Comprehensive and field study to design a buck converter for photovoltaic systems

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Abstract - *More sophisticated applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage and current at the load, control the power flow in grid-connected systems, and mainly track the maximum power point (MPP) of the device. Therefore, this paper tries to study an electronic converter in PV systems, namely the Buck converter, and propose an easy way to electronic converter designers to calculate component values needed to realize it.*

Résumé - *Une connexion directe entre une charge et un générateur photovoltaïque pose beaucoup de problèmes concernant l'optimisation de la puissance, l'influence sur le rendement du système et la mauvaise adaptation. En plus, si cette charge est une batterie, le bon fonctionnement et la protection de cette dernière ne seront jamais assurés par cette connexion directe. Pour cela, la majorité des études qui sont faites montrent la nécessité d'intercaler un étage d'adaptation entre le GPV et la charge. Cet étage n'est qu'un convertisseur DC/DC 'élévateur (Boost) ou abaisseur (Buck)' de la tension de sortie par rapport à celle d'entrée. Puisque l'objectif principal lors de la conception de ce type de convertisseurs est de réduire au maximum le coût et la consommation d'énergie, cet article présente une méthode pour calculer les différentes valeurs des composants électroniques, lors d'une réalisation d'un convertisseur statique où on essaye de minimiser au maximum les pertes afin d'optimiser la consommation en choisissant le convertisseur Buck comme application.*

Mots clés: Photovoltaïque - Optimisation – Puissance – Régulation – Rendement.

1. INTRODUCTION

The reason to choose a Buck converter is that our load is a 12 V lead-acid battery, where we will charge it with only one PV module which generates the most watts running at around 17 V. Thus, we need a DC/DC converter which takes a higher input voltage and converts it to a lower output voltage. This can only be done by the Buck converter. We will, first, start by a brief introduction to the functioning of a Buck converter, and then, write its basic equations.

2. HOW DOES A BUCK CONVERTER WORK

2.1 Circuit description

The basic circuit of a Buck converter is shown below in Figure 1.

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Two switches are used in this basic circuit, usually one controlled (MOSFET) and one uncontrolled (diode), to achieve unidirectional power flow from the input to the output.

This circuit, also, uses one capacitor and one inductor to store and transfer energy from input to output. They, also, filter or smooth voltage and current.
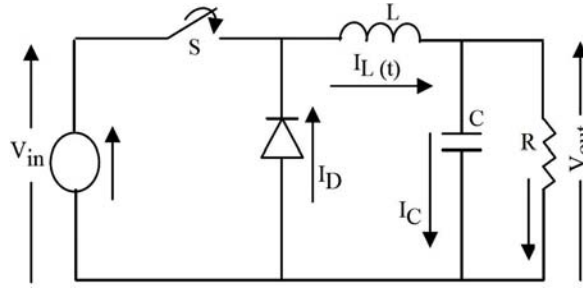

Fig. 1: Basic circuit of a Buck converter

2.2 Circuit operation

We used inductors and capacitors as energy storage components to control the energy flow from the input to the output by continuously opening and closing the switch which is usually an electronic device that operates in two states:

When the switch is ON for a time duration αT (α is the duty cycle), the switch conducts the inductor current and the diode becomes reverse biased. This results in a positive voltage $V_L = V_{in} - V_{out}$ across the inductor.

This voltage causes a linear increase in the inductor current I_L. When the switch is turned OFF, because of the inductive energy storage, I_L continues to flow.

This current now flows through the diode, and $V_L = - V_{out}$ for a time duration $(1 - \alpha) T$ until the switch is turned ON again. [1]

2.3 Analytical expressions

The basic circuit of the Buck converter showed in Figure 1 has two energy storage elements: the inductor and capacitor which can be calculated in a second order differential equation.

We start by the differential equation for the capacitor voltage, in the ON state, which given by:

$$L \times C \frac{d^2 V_c}{dt^2} + \frac{L}{R} \times \frac{d V_c}{dt} + V_c(t) = V_{in} \tag{1}$$

Assumption: $V_c(t)$ is constant, so the differential equation above can be simplified and can be written for the current through the inductor as:

$$L \times \frac{d I_L(t)}{dt} = V_{in} - V_{out} \tag{2}$$

For a steady state, and when $t \rightarrow T_{ON} = \alpha T$ the inductor current attains it final value:

$$I_L = \frac{V_{in} - V_{out}}{L} \times \alpha T + I_{L_0} \tag{3}$$

Where I_{L_0} is the initial value of the inductor current (just before the switch is turned on). The peak-to-peak current ripple ΔI_L is the difference between the final and initial value of I_L and is given by:

$$\Delta I_L = I_L - I_{L_0} = \frac{V_{in} - V_{out}}{L} \times \alpha T \tag{4}$$

This proportionality between the current ripple and the duty cycle prove that ΔI_L can be controlled by α.

