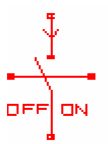
PECS PRIMER

by Richard Tymerski

The ideal switch in PECS is represented as follows:



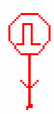
It features two electrical terminals and two control terminals which are labeled ON and OFF. The connection to the control terminals is not electrical. Only specific switch control elements may be connected to these terminals. These elements are:

1) Clock
2) Upper limiter
3) Lower limiter
4) PWM Modulator
5) Threshold
6) VCO

Also a Label element may be connected to the control terminals of a switch.

Each of these elements will be explained and their use will be demonstrated below.

CLOCK



A clock has only one terminal which can only be connected to a switch ON or OFF node. The parameters of a clock element are:

1) Delay time
2) Period

With reference to Figure 1, we see that after an initial delay of Delay seconds the switch is then turned ON (OFF) with period, Period seconds if the clock element is connected to the ON (OFF) terminal of the switch.

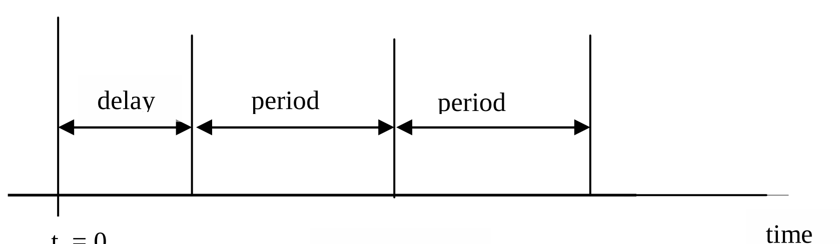


Figure 1

Note that once a switch turns ON or OFF by the (conceptual) impulses driving it, it remains in this state until the time instant of an alternative impulse signal.

We can implement fixed duty ratio control of a PWM converter by the use of two clock elements as shown in the buck converter circuit of Figure 2.

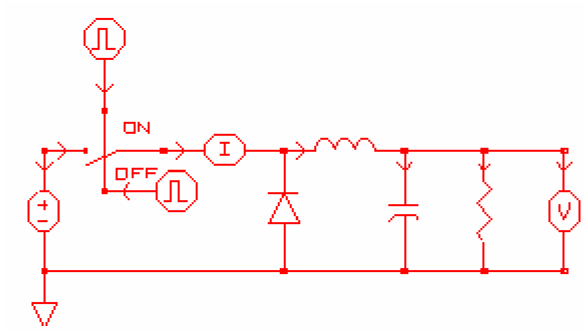


Figure 2. Buck converter (bkclk.ckt file)

The converter is driven at 100kHz with a duty ratio of 0.4. Thus each clock has a period of 10μs and we set the delay parameter associated with clock connected to the ON terminal to 0 so that the switch will turn ON immediately at the beginning of the simulation. The other clock connected to the OFF terminal has a delay of 4μs.

The steady state response of the circuit, using a step size of 0.2μs, is shown in Figure 3.

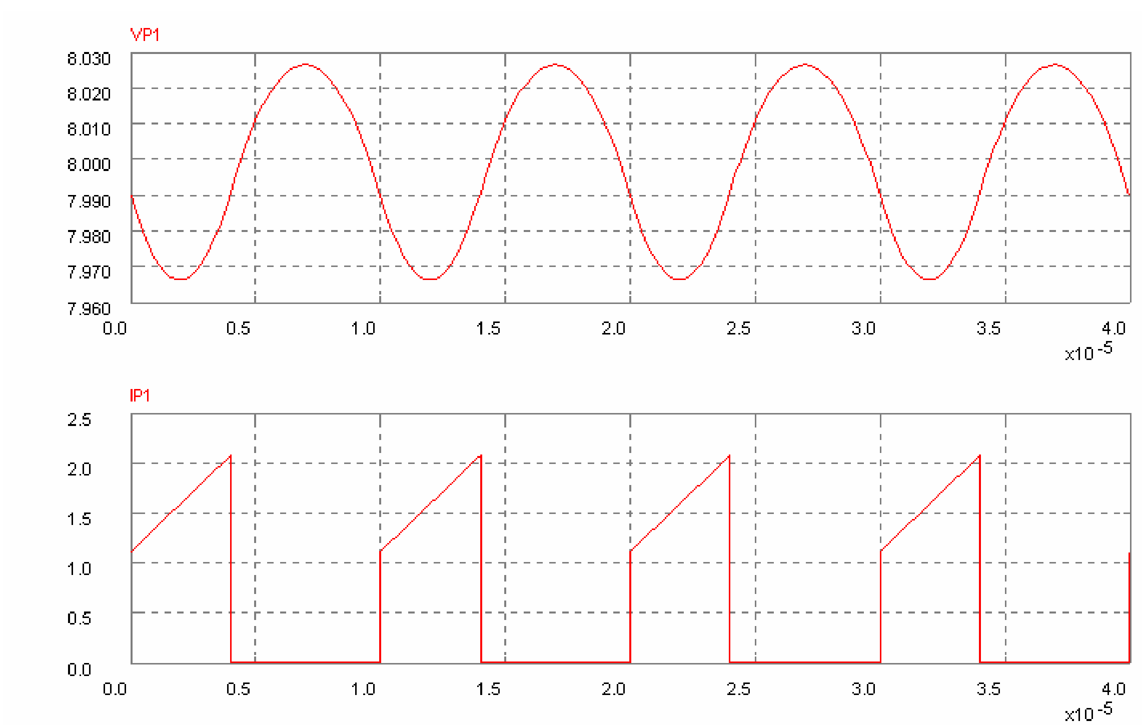
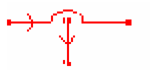


Figure 3. Output voltage and switch current of the buck converter.

