RESUMEN

El objetivo del proyecto es analizar los problemas relacionados con la conversión DC-DC de tensiones ultra-bajas desde cero energía para poder utilizar como fuente de alimentación una sola celda fotovoltaica, pequeña y económica. En la primera parte del proyecto es posible encontrar la explicación del funcionamiento y un análisis del rendimiento de un Step-Up (Boost) converter, un Step-Up (Synchronous) converter y de un Switched Capacitor converter. Todos estos convertidores han sido construidos y analizados en las versiones discretas e integradas. Mediante el estudio de los convertidores en versión discreta se ha logrado dibujar mapas energéticos de las perdidas. De la versión integrada se han explicado los problemas relacionados al start-up desde cero energía de los circuitos integrados disponibles en el mercado. Gracias a los resultados obtenidos en el análisis previo, se ha logrado construir en Laboratorio un DC-DC converter que permite transformar la tensión desde 0.3V en entrada hasta 3V en salida a partir de cero cero energía almacenada. Dicho converter utiliza el charge pump IC S-882Z como starter circuit y el step-up IC S-8353 como main converter. El circuito construido funciona sin problemas alimentado por una normal celda de silicio policristalino o también mediante dos fotodiodos de dimensiones reducidas (A = 4.84 mm²) en paralelo [100 μW]. En la segunda parte, se explica el funcionamiento de ese circuito y como reducir ulteriormente la tensión de entrada incrementando el rendimiento.
ABSTRACT

The aim of the thesis is to analyse the issues about the ultra-low voltage and power DC-DC conversion in order to step up the voltage supplied by miniaturised solar harvesters. The boost converter must be able to start up from zero energy.

In the first part of the thesis, the operation of three different typologies of DC-DC converters (step-up, synchronous and switched capacitor converter) has been investigated; discrete and integrated versions have been built for each typology. An efficiency analysis of the discrete converters is carried out: energetic maps of the losses have been drawn in order to make a comparison. The analysis of the circuits built by using commercially available integrated DC-DC converters has pointed out that they are not able to start-up from zero energy and therefore they cannot be used to step up the voltage supplied by miniaturised solar harvesters.

In order to solve the issue of the start-up from zero energy a new DC-DC converter has been built. It uses a low voltage start-up integrated charge pump (S-882Z) as starter circuit and an integrated step-up boost converter (S-8353) as the main converter. Such converter is able to start up from zero energy with 0.3 V in the input; 3 V are reachable in the output by powering the converter with a single photovoltaic cell (made by polycrystalline silicon). The converter can also reach 3 V powered by two ultra small photodiodes in parallel [100 µW]. The second part of the thesis explains the operation of this converter and focuses on how to increase the efficiency and further to reduce the size of the solar harvester.
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Chapter I

1 Introduction

1.1 Aims of the thesis

Pollution caused by a widespread use of fossil fuel and the political and social risk related with these traditional resources have increased during the last decades the development of renewable energy. Nowadays through the introduction of energy policies, the provision of energy from renewable sources is becoming compulsory; among these sources the most feasible are solar and wind energy. The technology that allows the extraction of power from the sun and the wind is well known and many plants have been already installed in order to produce megawatts of electric power. The efficiency of the photovoltaic panels is increasing and the costs are reducing thanks to new low-cost materials and the implementation of economic production’s processes.

In the last few years branches of research in solar energy have focused on low power applications in order to reduce the battery usage. Ultra small solar harvesters can be used in the energy management of several monitoring and control systems; the energy stored in small micro-cells (for example a single photodiode) can be employed to power sensors and auxiliary systems. A typical example would be energy management in buildings. The power supplied by these sources is ultra-low (the order of magnitude is around 100 µW) and also the voltage presents an ultra-low level (0.2 - 0.5 V). Therefore, to be used in the energy management applications a DC-DC converter must be employed in order to step up the voltage and to reach standard electronic levels (3 - 5 V). Fig. 1.1 shows a block diagram.
Fig. 1.1 Block diagram that shows how solar energy harvesters can be used in energy management.

Because of the ultra-low input voltage and power, the first issue relating to the choice of the DC-DC converter is limiting the losses in order to not dissipate all the energy in the voltage conversion. Furthermore, the boost converters commercially available present another problem: they are not able to start-up from zero energy seeing that the internal equipment needs to be powered with at least 0.7 - 0.8 V while the voltage provided by the source is lower. Therefore, there are two aims of this thesis:

- Firstly to characterise the operation of different typologies of DC-DC converters and to compare the efficiency analyses.
- Secondly, to solve the start-up from zero energy issue and to build the ultra-low input DC-DC (boost) converter required in Fig. 1.1 which can start up with zero onboard stored energy.

1.2 Thesis outline

This thesis is composed of eight chapters.

Chapter I explains the aims of the project and the issues in the ultra-low voltage DC-DC conversion.

Chapter II includes a brief background; power harvesting in energy management applications is introduced and some low voltage start-up techniques are proposed and
In Chapter III, a polycrystalline silicon photovoltaic cell is characterised: measurements are taken in order to draw the I-V characteristic and to find the Maximum Power Point.

In the first part of Chapter IV, the efficiency of a discrete DC-DC step-up converter built in the Laboratory is studied in order to draw a map of the losses. In the second part, commercially available step-up converters are analyzed. A version has been built using an integrated converter (MAX 757 IC) and the problem of the start-up from zero energy is investigated.

In Chapter V, the DC-DC synchronous boost converter is studied. In order to compare the losses, a discrete version has been built and investigated. In the second part, the proprieties of an integrated synchronous boost converter (LTC 3429) are studied in reference to the possible applications with solar harvesters.

In Chapter VI a new family of step-up DC-DC converter is investigated. These converters are called switched-capacitors circuits or charge pump circuits. A discrete version with gain 3 is investigated so as to study the operation and to analyse the efficiency. In the second part of this chapter an integrated version of Charge Pump (S-882Z) is introduced.

In the first part of Chapter VII the possible uses of the Charge Pump S-882Z together different kinds of boost converters are investigated in order to solve the problem of the start-up from zero energy. In the second part a converter built in the Laboratory that reaches 3 V in the output from ultra-low input voltage (0.3 V) is characterised in order to explain how the start-up problem from zero energy has been solved. The operation of this converter powered by micro-power solar harvesters is explained.

In the last chapter the results are summarised and possible further work is suggested in order to miniaturise the photosensitive area and to increase the efficiency.
Chapter II

2 Background research

2.1 Power harvesting

Nowadays costumers can find a large amount of small sensors at low cost in the market. Thanks to these sensors we can monitor and control different stages of processes, systems and plants. These sensors can send the acquired data employing wireless methods. To exploit the advantages supplied by these technologies is difficult because an external source must supply the energy that sensors need to monitor the system and to send the data. Furthermore, often they are positioned in places where power supplied by cable is not available. In these cases we need a source close to the sensors. Many micro-power technologies can supply energy in-lococ. Small quantities of energy can be extracted from:

- Motion (magnetic transducers)
- Vibrations (piezoelectric or magnetic transducers)
- Light (photovoltaic cells)
- Thermal gradients (thermoelectric energy) [1]

Other forms of power transmission can be used to supply energy without cable. They are power transmission by microwave and electromagnetic induction. Such techniques are older and better-known than those mentioned before. On the other hand there are important reasons that limit the implementation of these techniques. The amount of power that can be transported is small and radiation often implies health concerns. Solar power seems the most viable power supply technology for sensors among the primary sources before quoted [1]. The most important problem of such sources is the efficiency. The power supplied by the cell drops to 5%-20% of the peak value in cloudy conditions. In order to avoid this problem, systems should be furnished with a backup battery where stored the energy. Prospects of solar power are nowadays more interesting than a few years ago. On the one hand, the development of new materials and new technologies has increased the efficiency and on the other hand it has reduced cost and size. A brief overview of such new technologies and materials is given
in Section 2.2. Another problem of solar energy is that cells provide power only during daytime. A battery must be employed to provide the energy during the night. This is an important limitation but all sources mentioned above suffer this problem. For example magnetic transducer does not provide any energy without motion. That is an intrinsic problem. Motion creates magnetic flux variations inside the coil and, hence, an electromotive force [1]. Piezoelectric suffers the same limitation: without vibrations there is no energy. Despite of such problem the sources mentioned can be used in energy management applications. Fig. 2.1 illustrates a simplified block diagram of a system where various sources supply energy to recharge a Li-ion battery, in order to collect the maximum possible amount of energy. The rectifiers implement the maximum-power point tracking (MPPT) technique in order to increase the efficiency [1].

![Fig. 2.1 Simplified block diagram where various sources supply energy to recharge a Li-ion battery [1].](image)

The power supplied by such micro-harvesters is low and also the voltage often does not reach 0.5 V. Even if in the energy management applications the power required is low the voltage must be boosted up to standard electronic levels (3 - 5 V). Hence, the challenging aspect in energy management from micro-harvesters is designing the DC-DC converter.

### 2.2 Photovoltaic research and development

As previously pointed out at the moment solar power is the most available solution to provide energy in those applications where it is not possible to use common supply sources.
Appendix A gives a brief description about how a photovoltaic cell works. This section reports some information concerning photovoltaic research and development. A short overview is now given about the materials and technologies employed to build a single solar cell [11]. There are three main types of materials used to make solar cell:

1. Silicon (Si)
2. Polycrystalline thin films
3. Single crystalline thin films

The first type is still the most common material used to build photovoltaic cell. To be useful silicon must be refined to a purity of 99.9999%. Silicon can be used in three different molecular structures. They are single-crystalline, multi-crystalline and amorphous. The first one is a uniform structure, grown from the same crystal. The efficiency of a cell made by this type of silicon is relatively high; it is around 18-20%. Single-crystalline silicon is expensive because the “growing process” of a crystal is not trivial. The multi-crystalline structure consists in several smaller crystals bordered by boundaries. Such boundaries limit the flow of electrons and hence the efficiency is lower: it is around 14-16%. The multi-crystalline structure is cheaper than the first one. The amorphous structure is made by silicon’s atoms arranged in a random order. The efficiency is very low, around 8-10%. Otherwise amorphous silicon has very interesting proprieties. It absorbs solar radiation 40 times more efficiently than does the single-crystal silicon, so we need only a thin film –about 1 µm- to absorb a large amount of the light energy. Other economic advantages are that it can be produced at lower temperatures and can be deposited on low-cost substrates such as plastic, glass, and metal. This makes amorphous silicon ideal for building-integrated photovoltaic products.

The polycrystalline thin-film type takes its name from the method used to deposit the film: thin-film cells are deposited in ultra thin, consecutive layers of atoms, molecules, or ions. Thanks to this technology we can use less material than the standard silicon wafer technology; furthermore, we can exploit the advantages of using flexible substrate materials. Like amorphous silicon, the layers can be deposited on various low-cost substrates (or "superstrates") such as glass, stainless steel, or plastic. Several different deposition techniques are used, such technologies are cheaper then the required ones for crystalline silicon. Often, multi-layer thin films techniques are used to increase the efficiency. In these conditions
efficiency can be higher than the efficiency of standard mono-crystalline silicon cells. Usually polycrystalline thin-film cells do not use metal contact as electrodes. A thin layer of a transparent conducting oxide is used (Fig. 2.2), which often is transparent and conducts electricity very well.

![Fig. 2.2 Typical polycrystalline thin-film cells with a heterojunction structure [11].](image)

Principal polycrystalline thin-film materials are CIS, CdTe and amorphous silicon. CIS (Copper indium diselenide) has an extremely high absorptivity, which means that 99% of the light shining on CIS will be absorbed in the first micrometer of the material. Usually this kind of cells uses heterojunction structure. The manufacturing process is low-cost. CdTe (Cadmium telluride) is another polycrystalline thin-film material with a very high absorptivity and manufacturing low-cost. Concerning the amorphous silicon we can match the propriety previously mentioned with the advantage of the polycrystalline thin-film technology.

The third structure is the single crystalline thin films. Essentially such structure is focussed on cells made with gallium arsenide. GaAs is a mixture of two elements, gallium and arsenic. Gallium is a by-product of other metals’ smelting, and it is rarer than gold. Arsenic is not rare, but it is poisonous. GaAs find application in multijunction and high-efficiency solar cells thanks to [11]:

- High absorptivity
- Ideal band-gap
- Relatively insensitive to heat
- Highly resistant to radiation damage
- Amenability to a wide range of designs
The main restriction of a large implementation of GaAs is the high cost of a single-crystal GaAs substrate. However, in these last years GaAs has found application in concentrator systems. In such systems, called CPV (concentrating photovoltaic systems) a large lens (typically a Fresnel lens) or mirrors are used to focus sunlight on a small area of photovoltaic cells (*Fig. 2.3*). In this way the GaAs used is little, typically a cell used in this application can be 0.25 cm². In this configuration, the cost is low enough to make GaAs cells competitive, assuming that module efficiencies are between 25% and 30%.

*Fig. 2.3* Concentrating photovoltaic systems (CPV) [12].

Until now we have focused our attention on the materials employed to build the cell: let us see now how these materials are arranged to make the photoelectric conversion. We can recognize four different structures [11]:

1. Homojunction
2. Eterojunction
3. p-i-n / n-i-p
4. Multijunction

Primary example of homojunction structure is the crystalline silicon. A single material is altered so that one side is p-type, dominated by positive holes, and the other side is n-type, dominated by negative electrons. Instead in eterojunction devices the junction is formed by two different semiconductors, a good example is CdTe (cadmium + telluride). The advantages of eterojunction structure are evident; it is more difficult to find a semiconductor that can be doped both p- and n-type than one can be doped either p-type or n-type. Eterojunction
structure is used in polycrystalline thin-film cells. The third structure (Fig. 2.4) is used in amorphous silicon cells. An intrinsic layer (i-layer) is sandwiched between a p-layer and an n-layer.

![Fig. 2.4 Example of p-i-n/n-i-p structure. Typically it is employed in amorphous silicon cells [11].](image)

The multijunction structure, also called a cascade or tandem cell, can achieve higher total conversion efficiency by capturing a larger portion of the solar spectrum. In the typical multijunction cell, individual cells with different bandgaps are stacked on top of another one. The individual cells are stacked in such a way that sunlight falls first on the material having the largest bandgap (Fig. 2.5). Photons not absorbed in the first cell are transmitted to the second cell, which then absorbs the higher-energy portion of the remaining solar radiation while remaining transparent to the lower-energy photons. These selective absorption processes continue through to the final cell, which has the smallest bandgap [11].

![Fig. 2.5 Example of multijunction structure where individual cells with different bandgaps are stacked [11].](image)

As previously written, much of today's research in multijunction cells focuses on gallium arsenide as one (or all) of the component cells.
All the materials, the technologies and the devices introduced in this section are developing very fast. Currently second generation of photovoltaic cells is becoming commercially available. These cells are made by using thin-film deposits of semiconductors and heterojunction structure. Even if the efficiency is lower than the first generation cells (based on crystalline silicon wafer) the manufacturing costs are lower so the commercial price is decreasing. The purpose of the scientists that are studying such generation of solar cells is to combine low-cost processes with high efficiency. The goal is to improve efficiency of commercial modules to levels above 10%. Furthermore new concepts are rising. A third generation of solar cells is studied by researchers. They are focusing on:

- Polymer solar cells
- Photo-electrochemical cells (Graetzel cells, Photogeneration cells)
- Nanocrystal solar cells
- Organic solar cells

This generation of cells is quite different from the first or the second one, because they are not based on a traditional p-n junction. For example the dye-sensitized solar cell, known as Graetzel cell, uses a phenomenon called photoexcitation that is comparable with photosynthesis. The materials used to build the third generation of PV cells are dramatically cheaper than silicon and the manufacturing processes seem to be low-cost. However it is difficult for these new cells to compete in the market with traditional silicon cell because silicon-based PV cells exploit a well-developed industry. Infrastructures of such industry are the same that are used to electronic and computer manufacture.

