APPLICATION NOTE ANP1

Using Sipex PWM Controllers for Boost Conversion

Introduction:

Sipex PWM controllers can be configured in boost mode to provide efficient and cost effective solutions. Circuit operation and design procedure are explained in the following.

Circuit Operation:

A boost circuit using Sipex's SP6136 controller is shown in figure 1. When MOSFET M1 is on, inductor L1 gets charged while the output capacitor sustains the load current. When M1 turns off, L1 replenishes the capacitor's charge through D1. Under light load conditions, the energy stored in the inductor is discharged before the next switching cycle begins (i.e., inductor current reduces to zero). This is referred to as Discontinuous Conduction Mode (DCM).

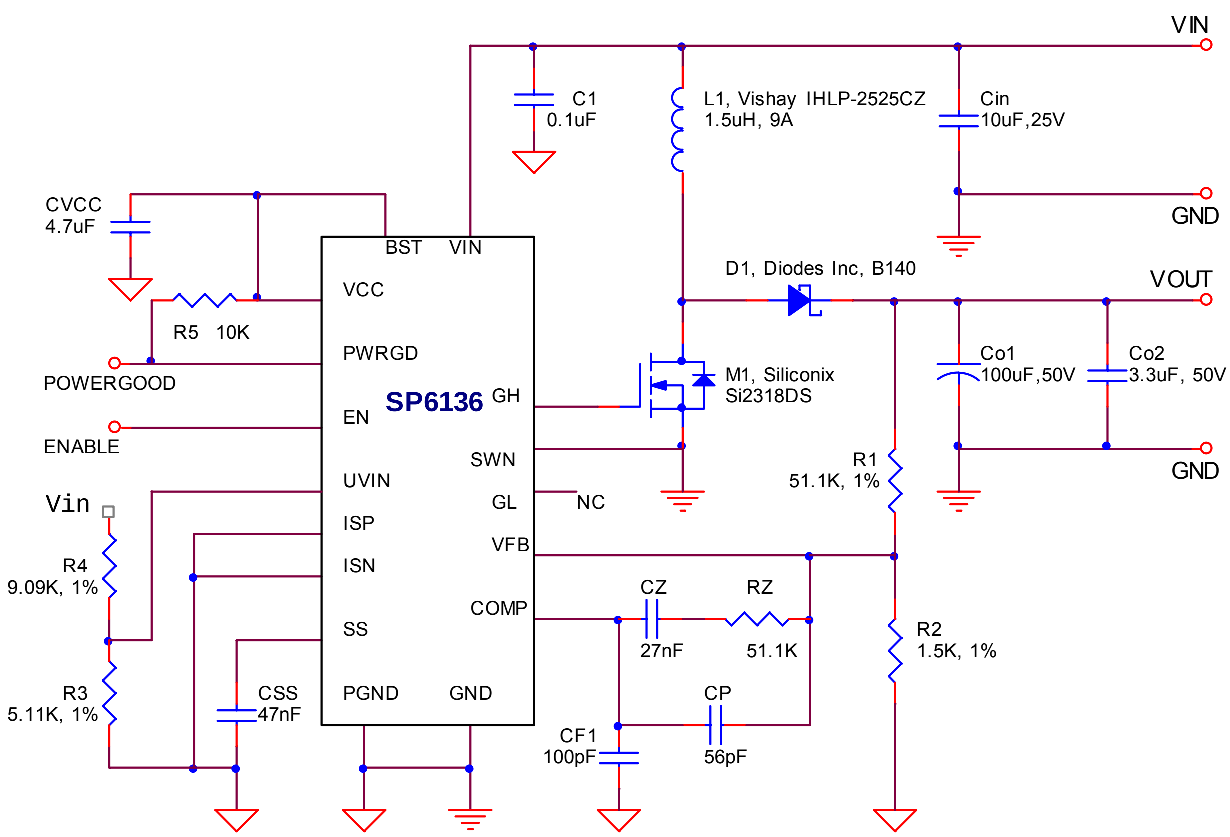

Figure 1- Boost converter based on SP6136, V_{IN}=7 to 18V, V_{OUT}=28V, I_{OUT}=0 to 0.5A, converter operates at Discontinuous Current Mode under all line and load conditions

Design Strategy:

As far as Conduction Mode is concerned, there are basically two choices in designing a boost converter:

1- Design for Discontinuous Conduction Mode (DCM) over full operating conditions: This approach offers easy control of the boost converter. With DCM, the converter transfer function has a single pole (second pole and Right Half Plane (RHP) zero are insignificant). Peak current (and I_{RMS}) however, will be high at low V_{IN} and/or high load conditions.