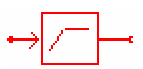
Looking at the switch current waveform it can be seen that the inductor current has a low value of 1.1A and a high value of 2.1A. We may modify the circuit of Figure 2 to use the "inductor current reaching 2.1A" event as the triggering signal to turn OFF the switch. To do this we need to monitor the inductor by inclusion of a current sense element and an upper limiter element.

CURRENT SENSE



The current sense element has no parameters.

UPPER LIMITER



The upper limiter takes the limit value as a parameter. The input of the limiter must be connected to a voltage signal and the output can only be connected to a switch control terminal.

The modified buck converter is shown in Figure 4.

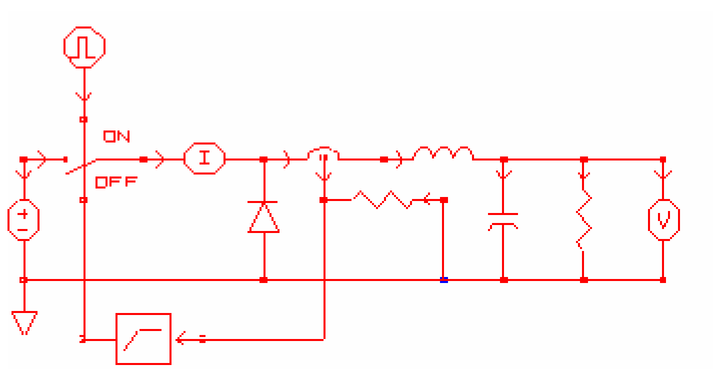
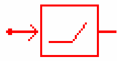


Figure 4. Modified buck converter. (bkul.ckt file)

To convert the current signal that appears at the output of the current sense element to a voltage, as needed by the upper limiter element, a (1ohm) resistor to ground is connected to the output of the current sense element. The output of the limiter is connected to the OFF terminal of the switch. When the voltage signal at the input of the limiter reaches the limit value the switch will turn OFF. If the upper limiter parameter is set to 2.1 identical steady state waveforms as shown before will be achieved.

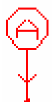
The circuit of Figure 4 can have both the ON and OFF instants controlled by the high and low levels of the inductor current. The ON instant may be initiated when the inductor current reaches its lower limit which we will determine with a lower limiter element. We will also use a label component to simplify the connections.

LOWER LIMITER



Similar comments as for the upper limit apply to the lower limiter.

LABEL



Circuit nodes connected with similar labels are collapsed to a single node. There are a maximum of 26 labels, one for each letter of the alphabet, which may be used.

Further modifying our buck converter results in the circuit of Figure 5.

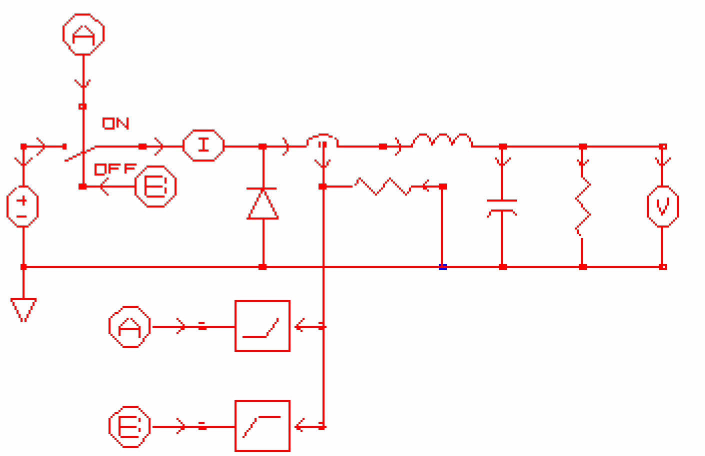
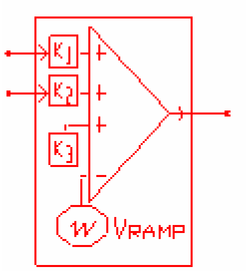


Figure 5. The limiters control the switching instants. (bkllul.ckt file)

With the upper limit value set at 2.1 and the lower limit set at 1.1, the steady state waveforms appear as before.

PWM MODULATOR



The PWM Modulator is represented by a symbol which contains a four input comparator and a sawtooth generator. Whenever the sum of the four inputs (three are added and one is subtracted) becomes negative the output, which can only be connected to a switch control terminal, will issue an appropriate turn ON or OFF signal. Two external inputs are provided to the modulator. These inputs are fed through gain blocks K1 and K2. The third input to the comparator is a constant, K3. K1, K2 and K3 are all input parameters of the modulator element. The last comparator input is from a (conceptual) sawtooth generator where the slope of the ramp is the fourth and final element parameter.