2.3 Step up DC-DC converters overview

In the first section of this chapter it has been highlighted that in order to exploit the energy provided by a single solar cell we need to build a boost converter. Fig. 2.6 illustrates the basic diagram of a step-up converter. In this converter the output voltage is greater than the input voltage.
When the switch $S_1$ is ON the diode is reversed biased and hence the output stage is isolated. During this stage the input supplies energy that is stored in the inductor. When the switch $S_1$ is OFF the output stage receives energy from the inductor and from the input [3]. Ideally, by changing the duration of the ON stage, namely setting the duty cycle, it is possible to control the value of the output voltage. More details about the functioning are given in Appendix B.

Often, the diode is replaced with another switch in order to avoid the losses related to the on-state voltage. This new configuration is said synchronous boost converter. Fig. 2.7 shows the diagram. In Chapter V a discrete and an integrated version are analysed in order to point out the advantages.

A new family of step up converter has become quite popular during the last years. The name of this converter is charge-pump and basically it is a switched-capacitor (SC). This converter presents a lot of advantages. There are not any magnetic devices (inductors or transformers) so the size is small and the weight is light. Furthermore charge-pump does not give EMI problems and it is ideal to monolithic integration [4]. Thanks to these characteristics SC- converter seems to be one of the best solutions for low-power step-up conversion. In Fig.
2.8 is shown the circuit of a step-up SC-converter where the output voltage is double than the input voltage.

Fig. 2.8 Switched capacitor converter with gain 2.

In the circuit shown in Fig. 2.8 the switches S₁ and S₂ are driven by the signals shown in Fig. 2.9. When S₁ is open S₂ is closed; a stage where both switches are ON must be avoided because in such case the source is short-circuited.

Fig. 2.9 Diagram of the signals that driven the switches S₁ and S₂ in the switched capacitor converter with gain 2.

When S₁ is OFF and S₂ is ON (stage I) the source charges the capacitors C₁ and it raises its potential up to the value of \( V_{in} \). During this stage C₁ and the source are isolated from the output stage because the diode D₁ is reversed biased. When S₁ is OFF and S₂ is ON (stage II) the diode D₂ is reversed biased while D₁ is conducting. Ideally, in this stage, C₂ is charged by the source and the capacitor C₁. Its potential raises up to the value given by:

\[
V_{c₂} = V_{in} + V_{c₁} = 2V_{in}
\]
C₂ voltage is also the output voltage $V_{out}$. Therefore, the output voltage is the double of the input voltage. *Fig. 2.10* shows the two stages.

![Fig. 2.10](image)

*Fig. 2.10* On the left the equivalent circuit of the switched capacitor converter when $S₁$ is OFF and $S₂$ is ON. On the right the circuit when $S₁$ is ON and $S₂$ is OFF.

In Chapter VI a discrete version of a switched capacitor converter with gain 3 is studied.

### 2.4 Low voltage power conversion

To reach an available voltage in output from ultra-low voltage in input is very challenging. As it has been stated before, solar cell technology is developing very fast but power conversion techniques from low voltage have been considered an important field of research only during these last years. As regards the solar power, this restriction has led to the necessity of interconnecting cells in series to build up the required voltage. Current from a series array is limited by the weakest or least illuminated cell; therefore care must be taken to match cells and ensure they are evenly illuminated. Because cell anodes must be electrically isolated from each other, series arrays also impose limitations on thermal resistance between the cells and the heatsink [7]. All these restrictions affect the efficiency and the applications studied in this thesis do not often need a large amount of power. Furthermore, size should be a problem in such applications. Another restriction concerns the price because the cost of more cells in a series configuration is bigger than the cost of one single cell.

Before explaining in details why low power conversion is challenging, it may be helpful to try to define an “ultra-low voltage” and to point out advantages of decreasing
operating voltage for electronic components. No standard definition for ultra-low voltage exists [8]. Typical semiconductor industry use is now 1.0 V and below. Lowering the operating voltage permits more transistors on a single silicon chip while reducing power dissipation. This involves reducing transistor channel length and improving gate dielectrics to achieve higher circuit densities, which allows reduced spacing between neighboring transistors. Semiconductor Industry Association (SIA) forecasts in the International Technology Roadmap for Semiconductors (ITRS) the trend shown in Fig. 2.11 for the operating voltage of low-powered ICs. For the next decade operating voltage should drop to 0.5 V.

![Fig. 2.11 Forecast for the operating voltage of low-powered ICs [8]. Source: SIA (Semiconductor Industry Association).](image)

In low power conversion with very low input voltage problems are basically two: efficiency and converter’s start-up. With ultra-low input voltage the input current is relatively high. For example if the expected power supplied by a single solar cell is around 100 mW and a reasonable input voltage is 0.5 V in normal lighting conditions, the current provided by the cell is 200 mA. This current flows through the components of DC-DC converter; in these components ohmic losses are the most important and we know that such losses depend of the square current. So the risk is that all the input power is absorbed by the DC-DC converter. In a synchronous DC-DC converter the majority of losses are concentrated in the inductor (ohmic losses due to the DC resistance) and in the switch (also ohmic due to the on-resistance). Other losses are due to switching, to the trace resistance (for a discrete circuit) and to the equivalent resistance of the capacitor [9]. In reference to Fig. 2.7 a power balance can
be written:

\[ V_{in} I_{in} = P_{out} + K I_{in} + R I_{in}^2 + r_c I_c^2 + P_{oh} \]  \hspace{1cm} (2.4.1)

\(V_{in}\) = Input voltage  
\(I_{in}\) = Input current  
\(P_{out}\) = Output power  
\(r_c\) = Equivalent resistance of the capacitor  
\(I_c\) = Current that flows through the capacitor  
\(P_{oh}\) = Control power (typically constant and < few mW)

\(R\) is defined by:

\[ R = R_l + R_t + R_{sw} \]  \hspace{1cm} (2.4.2)

\(R_l\) = DC resistance of the inductor  
\(R_t\) = Trace resistance  
\(R_{sw}\) = On-resistance of both switches

\(K\) is a factor that accounts the switching loss. It is calculated by the switching energy loss of one switch [9]:

\[ W_{switch} = \frac{V_{off} I_{on} I_{switch}}{6} \]  \hspace{1cm} (2.4.3)

\(V_{off}\) = Off-state voltage  
\(I_{on}\) = On-state current  
\(I_{switch}\) = Sum of on and off switching transition times

In the synchronous converter shown in Fig. 2.7, \(V_{off}\) is the output voltage and \(I_{on}\) is the input current. To find power loss from switching energy loss is sufficient multiplying (2.4.3) for the switching frequency \(f\). Thus, for both switches:
(2.4.1) highlights that input current is the critical factor related with the value of $R$, $r_c$, and $K$. A common definition of efficiency is:

$$\eta = 100 \frac{P_{out}}{V_{in}I_{in}}$$  \hspace{1cm} (2.4.5)$$

Usually $P_{out}$ like $V_{out}$ is given; if input voltage is low the input current must be high. (2.4.5) shows that efficiency will reduce quadratically as input voltage is reduced linearly [9].

As previously written, another critical aspect of low-power conversion and ultra-low input voltage is to start-up the circuit. In the further section a brief explanation of this problem is yielded.

### 2.5 Start-up from low voltage

*Fig. 2.11* points out that commercially available boost converters for low voltage applications require at least 0.7 - 0.8 V to start up. The main application of these converters is related to battery management; often commercial circuits are used in order to regulate the voltage supplies from the battery. The purpose is keeping output voltage constant even if the battery is discharging. Therefore start-up occurs when the battery is still charged and the voltage is high enough to switch on the circuit. During one cycle, the voltage supplies by the battery decreases slowly but thanks to the converter the output voltage does not change. With commercial boost converter system collapses when the voltage supplied by the battery reaches low value like 0.5 - 0.6 V. This thesis aims to study how supplying helpful energy using solar energy harvesters so commercial boost converters are useless. How stated above the converter employed must start-up from at least 0.5 V.
Nowadays most of converters available on the market use a low-power MOSFET as switching device. Advantages of using these power transistors are their low on-resistance and their zero gate current. Thanks of these characteristics losses are very low. Drawback of MOSFETs is that they need a relatively high gate voltage to switch on. Other kinds of transistors are not used because of efficiency problem. For example Bipolar Junction Transistors (BJT) need a low voltage to switch on (at least 0.7 V) but they have an important collector-emitter voltage drop-off. Therefore MOSFETs are still the best solution as switching devices but at the beginning they have to reach the threshold voltage to build up the output voltage. Afterwards MOSFETs will be driven by such voltage in the output. So the critical stages are the first: how reach the threshold voltage (typical no less of 1 V) from a very low input voltage. In literature some circuits are recommended to solve this problem.

A starter circuit must be designed. Such circuit provides voltage at the beginning to initialize the conversion. A resonant transformer circuit can be used to step up the low input voltage. The main circuit contains the chief converter which provides the output voltage with high efficiency [2]. Fig. 2.12 shows a block diagram of this solution.

![Block diagram of a solution proposed in order to solve the start-up problem. A starter circuit is required [2].](image)

The resonant transformer circuit used to start-up the main converter is complicated and space-consuming for portable electronics applications. Fig. 2.13 shows a simpler way to start a low voltage synchronous converter [9].
This technique is founded on a resistance with a mechanical switch in series; these two components are placed in parallel with the lower MOSFET $S_1$. The mechanical switch is not an extra component. It could be the same switch that allows the turn on of the circuit.

When such switch is on the current flows through the inductor and it is limited only by the $r_{\text{start}}$. The inductor is charged very quickly. The mechanical switch should remain on for at least 4-5 time constants, typically few milliseconds. After this time, the switch is released and the current flows through the diode and finally charges the capacitor. The charge stored in the capacitor should supply to the regulator circuit enough energy to self-sustain the conversion during the first stage. This is possible only if $r_{\text{start}}$ is selected appropriately. The equations that allow choosing a correct value for $r_{\text{start}}$ are:

\[
W = \frac{1}{2} L \left( \frac{V_{\text{in}}}{r_{\text{start}}} \right) \quad (2.5.1)
\]

\[
r_{\text{start}} = \sqrt{\frac{L}{C} \frac{V_{\text{in}}}{V_{\text{out}}}} \quad (2.5.2)
\]

(2.5.1) gives the energy stored in the inductor when the mechanical switch is on. (2.5.2) yields the value of $r_{\text{start}}$ if all energy is transferred (neglecting loss). Generally, $r_{\text{start}}$ is a
small resistance, but still significantly larger than $r_L$ [9]. The start-up technique above-mentioned is clever because it is not complicated and space-consuming. Furthermore it is very cheap; hence it seems appropriate for the applications studied in this thesis. The only drawback is that such system needs an external help to work, somebody has to press the mechanical switch. Therefore using the converter shown in Fig. 2.13 combined with a solar cell as primary source implies that every morning someone has to switch on the system. It is not automatic by the sun light.
Chapter III

3 Measurements on a single photovoltaic cell

3.1 Measurements of I-V characteristic and Maximum Power Point

The size of the cell that has been used is 126mm x 126mm and it is made by polycrystalline silicon.

![Fig. 3.1 Photovoltaic cell employed to take the I-V measurement. It is made by polycrystalline silicon.](image)

In order to measure the I-V characteristic it has been used the circuit illustrated in Fig. 3.2. The radiation source used to light the cell was a desk lamp. Such lamp was positioned close to the cell (10 cm). In these conditions 7000 lux has been measured.

![Fig. 3.2 Circuit used to collect the data in order to draw the I-V characteristic.](image)
When increasing the output resistance, the output voltage increases up to the open-circuit value and the output current decreases up to zero. When reducing the output resistance, the output current reach the short-circuit value and the output voltage decreases up to zero. Due to the low power levels, the current needs to be measured using accurate shunt resistance in place of an Ampere-meter. In order to measure small value of resistance it has been used a high precision Ohm-meter called “Double Thomson’s Bridge”. In correspondence of small value of the output resistance the internal resistance of the Volt-meter affects the measurements. *Fig. 3.3* shows the I-V characteristic that is similar to the expected curve.

![I-V characteristic of the photovoltaic cell (radiation E = 700 lx)](image)

*Fig. 3.3* I-V characteristic of the photovoltaic cell (radiation E = 700 lx)

As shown in *Fig. 3.3* we can divide the characteristic in three parts:

A → B: It is similar to an ideal current generator

C → D: It is similar to an ideal voltage generator

B → C: This is a connection part between the two ones mentioned above. Typically it has the shape of a knee. *Fig. 3.3* points out that in this part we can find the working point that gives the maximum power. It is important working with the current and the voltage that correspond such point as it is possible to extract the maximum amount of energy from the photovoltaic
cell. Fig. 3.4 illustrates the graph of the power supplied by the solar cell.

![Graph of the power supplied by the solar cell]

*Fig. 3.4* P-I characteristic of the photovoltaic cell. The Maximum Power Point is highlighted (radiation $E = 700$ lx).

The Maximum Power Point (MPP) is:

$$P_{MPP} = 53.87mW$$

The output voltage and the output current in correspondence of the Maximum Power Point (MPP) are:

$$V_{(MPP)} = 352mV$$

$$I_{(MPP)} = 0.153A$$

These values are related to the irradiance condition during the measure time and to the temperature. *Fig. 3.5* shows when decreasing the irradiance, the current supplied by the cell decreases, while the open-circuit voltage does not change.
**Fig. 3.5** Example of the influence of the radiation condition in the I-V characteristic of a photovoltaic cell.

The relation with the temperature is shown in **Fig. 3.6**. When increasing the temperature, the short-circuit current does not change however the open-circuit voltage decreases proportionally.

**Fig. 3.6** Influence of the temperature in the I-V characteristic of a photovoltaic cell.
Chapter IV

4 Step-up DC-DC converter

In Chapter II the basic configuration of a step-up DC-DC (boost) converter has been introduced. In Appendix B further details about the operation are given. In the first part of this chapter the efficiency of a discrete step-up converter is studied in order to draw a map of the losses. In the second part commercially available step-up converters are analyzed. An integrated version has been built using MAX 757 IC and the problem of the start-up from zero energy is investigated.

4.1 Discrete step-up DC-DC converter

4.1.1 Selection of components

The aim of the boost converter that has been built was to reach at least 3 V in the output supplying a power around 100 mW from ultra-low input voltage (0.3 - 0.5V). *Fig. 4.1* illustrates the circuit.

![Discrete step-up DC-DC converter](image)

*Fig. 4.1* Discrete step-up DC-DC converter.

The boost converter must be a low power converter to provide the characteristics required by
the applications studied in this thesis. Therefore, components must be chosen very carefully in order to limit losses.

SOURCE: Two sources have been used; in the first stage a “dual tracking DC power supply” in order to do the efficiency’s analysis and in the second stage the photovoltaic cell characterised in Chapter III. In order to keep the voltage constant during the measurements, the DC power supply has been employed in voltage control mode.

INPUT CAPACITOR \( (C_1) \): 100 nF ceramic capacitor has been chosen. The main function of this component is to reduce the input impedance and to stabilize the input current.

INDUCTOR: This component has been chosen in order to work in a continuous mode of operation \([i_L(t) > 0]\). According to (4.1.1) if the voltage input is 0.6 V and the desired output voltage is 3 V the duty cycle must be 0.8. In order to have only positive values of current the inductor must satisfy:

\[
L > \frac{TV_o}{2I_{o,\text{MAX}}} D(1 - D)^2 \tag{4.1.1}
\]

The frequency has been set to 100 kHz, thus the period \( T \) is 10 µs. (4.1.2) gives the value of the maximum output current \( I_{o,\text{MAX}} \) by limiting the output power at 100 mW.

\[
I_{o,\text{MAX}} = \frac{P}{V_o} \tag{4.1.2}
\]

By substituting these values into (4.1.1) we obtain:

\( L > 14.41 \mu H \)

Therefore, a 22\( \mu \)H choke coil inductor with high permeability and a high flux density ferrite core has been selected. In order to reduce the ohmic losses the inductor has a low DC resistance (0.034 mΩ). Another important aspect in this choice is the allowable flux. It is not declared on the data-sheet of the inductor employed but it is supposed be between 200 and 500 mT for ferrite cores. Exceeding the allowable flux causes magnetic saturation of the core
and consequently a drop in the inductance value. In order to avoid the magnetic saturation of
the core the peak current of the inductor must be less than the saturation current. The inductor
chosen presents high flux density and the maximum allowable current is around 2000 mA.
Therefore, there is no risk of saturation being the inductor peak current less than 400 mA. Fig.
4.2 shows the graphs of the current and the voltage of the inductor measured with 0.537 V
input voltage. Such measurement is characterised in Section 4.1.3.