2- Design for Continuous Conduction Mode (CCM) for nominal operating conditions: With this approach the converter will transition to DCM at light loads. An RHP zero is present and hence, compensation is more difficult. The inductor current ripple, however, is significantly reduced.

DCM Boost Design Procedure:

For cases where output current requirement is low, less than 2A, a DCM design can be used as follows:

1- Controller selection

Sipex offers controllers with fixed operating frequency ranging from 300KHz to 2.5MHz. 600Khz controllers such as SP6136 and SP6134 offer a good compromise. This intermediate switching frequency helps reduce inductor size without incurring significant switching losses in the MOSFET M1. SP6134 is recommended for battery operated applications. This controller requires external V_{CC}, which can be shut down -- removing V_{CC} results in very low leakage current. SP6136 is recommended for applications where external V_{CC} is not available.

2- Inductor L1

Select an inductor based on required inductance (L1) and peak current (Ip). The following calculations assume that in order to ensure DCM operation a dead-time of 20% of full switching period is needed [1]. Hence, the combined conduction time of the MOSFET and diode is 80% of the switching period. This is the reason for K=0.8 used in following equations.

Calculate the required inductance from:

$$L1 = \frac{K \times \frac{Vo}{Io} \times Ton}{2 \times \left(\frac{Vo}{Vin, \min} \right)^2} \quad \text{...} \quad (1)$$

Where:

K = 0.8 is ratio of MOSFET and diode conduction time to T (T=1/f)

$\frac{Vo}{Io}$ is output impedance at full load Io

Vo is output Voltage

Vin,min is minimum input Voltage

T_{ON} is maximum on time of MOSFET M1.

Calculate T_{ON} from:

$$Ton = \frac{0.8 \times \frac{1}{f} \times (Vo - Vin, \min)}{Vo} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Calculate peak inductor current Ip from:

$$Ip = Ton \times \frac{Vin, \min}{L1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

Where:
T_{ON} is the maximum on time of the MOSFET calculated above
L1 is the inductance calculated above

3- MOSFET M1
Choose M1 based on Voltage rating (BVdss), current rating (Ids), ON resistance rating $R_{DS(ON)}$) and gate charge (Qg). BVdss must be greater than Vo of the converter. M1 must have the current capability to conduct Ip calculated in step 2. $R_{DS(ON)}$) can be up to twice the DCR of L1. Select a MOSFET with lowest Qg that meets the above requirements.

4- *Schottky diode D1*
Select D1 based on the reverse blocking Voltage (VR) and forward current (IF). VR must meet the output Voltage requirement of the converter and IF must meet the peak current requirement Ip calculated in step 2.

5- Input capacitor C_{IN}
Select C_{IN} based on input Voltage requirement, RMS ripple current rating and capacitance.
Calculate input rms current from equation for triangular current waveform:

$$Irms = Ip \sqrt{\frac{0.8}{3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

Where 0.8 is combined conduction time of the MOSFET and diode as explained in step 2 and Ip is peak inductor current also calculated in step 2. Since peak inductor current is supplied by the input capacitor, it is used for calculating I_{RMS} for C_{IN}.

Calculate capacitance from:

$$Cin = Irms \times \frac{T - Ton}{0.2 \times V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

Where T and T_{ON} are defined in step 2 of the procedure

6- Output capacitor C_{OUT}
For optimum performance use a combination of ceramic and electrolytic capacitors. A ceramic capacitor with its low ESR helps reduce output Voltage ripple.

A larger electrolytic capacitor is needed to keep a stiff output Voltage. The choice of this capacitor is critical since it dictates the frequency of converter's single pole (see section 7). In addition, its ESR introduces a "Zero" that limits system bandwidth. As a rule of thumb, select a 100uF low ESR capacitor and calculate the uncompensated transfer function and adjust the capacitance value if necessary.