Using our buck converter example we can set up constant duty ratio control using a modulator as shown in Figure 6.

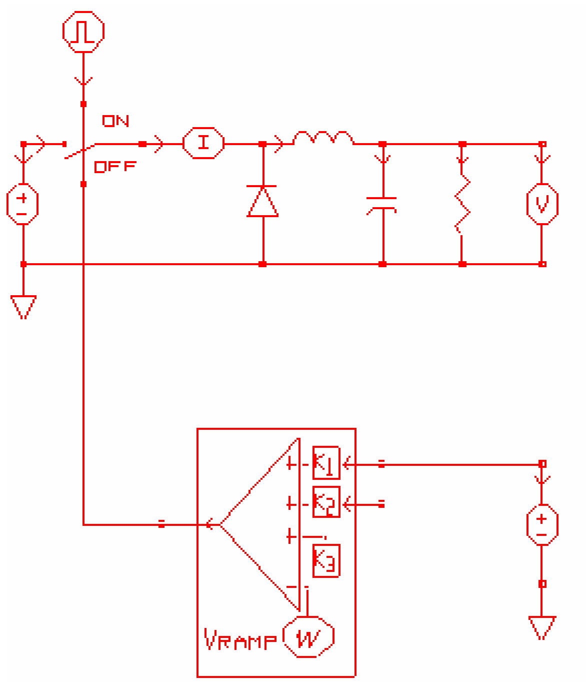


Figure 6. Modulator control of a buck converter. (bkmod.ckt)

To obtain a 0.4 duty ratio at 100kHz, we consider the sawtooth period to be 10μs with a peak to peak amplitude of 10V. This will set the ramp slope at 10e6 V/s. If the external voltage source input to the modulator is set at 4V, with K1 set to unity, then a 0.4 duty ratio will be obtained. Parameters K2 and K3 are not used and are set to zero.

If the external voltage source input to the modulator is dependent on the converter output voltage then closed loop voltage feedback will result. However, before we look at closed loop control, we will first examine the open loop response to input voltage source steps. For this purpose we will run circuit bkmodst.ckt which is the same as bkmod.ckt except that input voltage source to the buck converter is made to change from an initial 20V to 30V at time 4ms and then back to 20V at 7ms. The output voltage response is shown in Figure 7.

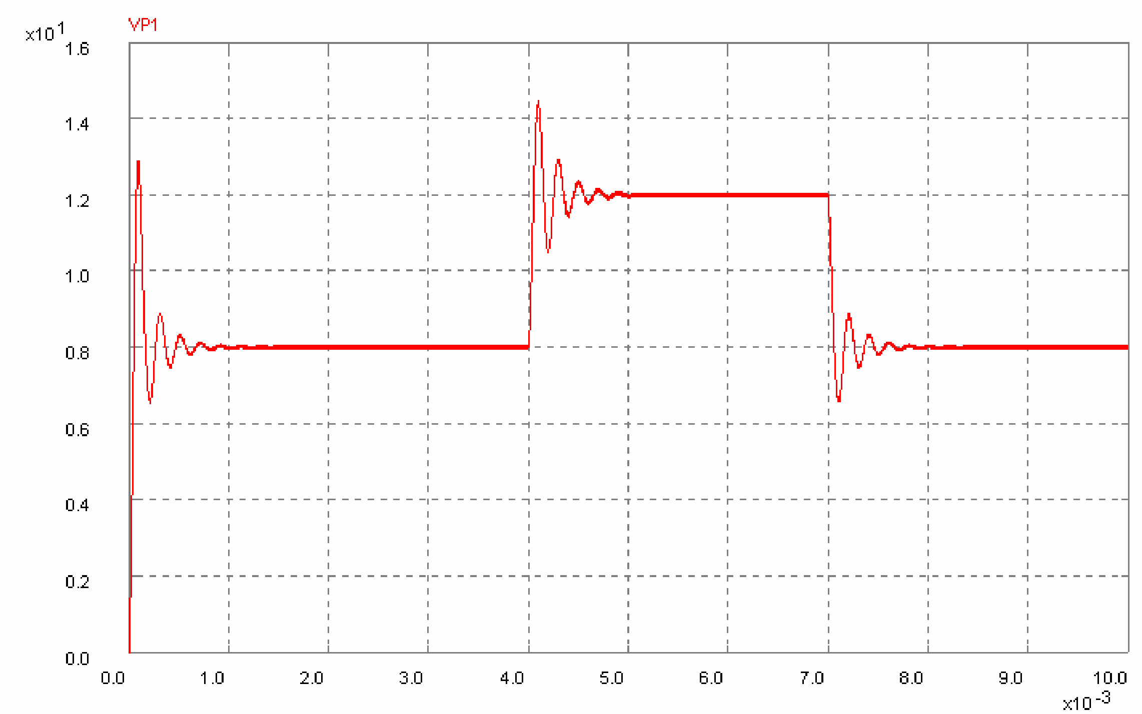


Figure 7. Open loop output voltage response to step changes in the input voltage. (bkmodst.ckt)

We see that at startup after an initial transient, the output voltage settles down to an average voltage of 8V (0.4*20V). After the input has increased to 30V, again after an initial transient, the output voltage settles down to an average voltage of 12V (0.4*30V).