![Graph of Inductor Current and Inductor Voltage](image)

*Fig. 4.2 Inductor current and inductor voltage wave forms measured with $V_{in} = 0.537$ V, $P_{in} = 84.85$ mW, $D = 80\%$.*

SWITCHING DEVICE: In order to limit losses a low power MOSFET has been employed.
The advantage of using this transistor is the low on-resistance and the zero gate current.
According to Fig. 4.1, when the switch is OFF between drain and source there is the output
voltage (ideally 3 V). When the switch is ON the input current flows through it. Ideally such
current is around 300 mA. In order to limit the ohmic losses the on-resistance must be low (<
50 mΩ).
Therefore, the transistor has been chosen with the following technical characteristics:

- $V_{DS} = 20V$
- $I_D @ 25^\circ C = 36A$
$R_{DS} = 0.02\Omega$

$V_{GS(\text{th})\text{max}} = 3V$

This last voltage represents the threshold voltage. Therefore, in order to drive the transistor, at least 3 V must be supplied between *gate* and *source*. This value is quite high; this is not a problem for the analysis of the efficiency given in this chapter because an external generator supplies such voltage. In the final circuit, objective of this thesis, gate-drive would be powered by the output voltage. Therefore the threshold voltage of the MOSFET must be less than 3 V being the output during the start-up time equals the input. MOSFET with $V_{GS}$ around 1 V are commercially available but their $R_{DS}$ is bigger. Consequently there are more losses. Further explanations about the losses in the switching device are given in the next section.

**FUNCTION GENERATOR:** In place to driving the transistor directly from the output by using the Pulse Width Modulation technique suggested in *Fig. B.4* and *Fig. B.5* an external functions’ generator has been used; the switching device has been driven by a square wave with the following characteristics:

$V_{pp} = 5V$

$f = 100kHz$

$OFFSET = +2.5V$

$DutyCycle(D) = 80\%$

*Fig. 4.3* shows the square wave that drives the transistor (the voltage $V_{GS}$ between *gate* and *source*).
DIODE: In place of a normal diode a Schottky diode has been employed. The advantages of this kind of diode are two; a low forward voltage drop and a very fast switching action. The technical characteristics of the diode employed are:

\[
\begin{align*}
I_F &= 3A \\
V_R &= 15V \\
V_{F,max} &= 0.35V \\
I_{R,max} &= 1mA
\end{align*}
\]

OUTPUT CAPACITOR (C_o): According to (B.11) a large electrolytic capacitor has been chosen in order to reduce the output voltage ripple.

\[C_o = 0.22F\]

Fig. 4.4 illustrates the graph of the output voltage measured with 0.537 V in the input. Such measurement is characterised in Section 4.1.3.
4.1.2 Analysis of the losses in the circuit

In the circuit built by using the components listed above there are some parasitic elements that affect the conversion. Such parasitic elements affect the efficiency and, as it is shown in Fig. 4.5, decrease the voltage transfer ratio [3].

![Fig. 4.5 Comparison between the ideal and the real voltage transfer ratio vs. the duty cycle of a DC-DC step-up boost converter [3].](image-url)
There are losses in the inductor, in the capacitor, in the transistor and in the diode. There are also losses associated with the way how the discrete circuit has been built. Table 4.1 and Table 4.2 give the values measured. Below the formulas that have been employed to find them are explained.

LOSSES IN THE INDUCTOR: Such losses are related with the DC resistance of the coil. They can be calculated by using (4.1.3).

\[
P_L = \frac{1}{T} \int_0^T R_L i_L^2 dt
\]

(4.1.3)

Where \(R_L\) is the DC resistance of the coil, \(i_L\) the instantaneous current that flows through the inductor and \(T\) is the period (that is the inverse of the switching frequency).

LOSSES IN THE MOSFET: The most important losses in the MOSFET are ohmic losses due to the on-resistance \(R_{DS}\) and switching losses. The first ones can be calculated by using (4.1.4) [3].

\[
P_{on} = V_{on} I_o \frac{t_{on}}{T}
\]

(4.1.4)

Fig. 4.6 gives a graphic explanation of (4.1.4).

![Fig. 4.6 Typical wave forms of transistor voltage and current.](image-url)
The other predominant contribution to the power loss in the transistor is the power dissipated during the switching. Such losses are shown in Fig. 4.7.

Fig. 4.7 Power dissipated in the MOSFET due to the switching.

The energy dissipated in the MOSFET during the turn-on transition is:

\[ W_{e(on)} = \frac{1}{2} V_d I_o t_{s(on)} \]  \hspace{1cm} (4.1.5)

And during the turn-off transition:

\[ W_{e(off)} = \frac{1}{2} V_d I_o t_{s(off)} \]  \hspace{1cm} (4.1.6)

The value of the power loss \( P_s \) is:

\[ P_s = \frac{1}{2} V_d I_o f_s \left( t_{s(on)} + t_{s(off)} \right) \]  \hspace{1cm} (4.1.7)
Where $f_s$ is the switching frequency (100 kHz), $t_{(on)}$ is the rise time and $t_{(off)}$ is the fall time.

Another way to calculate the losses in the switch is measuring the instantaneous value of the drain-source current and voltage. The power lost in the MOSFET is:

$$P_{\text{MOSFET}} = \frac{1}{T} \int_0^T v_{DS} i_{DS} \, dt$$  \hspace{1cm} (4.1.8)

Thanks to (4.1.8) we know the sum of the losses due to the on-resistance and the switching losses. In the analysis of the efficiency of the circuit this method has been used in order to know the power dissipated in the transistor.

LOSSES IN THE DIODE: There are two kinds of losses in the diode: the forward power losses and the inverse power losses. The losses associated to forward stage of the diode are bigger than the losses in the reverse biased stage because of the high forward voltage drop. In order to find the sum of them the method previously explained for the transistor has been employed. The diode current and the diode voltage have been measured in order to calculate the instantaneous value of the power loss. (4.1.9) gives the average value.

$$P_{\text{diode}} = \frac{1}{T} \int_0^T v_D i_D \, dt$$  \hspace{1cm} (4.1.9)

LOSSES IN THE CAPACITORS: These kinds of losses are due to the Equivalent Series Resistance (ESR) of the input capacitor and the output capacitor. These losses are smaller than the losses previously mentioned.

LOSSES RELATED TO CIRCUIT LAYOUT: In a discrete circuit care must be taken with the design and the placement of the components. All the components should be placed as close as possible in order to limit the traces and consequently the ohmic losses. Furthermore, trying to reduce the loops (minimising the area) is important in order to limit the parasitic inductance. Such inductance affects the operation of the transistor by introducing an over-voltage when it switches on and off. This parasitic inductance also causes a delay in the switching (Fig. 4.8).
Fig. 4.8 Effect of the parasitic loop-inductance in the MOSFET voltage and current during the switching. When the transistor opens the parasitic loop-inductance causes an over-voltage and a delay in the switching off of the current. The graph below shows the switching losses; most of them are concentrated during the transition ON-OFF. Measurement taken with $V_{in} = 0.194$ V, $P_{in} = 60$ mW, $D = 80\%$. 
Measuring these losses is difficult, however we can gain an upper limit for the losses due to the traces and the losses in the capacitors. Hence, by using (4.1.10) we can find them for difference from the input power and the sum of the output power and all the losses known.

\[ P_{\text{Others}} = P_{\text{Traces}} + P_{\text{Cap}} = P_{\text{in}} - P_{\text{out}} - P_L - P_{\text{MOSfet}} - P_{\text{diode}} \] (4.1.10)

### 4.1.3 Energetic map of the discrete step-up converter

In order to measure all the losses listed above the following instruments have been employed:

- Multimeter to measure the average values of voltages and currents
- Current prove amplifier to measure the instantaneous currents
- Oscilloscope to plot the signals

The current can be measured in two ways: an inductive measurement and a resistive one. The inductive uses an amperometric probe and influences the measurement by adding a parasitic inductance; the second one uses a shunt resistance and influences the results by adding a parasitic resistance. The first one has been used because the current in the circuit is relatively high due to the ultra-low voltage. The ohmic losses introduced by a resistive measurement of the current are proportional with the square of the current; therefore, the losses introduced by the resistive measurement of the current are larger. Furthermore, thanks to a current amplifier, measuring the current directly with an oscilloscope has been possible. Fig. 4.9 shows the circuit employed to take the measurements.

![Fig. 4.9 Circuit employed to collect the data in order to draw the energetic map of the discrete step-up converter built.](image)
In order to draw an efficiency’s map of the step up boost converter all the measurements of current and voltage in the circuit have been repeated for two different input voltages. It has been taken one with $V_{in} = 0.194 \, V$ and another with $V_{in} = 0.537 \, V$. In both it has been measured:

- Input voltage and input current ($V_{in}, I_{in}$)
- Inductor voltage and inductor current ($V_L, I_L$)
- Drain-source voltage and drain-source current of the transistor ($V_{DS}, I_{DS}$)
- Diode voltage and diode current ($V_D, I_D$)
- Output voltage and output current ($V_{out}, I_{out}$)

All these data have been taken by using the voltage probe and the current probe. Thanks to (4.1.3) (4.1.9) and (4.1.8) the losses in the inductor, in the switch and in the diode have been calculated. Fig. 4.10 shows a pie chart of the first measurement with $V_{in} = 0.194 \, V$. Table 4.1 gives the averages of the values measured.

Fig. 4.11 shows a pie chart with $V_{in} = 0.537 \, V$. Below the chart Table 4.2 gives the average values. In the pie graphs the sum of the losses due to the traces and the losses in the capacitors (4.1.10) is generically called “Others”. Also the losses due to the perturbations introduced by the current and voltage probes are included in “Others”.

**Fig. 4.10** Energetic map of the discrete step-up boost converter measured with $V_{in} = 0.194 \, V$, $P_{in} = 60.33 \, mW$, $D = 80\%$.

<table>
<thead>
<tr>
<th>$V_{in}$ (V)</th>
<th>$I_{in}$ (A)</th>
<th>$V_{out}$ (V)</th>
<th>$I_{out}$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.194</td>
<td>0.311</td>
<td>0.61</td>
<td>0.0607</td>
</tr>
<tr>
<td>P\text{in} (mW)</td>
<td>P\text{out} (mW)</td>
<td>P\text{Inductor} (mW)</td>
<td>P\text{Mosfet} (mW)</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------</td>
<td>-----------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>60.334</td>
<td>37.027</td>
<td>3.064</td>
<td>4.112</td>
</tr>
</tbody>
</table>

Table 4.1

![Energetic map of the discrete step-up boost converter](image)

*Fig. 4.11* Energetic map of the discrete step-up boost converter measured with $V_{\text{in}} = 0.537$ V, $P_{\text{in}} = 84.85$ mW, $D = 80\%$.

<table>
<thead>
<tr>
<th>$V_{\text{in}}$ (V)</th>
<th>$I_{\text{in}}$ (A)</th>
<th>$V_{\text{out}}$ (V)</th>
<th>$I_{\text{out}}$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.537</td>
<td>0.158</td>
<td>2.547</td>
<td>0.0250</td>
</tr>
</tbody>
</table>

Table 4.2

The average values of the input and output power and the efficiency give in *Table 4.1* and *Table 4.2* have been calculated using the follow formulas:

\[
P_{\text{in}} = \frac{1}{T} \int_{0}^{T} v_{\text{in}}i_{\text{in}}dt
\]  

(4.1.11)

\[
P_{\text{out}} = \frac{1}{T} \int_{0}^{T} v_{\text{out}}i_{\text{out}}dt
\]  

(4.1.12)
According to Fig. 4.10 and Fig. 4.11 the losses in the diode affects the efficiency more than the others. These losses are even more critical when the input voltage is ultra-low due to the high current. Appreciate that is possible by comparing the losses in the diode in bold in Table 4.1 and Table 4.2. The forward voltage drop off in the diode tends to be constant with a high range of input current. Fig. 4.12 and Fig. 4.13 show the graphs of the diode voltages for the two different input voltages stated above. In both, the forward voltage drop is around 0.25V.

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \quad \text{(4.1.13)}
\]

\[\text{Fig. 4.12} \text{ Graph of the diode voltage measured with the discrete step-up converter powered by } V_{\text{in}} = 0.194 \text{ V, } P_{\text{in}} = 60 \text{ mW, } D = 80\%. \]

The circle highlights the forward voltage drop (around 0.25 V).
Fig. 4.13 Graph of the diode voltage measured with the discrete step-up converter powered by $V_{in} = 0.537$ V, $P_{in} = 84.85$ mW, $D = 80\%$. The circle highlights the forward voltage drop (around 0.25 V).

### 4.1.4 Efficiency with constant input power

As concerns the step up boost converter it is important to know the curve of the efficiency vs. input voltage with constant input power conditions. In order to draw such graph a measurement has been taken. Fig. 4.9 illustrates the circuit used. The input power has been kept constant by changing the output resistance. The input voltage measurement has been taken directly to the terminals of the input capacitor in order to avoid that the voltage drop off in the Ampere-meter influences the results. The input and the output power have been calculated by means the follow formulas.

\[ P_{in} = V_{in} I_{in} \quad (4.1.14) \]

\[ P_{out} = \frac{V_{out}^2}{R_{out}} \quad (4.1.15) \]
\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \] (4.1.16)

Table 4.3 gives the data measured. The input power has been kept constant at 100 mW by changing the output resistance.

<table>
<thead>
<tr>
<th>( R_{\text{out}} ) (ohm)</th>
<th>( I_{\text{in}} ) (mA)</th>
<th>( V_{\text{in}} ) (V)</th>
<th>( V_{\text{out}} ) (V)</th>
<th>( P_{\text{in}} ) (mW)</th>
<th>( P_{\text{out}} ) (mW)</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3</td>
<td>525</td>
<td>0.192</td>
<td>0.552</td>
<td>100.748</td>
<td>57.491</td>
<td>0.570</td>
</tr>
<tr>
<td>10.3</td>
<td>422</td>
<td>0.236</td>
<td>0.811</td>
<td>99.508</td>
<td>63.856</td>
<td>0.641</td>
</tr>
<tr>
<td>17.4</td>
<td>348</td>
<td>0.291</td>
<td>1.143</td>
<td>101.303</td>
<td>75.083</td>
<td>0.741</td>
</tr>
<tr>
<td>20.4</td>
<td>325</td>
<td>0.308</td>
<td>1.248</td>
<td>100.100</td>
<td>76.348</td>
<td>0.763</td>
</tr>
<tr>
<td>24.3</td>
<td>302</td>
<td>0.333</td>
<td>1.393</td>
<td>100.566</td>
<td>79.854</td>
<td>0.794</td>
</tr>
<tr>
<td>30.3</td>
<td>272</td>
<td>0.371</td>
<td>1.592</td>
<td>100.912</td>
<td>83.646</td>
<td>0.829</td>
</tr>
<tr>
<td>40.3</td>
<td>243</td>
<td>0.413</td>
<td>1.848</td>
<td>100.359</td>
<td>84.742</td>
<td>0.844</td>
</tr>
<tr>
<td>60.2</td>
<td>205</td>
<td>0.489</td>
<td>2.28</td>
<td>100.245</td>
<td>86.352</td>
<td>0.861</td>
</tr>
<tr>
<td>82</td>
<td>178</td>
<td>0.564</td>
<td>2.68</td>
<td>100.392</td>
<td>87.590</td>
<td>0.872</td>
</tr>
<tr>
<td>99.1</td>
<td>165</td>
<td>0.607</td>
<td>2.93</td>
<td>100.155</td>
<td>86.629</td>
<td>0.865</td>
</tr>
<tr>
<td>118.6</td>
<td>153</td>
<td>0.657</td>
<td>3.2</td>
<td>100.521</td>
<td>86.341</td>
<td>0.859</td>
</tr>
<tr>
<td>238.1</td>
<td>131</td>
<td>0.763</td>
<td>4.5</td>
<td>99.953</td>
<td>85.048</td>
<td>0.851</td>
</tr>
</tbody>
</table>

Table 4.3

Fig. 4.14 shows the efficiency curve, derived from this data.

