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DC-DC Converter for PV Module Integration

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By signing the document, members of the group accepts that the entire group have participated in the work of the report. Therefore, all members vouch for the content of the report, and confirms that it doesn't include plagiarism.

Contents

Preface

This paper describes the "P0" report of the group project "DC-DC converter for PV module integration." It has been developed from the 10^{th} of September to the 9^{th} of October 2018, at Aalborg University, Institute of Energy, by the group INTRO-760.

The "P0" is an initially report which discusses research about maximizing the power from PV modules. Furthermore a theoretically comparison between different converter topologies has been done. After "P0" there will be a "P1" report which will include the entire project.

The literature references are shown in square brackets, with a number referring to a specific document which can be found in the bibliography. Pictures and tables will be denoted in the X,Y format, with X representing the chapter and Y the figure or table number.

The process and development of "P0" has been based on the Problem Based Learning (PBL) method. This method is explained in the appendix. The group will continue this way of doing it for the "P1" report.

Summary

A DC-DC converter is designed to maximize the power generation of PV modules under mismatch conditions. These mismatches might appear due to partial shading, uneven dirt distribution or manufacturing differences among others. The DC-DC converter is connected to each PV panel becoming a module integrated converter (MIC).

An overview of the different DC-DC topologies has been performed, the bidirectional buck-boost converter has been selected because it best fulfills the requirements of high efficiency, bidirectional energy flow and input voltage increase and decrease capability. An analysis of the input and output conditions has been done. For this, commercial grid inverters and PV modules' figures of merit have been evaluated.

The future work of this project will cover the design and implementation of a MIC valid for generic PV modules. Design, simulation, implementation and testing will be performed and conclusions on the project will be drawn.

Nomenclature

Abreviations:

AC	Alternating Current
DC	Direct Current
FET	Field-Effect Transistor
IC	Integrated Circuit
MIC	Module Integrated Converter
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
PV	Photovoltaic
PWM	Pulse Width Modulation
SEPIC	Single Ended Primary Inductance Converter
STC	Standard Test Conditions

Symbols:

η	Efficiency
ºC	Degree Celsius
D	Duty Cycle
E	Energy
I	Current
I_{mpp}	MPP Current
I_{sc}	Short Circuit Current
P	Power
P_{max}	Maximum Power Point
t	time
V	Voltage
V_{mpp}	MPP Voltage
V_{oc}	Open Circuit Voltage
W	Watt
W/m^2	Thermal Flux

Introduction 1

To this date, sustainable energy sources have become an area in focus worldwide in an attempt to reduce the environmental impact due to emissions of CO_2 and other greenhouse gasses. The development of competitive systems to exploit renewable energy sources is the best alternative to reduce the use of fossil fuels for the production of electricity. Over the last years there have been a considerable increase in electricity production from renewable energy sources being the fastest growing sector wind and solar energy. In 2017, solar photovoltaic was the renewable energy source which experienced the highest increased in newly installed capacity amounting a total installed capacity of approximately 402 GW[2].

Photovoltaic (PV) is referred to the production of electricity in the form of direct current (DC) directly from sunlight shining on solar cells. Solar cells are semiconductor devices which typically can produce around 0.5 V DC so they are series connected to form a PV module/panel which can also be connected to other PV panels resulting in a PV array [3]. This way, according to the system's requirements, the PV panels can be interconnected in series or parallel in order to get at the output a higher voltage or current, respectively. Connecting PV panels either in series or parallel will result in an increase of the system's overall electricity production.

Nevertheless, it is essential to keep into consideration the mismatches that may appear between the power generated by the different PV panels, which will result in losses in the PV system and thus in a lower efficiency. Mismatches occur when the PV modules operate in a different operating point than its maximum power point (MPP) due to partial shading, manufacturing tolerances, defects in the PV modules due to weather conditions and aging, among others. Even a small mismatch in one of the PV modules can result in a very high reduction of the power production from the entire PV array [4]. Mismatch losses in a PV system can be reduced by forcing every PV module to work at its MPP by using a technique known as Maximum Power Point Tracking (MPPT). This can be reached by using electronic devices called Module Integrated Converters (MICs) which basically consist on DC-AC micro inverters or DC-DC converters that incorporate a MPPT controller unit to ensure that the output power of the MIC is the one corresponding to the MPP of the PV module.