Now let us consider the closed loop regulator circuit of Figure 8.

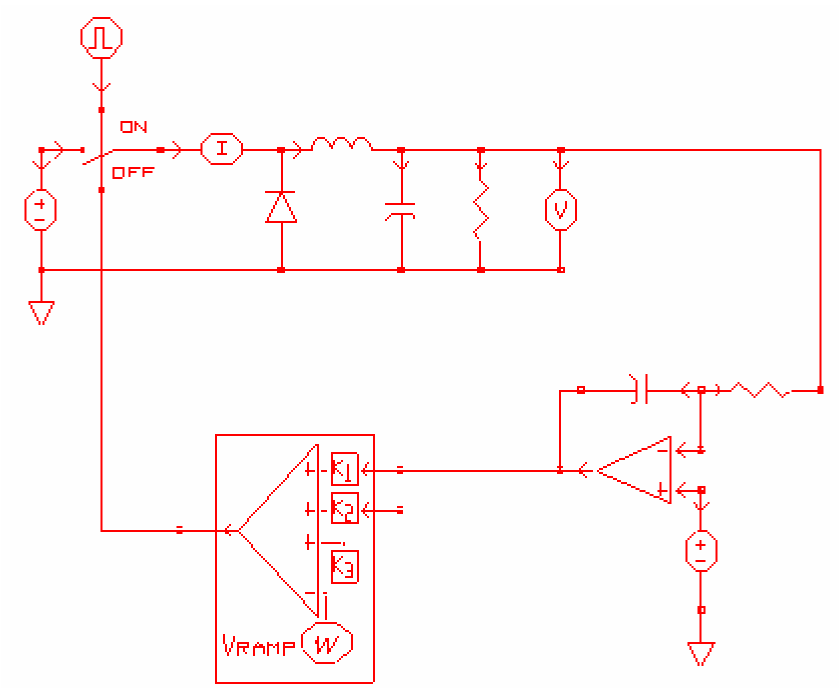


Figure 8. Closed loop buck voltage regulator. (bkfbks.ckt)

The converter output voltage is feed back to the modulator via an integrator which has a voltage reference of 8V at its non-inverting input. Thus the circuit will regulate the output voltage at 8V. The startup and output voltage step responses are shown in Figure 9.

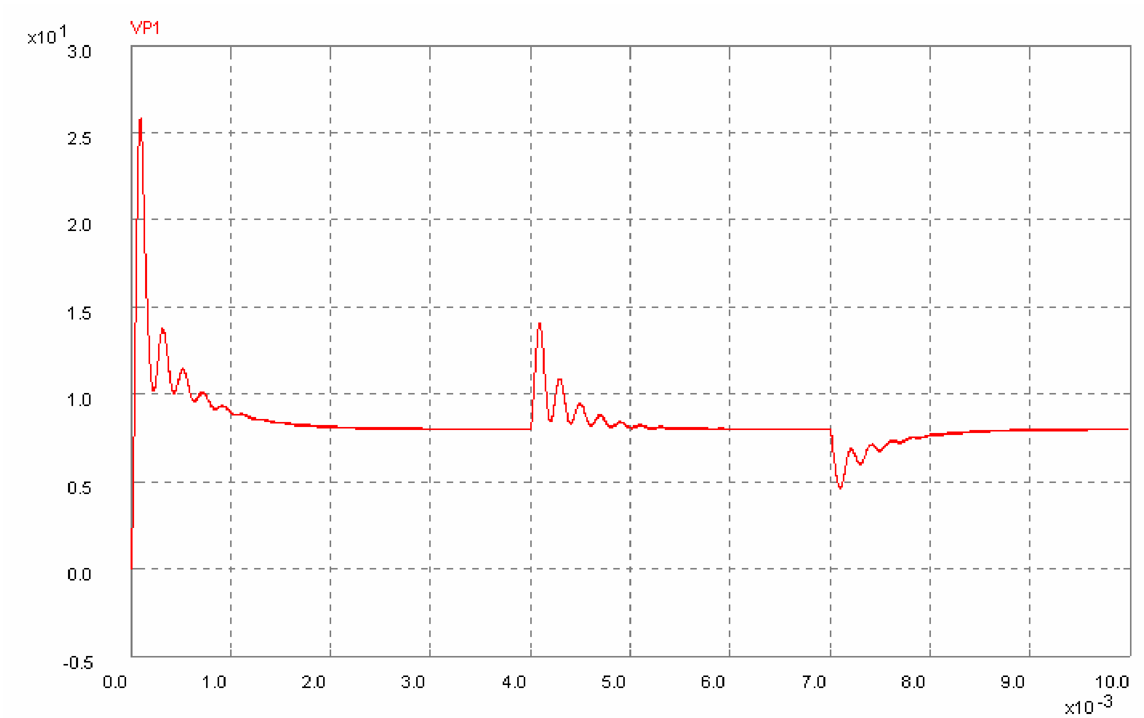


Figure 9. The output voltage response at startup and to input voltage changes.