7- Feedback loop compensation

The Control-to-Output transfer function of the converter is shown in figure 2. This is also referred to as an "uncompensated transfer function". The converter has essentially a single pole transfer function due to DCM. Pole frequency fp is determined by C_{OUT}. V_{IN} and I_{OUT} influence fp (and therefore crossover frequency fc) as shown in figure 2. There is a "Zero" due to ESR of Aluminum Electrolytic C_{OUT}. Use the equations of appendix 1 to plot this transfer function. Then use a type II compensator to increase the cross-over frequency and increase the low-frequency gain.

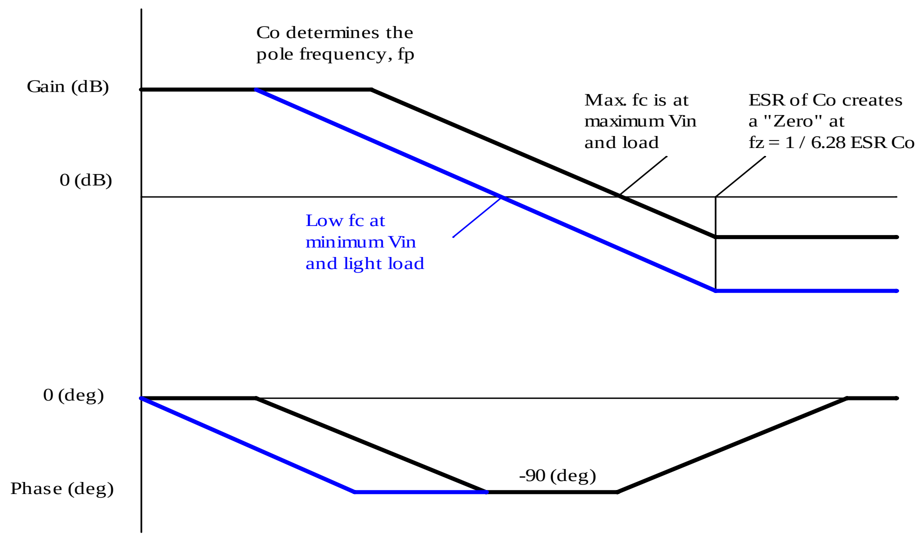

Figure 2- Control-to-Output transfer function of DCM boost converter, Gain/phase corresponding to low V_{IN} and light load are shown in blue.

Design example:

Design a boost converter that will meet the following requirements: V_{IN} = 7V to 18V with nominal value of 12V, V_{OUT} = 28V, I_{OUT} = 0.5A. An external V_{CC} is not available for this design.

Following the design procedure outlined in the previous page:

1- Use Sipex SP6136 for controller.

2- Calculate the required inductance for L1
First calculate the T_{ON} of M1 from (2)

$$Ton = \frac{0.8 \times \frac{1}{600000\ Hz} \times (28V - 7V)}{28V}$$

T_{ON} = 1us, then use (1) to calculate L1

$$L1 = \frac{0.8 \times \frac{28V}{0.5} \times 1us}{2 \times \left(\frac{28V}{7V}\right)^2}$$

L1 = 1.4 uH (use a 1.5uH standard value)
Calculate peak inductor current from (3)

$$Ip = 1us \times \frac{7V}{1.5uH}$$

Ip = 4.67A
Choose a 1.5uH inductor that meets this current rating. As an example Vishay's IHLP-2525CZ-1R5 can be used (l=1.5uH, DCR=15mOhm, I=9A, size= 6.47x6.86x3mm).

3- Select a 40V rated MOSFET that has a 4.67A peak current rating. For example Siliconix's Si2318DS can be used (BVdss = 40V, $R_{DS(ON)}$ = 58mOhm, Id=3.5A (continuous), Qg=10nC).

4- Select a 40V rated Schottky that has a 4.67A peak current capability (ex. Diodes Inc B140).

5- Use 25V ceramic input capacitor and calculate required I_{RMS} and C_{IN} from (4) and (5) respectively:

$$Irms = 4.67\ A \times \sqrt{\frac{0.8}{3}}$$

I_{RMS} = 2.41

$$Cin = 2.41\ A \times \frac{1.67\ us - 1us}{0.2V} = 8.1uF$$

Use a 10uF, 25V ceramic capacitor

6- Use a low ESR 100uF, 50V Aluminum electrolytic (ex., Sanyo 50MV1000WX). The low ESR helps maximize the “Zero” frequency (see figure 3). Use a 3.3uF ceramic in parallel to help reduce output ripple.

