Appendix A: Operation of a photovoltaic cell

A photovoltaic cell transforms energy provided by the sun into electric energy. This is possible thanks to the photovoltaic effect. Solar cells are made of semiconductor materials, typically silicon. Solar cell works like a diode; it is made by a p-n junction that is formed by combining N-type and P-type semiconductors together in very closed contact. Due to the movement of electrons and holes (recombination) in the contact zone there is an electric field. The contact zone is called depletion zone. When solar light, in form of photons, strikes the cell the electrons in the outer shell of the silicon’s atoms are moved by the electric field to the N-type layer. At the same time, for each free electron there is a hole that moves to the P-type layer thanks to the electric field.

![Diagram of a photovoltaic cell](image)

**Fig. A. 1** Operation of a photovoltaic cell [13].

**Fig. A. 1** shows that connecting N-type layer and P-type layer to an external circuit there is an electrons’ flow, which is a DC current.

![Diagram of photovoltaic cell structure](image)

**Fig. A. 2** Structure of a photovoltaic cell [14].
Fig. A. 2 shows that to collect the electrons’ flow we need two electrodes. The back contact usually covers the entire back surface and it is made by a thin aluminium layer. It is better to cover the entire surface in order to minimise the series resistance of the cell because silicon is a semiconductor and it is not as good as a metal for transporting current. The front contact is quite difficult to build. In order to collect the maximum amount of electrons, it should cover the entire front surface but in this way the photons do not reach the N-type and P-type layer. Therefore usually the front contact is usually a silver or aluminium grid that allows the electrons’ collection and at the same times the photons’ passage.

Fig. A. 3 Details about the structure of a photovoltaic cell.

The energy of the photon that strikes the cell must be contents in a definite range in order to allow the transformation from solar energy to electric energy. In fact if the energy is too low the electrons are not free and the holes do not move. When the photons’ energy is more than the required amount, the execs of energy is lost by heating the cell. Because of that, the efficiency of a photovoltaic cell is quite low. Efficiency is defined in (A.1):

\[
\eta = \frac{P_{\text{out}}}{P_R}
\]  

(A.1)

\(P_{\text{out}}\) = Electrical ratio power
\(P_R\) = Radiation power

Usually efficiency of commercial available solar cell is around 14%-17%. Others restrictions limit the efficiency. There are some photons reflected on the surface by the anti-reflecting coating. Furthermore some photons are blocked by the grid that can not be too small because of the semiconductor’s series resistance.
Appendix B: Operation of the DC-DC step-up (boost) converter

In order to explain the operation of the step-up boost converter illustrates in Fig. 2.6 we can split it into two stages.

1. When the switch $S_1$ is closed (during $t_{ON}$) the diode is reversed biased and hence the output stage is isolated. In Fig. B. 1 the new circuit is shown.

![Diagram of the step-up (boost) converter when the switch $S_2$ is closed.](image)

Fig. B. 1 Diagram of the step-up (boost) converter when the switch $S_2$ is closed.

(B.1) gives the inductor voltage.

$$V_L = V_{in} = L \frac{di_L}{dt} \quad \text{(B.1)}$$

In this stage the inductor current increases and the energy supplied by the input is stored in the coil.

2. When $S_1$ is open (during $t_{OFF}$) the diode conducts and the energy stored in the inductor plus the energy supplies by the input is transferred to the output. The inductor current decreases. Fig. B. 2 shows the corresponding circuit.

![Diagram of the step-up converter when the switch $S_1$ is open.](image)

Fig. B. 2 Diagram of the step-up converter when the switch $S_1$ is open.
The inductor voltage is:

\[ V_L = V_o - V_{in} = L \frac{di}{dt} \quad (B.2) \]

We can define continuous-conduction mode when the current that flows through the inductor is strictly positive \([i_L(t) > 0]\) during both stages. Fig. B. 3 illustrates graphs of the current and the voltage of the inductor.

![Diagram of inductor voltage and current](image)

*Fig. B. 3* Diagrams of the inductor voltage and current in continuous-conduction mode.

The switch duty ratio can be defined as:

\[ D = \frac{t_{on}}{T} \quad (B.3) \]

In steady state the inductor voltage must carry out this propriety:

\[ \frac{1}{T} \int_0^T v_L dt = 0 \quad (B.4) \]
Therefore:

\[ V_{in} t_{on} + (V_{in} - V_o) t_{off} = 0 \]  \hspace{1cm} (B.5)

By dividing both sides by \( T \) and rearranging terms we obtain

\[ \frac{V_o}{V_{in}} = \frac{T}{t_{off}} = \frac{1}{1 - D} \]  \hspace{1cm} (B.6)

(B.6) points out that it is possible change the voltage conversion ratio by changing the switch duty cycle. By making the hypothesis that the circuit is ideal (lossless),

\[ P_{in} = P_{out} \]  \hspace{1cm} (B.7)

\[ \therefore V_{in} I_{in} = V_o I_o \]  \hspace{1cm} (B.8)

Hence:

\[ \frac{I_o}{I_{in}} = (1 - D) \]  \hspace{1cm} (B.9)

Usually to generate the switch control signal a pulse width modulation technique is used. This signal controls the state (ON or OFF) of the switch \( S_1 \) and basically it defines, by means of the switch duty ratio \( D \), the voltage conversion ratio. It is generated by comparing a signal-level control voltage \( v_{\text{cont}} \) with a repetitive waveform (typically a sawtooth). Fig. B. 4 and Fig. B. 5 respectively show the block diagram and the signals. Generally the control voltage signal is obtained by amplifying the difference between the real output voltage and the desire output voltage [3]. The switching frequency is determined by the repetitive waveform: its normal range is from few kilohertz to a few hundreds of kilohertz.
Thanks to the output capacitor we can minimize the peak-to-peak ripple in the output voltage. Let us assume that all ripple component of the diode current $i_D$ flows through the output capacitor and its average value flows through the load resistor, the shaded area in Fig. B. 6 represents the charge $\Delta Q$ in a continuous mode of operation [3].
Fig. B. 6 Diagrams of the diode current and the output voltage.

Therefore, assuming that the output current is constant, the peak to peak voltage is:

\[
\Delta V_o = \frac{\Delta Q}{C_o} = \frac{I_o \cdot D \cdot T}{C_o} = \frac{V_o \cdot D \cdot T}{R \cdot C_o} \tag{B.10}
\]

\[
\frac{\Delta V_o}{V_o} = \frac{D \cdot T}{R \cdot C_o} = \frac{D \cdot T}{\tau} \tag{B.11}
\]

where \(\tau\) is the \(R\)\(C_o\) time constant. By increasing the value of the output capacitor we increase the discharge time and we reduce the peak-to-peak ripple \(\Delta V_o\) in the output voltage.