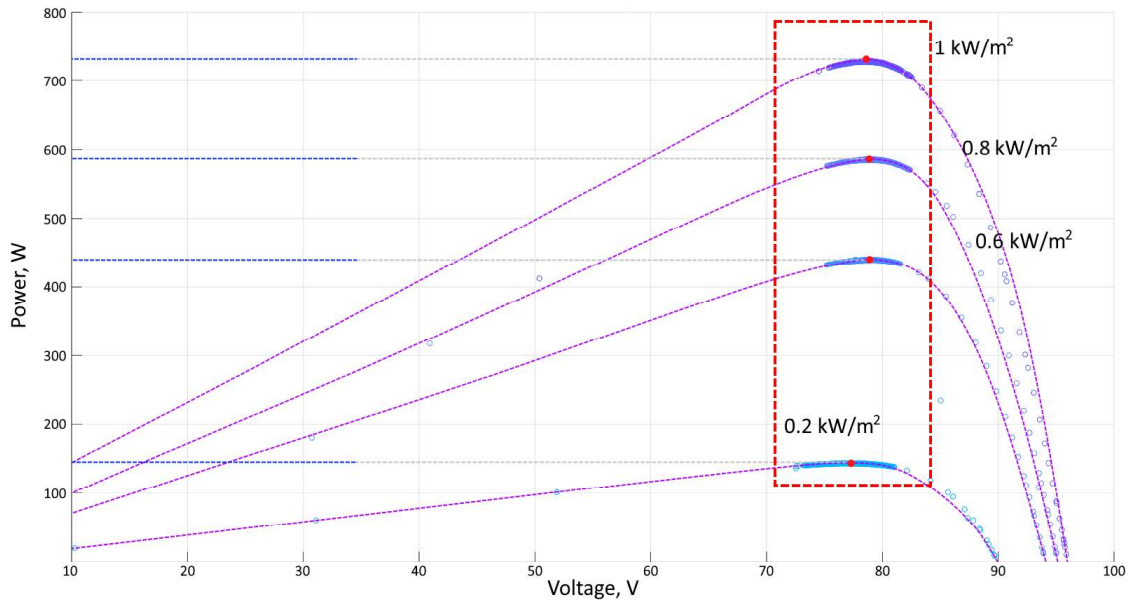


Figure 2.19: The MPPT curve and power points distribution around MPP with P&O algorithm (470uF capacitor and average measurement)

Comparing the graphical results of two algorithms the accuracy issue rises with the P&O algorithm. Voltage points spread wider. More detailed conclusions can be laid out by comparing errors.

2.4.3. Constant irradiance simulation comparison

During the simulation Root-Square-Mean Error and standard deviation were calculated for each case. Voltage dispersion is displayed graphically as well.

220uF, no average voltage			220uF, average voltage	
Irradiation, W/m^2	RMSE	STD	RMSE	STD
1000	1.166	1.156	0.841	0.841
800	1.338	1.234	1.069	1.062
600	1.009	0.951	0.672	0.659
200	2.326	2.126	2.176	2.09
470uF, no average voltage			470uF, average voltage	
Irradiation, W/m^2	RMSE	STD	RMSE	STD
1000	0.854	0.838	0.793	0.971
800	1.097	1.077	0.999	0.999
600	0.535	0.525	0.519	0.51
200	1.61	1.567	1.643	1.541

Table 2.3: Standard Deviation and RMSE results from MPPT charger controlled by Open Voltage Algorithm.

The **table 2.3** contains errors and standard deviations for each simulation case with different irradiation. Results show that the Open Voltage algorithm performs worse at low irradiance. However, there is a tendency for error to rise when irradiance is around $800 W/m^2$. This phenomenon might occur due to a lack of tuning in that irradiance range. When irradiance is high, the open-circuit voltage dependence seems to have a more curved shape, and MPPT becomes less accurate.

Calculations show clearly that results are the best when hardware and software improvements are combined. Higher capacitance only seems to show a bigger improvement than average from several samples only when irradiance is higher but in low irradiance cases, higher capacitance seems to perform better than the average-voltage-only case. In general contribution significance does not differ a lot in these two cases.

220uF, no average voltage			220uF, average voltage	
Irradiation, W/m^2	RMSE	STD	RMSE	STD
1000	1.807	1.675	1.715	1.673
800	1.639	1.633	1.707	1.55
600	1.906	1.907	1.784	1.774
200	2.197	2.14	2.207	2.194
470uF, no average voltage			470uF, average voltage	
Irradiation, W/m^2	RMSE	STD	RMSE	STD
1000	1.415	1.391	1.301	1.239
800	1.486	1.483	1.449	1.395
600	1.528	1.501	1.442	1.44
200	1.66	1.59	1.895	1.872

Table 2.4: Standard Deviation and RMSE results from MPPT charger controlled by P&O Algorithm.

Results in **table 2.4** show similar results — error and voltage dispersion increases with lower irradiance. This algorithm is simpler from a tuning perspective, thus results are more predictable. With this algorithm more clear contribution of different improvement methods difference is visible. P&O algorithm is more sensitive to noise because this algorithm uses two feedback variables which are multiplied to find power thus, the fluctuation range significantly increases.

Voltage dispersion histograms for both algorithms show that voltage spreads more on low irradiation conditions — dispersion becomes more square-shaped rather than parabolic-shaped. Implementation of one of the improvements led to a voltage range reduction of 1-2 volts and combined improvement resulted in a voltage range reduction of 2-4 volts.