7- Feedback loop compensation

Using the procedure outlined in appendix 1, the control-to-output transfer function is calculated and plotted in figure 3. Using an Error Amplifier (EA) with type II compensation as shown in figure 4, it is desirable to increase the cross-over frequency fc shown in figure 3 to a maximum of 1/5 of switching frequency fs. In this example, however, fc cannot be increased due to the ESR zero. In order to leave fc unchanged, compensation should have a gain of 0dB, hence RZ=R1=51.1KΩ. Place compensator “Zero” at Max fp=108Hz. Since RZ is already set at 51.1KΩ, then CZ=28nF (use 27nF). Set the compensator pole at a sufficiently low frequency to obtain good noise attenuation at the given switching frequency. For example, in order to obtain a 20dB attenuation at 600khz, set the pole frequency to 60KHz. Solving for CP, we get CP=52pF (use 56pF).

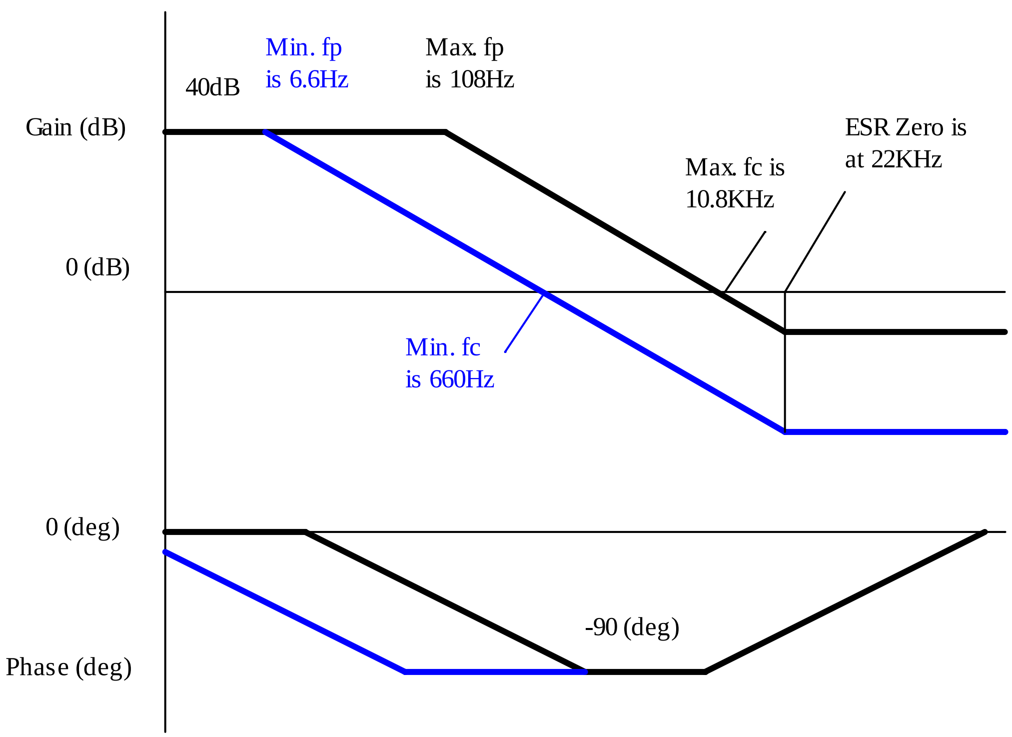

Figure 3- Design example Control-to-output transfer function, gain/phase corresponding to V_{IN}=7V and Io=50mA are shown in blue.