This project focuses on the design and test of a MIC based on a non-inverting buck-boost DC/DC converter for integration with a PV module in order to operate at its MPP and thus harvest maximum energy from the sunlight.

1.1 PV generation

The phenomenon on which the transformation of solar energy to electrical energy is based is known as the *Photovoltaic effect*. This phenomenon was first discovered by a French physicist named Edmond Becquerel in 1839 and is based on the emission, from the sunlight or light, of massless photons which collate on two superimposed layers of semiconductor material causing some of the electrons to flow and, hence, allowing the generation of voltage and electric current. Solar PV cells are made of a negative charged layer (n-layer) and a positive charged layer (p-layer) of a semiconductor material, usually crystalline silicon, joined establishing a pn-junction. If photons emitted by the light, when they collide with the n-layer, have enough energy to excite the electrons an electric field will be formed in the p-n junction due to the attraction of electrons and holes. This electric field will work as a diode permitting the separation of the positive and negative charge carriers. This way electric current will flow across the pn-junction allowing the generation of electric energy. The greater the intensity of the light (irradiance) that is absorbed by the PV panel the higher the amount of electric power generated. On the other hand, the efficiency of the panel will decrease with the temperature. Usually, PV panels are tested under standard test conditions (STC) which is at 25°C and 1000 W/m^2. Some of the most important characteristics associated with a PV panel's datasheet are the following: maximum power point (Pmax), open-circuit voltage (Voc), short-circuit current (Isc), MPP voltage (Vmpp), MPP current (Impp) and efficiency (η). These features are important to define the I-V curves of the PV panel in order to develop the MPPT controller unit. Figure 1.1 shows a block diagram with the main parts of a PV system.

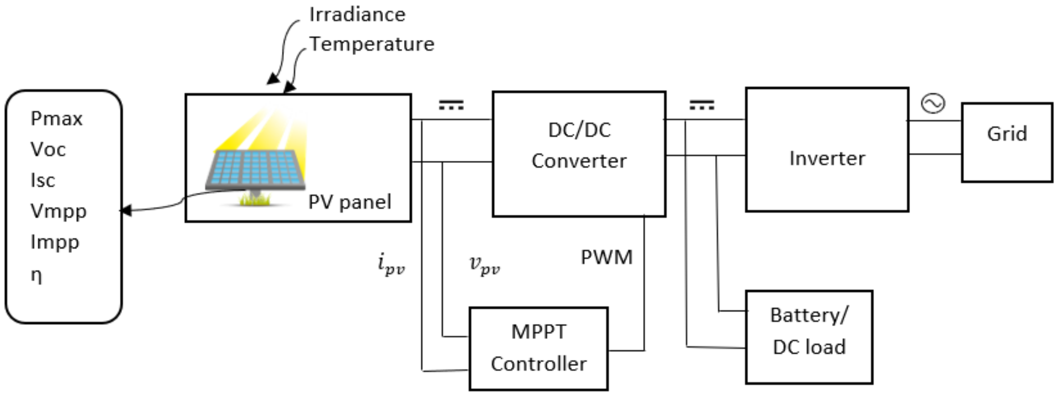

Figure 1.1. Basic diagram of a PV grid-tie with battery backup system.

PV systems can be classified in three main types: off-grid, grid-tie and grid-tie with battery backup (hybrid) systems. Off-grid systems are not connected to the grid which means that the power generated by the PV modules is storage in a battery bank for later use. In grid-tie systems the DC current is converted, using an inverter, into a high voltage AC current compatible with the grid. Nowadays, grid-tie systems are the most common, however, its main disadvantage is that it does not have battery backup which means that if there is a power outage the PV system will also be cut. The solution to this problem is the grid-hybrid system which is a combination of a grid-tie system with a bank of batteries. This way it is possible to store energy and there is a battery backup in case of power outage.