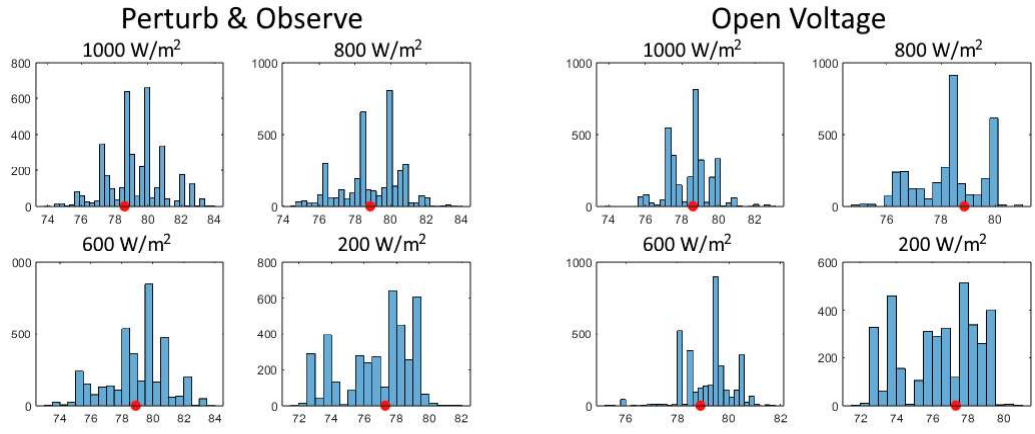


Figure 2.20: Voltage dispersion in case of both algorithms when input capacitor is 220uF and no sample averaging is implemented.

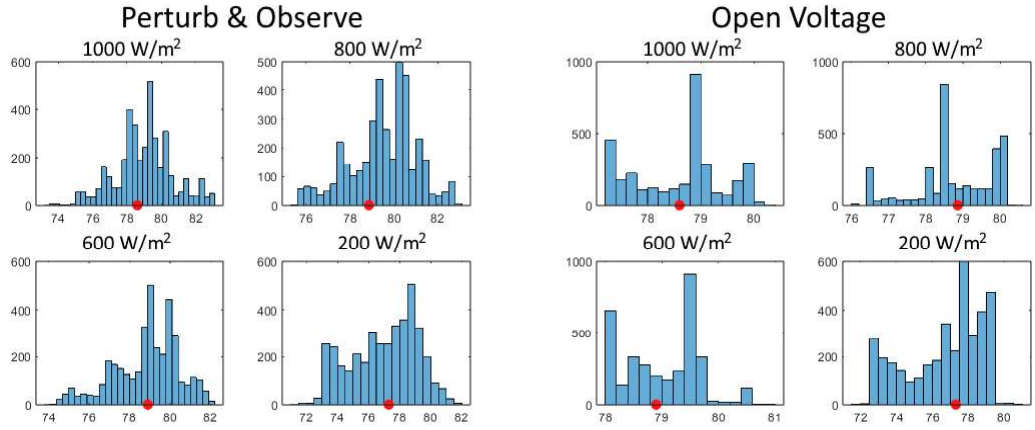


Figure 2.21: Voltage dispersion in case of both algorithms when input capacitor is 220uF and sample averaging is implemented.

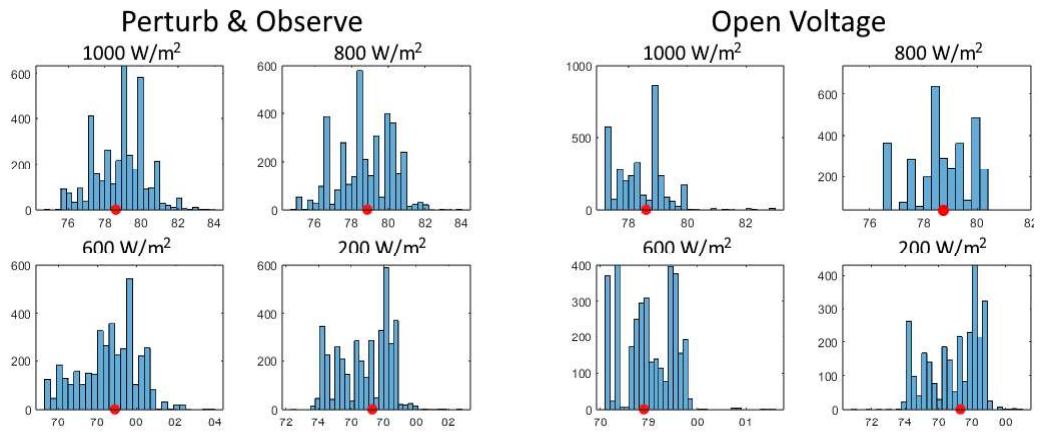


Figure 2.22: Voltage dispersion in case of both algorithms when input capacitor is 470uF and no sample averaging is implemented.

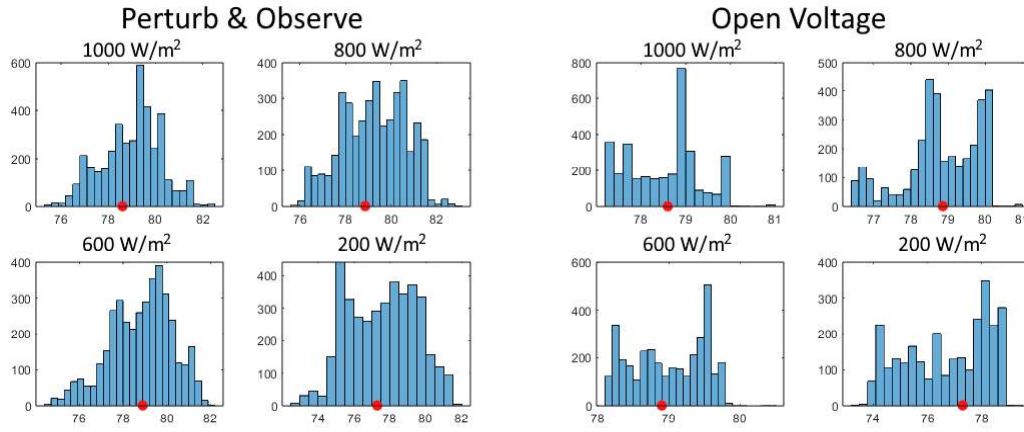


Figure 2.23: Voltage dispersion in case of both algorithms when input capacitor is 470uF and sample averaging is implemented.

