CHAPTER 5: REGULATED POWER SUPPLIES

A regulated power supply can be built using a simple zener diode as a voltage regulator. Reverse breakdown voltage of the zener diode is used to hold the output voltage constant at a certain load condition. To improve voltage regulation, a negative feedback configuration is used in the regulator. Higher efficiency power supplies use switching regulators which employ fast switching devices. The quality of a power supply depends on its load regulation, line regulation, and output resistance.

I. SUPPLY CHARACTERISTICS

1. Load regulation

The load regulation indicates how much the load voltage changes when the load current changes. The load regulation is defined as:

\[ \text{Load regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% \]

where

- \( V_{NL} \) = load voltage with no load current (\( I_L = 0 \))
- \( V_{FL} \) = load voltage with full load current (\( I_L = I_{L_{max}} \))

The smaller the load regulation, the better the power supply. A well-regulated power supply can have a load regulation of less than 1% (i.e., the load voltage varies less than 1% over the full range of load current).

2. Line regulation

Any change in the line voltage out of the nominal value (i.e., 120V ac) will affect the performance of the power supply. The line regulation is defined as:

\[ \text{Line regulation} = \frac{V_{HL} - V_{LL}}{V_{LL}} \times 100\% \]

where

- \( V_{HL} \) = load voltage with high line
- \( V_{LL} \) = load voltage with low line

The smaller the line regulation, the better the power supply. A well-regulated power supply can have a line regulation of less than 0.1%.

3. Output resistance

The output resistance of a power supply determines the load regulation. If a power supply has a low output resistance, its load regulation will also be low by the relationship:
\[ R_{TH} = \frac{V_{NL} - V_{FL}}{I_{FL}} \]

Load regulation = \( \frac{R_{TH}}{R_{L(min)}} \times 100\% \)

where
- \( R_{TH} \) = output resistance of the power supply
- \( I_{FL} \) = full load current (occurs when the load resistance is minimum)
- \( R_{L(min)} \) = minimum load resistance

II. SHUNT REGULATORS

The line regulation and load regulation of an unregulated power supply are too high for most applications. The regulations can be improved by using a voltage regulator. A linear voltage regulator uses a device operating in the linear region to hold the load voltage constant. The shunt voltage regulators have the regulating device in parallel with the load. Some of the shunt regulators are shown below.

**Zener Voltage Regulator**

\[ V_{out} = V_Z \]
\[ I_S = \frac{V_{in} - V_{out}}{R_S} \]
\[ I_L = \frac{V_{out}}{R_L} \]
\[ I_Z = I_S - I_L \]

**Improved Zener Voltage Regulator**

\[ V_{out} = V_Z + V_{BE} \]
\[ I_S = \frac{V_{in} - V_{out}}{R_S} \]
\[ I_L = \frac{V_{out}}{R_L} \]
\[ I_C = I_S - I_L \]
One advantage of shunt regulators is that they have built-in short circuit protection. If there is a short circuit across the load terminals, none of the components of the regulator will be damaged, all that happens is that the input current increases to $I_S$.

The regulator has an efficiency of:

$$\text{Efficiency} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

The shunt voltage regulators have low efficiency due to the power wasted by the regulator components, $P_{\text{reg}}$, and most of this power is dissipated across series resistor $R_S$. This type of regulator is used in applications where efficiency is not important. In addition, this regulator is very simple.

$$P_{\text{reg}} = P_{\text{in}} - P_{\text{out}}$$

*Example: 24-1, 24-2, 24-3 (page 914)*
III. SERIES REGULATORS

Compared to the shunt voltage regulators, the series regulators have higher efficiency (50%-70%), fairly simple to design and good enough for small load power applications (<10W).

1. Simple series regulators

The Zener follower

Two-transistor regulator

The headroom voltage is defined as the different between the input and output voltage:

\[ \text{Headroom voltage} = V_{\text{in}} - V_{\text{out}} \]

The lower the headroom, the higher the efficiency (i.e., the best efficiency is obtained when the output voltage as large as input voltage). Transistors Q1 and Q2 is usually replaced by a Darlington connection (a low power transistor, Q1, drives the power transistor, Q2). This connection allows larger values of R1 and R4 to be used in order to improve the regulator efficiency further.