![Efficiency curve](image)

Fig. 4.14 Efficiency curve of the discrete step-up converter vs. input voltage measured with constant input power \( P_{\text{in}} = 100 \text{ mW} \) and \( D = 80\% \). The optimum is from 0.5 V to 0.7 V.
With input voltage from 0.4 V to 0.7 V the efficiency is quite high. In correspondence of high value of input voltage the efficiency decreases slowly. When decreasing the input voltage down to 0.4 V, the efficiency collapses.

4.1.5 Measurements in the step-up converter powered by the solar cell

Until now in all the measurements analysed in this chapter a DC power supply has been used to powered the boost converter. In this section some power measurements taken by using the photovoltaic cell as energy source are shown. The solar cell is the same used to draw the I-V characteristic illustrated in Fig. 3.3. Also in the measurements analysed in this section the cell has been lighted by a desk lamp. Respected to the measurements taken in Chapter III the current supplies by the cell is higher due to better irradiance conditions of the environment (10000 lx). Fig. 4.15 illustrates the circuit employed.

![Fig. 4.15 Circuit used to collect the data with the discrete step-up converter powered by a photovoltaic cell.](image)

Table 4.4 gives the data collected in order to draw the output-input voltage characteristic. To reach 3 V in the output by powering the discrete converter by the solar cell was not possible.
<table>
<thead>
<tr>
<th>$V_{in}$ (V)</th>
<th>$I_{in}$ (mA)</th>
<th>$R_{out}$ (Ω)</th>
<th>$V_{out}$ (V)</th>
<th>$I_{out}$ (mA)</th>
<th>$P_{in}$ (mW)</th>
<th>$P_{out}$ (mW)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.41</td>
<td>120</td>
<td>118.6</td>
<td>1.94</td>
<td>16.0</td>
<td>49.20</td>
<td>31.04</td>
<td>0.631</td>
</tr>
<tr>
<td>0.39</td>
<td>130</td>
<td>99.0</td>
<td>1.83</td>
<td>18.1</td>
<td>50.70</td>
<td>33.12</td>
<td>0.653</td>
</tr>
<tr>
<td>0.39</td>
<td>140</td>
<td>82.1</td>
<td>1.78</td>
<td>21.1</td>
<td>54.60</td>
<td>37.56</td>
<td>0.688</td>
</tr>
<tr>
<td>0.37</td>
<td>166</td>
<td>60.2</td>
<td>1.68</td>
<td>27.3</td>
<td>61.42</td>
<td>45.91</td>
<td>0.748</td>
</tr>
<tr>
<td>0.34</td>
<td>210</td>
<td>40.3</td>
<td>1.51</td>
<td>36.2</td>
<td>71.40</td>
<td>54.66</td>
<td>0.766</td>
</tr>
<tr>
<td>0.33</td>
<td>250</td>
<td>30.4</td>
<td>1.38</td>
<td>43.2</td>
<td>82.50</td>
<td>59.62</td>
<td>0.723</td>
</tr>
<tr>
<td>0.28</td>
<td>320</td>
<td>17.5</td>
<td>1.07</td>
<td>57.0</td>
<td>89.60</td>
<td>60.99</td>
<td>0.681</td>
</tr>
<tr>
<td>0.23</td>
<td>375</td>
<td>10.2</td>
<td>0.83</td>
<td>68.0</td>
<td>86.25</td>
<td>56.44</td>
<td>0.654</td>
</tr>
<tr>
<td>0.20</td>
<td>430</td>
<td>5.4</td>
<td>0.55</td>
<td>81.0</td>
<td>86.00</td>
<td>44.55</td>
<td>0.518</td>
</tr>
</tbody>
</table>

Table 4.4

In all the measurements taken we can appreciate a medium efficiency. *Fig. 4.16* shows the input-output voltage characteristic.

![Input-output voltage characteristic](image)

*Fig. 4.16* Input-output voltage characteristic of the discrete step-up converter powered by the solar cell. The duty cycle has been kept constant at 80% that was the optimum value for each measurements.

The points corresponding to the data measured have been interpolated with the red trend-line which equation is given in (4.1.17).

$$V_{out} = 6.457V_{in} - 0.713 \quad (4.1.17)$$
Fig. 4.16 shows that in order to reach 3 V in the output we need 0.575 V in the input. That is not possible with the solar cell employed.

4.2 Integrated step-up DC-DC converter (MAX757)

4.2.1 Selection of components

Several integrated step up converters are commercially available. The main application of these components is supplying the energy stored in a battery to electronic devices. Such devices can be portable data-collection equipments, µP of portable personal computers, medical instrumentations, mobile phones, MP3 players. The main function of the integrated boost converter is to keep constant the output voltage when the battery is discharging. In this section the MAX 757 DC-DC converter has been analyzed in order to describe the operation and the possible applications in energy management.

The MAX 757 is a boost converter that accepts an input voltage down to 0.7 V and generates a higher adjustable output voltage in the range from 2.7 V to 5.5 V. The start-up voltage minimum declared is 1.1 V and the consumption current is 60 µA. The efficiency in full-load condition is greater than 87%. The internal switch is an N-channel MOSFET that has a very low gate threshold voltage in order to ensure start-up under low-battery voltage conditions. The MAX 757 uses a “pulse frequency modulation” (PFM) technique to generate the switch control signal [15].

In order to measure the efficiency and the start-up voltage the circuit shown in Fig. 4.17 has been built.
Fig. 4.17 Diagram of the circuit employed in order to measure the efficiency and the start-up voltage of the integrated step-up converter MAX757.

The external components shown in Fig. 4.17 have been chosen following the same criteria explained for the discrete version. Low power and input voltage levels have been considered in order to select the components.

**INDUCTOR** (L₁): The same inductor used for the discrete circuit has been employed. Therefore the inductance is 22 µH and the DC parasitic resistance of the coil is 34 mΩ.

**INPUT CAPACITOR** (C₁): In order to limit the equivalent series resistance (ESR) three electrolytic capacitors have been used in a parallel configuration. The capacitance of each capacitor is 47 µF.

**OUTPUT CAPACITOR** (C₂): Because of the same reasons explained for the input capacitor two capacitors with capacitance of 47 µF have been employed.

**OUTPUT RESISTANCE** (R₁, R₂): The output voltage in the MAX 757 is set by two resistors, R₁ and R₂, which form a voltage divider between the output and the FB pin. Therefore,
according to (4.2.1), the two resistors have been selected in order to reach at least 3 V in the output. The reference voltage $V_{\text{REF}}$ is 1.25 V [15].

$$V_{\text{out}} = V_{\text{REF}} \left( \frac{R_1 + R_2}{R_2} \right) > 3$$  \hspace{1cm} (4.2.1)

The follow values of $R_1$ and $R_2$ have been chosen:

$$R_1 = 150k\Omega$$
$$R_2 = 39k\Omega$$

REFERENCE CAPACITOR ($C_3$): A Capacitor of 0.1 $\mu$F has been chosen because there is no external reference load [15].

DIODE: Because of the same reason explained in the section 4.2.1 a Schottky diode has been employed.

4.2.2 Measurements of the start-up voltage and the collapse voltage

In order to know the possible applications of the MAX 757 in energy management the start-up voltage has been measured. Fig. 4.18 shows the circuit built.

Fig. 4.18 Diagram of the circuit built in order to measure voltages and currents of the integrated step-up converter.

The output resistance has been set at 82 $\Omega$ in order to have around 100mW in the input power. 

Table 4.5 gives the data measured.
The start-up voltage measured in these conditions is lower than the minimum start-up voltage declared in the data-sheet (1.1 V). However, the start-up voltage measured is too high for the solar cell studied in the Chapter III. In order to use the energy supplied by the photovoltaic cell we need to find in the market a boost converter that start-up from zero energy at least with 0.5 V.

Another measurement has been taken with the same circuit; once “switch-on” the converter, the input voltage has been decrease up to the switching off of the chip. Table 4.6 gives the data collected.

<table>
<thead>
<tr>
<th>$V_{\text{start-up}}$ (V)</th>
<th>$I_{\text{in}}$ (mA)</th>
<th>$V_{\text{out}}$ (V)</th>
<th>$I_{\text{out}}$ (mA)</th>
<th>$P_{\text{in}}$ (mW)</th>
<th>$P_{\text{out}}$ (mW)</th>
<th>$R_{\text{out}}$ (Ω)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.89</td>
<td>119</td>
<td>2.65</td>
<td>34</td>
<td>106</td>
<td>90.1</td>
<td>82</td>
<td>0.85</td>
</tr>
</tbody>
</table>

*Table 4.5*

The voltage collapses down to 0.5 V and that is a good performance. However the problem is the corresponding output voltage that is too low (1.14 V) to be useful in energy management.

### 4.2.3 Efficiency of MAX 757 with constant input power

The measurement explained in Section 4.1.3 has been repeated using the MAX 757 in order to compare the efficiencies. Fig. 4.18 shows the circuit employed. The power input has been kept constant at 100 mW by changing the load. Theoretically, the IC converter can operate down to 1 mW (it needs at least 60 µW to start up). The discrete step-up converter investigated in the first part of this chapter cannot operate with ultra-low input power because of the gate-drive issue of the MOSFET. The data collected are given in Table 4.7 while Fig. 4.19 illustrates the efficiency’s graph.

<table>
<thead>
<tr>
<th>$V_{\text{collapse}}$ (V)</th>
<th>$I_{\text{in}}$ (mA)</th>
<th>$V_{\text{out}}$ (V)</th>
<th>$I_{\text{out}}$ (mA)</th>
<th>$P_{\text{in}}$ (mW)</th>
<th>$P_{\text{out}}$ (mW)</th>
<th>$R_{\text{out}}$ (Ω)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.48</td>
<td>49</td>
<td>1.14</td>
<td>16</td>
<td>23.52</td>
<td>18.24</td>
<td>82</td>
<td>0.78</td>
</tr>
</tbody>
</table>

*Table 4.6*
The minimum input voltage measured with a constant input power of 100 mW is 0.72 V. Decreasing more the input voltage and at the same time keeping constant the power is not possible.

The efficiency of the integrated boost converter is greater than the efficiency of the discrete version but, as Fig. 4.20 points out, the MAX 757 needs bigger voltage. It is possible working with the solar cell described in Chapter III only on the left of the black line shows of
the Fig. 4.20. Therefore, the MAX 757 is not able to manage the energy supplied by the photovoltaic cell.

![Graph showing efficiency of discrete vs. integrated converters](image1)

**Fig. 4.20** Comparison between the efficiencies of the discrete and the integrated step-up converter analysed in this chapter.

Another limit of the integrated version is the voltage transfer ratio. In order to reach 3 V in the output we need 0.93 V in the input while with the discrete version it was only 0.6 V. **Fig. 4.21** illustrates such concept for a constant input power of 100 mW.

![Graph showing input-output voltage characteristics](image2)

**Fig. 4.21** Comparison between the input-output voltage characteristics of the discrete and the integrated step-up converter analysed in this chapter.
Chapter V

5 Synchronous boost converter

In this chapter the DC-DC synchronous converter is studied. In such converters the losses due to the forward voltage drop in the diode are avoided by using another switch. A discrete and an integrated synchronous boost converter have been built and analysed; in the first section the problems related with the control of the switches in the discrete version are studied; afterwards, in the second section an analysis of the efficiency is given in order to compare the losses with that ones of the step-up boost converter. In the second part of this chapter the proprieties of an integrated synchronous boost converter are studied in reference of the possible applications in energy management.

5.1 Discrete version

5.1.1 Issues in the switching drive control

In order to increase the efficiency of the step-up converter it is possible to replace the diode with another transistor. This new configuration is called synchronous boost converter; Fig. 5.1 illustrates the diagram.

![Diagram of the synchronous DC-DC converter.](image)
The operation of the synchronous boost converter is the same as the step-up converter. Also in the synchronous converter it is possible to identify two stages: during the first one, when the inductor is charging, $S_1$ is closed and $S_2$ is open. In this stage the output is isolated. During the second stage $S_1$ is open while $S_2$ is closed. In this stage, the energy stored in the inductor plus the energy supplied by the input is transferred to the output. Errore. L'origine riferimento non è stata trovata. and Errore. L'origine riferimento non è stata trovata. illustrate the equivalent circuits of both stages. All the formulas given in Appendix B are still valid to explain the operation of the synchronous boost converter.

A discrete version of the circuit shown in Fig. 5.1 has been built in order to analyse the efficiency and to compare the losses with those of the step-up converter. The same components used for the step-up converter have been employed. More details are given in Section 4.1.1. The same type of MOSFET has been used for both $S_1$ and $S_2$.

As regards the two MOSFET It has been states above that when $S_1$ is open $S_2$ must be closed. In the step-up converter the transistor is driven by the signal shown in Fig. 4.3 and generated by the function generator. In the synchronous boost converter we need two signals where one must be the inverse of the other. Fig. 5.2 illustrates the two desired signals.

![Fig. 5.2 The two ideal control signal of the transistor $S_1$ and $S_2$.](image)
The control signal of the MOSFET S1 is a square wave with the same characteristics given in Section 4.1.1. The control signal of S2 cannot be generated directly with the same function generator. Therefore, in order to drive both transistors, some indirect solutions have been analysed. They are:

1. Using a self-driven configuration.
2. To build a circuit that inverts the signal generated by the function generator.

Afterwards advantages and drawbacks of such solutions are explained.

1. SELF-DRIVEN CONFIGURATION

Fig. 5.3 shows that the inverse of the inductor voltage is very similar to the desired voltage $V_{GS2}$ illustrated in Fig. 5.2. (5.1.1) gives the value of such voltage when it is high while (5.1.2) when it is low.

\[-V_L^+ = V_o - V_{in}\]  \hspace{1cm} (5.1.1)

\[-V_L^- = -V_{in}\]  \hspace{1cm} (5.1.2)

Fig. 5.3 Inverse of the inductor voltage: measurement taken from the discrete step-up converter characterised in Chapter IV with $V_{in} = 0.537\, V$, $P_{in} = 84.5\, mW$, $D = 80\%$.

The value of the inverse of the inductor voltage must be over 3 V when it is high in order to switch on the MOSFET S1 (the threshold voltage of the transistors employed is 3 V); because
of that a coil has been winding around the inductor in order to transform the voltage. Fig. 5.4 shows the circuit.

![Diagram of the self-driven synchronous boost converter.](image)

According to (5.1.3), to set the drive voltage of $S_2$ we must know the turns’ number of the inductor. Because of that a measurement has been taken in the discrete step-up converter analysed in Chapter IV. In that measurement the inductor has been winded by a 50 turns coil. The step up converter has been powered by an input voltage of 0.4 V; the output voltage is 1.6 V (see Table 4.3).

$$\frac{V_{GS2}}{-V_L^+} = \frac{N_2}{N_L} \quad (5.1.3)$$

$-V_L^+$ = High level of the inverse inductor voltage.

$N_L$ = Turns’ number of the inductor.

$V_{GS2}$ = Gate-source voltage of the longitudinal transistor.

$N_2$ = Turns’ number of the coil added.