For OFF state, we have a first order differential equation (the inductor current flows through the diode):

$$L \times \frac{d I_L(t)}{dt} = -V_{out} \tag{5}$$

The solution of the differential equation yields:

$$I_L(t) = \frac{-V_{out}}{L} \times t + I_L \tag{6}$$

Now, for $t \rightarrow T_{OFF} = (1 - \alpha) \times T$, the inductor current decreases to its minimum value I_{L_0} therefore:

$$I_{L0} = \frac{-V_{out}}{L} \times (1 - \alpha) \times t + I_L \tag{7}$$

So, we can obtain the equation of the current ripple:

$$\Delta I_L = I_L - I_{L_0} = \frac{V_{on}}{L} \times (1 - \alpha) \times T \tag{8}$$

By a simple comparison between (4) and (8) it is obvious that:

$$V_{out} = \alpha \times V_{in} \tag{9}$$
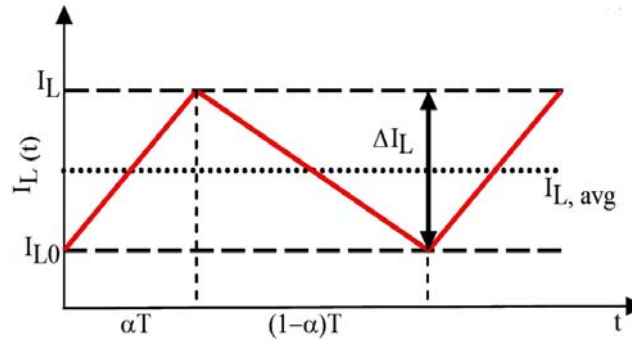

Fig. 2: Inductor current waveform

To obtain the average inductor current, we can use:

$$I_{L,avg} = \frac{V_{out}}{R} \tag{10}$$

Therefore, the maximum and the minimum current through the inductor are:

$$
\begin{aligned}
I_{L,max} &= I_{L,avg} + \frac{\Delta I_L}{2} \\
&= \frac{V_{out}}{R} + \frac{V_{out}}{2L} \times (1 - \alpha)\, t
\end{aligned}
\tag{11}
$$

$$
\begin{aligned}
I_{L,min} &= I_{L,avg} - \frac{\Delta I_L}{2} \\
&= \frac{V_{out}}{R} - \frac{V_{out}}{2L} \times (1 - \alpha)\, t
\end{aligned}
\tag{12}
$$

We can now with the same analysis obtain the maximum and minimum current trough the capacitor:

$$I_{c,min} = \frac{\Delta I_L}{2} = \frac{V_{out}}{2L} \times (1 - \alpha) \times T \tag{13}$$

$$I_{c,min} = -\frac{\Delta I_L}{2} = -\frac{V_{out}}{2L} \times (1 - \alpha) \times T \tag{14}$$

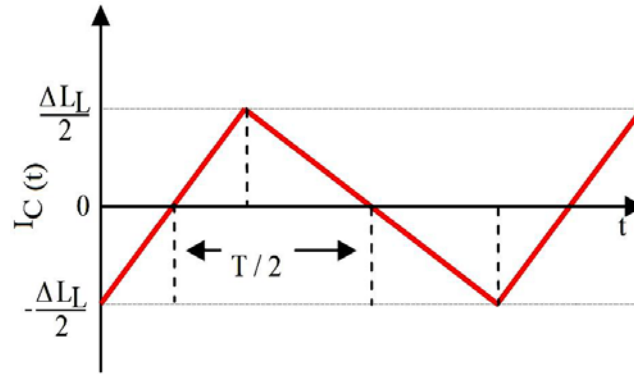The waveform for the current through the capacitor is shown below:

Fig. 3: Capacitor current waveform

From Figure 3, it's clearly that the average current through the capacitor is zero, but in one-half cycle the capacitor will charged and the increase in charge is:

$$\Delta Q = \frac{1}{2} \times \frac{\Delta I_L}{2} \times \frac{T}{2} = \frac{1}{8} \times \Delta I_L \times T \tag{15}$$

and because $V_c = V_{out}$, the increase in capacitor voltage is:

$$\Delta V_{out} = \frac{\Delta Q}{C} \tag{16}$$

Then from (8) and (15) we obtain:

$$\Delta V_{out} = \frac{1}{8L \times C \times f^2 \times V_{out}} \tag{17}$$

In continuous conduction mode (CCM), $I_{L,min} = 0$; (the minimum current can be zero at the time of switching), so from (12) we have:

$$\frac{V_{out}}{R} = \frac{V_{out}}{2L} \times (1-\alpha) \times T \tag{18}$$

Then if the desired switching frequency f and load resistance R are established, the minimum inductor current required for CCM is:

$$L_{min} = \frac{R}{2f} \times (1-\alpha) \tag{19}$$

Likewise we can obtain:

$$f_{min} = \frac{R}{2L} \times (1-\alpha) \tag{20}$$

$$R_{min} = \frac{2f \times L}{(1-\alpha)} \tag{21}$$

3. BUCK CONVERTER DESIGN EXAMPLE

Figure 4 shows the design of the Buck converter for which we will present an easy method to select component values: either a P-channel or an N-channel MOSFET may be used.

In order to determine input capacitor, diode, MOSFET characteristics, one first needs to calculate the required inductor and output capacitor specifications. We will then, with the selected components, calculate the system's efficiency.
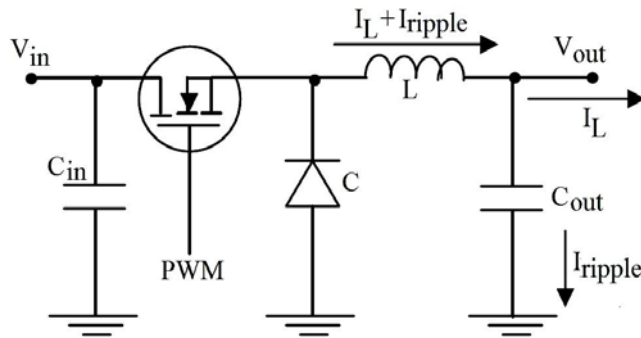

Fig. 4: Buck converter design example

3.1 Inductor selection

In our application we need to convert a 17 V power source to an output of 12 V to charge a lead-acid battery by using only one PV module (Photowatt PWX500) where we fixed the output current around 2 A for more efficiency.

Table 1: PWX 500 PV module characteristics

Typical power	**45 Watts**
Minimal power	40.1 Watts
Typical power voltage	17 Volts
Typical power intensity	2.65 Ampères
Intensity of short voltage	2.9 Ampères
Voltage of open circuit	21.4 Volts

The switching frequency is selected at 100 kHz and the current ripple will be limited at 30 % of maximum load.

We have now our input-output parameters values which are:

$$V_{in} = 17\,V\,,\ V_{out} = 12\,V\,,\ I_L = 2\,A$$

$$f_{sw} = 100\,kHz\,,\ \alpha = V_{out}/V_{in} = 0.705\,,\ I_{ripple} = 0.3 \times I_L$$

From Figure 4 we can obtain directly the value of the inductor L :

$$L = (V_{in} - V_{out}) \times \frac{\alpha/f_{sw}}{I_{ripple}}$$

Calculate: $L = 58.75\,\mu H$.

3.2 Output capacitor selection

An insufficient output capacitance and a high equivalent-series resistance, 'ESR' in the output capacitor caused a large overshoots and a large voltage ripple in the output. So we must include an output capacitor with ample capacitance and low ESR in order to resolve this problem.

From (17) we have: $C = \dfrac{1}{8\,L \times f^2 \times \Delta V_{out}} \times V_{out}$ (22)

Define ripple voltage: $\Delta V_{out} = 50\,mV$.

Calculate: $C_{out} = 128\,\mu F$ (minimum).

NB: The capacitor ESR value was selected from a vendor's catalog. Given the ripple current and the target output voltage ripple, an ESR value of 0.030 ohm was selected from a list of capacitors rated for 0.6 amp ripple current.

3.3 Input capacitor selection

Like the output capacitor, the input capacitor selection is primarily dictated by the ESR requirement needed to meet voltage ripple requirement.

