Experiment SMPS  Switch-Mode Power Supplies

Aims

Three switch-mode power supply (SMPS) designs will be investigated to establish their operating principles and to assess their performance in terms of open and closed loop output characteristics, efficiency, current limiting and output voltage ripple.

Background

The operation of the buck and the boost switch-mode power supplies are covered in section 2 of the notes for the second year course on Power Engineering (within 2.03 Power, Fields, Devices). Notes distributed week 1 Autumn. The following optional references are quoted in the text below:

[1] B.W. Williams, Power Electronics (Chapter 15), McMillan

Introduction

Switch-mode power supplies are, in general, more efficient than linear voltage regulators. This is especially so if the output voltage is a small fraction of the input voltage. They also offer the possibilities of stepping-up the voltage and providing electrical isolation by using a high-frequency switched transformer. The essential power components are a power transistor (operated as a switch at high frequency), a diode (to provide a current path when the transistor is off), an inductor (the energy storage component that facilitates voltage conversion) and a capacitor (for voltage smoothing).

The control elements include an error amplifier, a pulse-width modulator, a current limiter and an output driver. In this experiment, a standard IC is used to implement the control functions. The control may be open loop such that a reference voltage sets the transistor on-time and a relationship between on-time and output voltage is assumed, figure 1. The relationship is a non-linear function dependent on several circuit parameters. We shall represent it as \( f(.) \).

Alternatively, the control may be closed loop such that the output voltage is fed back, via an attenuator of gain \( B \) and subtracted from the reference value to form an error voltage, \( V_E \). The error voltage is used as the input to the power supply, \( f(.) \). The system will settle in a state where the on-time is set to keep the error small.

\[
\frac{V_o}{V_R} = f(.)
\]

The result is that the exact nature of the transfer characteristic of the power supply \( f(.) \) is not important because the transfer characteristic of the complete system depends only on the feedback attenuator, \( B \). The attenuator is normally a potential divider and is straight forward to design.

1. The Buck SMPS

The Buck SMPS is a step-down DC/DC voltage converter. It is widely applied from low powers to high powers. For instance, 3.3V CPUs run within 5V circuit boards often have a buck SMPS of about 5W. At the other extreme of the power range, at about 5MW, an electric railway locomotive with DC traction motors is usually controlled with variable voltage Buck SMPSs (although in this application they are normally known as Choppers).

1.1 The Circuit Principles

Figure 2 shows the essential power components of the circuit. The transistor is used only as a switch (i.e., it is either fully-on or fully-off and never kept in its linear region).

When the transistor is on the voltage marked \( V_X \) is almost equal to the input voltage; a positive voltage is applied to the inductor and the inductor current increases at \( \text{di/dt}=(V_X-V_L)/L \). When the transistor is turned off the inductor current must continue and so the diode is forced into conduction to provide a path. Thus \( V_X \) becomes slightly negative. The current in the inductor now reduces at \( \text{di/dt}=-V_L/L \).
The output voltage is the quantity of concern. It can be seen that $V_c$ is filtered by an LC combination to appear as $V_{oc}$. If the LC natural frequency is chosen well below the frequency at which the transistor is switched, then the output will be the average (i.e., DC) value of $V_c$. The average value of $V_c$ is dependent on the ratio of the on-time to the period of the switch (this ratio is known as the duty cycle).

The duration of the transistor on-time is the input variable we are able to manipulate. To do this we need a pulse-generator with variable pulse-width or a pulse-width modulator. A pulse-width modulator is normally implemented with a saw-tooth waveform, $V_s$ (from a fixed frequency oscillator) which is compared with a control signal, $V_c$, figure 3. The higher the control signal, the longer it exceeds the saw-tooth waveform and the longer the duration of the output pulse.

The full circuit diagram of the Buck SMPS is shown in Appendix A. The main power components are T1, D1, L1 and C4. (Note that T1 is a p-channel enhancement-mode MOSFET with a body-source short). The control functions are implemented by IC1, an LM3524D. Figure 5 is a block diagram of the features of the 3524 used in this SMPS. The output of IC1 is arranged as an active pull-down, pins 12&13, so that a level shifter can be implemented with ZD1, R9 and R10. (What advantage is gained by including T2 and D2?). The circuit is arranged so that the pulse-width modulator can be controlled by VR1 (open loop) or by the error between the output voltage and the voltage at VR1 (closed loop).

A current limited power supply has been implemented by using the comparator of the LM3524D (figure 5, pins 4&5). A small value resistor, R1, measures the current returning from the output smoothing capacitor (this is the same current as flowing in L1). The voltage drop across R1 is compared with a 0.2V reference. If the voltage drop, and hence the current, is excessive then the error amplifier output is pulled low and the on-time of the switch is reduced. This acts to limit the inductor current.