It is clear that the P&O algorithm is less precise than Open Voltage. Yet the Open Voltage algorithm causes the system to lose some power due to periodical calibration. However, the objective of this comparison is to find which algorithm is better for this particular charger. These simulations showed the advantages and disadvantages of these two algorithms but it is unclear which disadvantages are more significant.

2.4.4. Short time changing irradiance model simulation

The most straightforward method to find the better algorithm for the MPPT charger is to compare power generation. For this purpose, the rising irradiance model was created. Irradiance starts with $100W/m^2$ and rises in a parabolic shape. Several time ranges in rising and maximum irradiance areas were chosen to imitate clouds and other shade-generating obstacles by creating irradiance drops. The simulation lasts for 10 minutes. It is assumed that shade covers the entire solar panel and multiple MPPs do not appear. For each algorithm, the best-performing case model was selected (both algorithms were most precise with 470uF capacitor and voltage sample averaging) and simulations were run. The overall result is displayed in **figure 2.24**

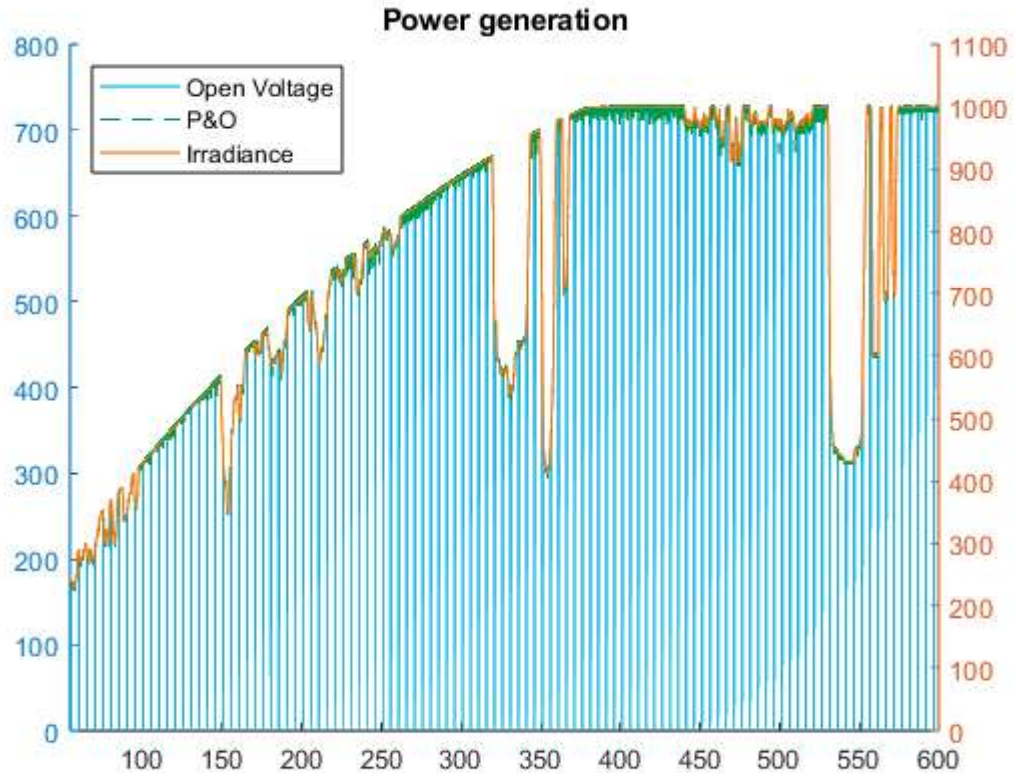


Figure 2.24: Power generation over a 600-second time period when irradiance is changing.

The detailed observation can show how power fluctuates in different situations. For example, it is clear how much power fluctuations differ between the two algorithms.

The **figure 2.25** displays a period of stable maximum irradiation value. During this time the Open Voltage algorithm is more stable than P&O. During the observation it was discovered that the only case of Open Voltage caused fluctuations being higher than P&O was when irradiation is below approximately $300W/m^2$ and is changing (**figure 2.26**). On the other hand, when irradiation is quickly changing in a higher range, the algorithm does not show a lower performance. This might be the case because open circuit voltage changes are not significant in the high irradiance range.