From the output response we see that after initial transients the output is being regulated to 8V with no steady state error as expected with integral control.

OTHER TYPICAL PWM POWER CIRCUITS

We next examine various typical PWM power circuits.

Flyback Converter

The first is the flyback converter shown in Figure 10.

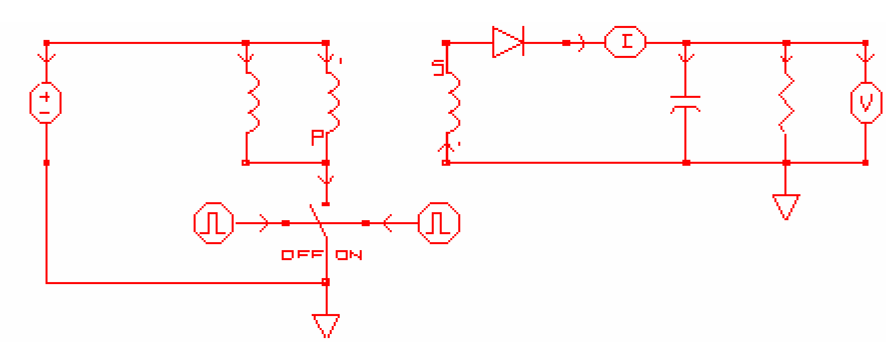


Figure 10. Flyback converter. (flybk.ckt)

Notice that the transformer in the flyback converter is modeled as an ideal transformer and a magnetizing inductance. The startup response of the output voltage and the diode current are shown in Figure 11. The steady state waveforms are shown in Figure 12.

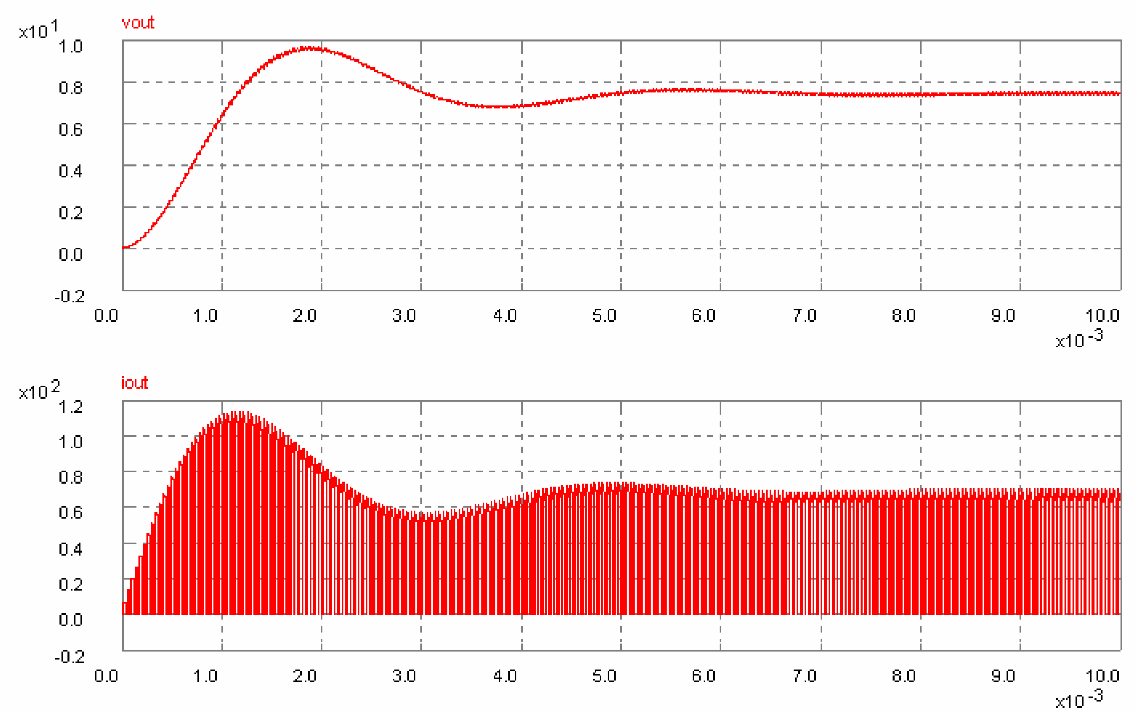


Figure 11. Output voltage and diode current startup response.