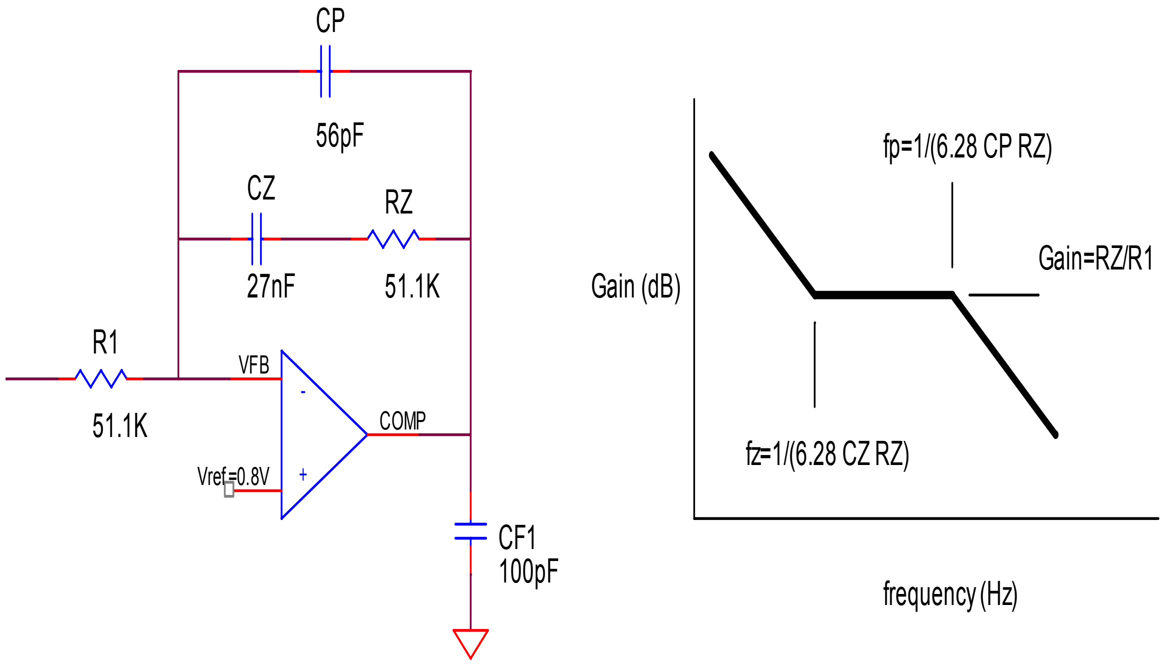

Figure 4- Error Amplifier (EA) and its transfer function for type II compensation, components shown are redrawn from figure 1, Error Amplifier is internal to SP6136 controller.

8-Miscellaneous

Select Voltage divider resistors as follows:
Let R2=1.5KΩ then

$$R1 = R2 \times \left[\left(\frac{Vout}{Vref} \right) - 1 \right]$$

$$R1 = 1.5K \times \left[\left(\frac{28V}{0.8V} \right) - 1 \right]$$

R1=51K (select 51.1KΩ standard)

Select Under Voltage Lock Out resistors for V_{IN}(start)=7V according to the procedure given in the data sheet. Choosing R3=5.11KΩ then R4=9.09KΩ.

Other small signal components, shown in figure 1, are standard components required for the operation of the SP6136.

[1] Switching Power Supply Design, A. Pressman, pages 27, 30.