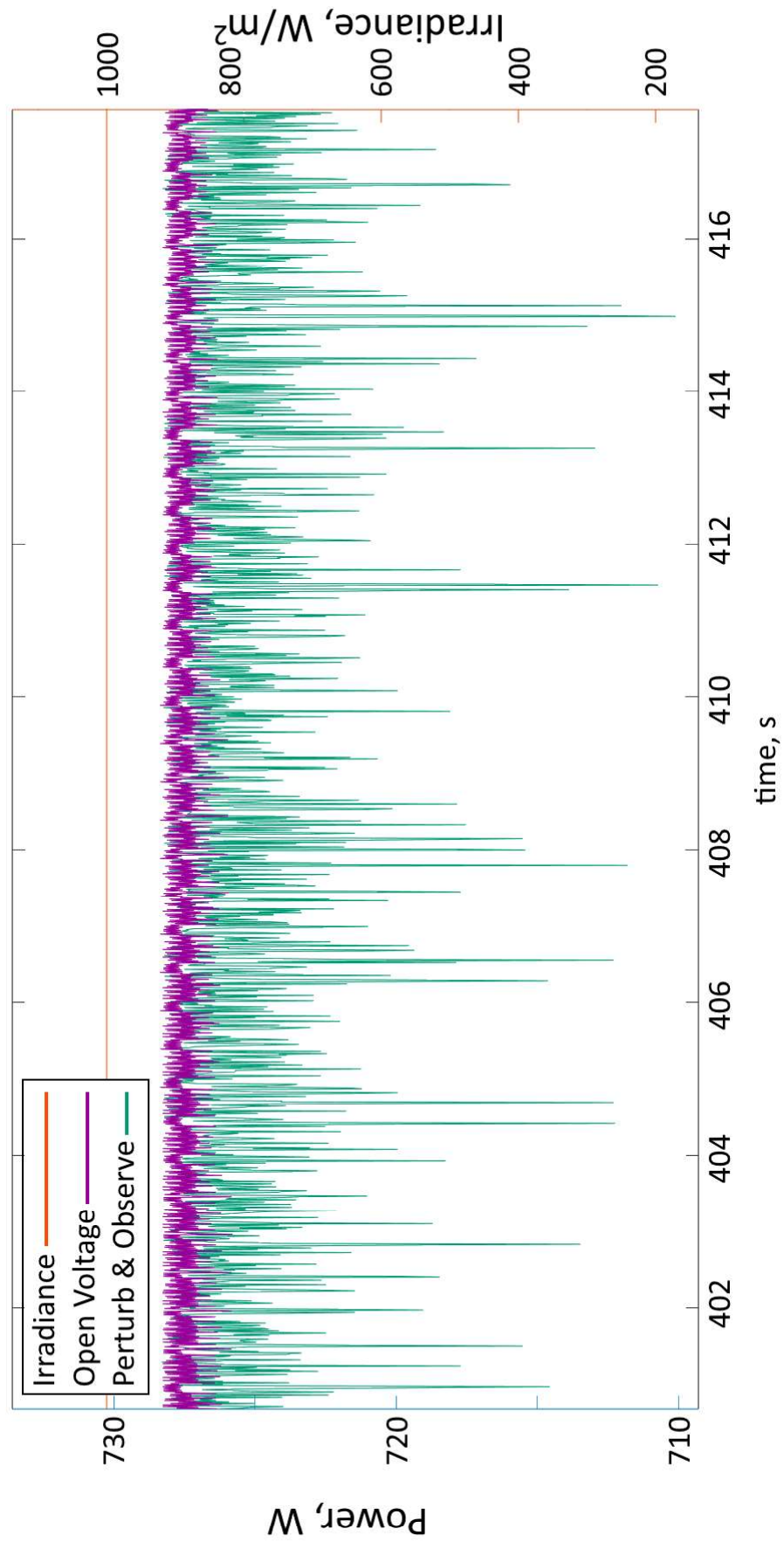


Figure 2.25: Power generation time when Irradiance is at the maximum point.