1.2 The Experimental Tasks

1.2.1 Initial Tests
- Set the initial active load current control to approximately 1A as follows. Turn the active load current control fully anti-clockwise. Disconnect the active load from any other circuit and connect it to a bench PSU with output voltage in range 5-24V and current limit greater than 1A. Turn up the active load current limit until the current of 0.3A flows. This will set a current which is small enough to allow the SMPS to start. Note that further current adjustment can be made using the active load current control when it is connected to the Buck PSU.
- Set the circuit to open loop mode. Set VR1 to approximately 1/4 (nearer the anti-clockwise end). Connect the Buck input to a bench power supply set to 24V. (Choose a PSU range or current limit to allow an input current of at least 1A.) Connect the active load to the Buck output.
- Observe the voltages at test points TP2, TP3, TP4 & TP5. (TP2 will be useful as a trigger signal in later work)
- Confirm that the pulse-widths at TP5 (active low) can be varied by VR1.
- Confirm that the power switch (TP7) operates as expected.

1.2.2 Open Loop Tests

Output Characteristic
- Accurately measure the input voltage.
Use VR1 to set the output voltage to 5V and record the period and duty-cycle of the transistor drive signal at TP5. (Invert the trace at TP5 because it is active low and use the Measure Time button)

- Vary the load current and record output voltage, output current and input current over as wide a range of output current as possible.
- Plot output voltage against output current.
- Establish the limits of the straight-line portion of the graph.
- Plot efficiency against output current.
- Observe the voltage drop across R1 (TP10) and look for continuous and discontinuous operation.
- Observe test points TP5 & TP7 under continuous and discontinuous modes of operation.
- Observe the shape and amplitude of the ripple voltage present at the output, TP8.

**Transfer Characteristic**
- Load the circuit to a current of 1A
- Vary the setting of VR1 and record the output voltage and the duty-cycle of the power switch while maintaining the load current at 1A. The bench power supply used at the input may current limit under some conditions.
- Plot output voltage against duty-cycle.
- Repeat the results for a load current of 0.2A

**Points for Comment**
- Is the relation between the duty-cycle and the output voltage as expected?
- What factors cause the output voltage to change with output current?
- Does current limiting occur at the expected point?
- What condition must be satisfied for the circuit to operate in continuous inductor current mode?
- Why is an oscillation seen at TP7 in discontinuous current mode?
- Why is the current sense signal at TP10 of poor quality?
- How does the efficiency of the power conversion in the SMPS compare with a linear regulator under similar conditions?
- What causes the output voltage ripple and how could it be reduced?

### 1.2.3 Closed Loop Tests

**Output Characteristic**
- Set the circuit to operate in closed loop mode.
- Set the initial active load current to 0.3A using a bench PSU as in 1.2.1. Now disconnect from the bench PSU and connect the active load to the Buck output.
- Accurately measure the input voltage.
- Use VR1 to set the output voltage to 5V
- Vary the load current and record input current, output voltage and output current.
- Plot output voltage against output current and efficiency against output current.

**Transfer Characteristic**
- Load the circuit to a current of 1A
- Vary the setting of VR1 and record the voltage at TP4, the duty-cycle of T1 and the output voltage while maintaining the load current at 1A.
- Plot output voltage and duty-cycle against $V_{TP4}$.

**Points for Comment**
- Is the relation between the setting of VR1 and the output voltage as expected?
- How much better is the closed loop output characteristic than the open loop characteristic?
2. The Boost SMPS

The Buck SMPS, like the linear regulator, is restricted to output voltages between zero and the input voltage. If, for instance, an RS232 output of 24V is required from a circuit with a 5V supply then a step-up converter is needed for the RS232 driver. The Boost SMPS provides an implementation.

2.1 The Circuit Principles

Figure 6 shows that the Boost SMPS is a simple re-arrangement of the components of the Buck SMPS. If the transistor were left off permanently then the output voltage would equal the input voltage.

![Figure 6 Boost SMPS](image)

Switching the transistor on applies the full input voltage across the inductor and the current increases according to \(\frac{di}{dt} = \frac{V}{L}\). When the transistor is turned off the inductor current must continue and so the diode is forced into conduction to provide a path. Thus \(V_X\) becomes slightly greater than \(V_o\). The energy stored in the inductor \(\frac{1}{2}L\frac{di}{dt}\) during the on-time is now released into the capacitor to increase its stored energy \(\frac{1}{2}Cv^2\) and the voltage rises above \(V_c\). The inductor current decreases at \(\frac{di}{dt} = \frac{V_o}{L}\). The longer the transistor is held on the more energy is stored in the inductor and the greater the charge delivered to the output capacitor. Appendix C contains a derivation of the relationship between the transistor duty cycle and the output voltage.