Example: 24-7, 24-8
2. Improved regulation

An op-amp can be used to improve regulation even further (using negative feedback).

\[ A_{CL} = \frac{R_2}{R_1} + 1 \]
\[ V_{out} = A_{CL} V_Z \]
\[ V_{out} = \frac{R_1 + R_2}{R_1} V_Z \]
\[ I_L = \frac{V_{out}}{R_L} \]
\[ P_D = (V_{in} - V_{out}) I_L \]

The series regulator has no short-circuit protection as the shunt regulator even it has higher efficiency, therefore some form of current limiting has to be included to protect the regulator. The resistor R4 in the figure below is a current sensing resistor in the regulator protection circuit. If the current is small such that the voltage across R4 is smaller than V_{BE}, the regulator works normally. When the load current increases such that V_{BE} is slightly greater than 0.7V, Q1 turns on, the collector current flows through R5. This decreases the base voltage to Q2, which reduces the load voltage and the load current.

When the load is shorted, Q1 conducts heavily and brings the base voltage of Q2 down to approximate 2V_{BE}, eventually reduces the output voltage delivered to the load (V_{BE}). The value of R5 has to be chosen such that it will provide the gain for CE amplifier Q1 and also provide enough current to drive Q2 under normal condition.

\[ V_{out} = \frac{R_1 + R_2}{R_1} V_Z \]
\[ I_{SL} = \frac{V_{BE}}{R_4} \]

Figure below depicts the current limiting circuit response.

Example: 24-11 (page 925)
3. Foldback current limiting

\[ V_{\text{out}} = \frac{R_1 + R_2}{R_1} V_Z \]
\[ K = \frac{R_7}{R_6 + R_7} \]
\[ I_{\text{SL}} = \frac{V_{\text{BE}}}{KR_4} \]
\[ I_{\text{max}} = I_{\text{SL}} + \frac{(1 - K)V_{\text{out}}}{KR_4} \]

IV. MONOLITHIC LINEAR REGULATORS

Positive voltage regulator: LM78XX

Negative voltage regulator: LM79XX

Example 24-12, 24-13, 24-24 (page 933)
V. DC-to-DC CONVERTERS

Sometimes, it is necessary to convert a DC voltage of one value to a DC voltage of another value. This is accomplished by using a DC-to-DC converter. DC-to-DC converters are very efficient because they switch the transistors on and off to convert voltage. Since the transistor is switching on and off, the power dissipation is greatly reduced and the converter has efficiency between 65%-85%.

VI. SWITCHING REGULATORS

A switching regulator falls into the general class of DC-to-DC converters because it converts a DC input voltage to a DC output voltage. The switching regulator includes a voltage regulation, typically pulse-width modulation controlling the on-off time of the transistor. By changing the duty cycle, a switching regulator can hold the output voltage constant under varying line or load conditions. The pass transistor is switched between cut off and saturation.

When the transistor is off, the power dissipation is zero. When the transistor is saturated, the power dissipation is still very low because $V_{CE(sat)}$ is much less than the headroom voltage of the series regulator. As the results, switching regulator can have the efficiencies from 75% to more than 95%. Many topologies of switching regulators have been developed. Depending on applications, the designer will pick the right topology for the voltage regulator, of course, the cost of the power supply is always a main factor in design.
1. **Buck regulator**

Figure below shows a buck regulator, the most basic topology for switching regulator. This regulator always step downs the voltage and the switching device, Q, can be either FET or BJT.

![Buck regulator diagram]

A comparator controls the duty cycle of the pulses and this duty cycle is controlled by the feedback voltage from the voltage divider R1 & R2. The rectangular signal out of the pulse modulator closes or opens the switch. When the pulse is high, the switch is closed. This reverse-bias the diode, so that the current flows through the inductor. This current generates a magnetic field around the inductor and the amount of stored energy in the magnetic field is given by:

\[
\text{Energy} = 0.5Li^2
\]

This current also charges the capacitor and supplies current to the load.