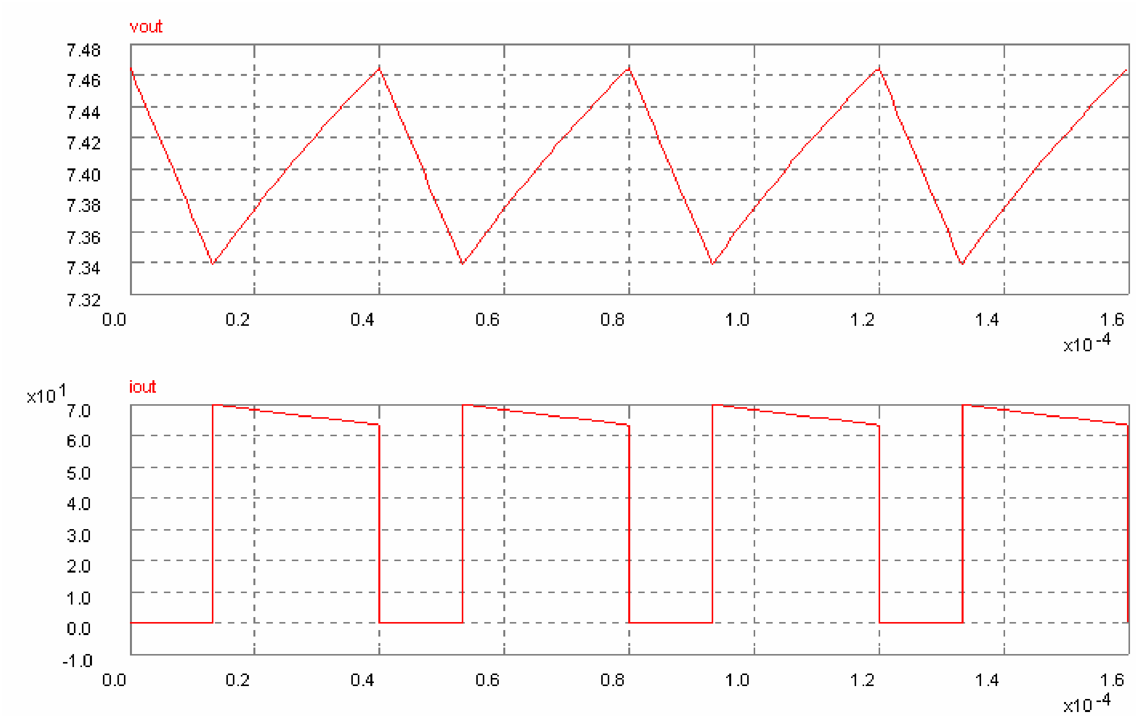


Figure 12. Output voltage and diode current steady state waveforms.

Forward Converter

A typical forward converter is shown in Figure 13.

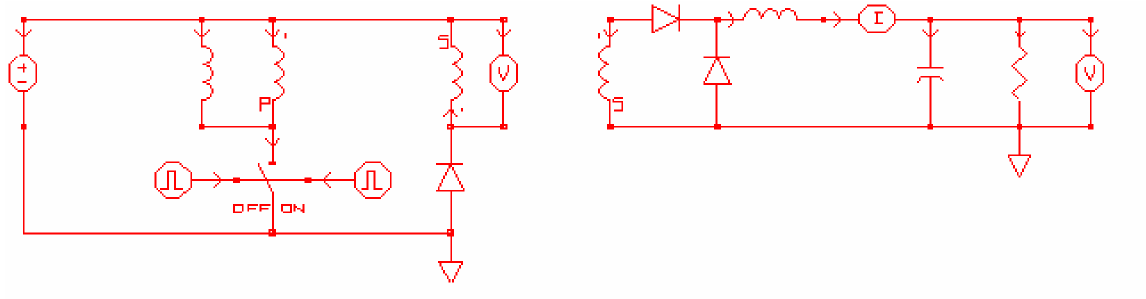


Figure 13. Forward converter. (fwd.ckt)

The steady state waveforms of the output voltage, output inductor current and voltage across the transformer tertiary (reset) winding are shown in Figure 14.