1.2 MIC implementation

One of the most important factors to take into consideration when implementing photovoltaic (PV) modules is to obtain the maximum energy possible out of the available hardware, if this is not done, energy that should have been obtained will instead be lost. Since energy (E) is equal to power (P) over time (t), power must be maximized when the energy is being extracted. To achieve such goal a maximum power point tracker needs to be implemented, this is an electrical system that is always on the search of the location of the point where power extraction can be peaked.

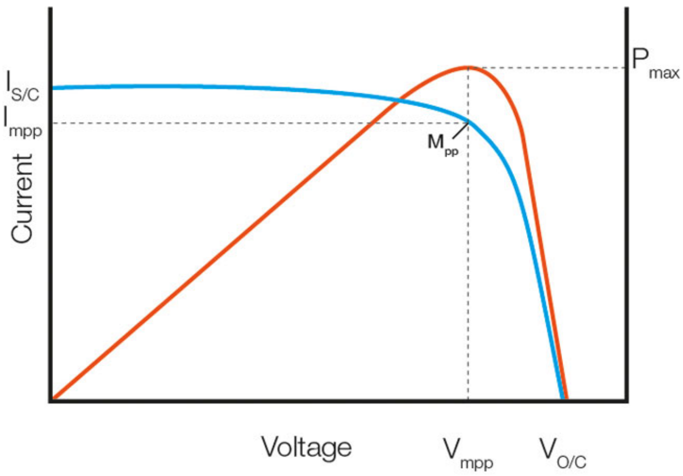

Figure 1.2. Maximum Power Point of generic solar panel [5].

MPPTs mostly consist on a power circuit that regulates either voltage drop or current flow across the PV terminals. There are many kinds of circuits that can be used to follow the maximum power point (MPP) of the PV, this topic will be further introduced in section blabla. However, solar plants and domestic used installations are composed of many modules, these modules are then connected to each other in series, parallel or in antiparallel configurations. To simplify the system, one MPPT is commonly used for many modules, this approach may lead to imperfections in the efficiency rates since the lower power generation of one module will then produce imperfections in the tracking system. This project focuses on the implementation of module integrated dc-dc converters (MICs). Using MICs for each module results in higher overall efficiencies, with this technology, events like partial shading, uneven dirt or wear distribution or imperfections produced in the assembly line are reduced and do not affect the rest of the modules in a line. Also, a more detailed control of the plant is achieved since separate data from each individual panel is obtained. Different implementation options for MIC devices are possible but the most important objective of these devices is to individually control each module, resulting on an overall better efficiency rate, as well as a more robust system against any kind of inclemency. Each PV module will then be connected directly to each MIC, with this setup the output voltage and current are regulated by the device that extracts the energy, either an inverter, a battery or a load, allowing the system to work at different voltage and current levels whilst maintaining the MPP at all time.

Background of converter topologies 2

2.1 Buck-converter

The task of a buck converter is to be changing the input voltage to a lower output voltage. The components, which are needed, are a DC-source for input voltage, a switch contained a diode and a MOSFET, an inductor, a capacitor and a resistor for the load. The equivalent diagram in figure 2.1 illustrated a buck-converter.

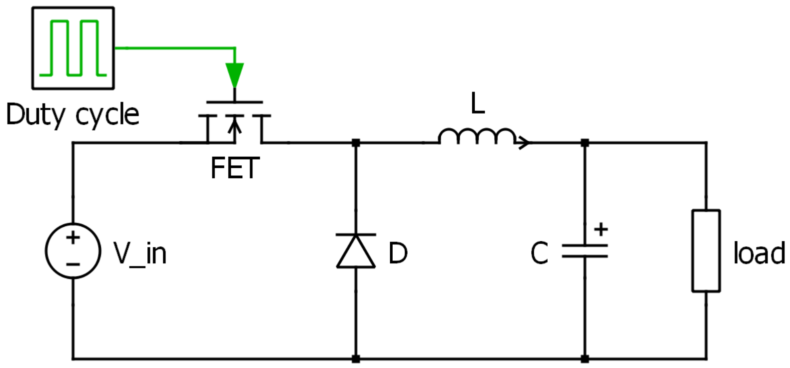

Figure 2.1. Buck-converter.