2.2 The Experimental Tasks

Appendix A gives the full circuit diagram of the Boost SMPS. The main power components are T1, D1, L1 and C4. (Note that T1 is now an n-channel enhancement-mode MOSFET). The control circuit is very similar to the Buck SMPS except that:

1. the output of IC1 (figure 5, pins 11&14) is arranged as an active pull-up to drive the n-channel MOSFET through a circuit that is the complement of that of the Buck SMPS,
2. the voltage ratio of the potential divider (R7 & R8) in the feedback network has been changed in order to accommodate the higher output voltages,
3. the current sense resistor (R1) has been doubled in value and moved to a position where it will still record the inductor current.

2.2.1 Open Loop Tests

Output Characteristic
- Set the active load current to 300mA using a bench PSU set to 12V.
- Set the Boost SMPS to operate in open-loop mode and connect it to the active load.
- Connect an input voltage of 12V (N.B. choose a range or current limit to allow a 2A input current) and confirm that the oscillator and power switch operate as expected.
- Use VR1 to set the output voltage to 20V and record the period and duty-cycle of the transistor drive signal at TP5. (The signal at TP5 is active high).
- Vary the load current and record load current, output voltage, and input current.
- Observe the voltage drop across R1 (TP10) and look for continuous and discontinuous operation.
- Observe test points TP5 & TP7 under continuous and discontinuous modes of operation.
- Plot output voltage against load current.
- Establish the limits of the straight-line portion of the graph.

Transfer Characteristic
- Vary the setting of VR1 and record the duty-cycle of the power switch and the output voltage for a load current of 1A.
- Plot output voltage against duty-cycle.

Points for Comment
- Does the current limit operate at the expected point?
- What condition is necessary for the circuit to operate in continuous mode?
- Is the relation between the duty-cycle and the output voltage as expected?

2.2.2 Closed Loop Tests

Output Characteristic
- Set the circuit to operate in closed loop mode.
- Set the active load to 300mA.
- Use VR1 to set the output voltage to 20V.
- Vary the load current and record output voltage and load current.
- Plot output voltage against output current.
- Observe the ripple voltage present at the output, TP8.

Transfer Characteristic
- Vary the setting of VR1 and record voltage at TP4, the duty-cycle of T1 and the output voltage while maintaining the load current at 1A.
- Plot output voltage and duty-cycle against \(V_{TP4}\).