It has been measured:

$-V_L^+ = V_o - V_{in} = 1.6 - 0.4 = 1.2V$

$V_{GS2} = 2.8V$

Therefore, using (5.1.3):

$N_L = 22V$

Once discovered the turns’ number of the inductor, the turns’ number of the coil added has been set in order to switch on $S_2$ in correspondence of very low input voltages. Hence, according to the data collected for the step up boost converter (see Table 4.3):

$V_{in} = 0.3V$
$V_o = 1.2V$

$-V_{L}^{+} = V_o - V_{in} = 1.2 - 0.3 = 0.9$

$N_2 = 90$

$V_{GS2} = -V_{L}^{+} \frac{N_2}{N_L} = 0.9 \frac{90}{22} = 3.68V$

Such voltage is high enough to drive $S_2$. The synchronous converter built in this manner is not efficient because of the parasitic inductance that affects the gate-source voltage of the MOSFET $S_2$. Such parasitic inductance is due to the loop from gate and source and can be minimized by closing to the gate the pins of the coil winded around the inductor. Furthermore, the noise in the gate voltage of the transistor $S_2$ can be reduced by adding a resistance in series with the gate. The new circuit is shown in Fig. 5.5.

![Diagram of the self-driven synchronous boost converter](image)

*Fig. 5.5 Diagram of the self-driven synchronous boost converter. A gate resistance has been added in order to smooth the noise of $S_2$ control signal.*

Even if now the signal is similar to the wished (*Fig. 5.6*) the series resistance introduces another problem. Between gate and source of the transistor there is a parasitic capacitance, therefore the series between such capacitance and the resistance causes a delay in the switch on and switch off of the MOSFET $S_2$. 
Fig. 5.6 Diagram of the MOSFETs’ control voltage signals. In the gate-source voltage of the transistor S2 we can appreciate the ripple due to the parasitic inductance and the delay introduced by the parasitic gate-source capacitance.

Because of that the gate resistance must be optimised in order to smooth the spikes due to the parasitic loop inductance and to reduce the delay due to the constant time $\tau$. Several attempts have been made in order to find the optimum gate resistance. The best voltage transfer ratio and the best efficiency have been measured in correspondence of:

$$R_G = 45\Omega$$

Fig. 5.7 shows the equivalent model of the longitudinal transistor’s gate.

Fig. 5.7 Equivalent model of the longitudinal transistor’s gate.

Even in this way the synchronous boost converter in the self-driven configuration is not so efficient like the step-up converter described in the previously chapter. The voltage transfer ratio is better only in correspondence of ultra-low voltage (0.2 - 0.3V) although the efficiency is low (around 30%).
2. INVERTER CONFIGURATION

It is possible to produce the gate voltage signal of the longitudinal transistor $S_2$ by employing a circuit that inverts the square wave generated by the function generator. Such circuit is given in Fig. 5.8. The control signal of $S_1$ is generated by the function generator, the characteristics are the same used for the discrete step-up converter (Section 4.1.1).

![Inverter circuit diagram](image)

**Fig. 5.8** Inverter built in order to generate the gate-source voltage of the MOSFET $S_2$.

In order to reduce the delay in the switch ON and OFF of the MOSFET the resistance in series with the gate must be a small one. Fig. 5.9 shows a graph with the gate source voltage signals of both transistors.
Fig. 5.9 Control voltages signals of S1 and S2 measured in the discrete synchronous converter built. The circle highlights the delay of $V_{GS2}$. During this time S1 and S2 are switch off.

The waveform of the gate source voltage of the MOSFET S2 is very similar to wished shown in Fig. 5.2. However there is a small delay that affects the efficiency. Because of that during a short time both transistors are switched off; the gate voltage does not reach the threshold level. In Fig. 5.9 the circle highlights that moment. Such problem disappears in correspondence of ultra-low voltage while is more prominent with relatively high input voltage (0.6 - 1V).

Thanks to the inverter configuration it has been possible built an efficient synchronous boost converter. The drawback of driving the two switches with such system is that we need another external source. Fig. 5.10 shows the diagram of the circuit built in order to measure the efficiency and to compare the losses with that ones of the step-up converter.
5.1.2 Energetic map of the synchronous boost converter

In the synchronous boost converter there are almost the same kinds of losses of the step-up boost converter. The only difference is that the diode losses are replaced by ohmic and switching losses in the transistor $S_2$. The aim of this section is demonstrated that replacing the diode with a MOSFET the losses are reduced and the transfer voltage ratio is increased.

(4.1.3) and (4.1.8) have been used in order to calculate the inductor and the MOSFET’s losses. The sum of the losses due to the equivalent series resistance of the capacitors and to the trace resistances have been calculated using (4.1.10). The measurements have been taken using the same input conditions explained for the step-up converter. All the voltages and the currents in the components have been measured in reference of two different input voltage levels. The instruments described in Section 4.1.3 have been employed to collect the data. Fig. 5.11 shows the circuit employed.
Fig. 5.11 Circuit employed to collect the data in order to draw the energetic map of the discrete synchronous converter.

In the first measurement the input voltage has been set at 0.190 V. Fig. 5.12 illustrates a pie-chart of the losses. Below Table 5.1 gives the average values of the data collected. Fig. 5.13 shows a pie-chart of the losses measured with 0.543 V input voltage. Table 5.2 gives the average values of the data measured with this input voltage.

![Energetic map of the discrete synchronous boost converter measured with $V_{in} = 0.1904$ V, $P_{in} = 57$ mW, $D = 80\%$.](image)

### Table 5.1

<table>
<thead>
<tr>
<th>$V_{in}$ (V)</th>
<th>$I_{in}$ (A)</th>
<th>$V_{out}$ (V)</th>
<th>$I_{out}$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1904</td>
<td>0.299</td>
<td>0.0557</td>
<td>0.0607</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$P_{in}$ (mW)</th>
<th>$P_{out}$ (mW)</th>
<th>$P_{Inductor}$ (mW)</th>
<th>$P_{Mosfet1}$ (mW)</th>
<th>$P_{Mosfet2}$ (mW)</th>
<th>$P_{Others}$ (mW)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
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<td>56.9207</td>
<td>45.1539</td>
<td>2.9913</td>
<td>5.5274</td>
<td><strong>3.1727</strong></td>
<td>0.0754</td>
<td>0.7933</td>
</tr>
</tbody>
</table>

Table 5.1
Miniaturisation of solar energy harvesters: efficiency analysis of converters and ultra-low voltage start up techniques

Fig. 5.13 Energetic map of the discrete synchronous boost converter measured with $V_{in} = 0.5426$ V, $P_{in} = 78$ mW, $D = 80\%$.

<table>
<thead>
<tr>
<th>$V_{in}$ (V)</th>
<th>$I_{in}$ (A)</th>
<th>$V_{out}$ (V)</th>
<th>$I_{out}$ (A)</th>
</tr>
</thead>
<tbody>
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<td>0.5426</td>
<td>0.1412</td>
<td>2.8543</td>
<td>0.0226</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$P_{in}$ (mW)</th>
<th>$P_{out}$ (mW)</th>
<th>$P_{Inductor}$ (mW)</th>
<th>$P_{Mosfet1}$ (mW)</th>
<th>$P_{Mosfet2}$ (mW)</th>
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<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.0825</td>
<td>64.6085</td>
<td>0.6674</td>
<td>3.3997</td>
<td>8.0725</td>
<td>1.3345</td>
<td>0.8274</td>
</tr>
</tbody>
</table>

The average values of the input and output power and the efficiency give in Table 5.1 and Table 5.2 have been calculated using the formulas (4.1.11), (4.1.12) and (4.1.13).

In order to state the advantages of the synchronous boost converter the losses previously shown must be compared with those measured for the step-up converter. Fig. 5.14 illustrates the comparison for 0.19 V input voltage. The diode losses in the step-up converter are almost five times more than the losses in the MOSFET $S_1$ in the synchronous converter. The other losses, as expected, are around the same values. Therefore, we can state that in correspondence of ultra-low input voltage the efficiency increases substituting the diode with another transistor.
**Fig. 5.14** Graph that compare the losses between the discrete synchronous converter and the discrete step-up powered by similar inputs ($V_{in} = 0.19$ V, $P_{in} = 60$ mW, $D = 80\%$).

The advantages introduced by the synchronous are even more evident if we also show a comparison between the input and output power in the measurements taken for both converter. As **Fig. 5.15** shows, the input power in the measurement taken with the synchronous converter is smaller that which one measured for the step-up converter but the output power is larger.

**Fig. 5.15** Losses’ comparison between the discrete step-up converter and the synchronous converter. The graph shows also input and output powers.

The same considerations can be obtained for 0.54 V input voltage. **Fig. 5.16** shows the...
comparison.

Fig. 5.16 Graph that compare the losses between the discrete synchronous converter and the discrete step-up powered by similar inputs ($V_{\text{in}} = 0.54 \text{ V}, P_{\text{in}} = 80 \text{ mW}, D = 80\%$).

In Fig. 5.16 the advantages introduced by the synchronous configuration are less evident; that is due to:

- The synchronous converter is less efficient in correspondence of medium input voltages because of the problem described in Fig. 5.9.
- The input power measured in the synchronous measurement was smaller than that one measured for the step-up. In order to give a more objective interpretation Fig. 5.17 shows a comparison where there are included also the input and output powers.
**Fig. 5.17** Losses’ comparison between the discrete step-up converter and the synchronous converter. The graph shows also input and output powers.

### 5.1.3 Efficiency with input constant power

The measurement described in Section 4.1.4 has been repeated with the synchronous converter in order to compare the efficiency with that one of the step-up boost converter in correspondence of different input voltage (0.2 V - 1 V). **Fig. 5.11** shows the circuit employed. The input power has been kept constant at 100 mW by changing the output resistance. The formulas (4.1.14), (4.1.15) and (4.1.16) have been used to calculate the input power, the output power and the efficiency. **Table 5.3** gives the data collected in order to draw the efficiency curve. The duty cycle has been kept constant (D = 80%).
Table 5.3

<table>
<thead>
<tr>
<th>Vin (V)</th>
<th>I_in (mA)</th>
<th>V_out (V)</th>
<th>R_out (ohm)</th>
<th>P_in (mW)</th>
<th>P_out (mW)</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.168</td>
<td>594</td>
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<td>5.2</td>
<td>99.792</td>
<td>64.692</td>
<td>0.648</td>
</tr>
<tr>
<td>0.213</td>
<td>471</td>
<td>0.91</td>
<td>10.2</td>
<td>100.323</td>
<td>81.186</td>
<td>0.809</td>
</tr>
<tr>
<td>0.264</td>
<td>378</td>
<td>1.23</td>
<td>17.4</td>
<td>99.792</td>
<td>86.948</td>
<td>0.871</td>
</tr>
<tr>
<td>0.282</td>
<td>356</td>
<td>1.34</td>
<td>20.3</td>
<td>100.392</td>
<td>88.453</td>
<td>0.881</td>
</tr>
<tr>
<td>0.303</td>
<td>329</td>
<td>1.47</td>
<td>24.2</td>
<td>99.687</td>
<td>89.293</td>
<td>0.896</td>
</tr>
<tr>
<td>0.335</td>
<td>298</td>
<td>1.66</td>
<td>30.3</td>
<td>99.830</td>
<td>90.944</td>
<td>0.911</td>
</tr>
<tr>
<td>0.380</td>
<td>265</td>
<td>1.93</td>
<td>40.2</td>
<td>100.700</td>
<td>92.659</td>
<td>0.920</td>
</tr>
<tr>
<td>0.456</td>
<td>221</td>
<td>2.35</td>
<td>60.1</td>
<td>100.776</td>
<td>91.889</td>
<td>0.912</td>
</tr>
<tr>
<td>0.510</td>
<td>189</td>
<td>2.68</td>
<td>81.9</td>
<td>96.390</td>
<td>87.697</td>
<td>0.910</td>
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<td>0.558</td>
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<td>0.893</td>
</tr>
<tr>
<td>0.604</td>
<td>165</td>
<td>3.22</td>
<td>118.5</td>
<td>99.660</td>
<td>87.497</td>
<td>0.878</td>
</tr>
<tr>
<td>0.788</td>
<td>127</td>
<td>4.22</td>
<td>239.0</td>
<td>100.076</td>
<td>74.512</td>
<td>0.745</td>
</tr>
</tbody>
</table>

Fig. 5.18 shows the graph of the synchronous efficiency compared with the efficiency of the step-up.

![Graph of Efficiency vs Input Voltage](image)

Fig. 5.18 Comparison between the efficiencies of the discrete boost converters built with constant input power (P_in = 100 mW, D = 80%).
The advantages of the synchronous converter are predominant in correspondence of ultra low input voltage (0.2 - 0.6 V). In such range the efficiency is over 80% and around 0.4 V input voltage there is the efficiency peak (92%). In correspondence of more than 0.6 V input voltage the efficiency tends to decrease faster than in the step-up probably because of the problem illustrated in Fig. 5.9.

The second important advantage of the synchronous converter concerns the voltage transfer ratio. The MOSFET that substitutes the diode does not have a large voltage drop (Fig. 5.19). Therefore, we can reach larger output voltage with the same input.

![Comparison between the diode voltage waveform in the step-up configuration and the voltage waveform of the transistor S2 in the synchronous converter. The circles highlight that in the synchronous converter the forward voltage drop is avoided (D = 80%).](image)

Fig. 5.19 Comparison between the diode voltage waveform in the step-up configuration and the voltage waveform of the transistor S2 in the synchronous converter. The circles highlight that in the synchronous converter the forward voltage drop is avoided (D = 80%).

Fig. 5.20 shows the increment in the transfer voltage ratio.
Fig. 5.20 Comparison of the input-output voltage characteristics between the two discrete boost converters. The characteristics have been measured at the optimum duty cycle (80%).

5.1.4 Measurements in the synchronous converter powered by the solar cell

The measurement explained in Section 4.1.5 has been repeated for the synchronous converter. The same irradiance conditions have been kept in order to compare the results. Table 5.4 gives the data collected.

<table>
<thead>
<tr>
<th>R_{out} (Ω)</th>
<th>V_{in} (V)</th>
<th>I_{in} (mA)</th>
<th>V_{out} (V)</th>
<th>I_{out} (mA)</th>
<th>P_{in} (mW)</th>
<th>P_{out} (mW)</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>118.5</td>
<td>0.43</td>
<td>145</td>
<td>2.46</td>
<td>20.8</td>
<td>62.35</td>
<td>51.07</td>
<td>0.819</td>
</tr>
<tr>
<td>60.1</td>
<td>0.39</td>
<td>230</td>
<td>2.18</td>
<td>36.3</td>
<td>89.70</td>
<td>79.07</td>
<td>0.882</td>
</tr>
<tr>
<td>40.2</td>
<td>0.37</td>
<td>290</td>
<td>2.01</td>
<td>50.0</td>
<td>105.85</td>
<td>100.50</td>
<td>0.949</td>
</tr>
<tr>
<td>30.3</td>
<td>0.34</td>
<td>333</td>
<td>1.83</td>
<td>60.4</td>
<td>114.22</td>
<td>110.52</td>
<td>0.968</td>
</tr>
<tr>
<td>24.2</td>
<td>0.32</td>
<td>390</td>
<td>1.70</td>
<td>70.2</td>
<td>125.97</td>
<td>119.42</td>
<td>0.948</td>
</tr>
<tr>
<td>17.4</td>
<td>0.29</td>
<td>464</td>
<td>1.48</td>
<td>85.1</td>
<td>135.49</td>
<td>125.89</td>
<td>0.929</td>
</tr>
<tr>
<td>10.2</td>
<td>0.23</td>
<td>544</td>
<td>1.03</td>
<td>101.0</td>
<td>123.49</td>
<td>104.01</td>
<td>0.842</td>
</tr>
<tr>
<td>5.3</td>
<td>0.16</td>
<td>600</td>
<td>0.59</td>
<td>111.3</td>
<td>96.00</td>
<td>65.68</td>
<td>0.684</td>
</tr>
</tbody>
</table>

Table 5.4
The data gives in Table 5.4 confirm that the synchronous converter is the best solution to step up from ultra-low input voltage. Fig. 5.21 shows the efficiency increment when the converter is powered by the solar cell.

Fig. 5.21 Comparison between the efficiencies of the two discrete converters powered by the photovoltaic cell characterised in Chapter III.