A buck-converter perform in two operating modes. In both operating modes have been an approach that the converter is in steady state. Because of that the average of a value is constant and we can assume a DC-voltage at the load. At the case, that the MOSFET conducts current, the diode will be closed and the voltage drops at the inductor. Thus, you can measure a lower voltage at the load. Besides that, the capacitor is loaded energy and the inductor is loaded current. If the MOSFET doesn't conduct current, the inductor will work as a current source and feeds the closed circuit with current. The capacitor is discharging and supplied the load.

The advantage for using a buck converter is that the structure is very simple and you need one power switch. The size for the component is small and the cost for this are low. Furthermore, the buck converter has a high efficiency of over 90%.

A disadvantage using a buck converter is, that the output ripple is high. With an elecrtronic filter it is possible to reduce the ripple.[**advantagebuck**]

2.2 Boost-converter

A boost converter produces a higher output voltage in comparison to the input voltage. The circuit exists of a switch, which obtains a diode and a MOSFET, an inductor, a conduct a resistor as a load and a DC-Source for the input voltage.Figure 2.2 shows an equivalent circuit diagram with the above-called components. Also we can apply for the boost-converter the steady state.

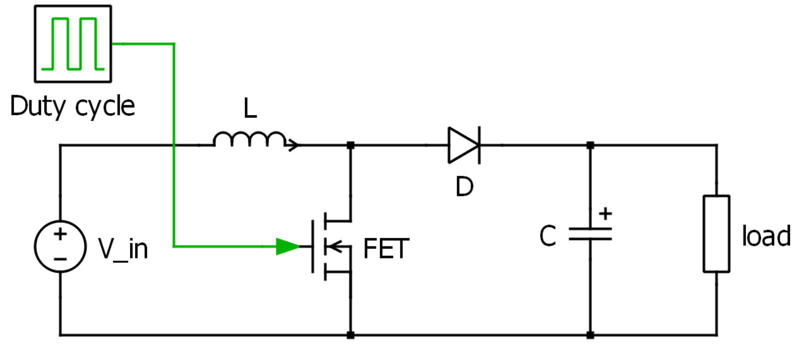

Figure 2.2. Boost-converter.

If the swit s closed, the inductor will increase the current in the circuit and it stored energy in itself. If the MOSFET is on, the current will flow only through the inductor because the diode is closed. The inductor increases the current in the circuit. Meanwhile, the capacitor releases the stored energy to the load. Thus, the output voltage decreases slowly. In the other case, when the MOSFET doesn't conduct, the diode lets the current flow through the right side of the circuit. The current decrease in the whole circuit because of the higher impedance in this mode and the polarity of the inductor inverses itself. Therefore, the inductor performs as a source and the output voltage will be higher than the input voltage. Furthermore, the capacitor is charged.

An advantage for a boost converter is that it can raise the output voltage without help from a transformer.

The size for the inductor and capacitor will have to be large, if you want a output without ripple urthermore changing the output voltage to big difference potential in the duty cycle can destroy components.[**advantageboost**

2.3 Flyback

The flyback converter is another option for a DC-DC converter. It comes with galvanic isolation between the input and outputs. The flyback converter is basically a buck-boost converter, but here the inductor is split to form a transformer. The windings of the transformer can have different turns ratio and in that way it is possible to step the voltage and current both up or down.

The basic circuit of the topology can be seen in figure 2.3. It uses a switch, a diode and a single control device.