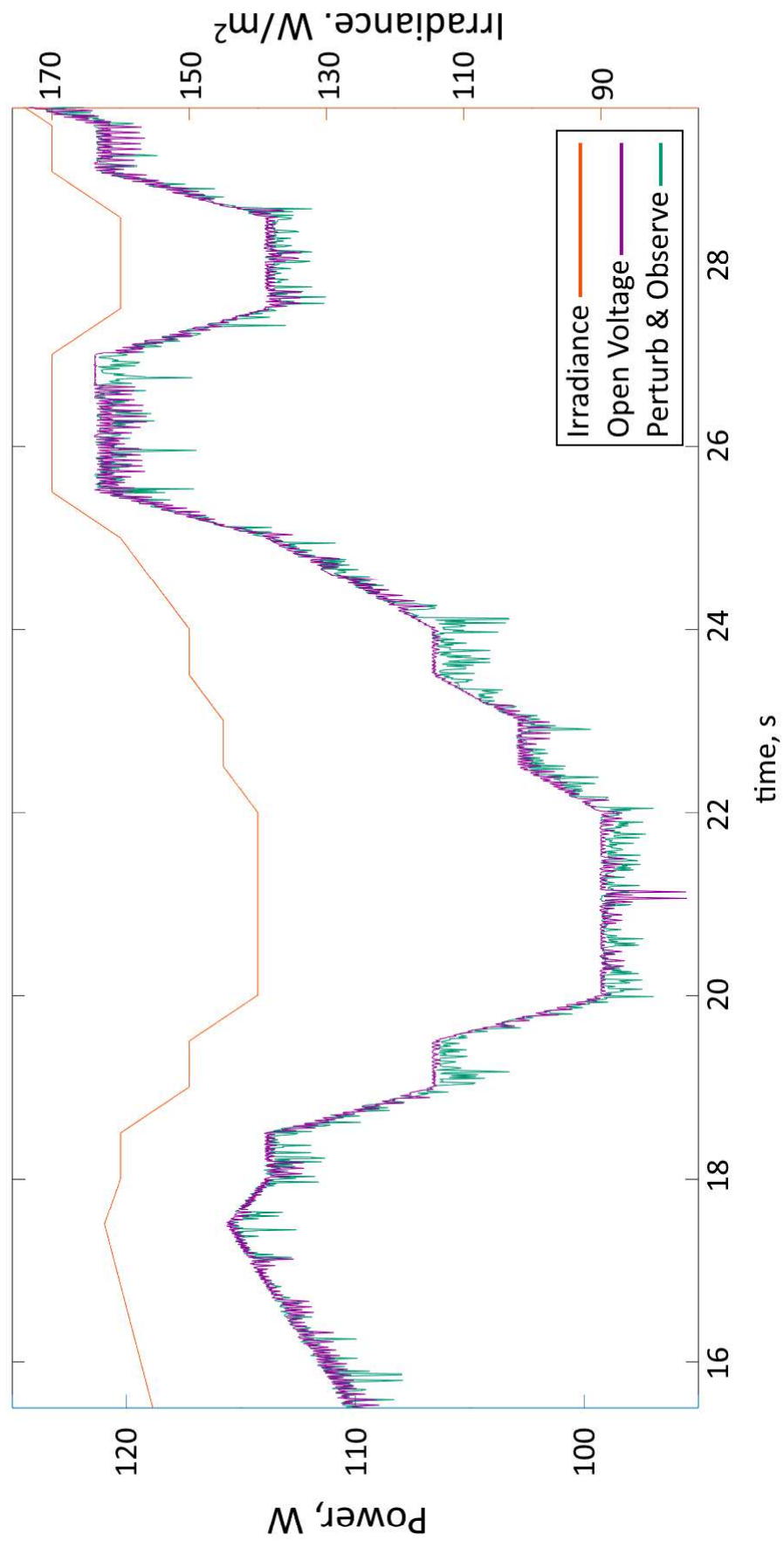


Figure 2.26: Power generation when irradiance is low.

These observations are important for algorithm improvement, however, these fluctuation differences are not significant for low-power solar devices such as the proposed MPPT charger. In order to find out the power extraction difference, the same simulation was run for both algorithms and the total generated energy was calculated. Calculation results show that despite high fluctuations P&O is generating more power than the OV algorithm.

Algorithm	Power, kW
Open Voltage	287,04
Perturb & Observe	306,42

Table 2.5: Power generation of OV and P&O algorithm

This difference occurs because the OV algorithm periodically measures open-circuit voltage. This process is periodical (visible in **figure 2.24**) and causes power drops for up to one second. This means that every several seconds power drops to half and over time nearly 7% of energy is lost. The problem could be reduced by reducing open-circuit voltage measurement frequency or by using a reference solar panel. this panel would not generate any power but work as an irradiation sensor. The charger system would not need to drop the duty cycle to measure the open circuit voltage. An auxiliary input should be integrated into the circuit of the MPPT charger for voltage measurement and additional options for the algorithm should be implemented.

To test the reference solar panel solution, an additional solar panel was added to the model, the voltage measurement routine was changed accordingly and calculations were made for the same time range and irradiation conditions. The new system eliminated duty cycle drop spikes and as a result, energy generation reached 307,17 kW. The OV algorithm indeed becomes even better than P&O but it is important to note that this much effort might be unreasonable. The system is designed for only 1kW and 0.2% improvement may not pay off, knowing the potential cost of additional hardware. Meanwhile, the P&O algorithm is cheaper and makes the system simpler.

2.5. Battery charging analysis

All previous simulations were run with constant load. Since the proposed buck converter is designed for battery charging purposes it is important to understand how it behaves by connecting a battery. In this simulation, several different voltage batteries were tested under different irradiation

values. Duty cycle change and PV curve were observed to find the most suitable battery voltage and potential issues. As the Perturb and Observe algorithm performed the best, it was used in this simulation too.

For this research batteries with nominal voltage of 12V, 24V, 36V and 48V were tested at irradiation values of $1000W/m^2$, $600W/m^2$ and $200W/m^2$. The state of charge (SOC) is below 10%. The first simulation **figure 2.27** shows that the duty cycle stays below 0.5 and drops as irradiation gets lower. As the simulation went through different battery voltages the tendency appeared that the P&O algorithm adjusts according to load conditions, still performing well while tracking maximum power point. However, the higher the battery voltage, the bigger the duty cycle is. A good example is in **figure 2.28** where the duty cycle increases over time as the battery is charging. Thus, it is possible to observe the duty cycle dependency on the load when the P&O algorithm is implemented.

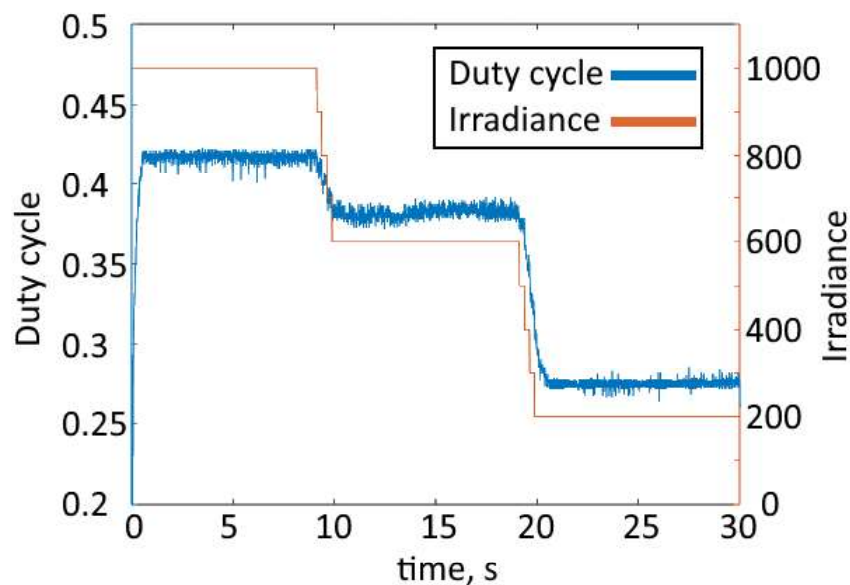


Figure 2.27: Duty cycle over time under different irradiation. Battery voltage at the output is 12V.