As for the step-up converter, reaching 3 V in the output is not possible in the measurement taken with the solar cell. In order to supply output power at 3 V we should have at least 0.51 V in the input. However such input voltage is lower that the value gives in section 4.1.5 for the step-up converter (0.575 V). The trend-line equation given in (5.1.4) interpolates the data shown in Fig. 5.22.

\[ V_{\text{out}} = 6.951 \cdot V_{\text{in}} - 0.539 \]  

(5.1.4)
5.2 Analysis of an integrated synchronous boost converter (LTC3429)

In the previously section a discrete synchronous boost converter has been analyses and the advantages respect the discrete step-up boost converter studied in chapter IV has been pointed out. In the second part of chapter IV an integrated step-up boost converter has been studied: in this section, in order to make a comparison, a integrated synchronous boost converter is analysed. The start-up from zero energy issues of such device have been studied for the purpose of finding the possible applications in energy management.

5.2.1 Selection of components

The synchronous boost converter analysed is the LTC3429 produced by Linear Technology. As for the integrated step-up converter (MAX757), the main function of LTC3429 is to convert the energy stored in a battery and to power with a constant voltage electronic devices as MP3 players, digital cameras, handheld instruments and GPS receiver [16]. The LTC3429’s technical characteristics declared in the datasheet are the following [16]:

- Input voltage range from 0.5 to 4.4 V
- Output voltage range from 2.5 to 4.3 V
- Start-up voltage from 0.85 V
- Efficiency in full-load condition up to 96%
- 380µA of consumption current in active operation
- 2.5 ms soft start-up time
- Duty cycle between 80% and 90%
- 500 kHz fixed switching frequency

The internal circuit presents two low on-resistance MOSFETs driven by a Pulse Width Modulation technique (PWM).

In order to measure the efficiency and the start-up voltage the circuit shown in Fig. 5.23 has been built.

![Diagram of the circuit employed in order to measure the efficiency and the start-up voltage of the integrated synchronous converter LTC3429.](image)

The external components shown in Fig. 5.23 have been chosen in order to supply in the output 100 mW at 3 V. In order to avoid the shutdown of the converter the shutdown pin (SHDN) has been connected to the input voltage pin.

INDUCTOR (L): The same inductor employed in the integrated step-up converter has been selected. The inductor’s characteristics are 22 µH of inductance and 34 mΩ of DC resistance.
INPUT CAPACITOR \( (C_1) \): 10 µF tantalum capacitor with low equivalent resistance (50 mΩ).

OUTPUT CAPACITOR \( (C_2) \): 47 µF tantalum capacitor with low equivalent series resistance (50 mΩ).

OUTPUT RESISTANCE \( (R_1, R_2) \): The output voltage in the LTC3429 is set by two resistors, \( R_1 \) and \( R_2 \), which form a voltage divider between the output and the FB pin. Therefore, according to (5.2.1), the two resistors have been selected in order to reach at least 3 V in the output. The reference voltage \( V_{\text{REF}} \) is 1.23 V [16].

\[
V_{\text{out}} = V_{\text{REF}} \left( \frac{R_1 + R_2}{R_2} \right) > 3
\]  

(5.2.1)

The follow values of \( R_1 \) and \( R_2 \) have been chosen:

\[
R_1 = 680k\Omega
\]

\[
R_2 = 150k\Omega
\]

### 5.2.2 Measurements of the start-up voltage and the collapse voltage

The start-up voltage and the collapse voltage of the LTC3429 have been measured. Fig. 5.24 shows the circuit employed.

![Diagram of the circuit built in order to measure voltages and currents of the integrated synchronous converter.](image)
The output resistance has been set at 280 Ω in order to have around 100 mW in the input power when the circuit starts up. *Table 5.5* gives the data collected in the start-up voltage measurement. *Table 5.6* gives the data measured in correspondence of the lowest voltage before the collapse.

<table>
<thead>
<tr>
<th>V_{start-up} (V)</th>
<th>I_{in} (mA)</th>
<th>V_{out} (V)</th>
<th>I_{out} (mA)</th>
<th>P_{in} (mW)</th>
<th>P_{out} (mW)</th>
<th>R_{out} (Ω)</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.78</td>
<td>133</td>
<td>4.98</td>
<td>19</td>
<td>103.74</td>
<td>94.62</td>
<td>280</td>
<td>0.912</td>
</tr>
</tbody>
</table>

*Table 5.5*

<table>
<thead>
<tr>
<th>V_{collapse} (V)</th>
<th>I_{in} (mA)</th>
<th>V_{out} (V)</th>
<th>I_{out} (mA)</th>
<th>P_{in} (mW)</th>
<th>P_{out} (mW)</th>
<th>R_{out} (Ω)</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>97</td>
<td>2.69</td>
<td>9</td>
<td>42.68</td>
<td>24.21</td>
<td>280</td>
<td>0.567</td>
</tr>
</tbody>
</table>

*Table 5.6*

The start-up voltage measured is similar to the declared in the datasheet. It is lower than the MAX757 start-up voltage but not enough to converter the energy stored in the photovoltaic cell characterised in Chapter III. Nowadays in the market there are not step-up and synchronous boost DC-DC converter able to step-up from zero energy the voltage stored in that solar cell.

### 5.2.3 Efficiency of LTC3429 with constant input power

For the sake of comparing the efficiency of the integrated DC-DC converters the measurement explained in Section 4.2.3 with 100 mW constant input power has been repeated also for the synchronous converter LTC3429. *Fig. 5.24* shows the circuit employed to collect the data give in *Table 5.7*. 
The efficiency measured presents a step in correspondence of 0.7 V of input voltage. Up to such value the LTC3429 presents medium-low efficiency. Over 0.7 V the synchronous converter is operating with high efficiency. As expected, with input voltage higher than 0.7 V the LTC3429 is more efficient than the MAX757; the same advantages point out for the discrete versions in Section 5.1.3 are confirmed for the integrated versions. *Fig. 5.25* shows a comparison of the efficiency between the two integrated converters.

![Efficiency Comparison](image)

*Fig. 5.25* Comparison between the conversion efficiency (LTC3421 and MAX757).

<table>
<thead>
<tr>
<th>$R_{\text{out}}$ (Ω)</th>
<th>$V_{\text{in}}$ (V)</th>
<th>$I_{\text{in}}$ (mA)</th>
<th>$V_{\text{out}}$ (V)</th>
<th>$I_{\text{out}}$ (mA)</th>
<th>$P_{\text{in}}$ (mW)</th>
<th>$P_{\text{out}}$ (mW)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.48</td>
<td>216</td>
<td>2.27</td>
<td>22</td>
<td>103.68</td>
<td>49.94</td>
<td>0.482</td>
</tr>
<tr>
<td>146</td>
<td>0.52</td>
<td>200</td>
<td>2.59</td>
<td>20</td>
<td>104.00</td>
<td>51.80</td>
<td>0.498</td>
</tr>
<tr>
<td>173</td>
<td>0.58</td>
<td>176</td>
<td>3.11</td>
<td>19</td>
<td>102.08</td>
<td>59.09</td>
<td>0.579</td>
</tr>
<tr>
<td>206</td>
<td>0.63</td>
<td>163</td>
<td>3.44</td>
<td>18</td>
<td>102.69</td>
<td>61.92</td>
<td>0.603</td>
</tr>
<tr>
<td>240</td>
<td>0.69</td>
<td>152</td>
<td>3.83</td>
<td>17</td>
<td>104.88</td>
<td>65.11</td>
<td>0.621</td>
</tr>
<tr>
<td>258</td>
<td>0.73</td>
<td>134</td>
<td>4.53</td>
<td>19</td>
<td>97.82</td>
<td>86.07</td>
<td>0.880</td>
</tr>
<tr>
<td>270</td>
<td>0.76</td>
<td>132</td>
<td>4.72</td>
<td>19</td>
<td>100.32</td>
<td>89.68</td>
<td>0.894</td>
</tr>
<tr>
<td>360</td>
<td>0.88</td>
<td>113</td>
<td>5.45</td>
<td>17</td>
<td>99.44</td>
<td>92.65</td>
<td>0.932</td>
</tr>
<tr>
<td>434</td>
<td>0.98</td>
<td>103</td>
<td>6.06</td>
<td>16</td>
<td>100.94</td>
<td>96.96</td>
<td>0.961</td>
</tr>
<tr>
<td>470</td>
<td>1.36</td>
<td>79</td>
<td>6.53</td>
<td>15</td>
<td>107.44</td>
<td>97.95</td>
<td>0.912</td>
</tr>
</tbody>
</table>

*Table 5.7*
Fig. 5.26 illustrates the comparison between the voltage transfer ratios.

The LTC3429 voltage transfer ratio is higher because of the follow reasons:

- The LTC3429 duty cycle is bigger than the MAX757 one.
- The forward voltage drop of the diode is avoided being the LTC3429 a synchronous converter.

Fig. 5.26 shows that once started-up the converter 3 V can be reached in the output with only 0.57 V in the input.

The LTC3429’s analysis given in the last two sections highlights that the integrated synchronous converter could be used in order to transform the energy stored in micro-power harvesters only solving the start-up issue. In Chapter VII a solution to such problem is given.
Chapter VI

6 Switched-capacitor converter

Section 2.3 introduces a family of step-up DC-DC converter called switched-capacitors converters or charge pump converters. Only during recent years such converters have become popular due to the possible uses in low-power and ultra-low voltage DC-DC conversion. In order to study the operation and to analyse the efficiency a discrete charge pump with gain 3 has been built. In the second part of this chapter an integrated version of Charge Pump is evaluated.

6.1 Discrete switched capacitor converter with gain 3

6.1.1 Selection of components

For the sake of investigating the operation of switched capacitor converters a discrete version with gain 3 was built. Fig. 6.1 shows the circuit diagram.

---

**Fig. 6.1** Diagram of a switched capacitor converter with gain 3.
In the circuit there are 3 capacitors and 7 switches. The diode used in the charge pump introduced in section 2.3 has been substituted by switches in order to avoid the forward voltage drop during the ON-state. For the purpose of simplifying the analysis of the converter’s operation, identical capacitors and identical switches have been chosen. The selection of components has been made in order to limit the losses, in view of the low power and ultra-low voltage applications studied in this thesis. Later, the technical characteristics of the components employed are discussed.

SOURCE: A “dual tracking DC power supply” has been used. In order to keep the voltage constant during the measurements, the DC power supply has been employed in voltage control mode.

CAPACITORS: In order to limit the losses capacitors with low equivalent series resistance have been chosen. In the next section more details are given as regards the influence of such parasitic resistance on the efficiency. 47 µF electrolytic capacitors have been chosen for the purpose of reducing the output ripple.

SWITCHING DEVICES: MOSFETs with low on-resistances have been chosen. The same transistors used in the step-up and in the synchronous boost converter have been employed because of the reasons discuss in Section 4.1.1. The technical characteristics from the data sheet are:

\[ V_{DS} = 20V \]
\[ I_D @ 25°C = 36A \]
\[ R_{DS} = 0.02Ω \]
\[ V_{GS(th)\max} = 3V \]

FUNCTION GENERATOR: A function generator has been used to drive the transistors marked by 1 in Fig. 6.1. A square wave with the follow characteristics has been generated:

\[ V_{pp} = 5V \]
\[ f = 100kHz \]
\[ OFFSET = +2.5V \]
\[ \text{DutyCycle}(D) = 50\% \]

The peak to peak voltage is high enough to drive all the transistors marked \( S_1 \) (the maximum high side transistor voltage is 6 V if in the output we have 3 V).

The transistors marked \( S_2 \) have been driven by the inverse wave generated using the inverter configuration explained in section 5.2.1 and illustrated in Fig. 6.2.

\[ V_{cc} = +5 \text{ V} \]
\[ R_{cc} = 47 \Omega \]
\[ R_G = 2.3 \Omega \]

![Diagram](image)

*Fig. 6.2 Diagram of the circuit that was built in order to generate the control signals of \( S_1 \) and \( S_2 \)*

### 6.1.2 Operation and efficiency

In section 2.3 the operation of a switched capacitor with gain 2 has been explained. The operation of a charge pump with gain 3 is similar. We can identify two stages:

- **STAGE 1**: During this stage the switches marked \( S_1 \) in Fig. 6.1 are closed while the switches marked \( S_2 \) are open. *Fig. 6.3* illustrates the equivalent circuit.
In this stage the capacitors $C_1$ and $C_2$ are charged by the source to $V_{in}$

\[ V_{C_1} = V_{C_2} = V_{in} \quad (6.1.1) \]

- **STAGE 2**: During this stage the MOSFETs marked $S_1$ are open and that ones marked $S_2$ are closed. *Fig. 6.4* shows the equivalent circuit.

\[ C_1 \quad C_2 \quad C_3 \quad R_{out} \]

*C Fig. 6.4 Diagram of the switched capacitor converter during the stage II (S₁ OFF and S₂ ON)*

$C_1$ and $C_2$ are connected in series with the source to produce a voltage of:
\[ V_{C_3} = V_{in} + V_{C_1} + V_{C_2} = V_{out} = 3V_{in} \] (6.1.2)

This voltage is discharged into C_3 and reaches three times the input voltage.

For a more general configuration of a switched capacitor we can state that the ideal conversion ratio depends on the number of capacitors and switches. For an “ideal no-loaded” charge pump the ideal conversion ratio is given by:

\[ M = \frac{V_{out}}{V_{in}} = \frac{P}{Q} \] (6.1.3)

Where P and Q are integer values that depend only on the number of capacitors and how they are interconnected in the stage 1 and in the stage 2. Therefore, the ideal voltage gain does not depend of the value of capacitances, switching frequency, clock duty ratios; it is related only to pure topological aspects [6].

In a real SC-converter there are several factors that affect the conversion ratio, decrease the efficiency and cause a ripple in the output voltage. The most important are:

- The equivalent series resistance of the capacitors (R_c)
- The conduction resistances of the switches (R_s)
- The load current.

*Fig. 6.5* shows the equivalent circuit for both stages considering such factors.

![Equivalent circuit for both stages of the switched capacitor converter](image)
With the circuit being built from discrete components, we should also consider as parasitic elements:

- The trace resistances
- The inductance due to tracks loops
- The delay introduced in the synchronization of the driven signals (see Fig. 5.9).

*Fig. 6.6* shows the diagrams of the output voltage measured in correspondence of the input data given in *Table 6.1*.

<table>
<thead>
<tr>
<th>$V_{in}$ (V)</th>
<th>$I_{in}$ (mA)</th>
<th>$V_{out}$ (V)</th>
<th>$R_{out}$ (Ω)</th>
<th>$P_{in}$ (mW)</th>
<th>$P_{out}$ (mW)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.01</td>
<td>76</td>
<td>2.85</td>
<td>120.1</td>
<td>76.76</td>
<td>67.63</td>
<td>0.881</td>
</tr>
</tbody>
</table>

*Table 6.1*

*Fig. 6.6* Graph of the output voltage measured with the switched capacitor converter powered at 1 V.

The measurements taken on the SC-converter built point out that:

- when the output resistance decreases the real conversion ratio is closer to the ideal one ($M=3$)
- The efficiency is medium-high (> 75%) even at ultra-low voltages (0.2 - 0.3 V)
- The ripple in the output voltage is higher with low output resistances
- We have the best conversion ratio and the best efficiency working with duty-cycle $D = 50\%$.  

In order to increase the efficiency and reach the ideal conversion ratio we should:

- Substitute the capacitor with low equivalent series resistance (tantalum for example)
- Miniaturise the circuit’s size
- Change the transistors with other ones with a lower on-resistance (< 20 mΩ)
- Reduce the delay in the gate voltage of the transistors marked by 2 by either decreasing the gate resistance or substituting the transistors with other ones with low parasitic gate-source capacitance.

Even adopting these optimisations we cannot use the circuit above to transform the energy supply from the solar cell or other forms of micro-power harvesting. The main restriction of the SC-converter built is that it is not able to start-up from zero energy.