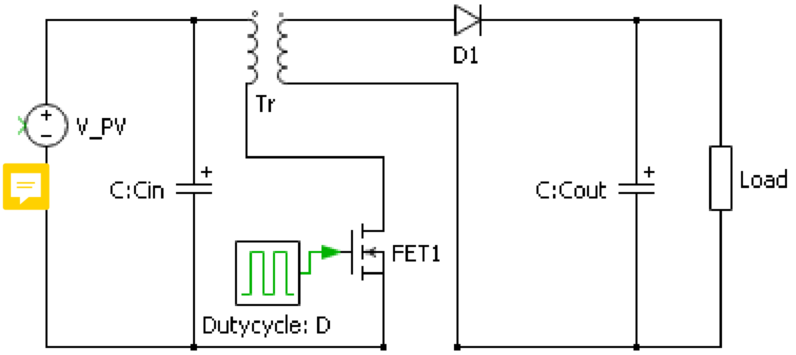

Figure 2.3. Flyback converter

When the MOSFET is on, the energy is transferred from the input voltage source to the transformer. In this state the output capacitor will supply the load with the output voltage. In the off-state the transformer will supply the output load with energy while it charges the capacitor as well. [7]

Because of the single control device another advantage of the flyback converter is a wide choice of controllers. For example it is possible to directly connect a PWM controlled IC to control the MOSFET, and by that the converter.

The drawbacks are primary the current and voltage waveforms. The stress on the switch and diode can be high and comes as a function of the turns ratio of the transformer. Furthermore the leakage inductance from the transformer will result in a big voltage spike at the rising edge of the MOSFET. This needs to be reduced by a snubber circuit. This will increase the power loss and efficiency though. The leakage inductance will also produce transients which will make the voltage stress at the MOSFET bigger and give high-frequency ringing at the input. Lastly there will be increased noise at both terminals due to the fact that the input and output currents are discontinous.[8]

2.4 Non-inverting buck-boost converter

The Non-inverting Buck-Boost converter is a DC to DC converter that allows the voltage at its output to be higher or lower than the voltage at its input. The topology can be seen in figure 2.4. It uses 4 switches, of which 2 are controlled devices.

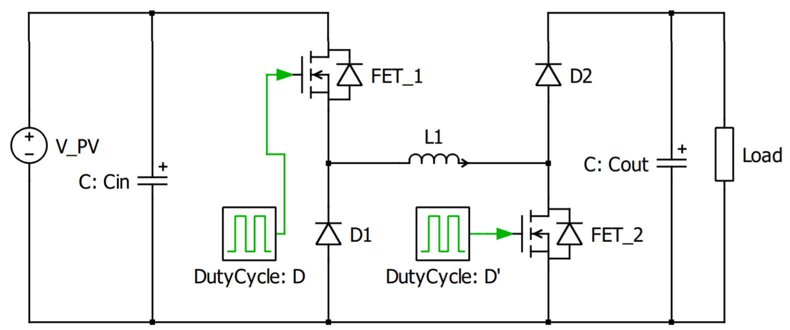

Figure 2.4. Non-inverting buck-boost converter.

The controller can force the system to work in any of the following modes:

1. Buck $\rightarrow D \subset [0, 1]; D' = 0$
2. Boost $\rightarrow D = 1; D' \subset [0, 1]$
3. Buck-Boost $\rightarrow D \subset [0, 1]; D' \subset [0, 1]$

One of the main drawbacks of the topology is the control's complexity, which must calculate the appropriate duty cycle D and D' in any of the modes and also the transition between these modes.

Usually the inverter's input voltage is fixed to some value higher than the grid's voltage. The possibility of higher and lower voltages at the converter's output allows different ways of associating photovoltaic modules. Then the user is able to arbitrarily decide how many PV modules to link in series. Differently of what would happen in the case of Buck or Boost converters where the constraints regarding the number of panels are tighter.

Compared with other topologies that can have both higher and lower voltages at the output, such as the SEPIC or ZETA converters, this converter features a single inductor and no intermediate capacitor. With such reduction in passive components the price, efficiency and power density rises significantly [Under the hood of a noninverting buck-boost converter].