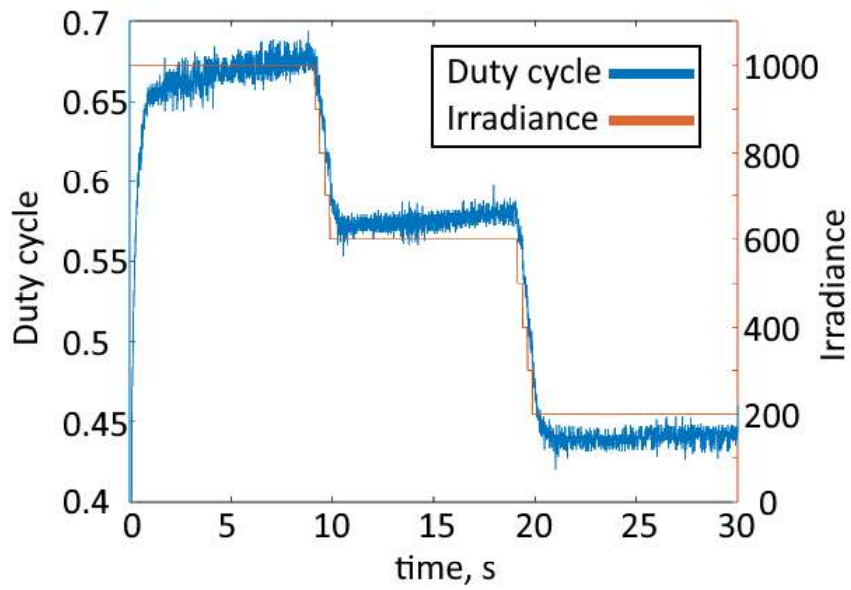


Figure 2.28: Duty cycle over time under different irradiation. Battery voltage at the output is 24V.

Following the duty cycle change tendencies it is interesting to find out when the duty cycle reaches 1 and what effect this condition will have on the MPPT algorithm. 48V battery simulation reached a stable duty cycle value of 1 under maximum irradiation. The 36V battery simulation seems to reach a duty cycle value of 0.9 but it is important to remember that the SOC of all batteries at the beginning of the simulation was below 10% which means that load is just beginning to increase.

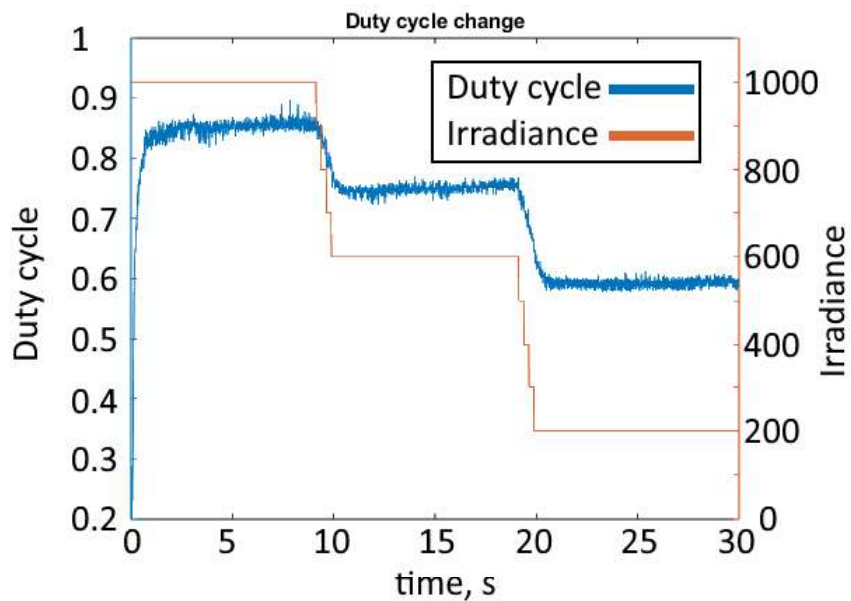


Figure 2.29: Duty cycle over time under different irradiation. Battery voltage at the output is 36V.

Additional testing showed that a 36V battery at the output causes the duty cycle to reach 1 when SOC reaches approximately 43%. As the duty cycle is 1, the battery is charging directly from the solar panel. This research is based on computer simulations thus it is not possible to precisely predict the potential results of such operating conditions. However, some predictions could be derived. One of them is that the primary MOSFET transistor in the input of the buck converter may overheat and get permanently damaged. The suggestion would be to limit the duty cycle but the exact limitation could be derived only by testing a physical device. Another prediction is that high voltages in the output can create a reverse current. The reverse current can appear in case of high capacitance or voltage in the output [52]. The proposed MPPT charger has reverse current protection but to ensure robust operation of the MPPT charger it would be better to limit battery nominal voltage as the duty cycle stays at lower levels over the entire charge cycle when 12V and 24V batteries are connected.

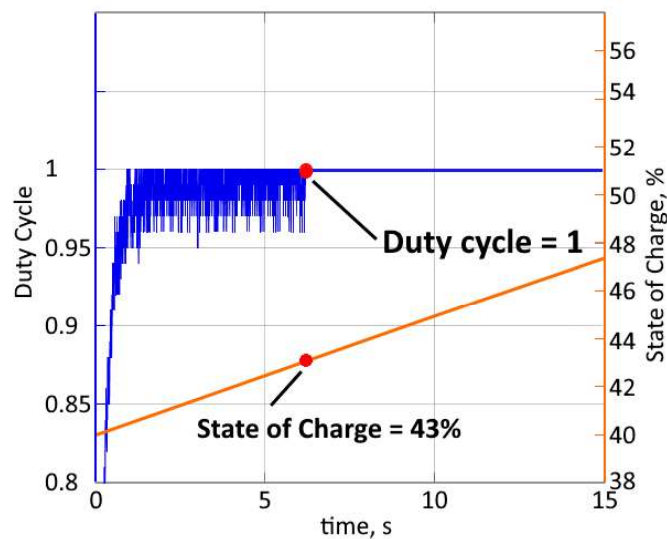


Figure 2.30: The SOC when the duty cycle reaches a stable value of 1. Battery voltage is 36V.