Points for Comment
- Is the relation between the setting of VR1 and the output voltage as expected?
- How much better is the closed loop output characteristic than the open loop characteristic?
- How does the output voltage ripple compare with that of the Buck SMPS?
<table>
<thead>
<tr>
<th>Buck SMPS</th>
<th>Boost SMPS: as Buck except</th>
<th>Push-Pull Isolated SMPS: as Buck except</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC1</td>
<td>LM3524D</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>IRF9530</td>
<td>T1  IRF530</td>
</tr>
<tr>
<td>T2</td>
<td>ZTX651</td>
<td>T2  ZTX751</td>
</tr>
<tr>
<td>D1</td>
<td>STPS735</td>
<td>D1  1N4148</td>
</tr>
<tr>
<td>D2</td>
<td>1N4148</td>
<td>D2  1N4148</td>
</tr>
<tr>
<td>D3</td>
<td>STPS735</td>
<td>D3  STPS735</td>
</tr>
<tr>
<td>D4</td>
<td>STPS735</td>
<td>D4  STPS735</td>
</tr>
<tr>
<td>D5</td>
<td>STPS735</td>
<td>D5  STPS735</td>
</tr>
<tr>
<td>D6</td>
<td>FEC5082-2835</td>
<td>D6  FEC5082-2835</td>
</tr>
<tr>
<td>D7</td>
<td>FEC5082-2835</td>
<td>D7  FEC5082-2835</td>
</tr>
<tr>
<td>D8</td>
<td>FEC5082-2835</td>
<td>D8  FEC5082-2835</td>
</tr>
<tr>
<td>ZD1</td>
<td>15V</td>
<td>ZD2  15V</td>
</tr>
<tr>
<td>L1</td>
<td>100µ / 10A</td>
<td>L2  39m / 50mA</td>
</tr>
<tr>
<td>VR1</td>
<td>10K</td>
<td></td>
</tr>
<tr>
<td>R1a</td>
<td>0R1 / 2W</td>
<td>R1  0R1 / 2W</td>
</tr>
<tr>
<td>R1b</td>
<td>0R1 / 2W in // with R1a</td>
<td></td>
</tr>
<tr>
<td>R2</td>
<td>220R</td>
<td>R2  33R</td>
</tr>
<tr>
<td>R3</td>
<td>2K2</td>
<td></td>
</tr>
<tr>
<td>R4</td>
<td>3K3</td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td>1K0</td>
<td></td>
</tr>
<tr>
<td>R6</td>
<td>13K</td>
<td>R6  10K</td>
</tr>
<tr>
<td>R7</td>
<td>56K</td>
<td>R7  100K</td>
</tr>
<tr>
<td>R8</td>
<td>56K</td>
<td>R8  15K</td>
</tr>
<tr>
<td>R9</td>
<td>100R</td>
<td></td>
</tr>
<tr>
<td>R10</td>
<td>2K2</td>
<td></td>
</tr>
<tr>
<td>R11</td>
<td>100R</td>
<td>R11  100R</td>
</tr>
<tr>
<td>R12</td>
<td>2K2</td>
<td>R12  2K2</td>
</tr>
<tr>
<td>C1</td>
<td>1000µ / 35V</td>
<td>C4  470µ / 63V</td>
</tr>
<tr>
<td>C2</td>
<td>100n</td>
<td>C4  1000µ / 16V</td>
</tr>
<tr>
<td>C3</td>
<td>100n</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>1000µ / 35V</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>10n</td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>4n7</td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>100n</td>
<td></td>
</tr>
<tr>
<td>C8</td>
<td>4n7</td>
<td>C8  1n0</td>
</tr>
<tr>
<td>C9</td>
<td>omitted</td>
<td></td>
</tr>
<tr>
<td>C10</td>
<td>100n</td>
<td></td>
</tr>
</tbody>
</table>

**Experiment SMPS Appendices**
Appendix B - Buck SMPS Transfer Equation

In steady-state, any increase in inductor current during the time that the transistor is on must be balanced by a decrease during the time that the diode conducts.

\[ \Delta I(\text{on}) + \Delta I(\text{diode}) = 0 \]

\[ \Delta I(\text{on}) = \frac{V_i}{L} \cdot t_{on} \]

\[ \Delta I(\text{diode}) = -\frac{V_o}{L} \cdot t_{\text{diode}} \]

\[ \frac{V_o}{V_i} \cdot \frac{t_{on}}{t_{on} + t_{\text{diode}}} \]

If the inductor current is continuous then the diode conducts for all of the time that the transistor is off.

\[ T = t_{on} + t_{\text{diode}} \]

\[ \frac{V_o}{V_i} \cdot \frac{t_{on}}{t_{diode}} = \delta \]

where \( \delta \) is the duty cycle of the switch.

If the inductor current is discontinuous then there is a period for which neither the transistor nor the diode conducts and the rate of change of inductor current is zero. Using the fact that the output current and the average inductor current must be equal (in steady-state), \( t_{on} + t_{\text{diode}} \) can be related to the period. We note that the inductor current is a triangle wave of amplitude \( \Delta I(\text{on}) \)

\[ t_o = t_L(\text{ave}) = \frac{1}{2} \Delta I(\text{on}) \cdot \frac{t_{on} + t_{\text{diode}}}{T} \]

This yields a relationship between output voltage and input voltage, duty cycle & input current.

\[ \frac{V_o}{V_i} = \frac{1}{1 - \frac{2 \delta I_o}{V_i \delta^2}} \]

Appendix C - Boost SMPS Transfer Equation

As with the buck converter, any increase in inductor current during the time that the transistor is on must be balanced by a decrease during the time that the diode conducts. The differences appear in the voltages imposed across the inductor.

\[ \Delta I(\text{on}) + \Delta I(\text{diode}) = 0 \]

\[ \Delta I(\text{on}) = \frac{V_i}{L} \cdot t_{on} \]

\[ \Delta I(\text{diode}) = \frac{V_i - V_o}{L} \cdot t_{\text{diode}} \]

\[ \frac{V_o}{V_i} = \frac{t_{on} + t_{\text{diode}}}{t_{\text{diode}}} \]

For the continuous inductor current case:

\[ \frac{V_o}{V_i} = \frac{t_{on} + t_{\text{diode}}}{t_{\text{diode}}} = \frac{T}{t_{\text{diode}}} = \frac{1}{1 - \delta} \]

For the discontinuous inductor current case it is noted that the average inductor current is equal to the input current.