Although this topology exhibits appropriate features, it can be further improved by replacing the diodes by MOSFETs. The circuit may be seen in figure 2.5, it's called Bidirectional Non-Inverting Buck-Boost converter. With this variation, the following changes occur:

1. The system becomes bidirectional.
2. The conduction losses are decreased. −> **Discuss with supervisor**

If the system is bidirectional it can be used in different MIC strategies, such as ++**reference to the introduction figure with the MICs outputting power to the PV**++. Or even implement diagnosis features with the panels' electroluminescence, whenever these are fed enough power.

As seen in figure 2.5, notice that duty cycles of the switches that replace the diodes are $\overline{D}$ and $\overline{D'}$.

The main drawback is the increased difficulty of the driver circuitry. And the requirement of a dead time in order to avoid the short circuit of FET_1 and FET_3 or FET_2 and FET_4 which could damage the system. When using diodes, the system is intrinsically protected against a shoot-through event.

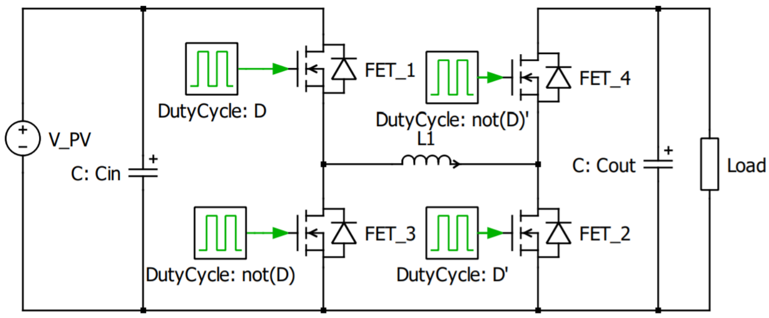

Figure 2.5. Bidirectional Non-inverting buck-boost converter.

2.5 Selection of topology

The selection of converter topology will be made from the research discovered earlier in this chapter. The converter should be able to allow both a higher and a lower output than the input. This requirement will stress the buck and boost converters, which only converts either up or down. This means that before the requirement is meet, both a buck and boost converter must be a part the implementation. This is not desirable, because it will introduce unnecessary work.

The next requirement states that the converter should have as high an efficiency as possible. The flyback converter will have a lower efficiency than the buck-boost, because of the transformer. This will introduce a loss in the extra inductor winding, and a larger loss in the FET because of the turns ratio in the transformer. Using a 4-switch buck-boost converter, in stead of a 2-switch, it is possible to further optimizing the power loss because of the use of FET's instead of diodes.

The 4-switch buck-boost converter does also has the advantage of being bidirectional. This means that it's possible to either extract a current from the PV-module to the inverter at the output, or to inject a current from the inverter to the PV-module. Because that the PV-modules acts like photodiodes, they will radiate an infrared light if current are injected. If the PV-modules are damaged in some way, i.e. having cracks, the radiation will be affected. This means that it is possible to discover faulty modules before efficiency drops. This will increase the overall efficiency of the system, and ease the maintenance sequence significantly.

The Bidirectional Non-Inverting Buck-Boost converter is chosen because of these arguments. How ever the bidirectional functionality will not be addressed in this project, but could be a part of further development of the converter.

Problem Analysis 3

As discussed in chapter 1, uneven module power generation due to mismatches in irradiance, temperature, construction, aging or other factors may lead to inefficient overall power generation. If one of the modules of the PV array is generating below average, it will effect the overall power generation. This situation can be addressed by placing a bypass diode in parallel with every PV panel as shown in figure 3.1. This way the current can flow through the diode, maintaining a higher current in the string. However this solution will drive the power generation in the bypassed module to 0 and will cause a small power loss in the diode. Notice that the total power generated in the string is 120 W instead of 150 W.