Usually, the input voltage ripple requirement is not as stringent as the output voltage ripple requirement. In our application the PV module generates the most watts running

at around 17 V, so after consulting catalogue a capacitor $C_{in} = 330\,\mu F \,(35\,V)$ was selected with ESR value of 0.12 ohm for more efficiency.

3.4 Diode selection

Power dissipation is the limiting factor when choosing a diode. This power can be calculated by the following equation:

$$P_{diode} = (1 - \alpha) \times I_L \times V_D \tag{23}$$

where V_D is the voltage drop across the diode at the given output current $I_{out,\,max}$ (Typical values are 0.7 V for a silicon diode and 0.3 V for a Schottky diode). By using a schottky diode, switching losses are negligible. Ensure that the selected diode will be able to dissipate that much power.

The maximum reverse voltage on the diode in this application is V_{in} which is 17 volts. A MBR735, 35V, 7.5A Schottky meets requirements was selected.

3.5 MOSFET selection

Assume: $V_{in} = 17\,V$, $I_L = 2\,A$, $\alpha = 0.705$, $f_{sw} = 100\,kHz$.

An IRFZ44 N-fets were chosen for their low Rdson (0.02 Ω) in order to minimizes both the power dissipation and the temperature rise.

4. VERIFYING PERFORMANCE

Our Buck converter (Fig. 6) was simulated to check performance by using the equations in this article to calculate values for the critical components and characteristics required.

NB: Replacing the diode D (in Fig. 1) with a MOSFET synchronous rectifier further increases the efficiency of our buck converter. [3]

The Buck converter is controlled by the PIC16F876 microcontroller [5].

The microcontroller is clocked at 8 MHz by the crystal XTAL1.

The PWM output of the PIC on pin 13 is used to control the duty cycle which sets its voltage conversion ratio.

The frequency of the PWM is set to 100 kHz by the PIC software.

The PWM duty cycle is controlled by the PIC software to stabilize the output voltage at around 13.5 V to keep the battery at its fully charged value.
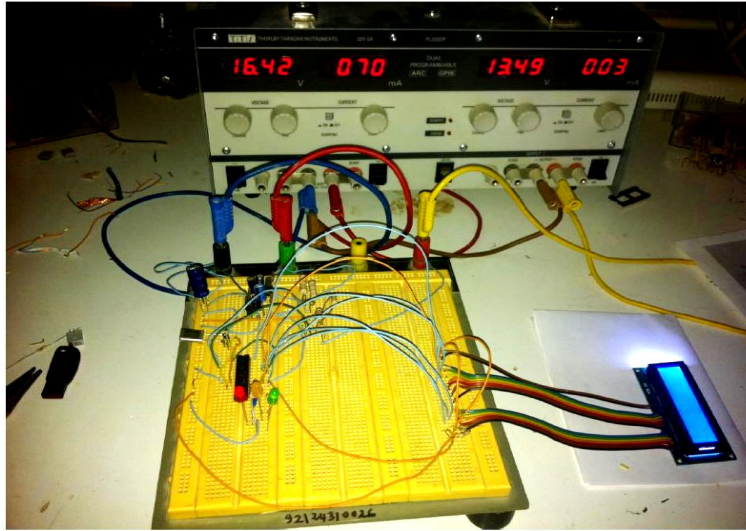
Fig. 5: Buck converter with a MOSFET synchronous rectifier

The PIC reads the input and the output voltage of the Buck converter through the A/D converter on pins 2 and 3.

(R1, R2) and (R3, R4) make a voltage divider used to drop the input and output voltage into the 5 V range that can be read by the PIC.

The PIC uses the LEDs as indicators to show the software state. [4]

And for more efficiency, an (LM35) was used to take care of temperature variations.

Fig. 7: First prototype of our Buck converter

5. CONCLUSION

Minimizing power loss throughout the converter will extend battery life and reduce heat dissipation and from catalogs and data sheets we can obtain and calculate power loss in each section of the converter.

In this application, the output Power is **24 watts** (12V @ 2 amps);

Input capacitor loss:	0.12 W
MOSFET Loss:	0.30 W
Diode Loss:	0.47 W
Inductor Loss:	0.15 W
Output Capacitor Loss:	0.01 W
Total losses:	1.05 W

Efficiency = 24 W / (24 W + 1.05 W) = 95%.

The lab-test of this circuit verified final electrical and thermal specifications and proved that the synchronous rectification can increase a power converter's efficiency significantly and for minimal cost.

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