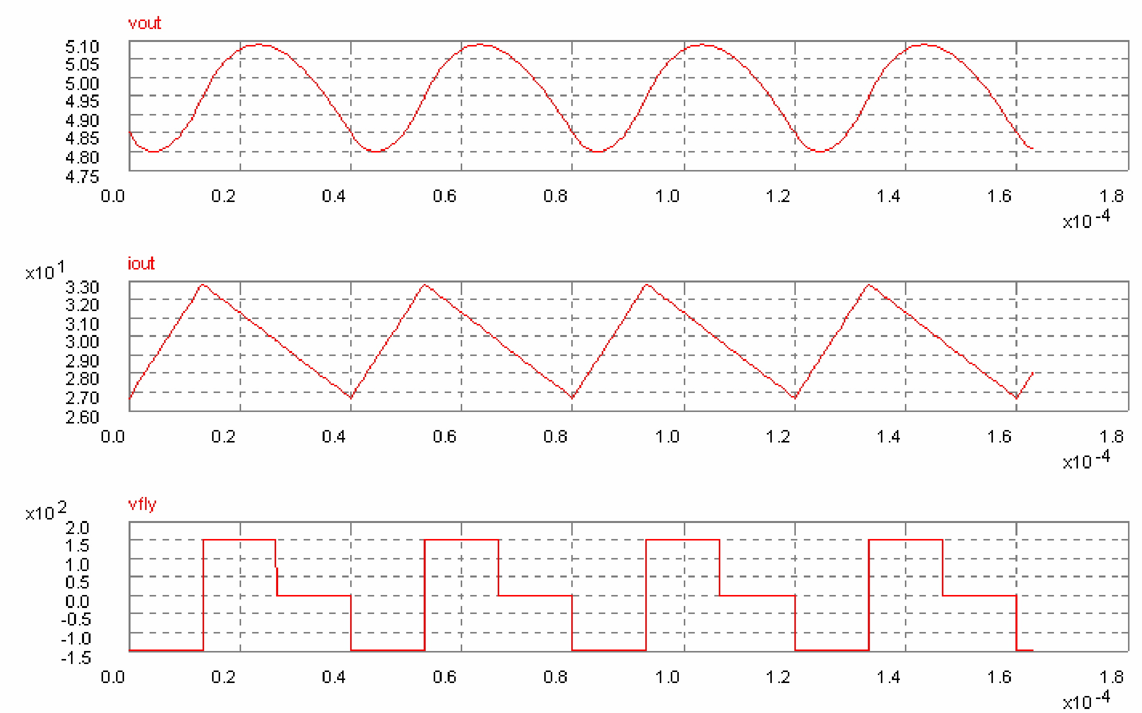


Figure 14. Selected steady state waveforms of the forward converter.

CUK CONVERTER

The Cuk converter will next be examined, both for uncoupled and coupled inductor cases. The uncoupled Cuk converter is shown in Figure 15 and steady state waveforms are shown in Figure 16.

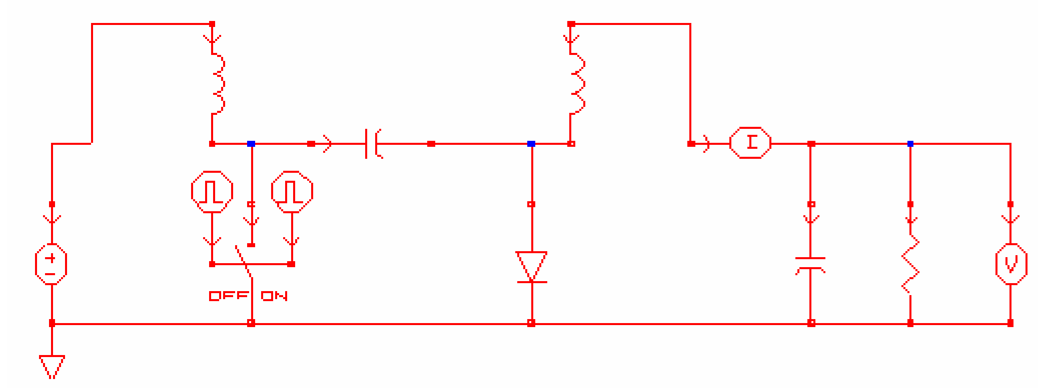


Figure 15. Uncoupled Cuk converter. (cuk.ckt)

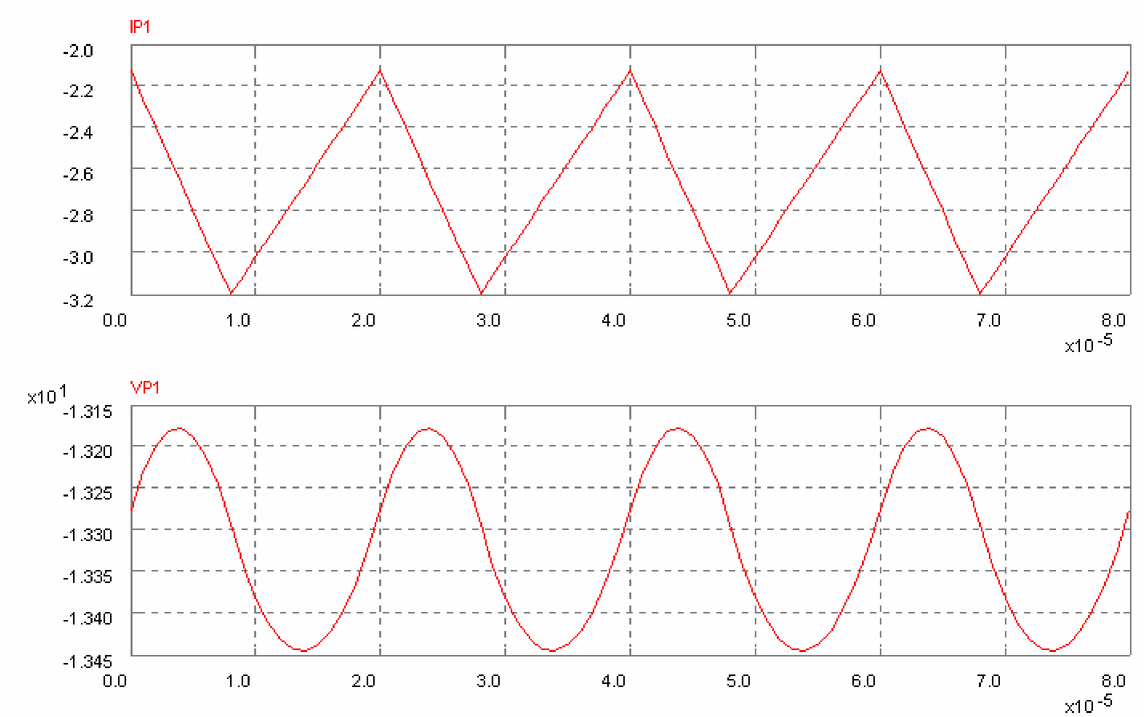


Figure 16. Output inductor current and output voltage steady state waveforms of the Cuk converter.