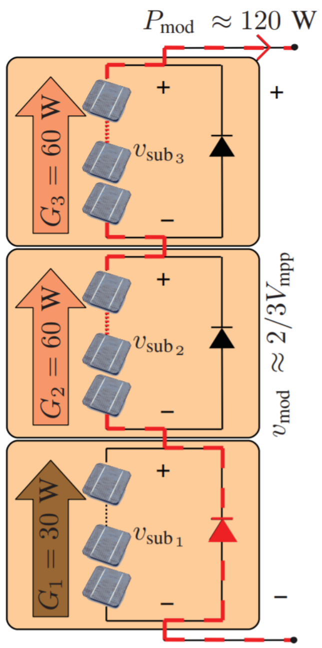

Figure 3.1. PV module being bypassed by a diode.

For avoiding the loss of the power generated by the bypassed module, a module integrated converter (MIC) may be used. These MICs are usually micro-inverters or DC-DC converters which incorporate a MPPT algorithm in order to maximize the power generated by the module. Micro-inverters convert the DC current from the PV directly to grid current. DC-DC converters need an inverter at their output if the desired load is the grid. As the micro-inverters have reported higher cost and slightly lower efficiency the project will be focused in developing a DC-DC MIC for integrating it with a single PV panel.

3.1 System requirements

For the design and test of the MIC it is of great importance to have the requirements of the system defined. The group decided to develop a DC-DC converter to integrate it with a generic PV module which is capable to deliver a maximum power of 300 W. The electrical characteristics of the PV panel under Standard Test Conditions (STC) are shown in table 3.1:

Maximum power (Pmax)	300 [W]
Optimum Operating Voltage (Vmpp)	32.6 [V]
Optimum Operating Current (Impp)	9.21 [A]
Open Circuit Voltage (Voc)	39.9 [V]
Short Circuit Current (Isc)	9.65 [A]
Module Efficiency (η)	18.3 %

Table 3.1. Electrical characteristics *STP300S-20/Wfb* PV panel.[REF]

The values from the previous table will be the input for the DC-DC converter. The group decided to connect the MIC's output to a commercial inverter *"Power-one STGU-105"* in order to have the output voltage defined. From the inverter's datasheet it is found that the nominal voltage in the DC-link is 360 V. The development of this project will be based on these requirements because they are based on real commercial products that the user can purchase.

Question supervisors: According to these requirements could we estimate the number of panels to be used? We calculated the necessary duty cycles when working with n panels, and the result can be found in the table below. However we know that when working with duty cycle around 0.75 the currents get quite high, and that depends on the inductance and the switching frequency. Then should we wait until deciding this parameters for deciding the minimum number of panels or should we arbitrarily decide a minimum number of panels and then calculate switching frequency and inductance?

Number of PV panels	Buck-boost Duty Cycle	Boost Duty Cycle
1	0.91	0.91
3	0.78	0.73
5	0.69	0.54
10	0.52	0.1

Table 3.2. .

3.2 Problem statement

The problem statement for this project can be formulated as the following question:

How can a module integrated converter be designed to maximize the PV power generation under real conditions?

The problem statement will be answered by fulfilling the following objectives:

- Design an efficient DC-DC converter for integration with a PV panel.
- Analyze different implementations of MPPT techniques and implement the selected control system.
- Hardware implementation of the MIC components including PCB layout.
- Test of the system using a PV simulator and validation of the results.

Future Work 4

The following list contains the subjects which will be addressed after the hand-in of the P0 report.

4. **Non-inverting Buck-Boost converter design**
   1 Circuit analysis
   2 Component sizing
   3 simulation and results
5. **Design of control system**
   1 Small-signal model
   2 Evaluation of main MPPT techniques
   3 Selection of MPPT
   4 Simulation and result
6. **Hardware implementation**
   1 Selection of components
   2 PCB layout
7. **Test & validation of the MIC**
8. **Conclusion & further development**

Appendix 5

5.1 PBL

Problem Based Learning (PBL) is a method to organize the group work which will help to approach the projects objectives. Collaboration in the group is a very important factor to get the project working as efficient and fluent as possible. Therefore there has initially been put some work into a way to work and organize the project. By doing that in the beginning we will save important time later on. First of all this is a group of 6 people so it is important to give different tasks to different people to keep it efficient.