### 6.2 Low voltage start-up integrated charge pump: S-882Z

In this section the integrated charge pump S-882Z is presented. The difference with other conventional switched capacitor converters is in the use of a fabrication processes called SOI (Silicon on Insulator) that enables ultra-low voltage operation [17].

#### 6.2.1 Characterisation and operation of S-882Z

The S-882Z charge pump is capable to step-up input voltages from 0.3 V. As previously stated that is possible because the chip uses a full-depletion silicon-on-insulator (SOI) substrate. In such technology the source-drain leakage current is extremely low. Because of that the transistor’s threshold voltage can be minimized. To make directly an integrated boost converter (either step-up or synchronous) by such technology is not economically available because of substrate’s high cost. The drawback of the full depleted SOI (silicon on Insulator) technology is in the efficiency; the leakage current and the switching losses cause a decrement of the S-882Z efficiency down to 20% [18].

According to Fig. 6.7 the operation is characterized by the follow steps [17]:

1. When the input voltage is 0.3 V or higher (pin 4) the oscillation circuit starts operating in order to generate a CLK (clock) signal.

2. The clock signal drives the charge pump. In this circuit the input voltage is converted with the switched capacitors technique analyzed in the previously section.

3. The stepped up electric power output transformed by the charge pump is employed to charge the start-up capacitor $C_{CPOUT}$. Therefore the potential of such capacitor (pin 5) gradually rises.

4. When the start-up capacitor voltage reaches or exceeds the discharge start voltage ($V_{CPOUT1}$), the output signal of the comparator $COMP_1$ changes from high level to low. Because of that, the transistor $M_1$ switches ON.

5. When such transistor is ON the energy stored in the capacitor $C_{CPOUT}$ at the discharge start voltage level is discharged from the output pin (pin 1).

6. When the potential of the output pin falls below to the discharge stop voltage level ($V_{CPOUT2}$) the transistor $M_1$ switches off and the discharge is stopped.

7. When the VM pin voltage (pin 4) reaches or exceeds the shutdown voltage ($V_{OFF}$), the output signal (EN-) of the comparator ($COMP_2$) changes from low level to high. Therefore, the oscillation circuit is switched off and the S-882Z enters the shutdown state. In this way power consumption is reduced.

8. When the VM pin voltage is lower than the shutdown voltage ($V_{OFF}$), the output signal (EN-) of the comparator $COMP_2$ is high and the oscillation circuit turns on again, returning to the operation specified in 2.
There are more types of S-882Z commercially available. They present different discharge start voltages. Table 6.2 gives the four types that we can find in the market.

<table>
<thead>
<tr>
<th>Discharge Start Voltage ($V_{CPOUT1}$)</th>
<th>Shutdown Voltage ($V_{OFF}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8 ± 0.1 (V)</td>
<td>1.9 ± 0.1 (V)</td>
</tr>
<tr>
<td>2.0 ± 0.1 (V)</td>
<td>2.1 ± 0.1 (V)</td>
</tr>
<tr>
<td>2.2 ± 0.1 (V)</td>
<td>2.3 ± 0.1 (V)</td>
</tr>
<tr>
<td>2.4 ± 0.1 (V)</td>
<td>2.5 ± 0.1 (V)</td>
</tr>
</tbody>
</table>

*Table 6.2*
Chapter VII

7 Low voltage start-up technique from zero energy

In the previously chapter the integrated charge pump S-882Z has been introduced. In the first part of this chapter, the possible uses of such device in the boost conversion from ultra-low voltages are investigated. Furthermore is explained how the problem of the start-up from zero energy has been solved. An operating circuit that reaches 3 V in the output has been built; such circuit can be powered either by the photovoltaic cell characterised in the chapter 3 or by a combination of small-size and ultra-low power [100 µW] photodiodes. Such applications are analysed in the second part of this chapter.

7.1 Start-up technique with zero onboard stored energy

In Chapters IV and V two different kinds of integrated boost converter have been analysed: a step-up converter (MAX757) and a synchronous converter (LTC3429). Both have the same limitation: they cannot be powered by a single photovoltaic cell or other forms of micro-power harvesters because they are not able to start-up from zero energy. The charge pump S-882Z is the solution of such limitation: it can supply to a DC-DC converter the initial energy at a relatively high voltage level in order to start-up it.

The operation of the charge pump plus a boost converter is characterised by the follow 5 steps:

1. The source supplies the energy to the S-882Z in order to charge the output capacitor.
2. When the capacitor voltage reaches the desired level the energy stored in the capacitor is delivered to the power supply pin of the boost converter in order to start-up it. The capacitor $C_{VDD}$ smoothes the power.
3. The boost converter starts transforming the input voltage supplied by the source in a high output voltage level (3 V).
4. The S-882Z detects that the output voltage of the boost converter is bigger than the shutdown voltage $V_{OFF}$ and consequently it stops operating.
5. The DC-DC boost converter operates by itself. 

*Fig. 7.1* shows a block diagram and *Fig. 7.2* a possible connection diagram.

![Block Diagram](image1)

*Fig. 7.1* Possible implementation of the charge pump S-882Z with a DC-DC boost converter (block diagram).

![Connection Diagram](image2)

*Fig. 7.2* Possible implementation of the charge pump S-882Z with a DC-DC boost converter (connection diagram).

The function of the Schottky diode circled in *Fig. 7.2* is preventing a voltage decline in the power supply pin (VDD pin) of the step-up converter due to the output capacitor $C_L$ during
the start-up time [17].

In order to make an efficient conversion the selection of the capacitance and the value of the discharge start voltage of the charge pump are the critical aspects. The follow three expressions must be respected in order to choose the start-up capacitor $C_{CPOUT}$, the power smoothing capacitor $C_{VDD}$ and the discharge start voltage $V_{CPOUT1}$ of the charge pump [17].

\[
\left( \frac{V_{CPOUT1}}{C_{CPOUT} + C_{VDD}} \cdot 0.1 \cdot I_{VDD} - V_{DDL} \right) \cdot \left( C_{CPOUT} + C_{VDD} \right) > 2 \cdot t_s \cdot I_{VDD} \quad (7.1.1)
\]

\[
V_{CPOUT1} > V_{DDL} + 0.2V \quad (7.1.2)
\]

\[
C_{CPOUT} > 10 \cdot C_{VDD} \quad (7.1.3)
\]

where:
$I_{VDD}$ = Consumption current value of boost DC-DC converter
$V_{DDL}$ = Minimum operation voltage of boost DC-DC converter
$t_s$ = Step-up DC-DC converter start-up time.

The expression (7.1.1) is related to the consumption current of the step-up converter. If such current is too high the energy stored in the start-up capacitor could not be enough to start-up the boost converter. Therefore when the consumption current of the boost converter is high we need a large start-up capacitor that presents the drawback of very long charge time.

The expression (7.1.2) states that the charge pump does not work with boost converters that present minimum operation voltage lower than the discharge start voltage.

The expression (7.1.3) states that the start-up capacitor must be bigger than the smooth capacitor (at least ten times) in order to charge it quickly and do not dissipate all the energy in such operation.
Fig. 7.3 shows the voltages waveforms in the circuit illustrates in Fig. 7.2.

The total start-up time of circuit is the time elapsed from the application of the input voltage to the instant when we have a high voltage in the output of the boost converter. It depends on the value of the discharge start voltage $V_{\text{CPOUT1}}$ and especially on the capacitance value of the start-up capacitor.
**S-882Z + MAX757**

The first combination studied was the charge pump plus the integrated DC-DC step-up converter analysed in Chapter IV (MAX757). Fig. 7.4 illustrates the circuit.

![Circuit Diagram](image)

*Fig. 7.4 Diagram of the converter built by using the charge pump S-882Z as starter circuit and the IC step-up MAX757 as main converter.*

The external components of the step-up boost converter are the same characterised in Section 4.2.1.

- \( L = 22 \, \mu H \)
- \( C_{IN} = 141 \, \mu F \)
- \( C_O = 84 \, \mu F \)
- \( R_1 = 150k\Omega \), \( R_2 = 39k\Omega \)

A charge pump S-882Z with 1.8 V discharge start voltage has been used. The start-up capacitor \( C_{CPOUT} \) and the power smoothing capacitor \( C_{VDD} \) have been selected by using (7.1.1)
, (7.1.2) and (7.1.3). In such formulas the follow values have been considered:

\[ V_{CPOUT} = 1.8\text{V}, \quad [17] \]

\[ I_{VDD} = 60\mu\text{A}, \quad [15] \]

\[ V_{DDL} = 0.48\text{V}, \quad \text{(directly measured, see Section 4.2.2)} \]

\[ t_s = 2ms, \quad [15] \]

In order to respected the conditions two 47 µF tantalum capacitors in parallel have been employed as start-up capacitor. As regards the power smoothing capacitor a 4.7 µF tantalum capacitor has been selected.

\[ C_{POUT} = 47 + 47 = 94\mu\text{F} \]

\[ C_{VDD} = 4.7\mu\text{F} \]

Thanks to the charge pump S-882Z the start-up problem has been solve and in this way the step-up boost converter MAX757 must start to operate from 0.3 V. The circuit built can also operate powered by the photovoltaic cell characterised in Chapter III. Fig. 7.5 shows the waveforms of the most important voltages in the circuit when it is powered by the cell.
In correspondence of the input voltage supplied by the cell (0.48 V) we reach in the output of the step-up converter 1.27 V; with this output voltage the charge pump does not enter in a shutdown mode because the output voltage is not higher than the shutdown voltage $V_{OFF}$ (1.9 V for the charge pump employed). Therefore, as Fig. 7.5 shows, the output voltage of the charge pump oscillates from the discharge start voltage $V_{CPOUT1}$ and the discharge stop voltage $V_{CPOUT2}$. The step-up converter is constantly driven by the charge pump.

Furthermore, the output voltage is too low for the purposes studied in this thesis: the measurements characterised in Section 4.2.3 show that in order to reach 3 V in the output with the step-up converter MAX757 we need 0.93 V in the input. The photovoltaic cell used can not supply such voltage.
It is interesting to point out that with a smaller start-up capacitor the circuit does not operate; with only 47 µF the charge pump cannot start up the step-up converter because the energy stored in the capacitor $C_{CPOUT}$ is not enough to drive the internal switch of the MAX757. By substituting such capacitance value in (7.1.1) the condition is not respected.

**S-882Z + S-8353**

In order to reach 3 V in the output a further combination has been investigated. The charge pump S-882Z with 1.8 V discharge start voltage has been used to start-up the DC-DC step-up boost converter S-8353. *Fig. 7.6* shows the internal circuit of the step-up converter.

![Fig. 7.6 Internal equipment of the step-up IC S-8353 [19].](image)

The technical characteristics of such integrated device are [19]:

- $V_{STARTUP} = 0.9 \, V$ (start-up voltage from zero energy)
- $V_{OUT} = 3 \, V$ (output voltage)
- $I_{VDD} = 18.7 \, \mu A$ (consumption current)
- $f_s = 50 \, kHz$ (switching frequency)
- $t_s = 6 \, ms$ (start-up time)

*Fig. 7.7* illustrates the circuit built.
The external components of both devices have been chosen in order to limit losses being the circuit for ultra-low input voltage and low input power applications. The criteria follow to choose the components are the same explained in Chapter IV. The components selected are:

- \( L = 44 \mu H \), choke coil with low DC resistance (0.068 \( \Omega \)).
- \( C_{IN} = 47 \mu F \) (electrolytic)
- \( C_{L} = 22 \mu F \) (electrolytic)
- Two Schottky diodes with low forward voltage drop off (0.25 V)
- \( C_{CPOUT} = 22 \mu F \) (electrolytic)
- \( C_{VDD} = 2.2 \mu F \) (electrolytic)

The start-up capacitor and the smoothing power capacitor have been selected respecting the conditions (7.1.1), (7.1.2) and (7.1.3).

The circuit built can start up from zero energy; furthermore, 3 V are reachable in the output by powering the DC-DC step-up converter with only 0.3 V. Three measurements have
been taken with different input voltages and different load conditions in order to measure the efficiency. The converter has been powered by a DC power supply. Fig. 7.8 shows the circuit employed to take the measurements. Table 7.1 gives the data collected.

![Diagram of the circuit employed to measure currents and voltages.](image)

**Fig. 7.8** Diagram of the circuit employed to measure currents and voltages.

<table>
<thead>
<tr>
<th>$V_{in}$ (V)</th>
<th>$I_{in}$ (mA)</th>
<th>$V_{out}$ (V)</th>
<th>$I_{out}$ (mA)</th>
<th>$P_{in}$ (mW)</th>
<th>$P_{out}$ (mW)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.303</td>
<td>26.0</td>
<td>3.045</td>
<td>1.8</td>
<td>7.88</td>
<td>5.48</td>
<td>0.696</td>
</tr>
<tr>
<td>0.382</td>
<td>48.6</td>
<td>3.009</td>
<td>3.7</td>
<td>18.57</td>
<td>11.13</td>
<td>0.600</td>
</tr>
<tr>
<td>0.456</td>
<td>58.8</td>
<td>3.003</td>
<td>5.4</td>
<td>26.81</td>
<td>16.22</td>
<td>0.605</td>
</tr>
</tbody>
</table>

**Table 7.1**

The diagram of the most important voltages in the circuit is the same shown in Fig. 7.3. Generally, the charge pump enters in shutdown mode after 6 ÷ 8 s. In such stage the boost converter is self-driven directly from the output. Therefore, the losses in the circuit in correspondence of 3 V in the output are due only to the power dissipated in the conversion. The power is dissipated because of:

- DC resistance of the inductor
- Equivalent series resistance of the input and output capacitors
- Forward voltage drop in the diode
- Internal consumption current of the integrated converter S-5383

In the three measurements taken, the efficiency is strongly affected by the internal consumption of the voltmeters and the ampere-meters being the power levels ultra-low. The decrement in the efficiency due to the power dissipated in such instruments is estimated be around 15%. Among the losses listed above the predominant are that ones associated with the
forward voltage drop in the diode. Around 5% of the input power is dissipated in this way. *Table 7.2* gives the data for the three measurements.

<table>
<thead>
<tr>
<th>P&lt;sub&gt;in&lt;/sub&gt; (mW)</th>
<th>P&lt;sub&gt;out&lt;/sub&gt; (mW)</th>
<th>V&lt;sub&gt;FD&lt;/sub&gt; (V)</th>
<th>D</th>
<th>P&lt;sub&gt;LFD&lt;/sub&gt; (mW)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.88</td>
<td>5.48</td>
<td>0.25</td>
<td>0.900</td>
<td>0.41</td>
<td>5.14</td>
</tr>
<tr>
<td>18.57</td>
<td>11.13</td>
<td>0.23</td>
<td>0.873</td>
<td>0.74</td>
<td>4.00</td>
</tr>
<tr>
<td>26.81</td>
<td>16.22</td>
<td>0.22</td>
<td>0.848</td>
<td>1.01</td>
<td>3.76</td>
</tr>
</tbody>
</table>

*Table 7.2*

The losses in the diode when it is forward biased have been calculated using:

\[ P_{LFD} = V_{FD} \cdot I_{out} \cdot D \]  

(7.1.4)

Where:

- V<sub>FD</sub> = Forward voltage drop
- I<sub>out</sub> = Output current
- D = Duty Cycle, calculated by using (7.1.5)

\[ D = \frac{V_{out} - V_{in}}{V_{out}} \]  

(7.1.5)

In the last column of *Table 7.2* the losses due to the forward voltage drop are given in percent respected to the input power. In order to increase the efficiency of the converter we should:

- Substitute the capacitors with low equivalent series resistance capacitor
- Change the inductor with another one with ultra-low DC-resistance (< 20 mΩ)
- Build a PCB for the purpose of decreasing the trace resistances.