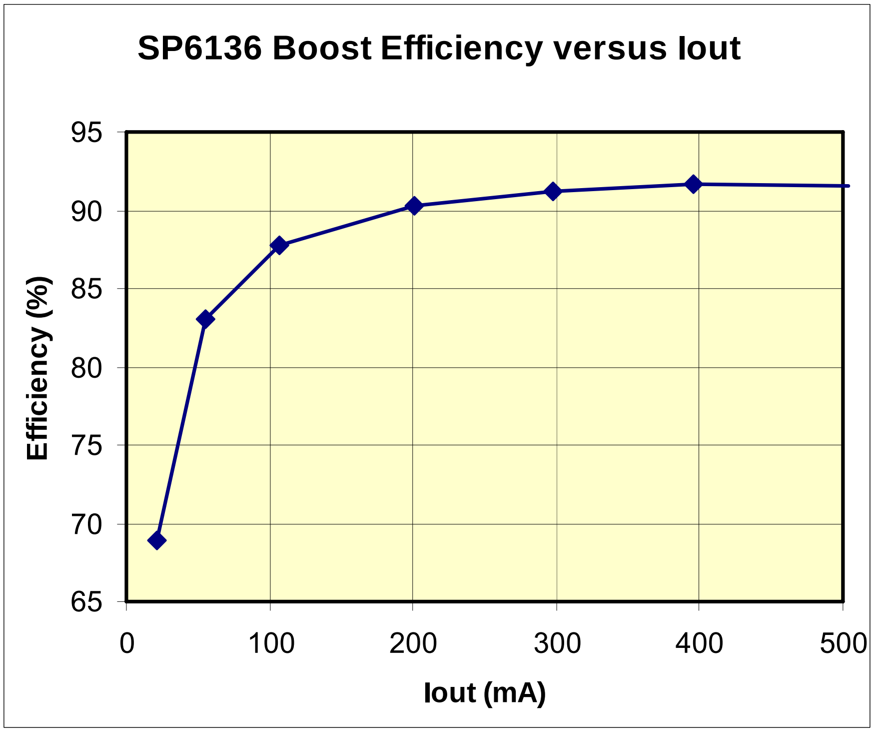

Figure 5- Efficiency at VIN=12V

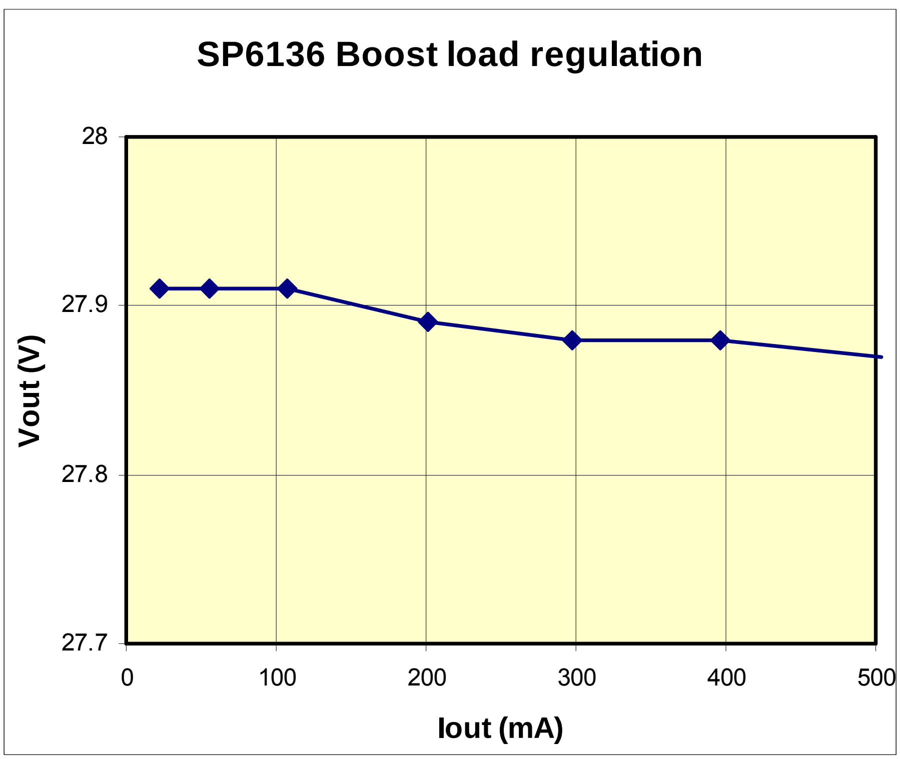

Figure 6- Load regulation at VIN=12V