From the above waveforms we observe the following. The average output inductor current is about 2.7A, with a peak to peak ripple of about 1A. Notice that the current ripple is predominantly linear. The average output voltage is 13.3V with peak to peak ripple of 270mV. Next we look at the effect of coupling the inductors together. No other changes are made. The coupled inductor Cuk converter is shown in Figure 17. Steady state waveforms are shown in Figure 18.

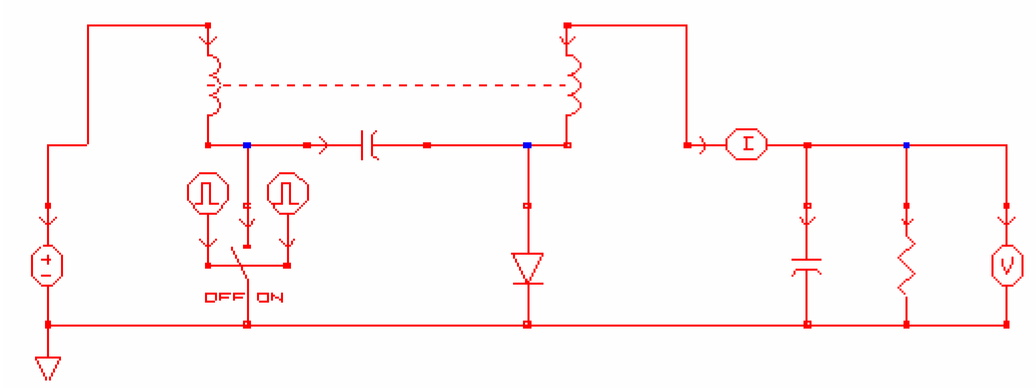


Figure 17. Coupled Cuk converter. (cukcup.ckt)

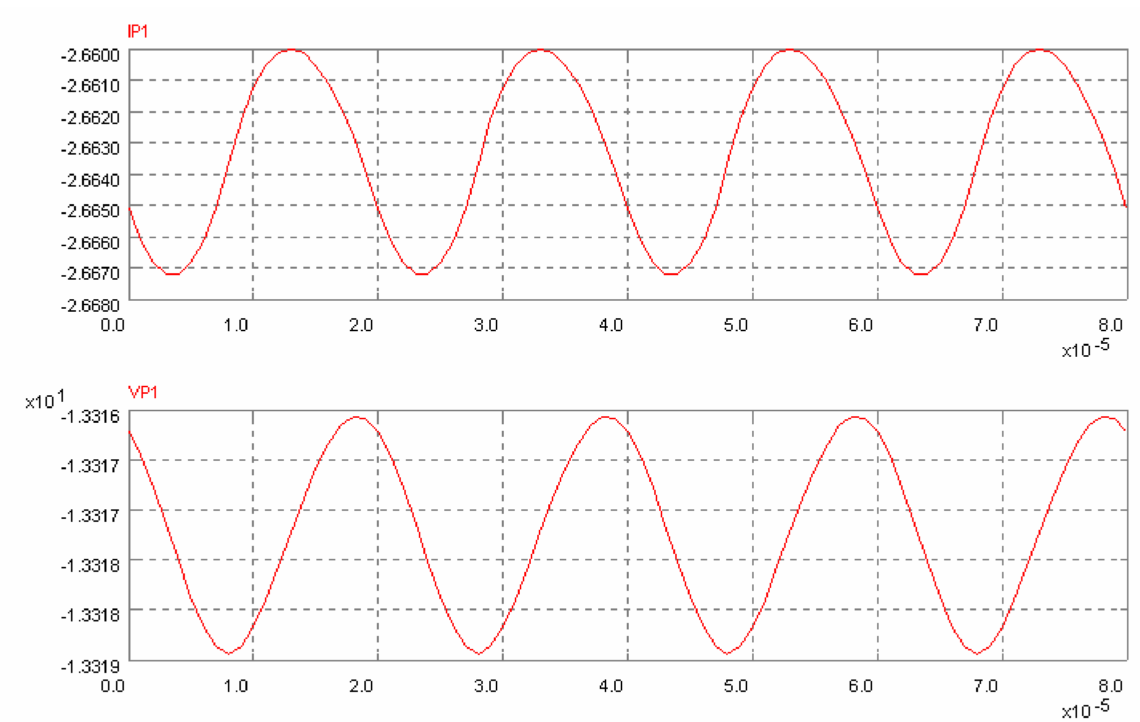


Figure 18. Steady state coupled inductor Cuk converter waveforms.

In coupling the inductors together the coupling was optimized to reduce the current ripple in the output inductor. To this end we find that we require the mutual inductance to equal the input inductor value. From the waveforms we see that the peak to peak output current ripple has been reduced from 1A to 7mA. The ripple current waveform consists of predominantly 2^{nd} and higher order components. The output voltage ripple has been reduced from 270mV for the uncoupled case to about 2.5mV, a reduction of over two orders of magnitude.