To make sure everyone know what is going on there will be a group meeting at least once a week. Usually there will be more. Here the group members presents their progress for each other and if there has been any problems, it will be discussed here. In these meetings there are one chair-person who needs to make sure that all the topics of the agenda is being discussed. Besides the chair-person there is a referent who writes the minutes-of-meeting.

A supervisor meeting will be held at least once every two weeks. Again with a chair-person and a referent. Before the meeting the agenda and questions has been sent to the supervisors and afterwards the group will sent the minutes-of-meeting. The goal here is to show the supervisors that the project is moving in the right direction and to get the questions answered. Furthermore the group sends the documentation to get feedback regularly.

To organize the tasks between the group members the web-page Trello is used as a taskboard. All the tasks that should be done is written here and divided the sections "To do", "Doing", "Done". This makes sure that everybody can see which tasks is in progress and who are working on them. A time-plan has been develop using a Gantt chart (Figure 5.1), so there is a common agreement on which tasks should be done at first.

5.2 Gantt chart

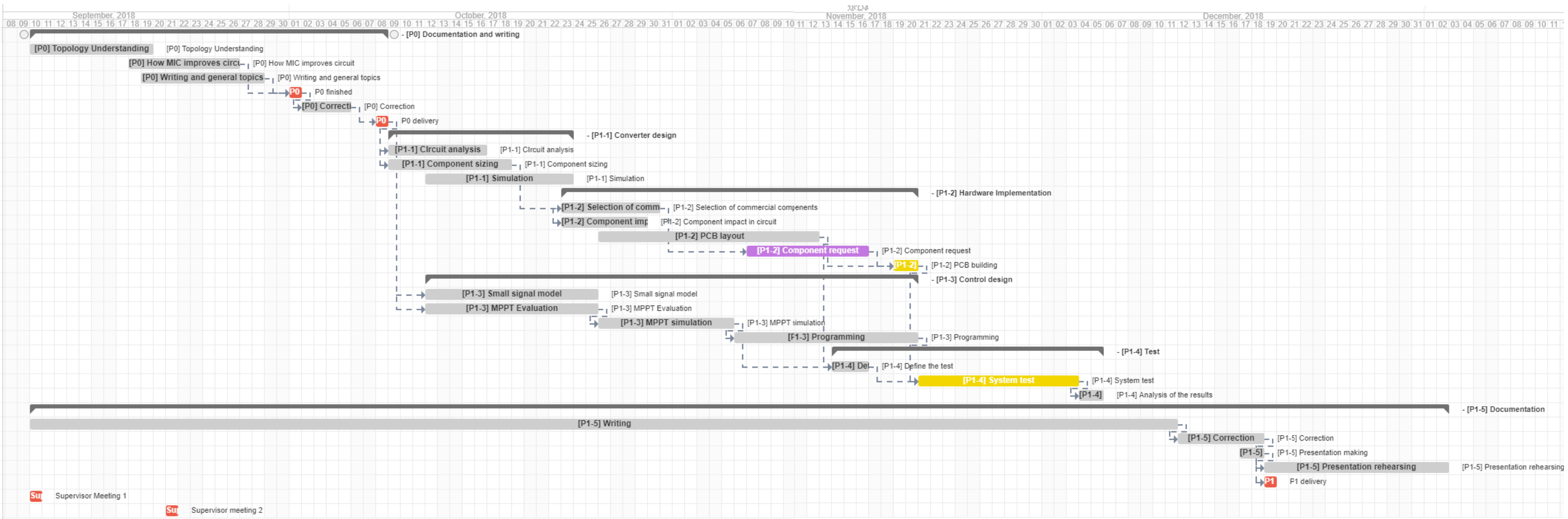

Figure 5.1. Gantt diagram updated on 27th of September.

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