**S-882Z + LTC3429**

In order to avoid the losses in the external diode the integrated step-up converter should be substituted by an integrated synchronous boost converter. In the second part of Chapter V the LTC3429 synchronous converter has been studied. Such device is not able to
start-up from zero energy in correspondence of voltage down to 0.78 V. The charge pump S-882Z with 1.8 V discharge start voltage cannot be used to start up the LTC3429 down to such voltage because it is driven from the output only when the voltage is over 2.3 V. In correspondence of output voltage down this level the internal components of the LTC3429 are driven directly from the input pin. In order to start-up the LTC3429, we should use the charge pump S-882Z that presents 2.4 V discharge start voltage. Fig. 7.9 shows the internal diagram of the synchronous converter. The switch circled sets how to drive it.

![Diagram of the internal equipment of the synchronous IC LTC3429](image)

*Fig. 7.9* Diagram of the internal equipment of the synchronous IC LTC3429. The switch circled in red sets how to drive the internal equipment. When the output voltage is higher than 2.3 V the MOSFETs are driven from the output while when the output voltage is lower than 2.3 V the two internal transistors are driven by the input. Adapted from [16].

Fig. 7.10 illustrates the possible circuit of the charge pump with 2.4 V discharge start voltage plus the LTC3429.
The start-up capacitor must present a large capacitance because the consumption current of the synchronous boost converter is high (380 µA).

### 7.2 Applications of the converter built by using the charge pump as starter circuit

In the previously section a boost DC-DC converter that transforms the voltage from an ultra-low level (0.3 V) to a high one (3 V) has been characterised. It uses the integrated step-up converter S-8353 to make the main conversion and the charge pump S-882Z as start-up circuit. Such converter can be transform from zero energy the voltage generated by several kinds of micro-power harvesters up to available electronic voltage level.

#### 7.2.1 Converter powered by the photovoltaic cell

The converter built can be powered by the photovoltaic cell characterised in Chapter III. A measurement has been taken by using the solar cell as primary source. Fig. 7.11 shows
the circuit built in order to collect the data. The cell was lighted by a desk lamp (radiation measured 700 lx).

![Diagram of the circuit built to measure currents and voltages with the converter powered by the solar cell.](image)

*Fig. 7.11* Diagram of the circuit built to measure currents and voltages with the converter powered by the solar cell.

<table>
<thead>
<tr>
<th>$V_{in}$ (V)</th>
<th>$I_{in}$ (mA)</th>
<th>$V_{out}$ (V)</th>
<th>$I_{out}$ (mA)</th>
<th>$R_{out}$ (Ω)</th>
<th>$P_{in}$ (mW)</th>
<th>$P_{out}$ (mW)</th>
<th>$\eta$</th>
<th>$t_s$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.468</td>
<td>69</td>
<td>3.045</td>
<td>5.98</td>
<td>509.3</td>
<td>32.292</td>
<td>18.205</td>
<td>0.56</td>
<td>3</td>
</tr>
</tbody>
</table>

*Table 7.3*

Being the input voltage and power ultra-low, the instruments employed affect the measurement causing an input voltage drop and losses. However, as *Table 7.3* shows, we can reach in the output 3 V in less than 3 s supplying 18 mW. Such power is enough to drive a large amount of sensors and to send the acquired data.

### 7.2.2 Converter powered by photodiodes

The DC-DC converter built using the integrated circuit S-882Z+S-8353 can be also powered by smaller solar harvesters than the cell previously mentioned. Such solar harvesters are known as photodiodes; usually they present ultra-reduced size and usually they are employed as light sensors. They have the follow technical characteristics [20]:

- Radiant sensitive area \( A = 4.84 \text{ mm}^2 (2.2 \times 2.2 \text{ mm}) \)
- Open-circuit voltage \( V_o = 360 \text{ mV} \) (at radiation \( E_V = 1000 \text{ lx} \))
- Short-circuit current \( I_{sc} = 50 \mu \text{A} \) (at radiation \( E_V = 1000 \text{ lx} \))
Fig. 7.12 shows a photo of one of them.

![Single photodiode](image)

**Fig. 7.12** Single photodiode [20].

The open-circuit voltage and the short-circuit current given above are measured at radiation \(E_V = 1000\) lx (typical TV studio lighting conditions). The luminance of a sunlight average day change between 32000 and 100000 lx; in order to simulate such external conditions in the Laboratory a desk lamp has been used as luminous source. Fig. 7.13 shows the I-V characteristic measured with the bulb of the lamp 3 cm away from two photodiodes in a parallel configuration. The luminous radiation measured was 40000 lx. Fig. 7.14 illustrates the graph of the power in function of the voltage. The Maximum Power is:

\[P_{\text{MAX}} = 650\,\mu W\text{ at } V_{\text{in}} = 305\,mV \text{ and } I_{\text{in}} = 2.14 mA\]

![Power vs Voltage](image)

**Fig. 7.13** I-V characteristic of two photodiodes in parallel.
Because of the ultra-low input power supplied by the two photodiodes the circuit presented in section 7.1 (Fig. 7.7) has been rebuilt in order to limit the losses. The follow optimisations have been introduced:

- The capacitors have been substituted by low equivalent series resistance capacitors.
- The inductance has been substituted by another one with lower DC-resistance.
- A PCB circuit has been built in order to minimise the trace resistances and reduce the size of the converter. Fig. 7.15 shows the draw.

*Fig. 7.14* Graph of the power vs. input voltage of two photodiodes in parallel.

*Fig. 7.15* Layout of the PCB designed in order to minimise the trace resistance.
The components chosen are:

- Input capacitor (C\textsubscript{IN}) \rightarrow 47 \, \mu\text{F} tantalum capacitor with equivalent series resistance ESR = 50 \, m\Omega.
- Output capacitor (C\textsubscript{L}) \rightarrow 47 \, \mu\text{F} tantalum capacitor with equivalent series resistance ESR = 50 \, m\Omega.
- Start-up capacitor (C\textsubscript{CPOUT}) \rightarrow 47 \, \mu\text{F} tantalum capacitor with equivalent series resistance ESR = 50 \, m\Omega.
- Power smoothing capacitor (C\textsubscript{VDD}) \rightarrow 4.7 \, \mu\text{F} tantalum capacitor with equivalent series resistance ESR = 50 \, m\Omega.
- Inductor (L) \rightarrow 39 \, \mu\text{H} choke inductor with 56 \, m\Omega DC-resistance.
- Two Schottky diodes with low forward voltage drop off (0.25 V).

The energy supply by the photodiodes is stored in the start-up capacitor and must be enough to start up the circuit. The value of such capacitor has been chosen in an experimental way. All the components (also the two photodiodes) have been assembled on the PCB shown in Fig. 7.15. The size of the converter is around 2.5 x 2.5 cm. Fig. 7.16 shows a picture of the circuit.

*Fig. 7.16* Picture of the converter that has been built.

The circuit built is able to reach 3 V in the output from an ultra-low input voltage (480 mV); the correspondent input power is around 80 \, \mu\text{W} (operation point OP in Fig. 7.14). The two photodiodes have been lighted by a desk lamp. The luminous radiation measured was 36000 lx; such value is similar to a medium-low sunlight radiation.
7.3 Costs and environmental impact of the converter

7.3.1 Costs

The prototype of the converter that has been built using the charge pump S-882Z as starter circuit and the step-up IC S-8353 as the main converter is a relatively low cost DC-DC converter. The cost of these two integrated components provided by Seiko is estimated to be around 4 £. Also the cost of the external components (four capacitors, one inductor, two Schottky diodes) is low. By using electrolytic capacitors (less expensive than the tantalum ones) the cost of the external components can be reduced down to 1 £. In conclusion the total cost of the DC-DC converter which circuit is shown in Fig. 7.7 is down to 5 £. The cost of the two photodiodes employed as primary source is around 1.5 £. Therefore, the total cost of the DC-DC converter plus the micro solar harvesters is down to 7 £. It can be further reduced considering that all the electronic components present the advantages introduced by the economy of scale (reduction in cost per unit resulting from increased production). Table 7.4 summarises the costs for each components.

<table>
<thead>
<tr>
<th>Components</th>
<th>Manufacturer</th>
<th>Costs (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated charge pump S-882Z</td>
<td>Seiko</td>
<td>2 £ (estimated)</td>
</tr>
<tr>
<td>Integrated step-up converter S-8353</td>
<td>Seiko</td>
<td>2 £ (estimated)</td>
</tr>
<tr>
<td>Input capacitor (47 µF, 25 V, aluminium electrolytic)</td>
<td>Nichicon</td>
<td>0.04 £</td>
</tr>
<tr>
<td>Output capacitor (47 µF, 25 V, aluminium electrolytic)</td>
<td>Nichicon</td>
<td>0.04 £</td>
</tr>
<tr>
<td>Start-up capacitor (47 µF, 25 V, aluminium electrolytic)</td>
<td>Nichicon</td>
<td>0.04 £</td>
</tr>
<tr>
<td>Power smoothing capacitor (4.7 µF, 25 V, alum. electrolytic)</td>
<td>Nichicon</td>
<td>0.04 £</td>
</tr>
<tr>
<td>Schottky diode (V_{mm} = 40V, I_p = 0.2 A, V_F = 0.25 V)</td>
<td>Philips</td>
<td>2 x 0.131 £</td>
</tr>
<tr>
<td>Inductor (39 µH, 56 mΩ DC resistance)</td>
<td>Panasonic</td>
<td>0.43 £</td>
</tr>
<tr>
<td>Photodiode (4.84 mm² photosensitive area)</td>
<td>Osram</td>
<td>2 x 0.75 £</td>
</tr>
<tr>
<td>Assembling</td>
<td></td>
<td>0.5 £</td>
</tr>
<tr>
<td>Total cost</td>
<td></td>
<td><strong>6.852 £</strong></td>
</tr>
</tbody>
</table>

Table 7.4
7.3.2 Environmental impact

The DC-DC converter presented in Chapter VII improves the use of renewable energy in ultra-low power applications. Until now batteries have been the most feasible solution in order to power sensors and monitoring systems. Now, using this converter, useful energy can be extracted from miniaturised solar harvesters and transformed in output power at standard voltage levels (3 V). The circuit shown in Fig. 7.16 is the proof. In this way all the environmental problems related with the batteries usage are avoided. Also the maintenance problems of the batteries are obviated.

The only drawback of the converter is the inductor. This components is the only one that cannot be integrated in one single chip. Furthermore, it can cause EMI problems. However, these problems are neglected due to the ultra-low voltages and currents.
Chapter IX

8 Discussions and conclusions

8.1 Discussions

The following results have been obtained from the efficiency analysis of discrete DC-DC converters that has been carried out in Chapters IV and V:

- The optimum duty cycle of the discrete converters investigated in Chapters IV and V is around 80%.
- The efficiency of such converter is strongly affected by the losses in the diode. In the measurement taken with 0.2 V input voltage and 60 mW input power such losses represent more than 60% of the total power dissipated (Section 4.1.3).
- In the discrete step-up converter the forward voltage drop of the diode affects the transfer voltage ratio. Even using a Schottky diode the forward voltage drop is more than 0.2 V (Fig. 4.12).
- With low input voltage (down to 0.6 V) the discrete synchronous converter is more efficient than the discrete step-up converter (Fig. 5.18). The efficiency peak (92%) has been measured with $V_{in} = 0.38$ V at $P_{in} = 100$ mW.
- The discrete synchronous converter and the discrete step-up converter are not able to reach 3 V in the output when powered by the photovoltaic cell characterised in Chapter III. The voltage supplied by such cell when it is lighted by a desk lamp ($E = 700$ lx) is around 0.48 V without load. The discrete converters that have been built need higher input voltages to reach in the output standard electronic voltage’s levels (Sections 4.1.5 and 5.1.4).
- The discrete DC-DC converters investigated in Chapters IV, V and VI cannot operate with ultra-low input power because of the MOSFET’s gate-drive issue. In order to achieve ultra-low power level (down to 1 mW) integrated converters must be employed. However, ICs commercially available present another problem: they are
not able to start up with low input voltage. The synchronous LTC3429 IC studied in Section 5.2 needs 0.78 V in the input to start up (at $P_{in} = 100 \text{ mW}$) while the step-up MAX757 IC investigated in Section 4.2 needs at least 0.89 V with the same load conditions. Because of that they cannot be powered by the solar cell characterised in Chapter III.

In order to solve the start-up from zero energy issue the low voltage start-up integrated charge pump S-882Z has been employed as starter circuit. The following results have been obtained:

- By using a 94 µF start-up capacitor the IC MAX757 starts operating with 0.3 V input voltage. Fig. 7.4 shows the circuit diagram (Section 7.1). In this way the step-up IC can be powered by the photovoltaic cell characterised in Chapter III. 1.27 V are reachable in the output.
- In order to reach 3 V in the output the step-up S-8353 IC has been used as main converter (Fig. 7.7). 18 mW at 3 V are available in the output of the DC-DC converter by using the solar cell as primary source (Section 7.2.1). The start-up time that has been measured is 3s (Table 7.3).
- The DC-DC converter that has been built can also operate powered by two ultra-reduced photodiodes in parallel (0.48 V supplied voltage). The start-up capacitor employed is a 47 µF tantalum capacitor (Fig. 7.16). 3 V are reachable in the output in few seconds by lighting the solar harvesters with a desk lamp ($E = 36000 \text{ lx}$); in these conditions 50 µW are available in the output.

### 8.2 Summary of conclusions

The two aims of this thesis stated in Chapter I have been achieved.

Three different kinds of DC-DC converters have been investigated. In the boost converters we can summarise that the substitution of the diode with another transistor in the synchronous configuration presents an efficiency’s increment; furthermore, the transfer ratio voltage tends to be higher.
The analysis of the integrated boost converters carried out in Chapters IV and V highlights that the commercially available converters cannot start-up from zero energy with input voltage down to 0.7 - 0.8 V.

The study of the third typology of DC-DC converter (switched capacitor) has been useful to understand the behaviour of the integrated Charge pump S-882Z; using this device the problem of the start-up from zero energy has been solved. According to Fig. 1.1 a DC-DC boost converter that steps-up the voltage from ultra-low levels has been designed and built in order to supply power at standard electronic voltage level (3 V). Such converter is able to start-up with zero onboard stored energy and can be powered by different kinds of energy harvesters (photovoltaic cells, photodiodes, thermoelectric generators, fuel cells and piezoelectric or magnetic transducers). The DC-DC converter powered by such harvesters can be used in several energy management applications. Furthermore it can supply energy to a wide range of sensors. Fig. 8.1 shows the block diagram.

Fig. 8.1 Block diagram that shows how the converter can be used in energy management.
8.3 Further work

In Section 7.2 the operation of the DC-DC converter powered by two photodiodes in parallel has been characterised. The graph illustrated in Fig. 7.14 shows that in correspondence of 480 mV input voltage the power extract from the source is around 80 µW. Such power is not the maximum that can be extracted from the two photodiodes. By moving the operation point closer to the Maximum Power Point we can extract more than 600 µW. The correspondent voltage of such power is 305 mV and it is high enough to build the discharge start voltage (1.8 V for the S-882Z employed, see Section 6.2). Working at the Maximum Power Point allows reducing the photosensitive area of the solar harvester. Potentially, reaching 3 V in the output should be possible with only one photodiode lighted by a 1000 lx luminous source (typical TV studio lighting conditions).

Concerning to the DC-DC converter as built, in order to increase the efficiency of the voltage conversion, the step-up boost converter S-8353 can be substituted by a integrated synchronous converter with lower consumption current. In this way the diode losses and the decrement in the voltage transfer’s ratio are avoided. One possibility is to employ the synchronous LTC3421 by Linear Technology that presents only 12 µA consumption current and extremely high efficiency (up to 96%). As starter circuit must be used the integrated charge pump S-882Z that presents 2.4 V discharge start voltage (Table 6.2) because the LTC3421 IC suffers the same limitation explained for the LTC3329 IC (Fig. 7.9).

The size of the circuit built can be further reduced by choosing other kind of inductor or by building one on the bottom of the circuit. Smaller inductors are commercially available but they present a larger DC resistance and hence they cause efficiency’s decrement. An optimised design and selection of components for system simplicity can be carried out in order to reduce the cost of the converter at the expense of efficiency.
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