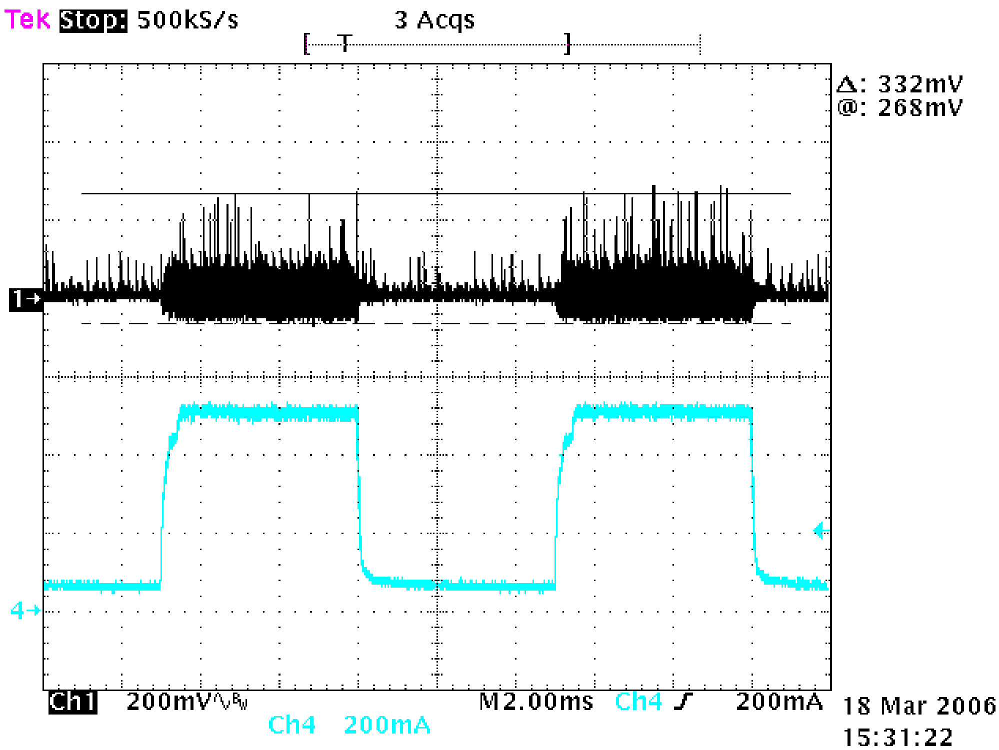

Figure 7- Step load response, I1=50mA, I2=500mA, f=1KHz, D=0.5, Ch1=VOUT, Ch4=IOUT