Even though the 12V battery does not drive the duty cycle up, it is worth mentioning that the low duty cycle could damage the Buck converter too. As the duty cycle gets lower for primary MOSFET, the longer low-side MOSFET stays switched on. If it is assumed that MOSFETs are not ideal devices, the conclusion can be drawn that the switching time of the MOSFET is not equal to 0. Thus, it is possible that when the duty cycle is low, the low-side MOSFET can be shorted and as a result, could overheat. Thus, the duty cycle should have not only a ceiling but a floor limit as well. The problem would be that in some cases the maximum power point would not be reachable. In conclusion, the best battery for the proposed charger is with a nominal voltage of 24V.

CONCLUSIONS

The research was conducted by running a series of simulations for the proposed BUCK converter-based solar MPPT charger. Simulation results were used to compare behavior and performance in hardware and firmware layers.

The parameters for the BUCK converter were calculated and tested in Spice simulation. The inductance was calculated and the result was 706 μ F but the simulation showed improvement in the transient process when inductance was 600 μ H. The transient process time dropped by 23%. The calculated minimum capacitance was 3.5 μ F and the simulation showed that increasing capacitance to 50 μ F does reduce ripple voltage and does not cause any overshoot. The transient process time drops by 40%. It is decided to carry on with an inductance of 600 μ H and a capacitance of 50 μ F.

The comparison of synchronous and asynchronous buck converters showed how diode replacement with MOSFET improves all in all efficiency up to 10%. However, it is important to address the design challenges of a synchronous buck converter. One of the challenges is reverse currents in high-level MOSFET.

Two most popular MPPT algorithms were compared. Several simulations were run. Each simulation was improved by increasing input capacitance, calculating the average of voltage and current samples, and combining both. These system improvements were differently affecting both algorithms, but the combination of improvements showed the best results in MPPT precision. The more precise algorithm turned out to be the Open voltage algorithm which demonstrated 40% lower fluctuations and range of MPP voltage. However, the constant duty cycle drop required for MPP voltage recalculation turns out to be a major reason for power loss. According to simulation results the P&O algorithm outperforms Open voltage by 7%. Of course, it is possible to improve the Open Voltage system, but it would require additional hardware for reference which would require additional investment and would potentially reduce precision. In an optimistic case, efficiency

improvement for small-size systems would be negligible. In general, P&O is cheaper and more simple to implement as well as more efficient.

The battery simulation showed the behavior of the MPPT charger when the output is with a different load. A 24V battery seems to be the best for usage. Higher or lower-voltage batteries can drive the duty cycle to boundaries. It is especially visible with higher voltage batteries. Safety mechanisms should be implemented to not overheat electronic components in the circuit. This would potentially reduce MPPT tracking capabilities thus, the recommendation would be to keep the nominal voltage which did not drive the duty cycle to limits.

In general, the investigated device could be a component of a microinverter and could add some wanted features for a small solar power plant. In case of a solar energy shortage, the battery could contribute to the Home AC network and charge up during sunny days, as the microinverter would supply surplus power to the network.

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ADDENDUM

Open Voltage algorithm with a single measurement

```
function D = mpptFind(Vpv, t)
persistent Vmppt lastTime tLast delay Dprev Dcalc vBuffer i
if isempty(lastTime)
    lastTime = 0;
end
if isempty(delay)
    delay = 0.015;
end
if isempty(Vmppt)
    Vmppt = 78.6;
end
if isempty(Dprev)
    Dprev = 0.7;
end
if isempty(Dcalc)
    Dcalc = 0;
end
if isempty(tLast)
    tLast = 0;
end
if isempty(vBuffer)
    vBuffer = [0,0,0,0,0];
end
```

```

if isempty(i)
    i = 1;
end

%Periodical derivation of MPP Voltage
if t - lastTime >= 0.015 && delay == 0.015
    if Vpv >= 87.26
        if Vpv >= 93.26
            if Vpv >= 95.13
                if Vpv >= 95.42
                    Vmppt = (Vpv-95.42)/(96-95.42)*(-0.66) +
                        + 79.26;
                else
                    Vmppt = (Vpv-95.13)/(95.42-95.13)*0.41 +
                        + 78.85;
                end
            else
                Vmppt = (Vpv-93.26)/(95.13-93.26)*(78.85-78.94) +
                    + 78.94;
            end
        else
            Vmppt = Vpv^4*(-2.9942e-05) + Vpv^3*0.007538 +
                + Vpv^2*(-0.6314) + Vpv*18.4591 -3.50399e-08 - 0.3;
        end
    else
        Vmppt = Vpv/87.26*75.23;
    end
    delay = 5;
    lastTime = t;
elseif t - lastTime >= 5 && delay == 5

```

```

        Dcalc = 0;
        lastTime = t;
        delay = 0.015;
    end

    %Moving Duty Cycle
    if delay ~= 0.015 && t - tLast >= 0.015
        if Vpv > Vmppt
            Dcalc = Dcalc + 0.01;
            if Dcalc > 1
                Dcalc = 1;
            end
        elseif Vpv < Vmppt
            Dcalc = Dcalc - 0.01;
            if Dcalc < 0
                Dcalc = 0;
            end
        end
    end

    tLast = t;
end

%Return Duty Cycle
D = Dcalc;
end

```

Open Voltage algorithm with an average of five measurements

```

function D = mpptFind(Vpv, t)
persistent Vmppt lastTime tLast delay Dprev Dcalc vBuffer i
if isempty(lastTime)
    lastTime = 0;
end

```

```

if isempty(delay)
    delay = 0.015;
end
if isempty(Vmppt)
    Vmppt = 78.6;
end
if isempty(Dprev)
    Dprev = 0.7;
end
if isempty(Dcalc)
    Dcalc = 0;
end
if isempty(tLast)
    tLast = 0;
end
if isempty(vBuffer)
    vBuffer = [0,0,0,0,0];
end
if isempty(i)
    i = 1;
end

%Periodical derivation of MPP Voltage
if t - lastTime >= 0.015 && delay == 0.015
    if Vpv >= 87.26
        if Vpv >= 93.26
            if Vpv >= 95.13
                if Vpv >= 95.42
                    Vmppt = (Vpv-95.42)/(96-95.42)*(-0.66) +
                        + 79.26;
                end
            end
        end
    end
end

```

```

        else
            Vmppt = (Vpv-95.13)/(95.42-95.13)*0.41 +
                + 78.85;
        end
    else
        Vmppt = (Vpv-93.26)/(95.13-93.26)*(78.85-78.94) +
            + 78.94;
    end
else
    Vmppt = Vpv^4*(-2.9942e-05) + Vpv^3*0.007538 +
        + Vpv^2*(-0.6314) + Vpv*18.4591 -3.50399e-08 - 0.3;
end
else
    Vmppt = Vpv/87.26*75.23;
end
delay = 5;
lastTime = t;
elseif t - lastTime >= 5 && delay == 5
    Dcalc = 0;
    lastTime = t;
    delay = 0.015;
end

%Moving Duty Cycle
if delay ~= 0.015 && t - tLast >= 0.003
    vBuffer(i) = Vpv;
    if i < 5
        i = i + 1;
    else
        i = 1;
    end
end

```

```

        tmp = mean(vBuffer);
        if tmp > Vmppt
            Dcalc = Dcalc + 0.01;
            if Dcalc > 1
                Dcalc = 1;
            end
        elseif tmp < Vmppt
            Dcalc = Dcalc - 0.01;
            if Dcalc < 0
                Dcalc = 0;
            end
        end
    end
end
tLast = t;
end
%Return Duty Cycle
D = Dcalc;
end

```

Perturb & Observe algorithm with a single measurement

```

function D = mpptFind(Vpv, Ipv, t)
persistent Dcalc Pprev Vprev lastTime tLast i vBuffer //
// iBuffer delay stepD

if isempty(Dcalc)
    Dcalc = 0;
    Vprev = 80;
    Pprev = 20;
    lastTime = 0;
    stepD = 0.01;
    delay = 0.003;

```

```

D = 0;
vBuffer = [0,0,0,0,0];
iBuffer = [0,0,0,0,0];
i = 1;
end

%Periodical calculation
if t - lastTime >= delay
    Ppv = Ipv*Vpv;
    if Vpv < Vprev && Ppv > Pprev
        Dcalc = Dcalc + stepD;
    elseif Vpv < Vprev && Ppv < Pprev
        Dcalc = Dcalc - stepD;
    elseif Vpv > Vprev && Ppv > Pprev
        Dcalc = Dcalc - stepD;
    elseif Vpv > Vprev && Ppv < Pprev
        Dcalc = Dcalc + stepD;
    end
    %Keeping Duty Cycle in boundaries
    if Dcalc > 1
        Dcalc = 1;
    elseif Dcalc < 0
        Dcalc = 0;
    end
    lastTime = t;
    Vprev = Vpv;
    Pprev = Ppv;
end

%Returning Duty Cycle

```

```
D = Dcalc;
```

```
end
```

Pertrub & Observe algorithm with an average of five measurements

```
function D = mpptFind(Vpv, Ipv, t)
persistent Dcalc Pprev Vprev lastTime tLast i vBuffer //
// iBuffer delay stepD
```

```
if isempty(Dcalc)
    Dcalc = 0;
    Vprev = 80;
    Pprev = 20;
    lastTime = 0;
    stepD = 0.01;
    delay = 0.003;
    D = 0;
    vBuffer = [0,0,0,0,0];
    iBuffer = [0,0,0,0,0];
    i = 1;
```

```
end
```

```
if t - lastTime >= delay
    %filling buffers
    vBuffer(i) = Vpv;
    iBuffer(i) = Ipv;
    if i<5
        i = i + 1;
    else
        %Periodical calculation
```

```

    Ptmp = mean(iBuffer)*mean(vBuffer);
    Vtmp = mean(vBuffer);
    if Vtmp < Vprev && Ptmp > Pprev
        Dcalc = Dcalc + stepD;
    elseif Vtmp < Vprev && Ptmp < Pprev
        Dcalc = Dcalc - stepD;
    elseif Vtmp > Vprev && Ptmp > Pprev
        Dcalc = Dcalc - stepD;
    elseif Vtmp > Vprev && Ptmp < Pprev
        Dcalc = Dcalc + stepD;
    end
    if Dcalc > 1
        Dcalc = 1;
    elseif Dcalc < 0
        Dcalc = 0;
    end
    i = 1;
    lastTime = t;
    Vprev = Vtmp;
    Pprev = Ptmp;
end
end

%Returning Duty Cycle
D = Dcalc;

end

```