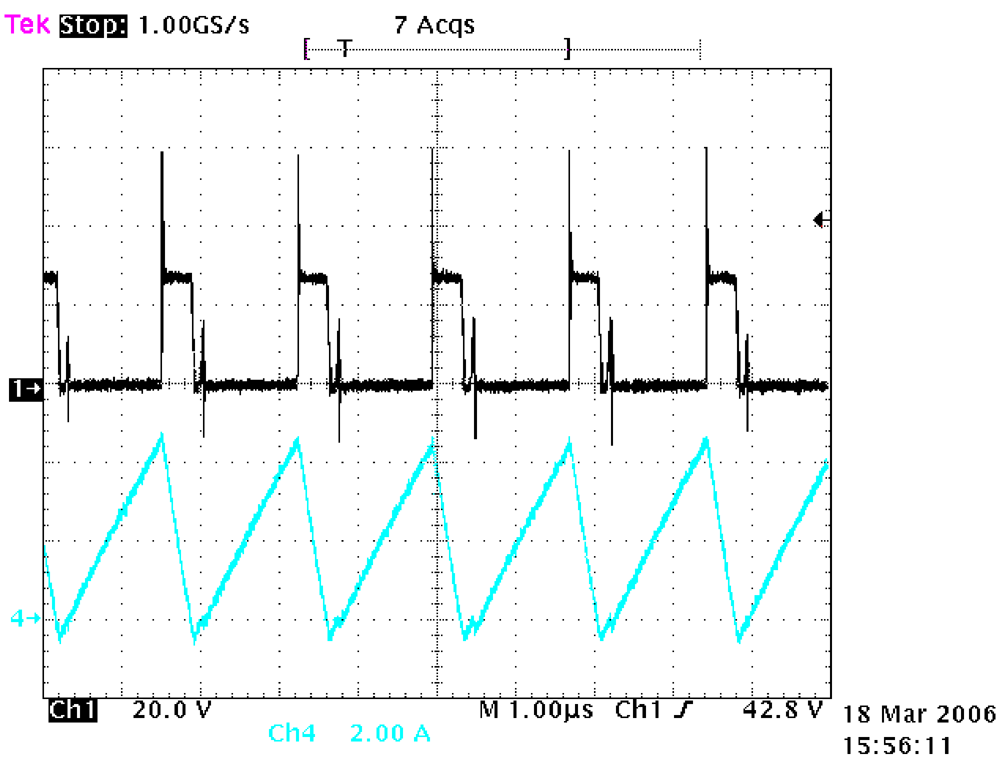

Figure 8- Converter waveforms at VIN=7V, IOUT=500mA, Ch1=SWN, Ch4=IL

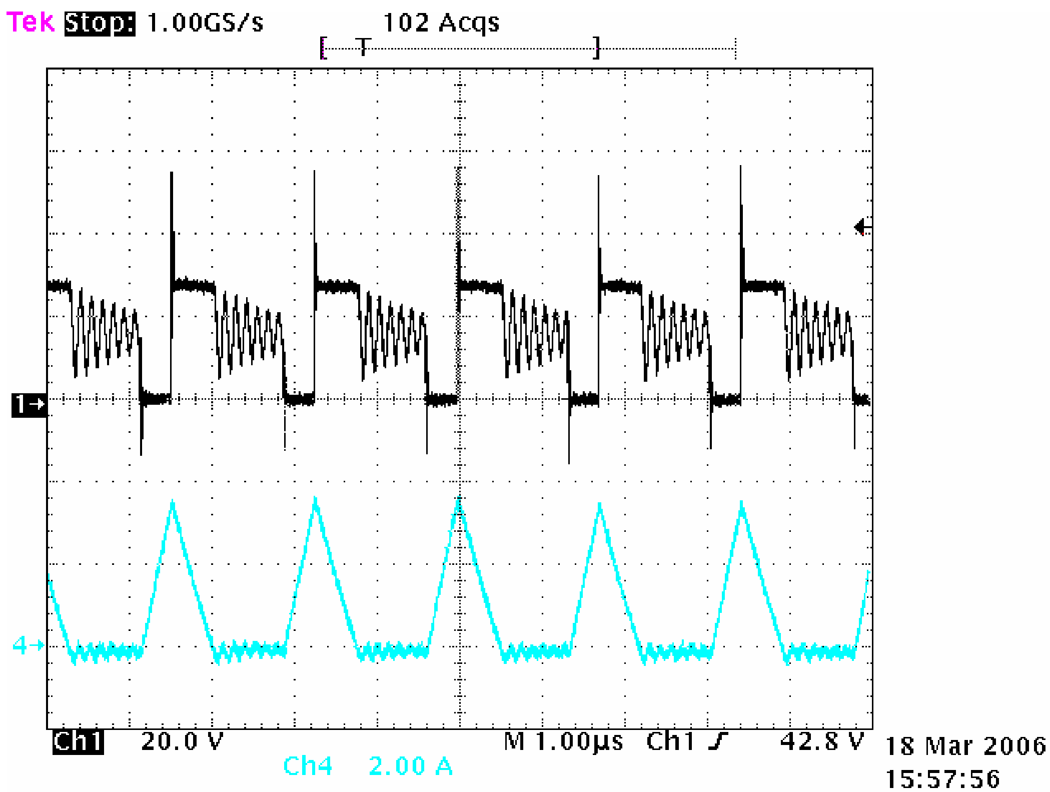

Figure 9- Converter waveforms at VIN=18V, IOUT=500mA, Ch1=SWN, Ch4=IL

Appendix 1: Calculation of Boost converter Control-to-Output transfer function

The following equations can be used to calculate the DC gain and corner frequency of a boost converter's Control-to-Output transfer function [2]

Calculate the pole's corner frequency (fp) from:

$$fp = \frac{(2 \times M) - 1}{2 \times \pi \times (M - 1) \times R \times C}$$

where:

$$M = \frac{Vout}{Vin}$$

$$R = \frac{Vout}{Iout}$$

C = output capacitance

Calculate the DC gain from:

$$Gdc = \left[\frac{2 \times Vout}{D}\right] \times \left[\frac{M - 1}{(2 \times M) - 1}\right]$$

Where :
D is steady state duty cycle

$$M = \frac{Vout}{Vin}$$

Calculate D from:

$$D = \sqrt{\frac{2 \times L}{\mathrm{Re} \times T}}$$

Where:
L is output inductance
T is switching period (1/f)
Re is the effective resistance of the small signal model of converter

Calculate Re from:

$$\mathrm{Re} = \frac{Vin^2}{Iout \times (Vout - Vin)}$$

[2]- Fundamentals of Power Electronics, Robert Erickson, page 389