While the switch is closed, the inductor voltage has the polarity as shown. As the current through the inductor increases, more energy is stored in the magnetic field. When the pulse goes low, the switch is open. At this instant, the magnetic field around the inductor starts collapsing and induces a reverse voltage across the inductor. This reverse voltage is called the *inductive kick*. The diode is forward-biased and the current through the inductor continues to flow in the same direction. At this time, the inductor returns its stored energy to the circuit, it acts as a source and continues supplying current to the load.

Current flows through the inductor until the inductor returns all of its energy to the circuit (discontinuous mode) or until the switch closes again to start a new cycle (continuous mode) whichever comes first. The capacitor will also source the load current during part of the time that the switch is open. This way, the ripple across the load is minimized.
The average value of the output voltage of the *choke-input filter* is related to the duty cycle and is given by:

\[ V_{\text{out}} = D V_{\text{in}} \]

The larger the duty cycle, the larger the DC output voltage. When the power is first turned on, there is no output voltage and no feedback to the comparator, the duty cycle approaches 100% out of the modulator. As the output voltage builds up, the feedback voltage, \( V_{\text{FB}} \), reduces the comparator output voltage, which in turn reduces the duty cycle.

At some point, the output voltage reaches an equilibrium value at which the feedback voltage produces a duty cycle that gives the same output voltage. In this case, the feedback voltage \( V_{\text{FB}} = V_{\text{REF}} \) and the output voltage can be derived as:

\[ V_{\text{out}} = \frac{R_1 + R_2}{R_1} V_{\text{REF}} \]

After equilibrium sets in, any attempted change in the output voltage (by the line or by the load), will be almost entirely offset by the negative feedback. If the output tries to increase, higher feedback will reduce the modulator duty cycle to reduce the output voltage. If the output voltage decreases, lower feedback will increase duty cycle to offset the loss.

2. **Boost regulator**

The boost regulator always steps up the voltage as shown in the figure below. When the pulse is high, the switch is closed and energy is stored in the magnetic field. When the pulse goes low, the magnetic field collapses and induces a reverse voltage across the inductor. The input voltage now adds to the inductive kick. This means the peak voltage on the right end of the inductor is

\[ V_p = V_{\text{in}} + V_{\text{kick}} \]

And of course, \( V_{\text{kick}} \) is proportional to the duty cycle.

The rectangular voltage appears at the input to the *capacitor-input filter*. Therefore the regulated output voltage, \( V_{\text{out}} \), approximately equals the peak voltage given above which is always greater than \( V_{\text{in}} \).
3. **Buck-Boost regulator**

The buck-boost regulator produces a negative output voltage when driven by a positive input voltage as shown in figure below.

When the pulse goes high, the switch is closed and energy is stored in the magnetic field. At this time, the voltage across the inductor equals to $V_{in}$ in the polarity shown.

When the pulse goes low, the switch opens. Again, the magnetic field collapses and induces a kick voltage across the inductor. This kick voltage is proportional to the energy stored in the magnetic field which is depending on the duty cycle. If the duty cycle is low, the kick voltage approaches zero, if the duty cycle is high, the kick voltage can be greater than $V_{in}$, depending on how much energy stored in the field.
The diode and capacitor-input filter produces an output voltage equal to $-V_p$. Since the magnitude of this output voltage can be greater or less than the input voltage, this regulator is call buck-boost regulator.

An inverting amplifier is used in the regulator to convert the feedback voltage before it reaches the inverting input of the comparator. The voltage regulation then works as previously described. Attempted increases in output voltage reduce the duty cycle, which reduces the peak voltage. Attempted decreases in output voltage will increases the duty cycle. Either way, the negative feedback holds the output voltage almost constant.

4. Monolithic switching regulator

Switching regulators have been manufactured in monolithic form (i.e., integrated circuit). The monolithic switching regulators usually require external components which could not be integrated such as inductors or capacitors. Some regulators provide the external feedback connection in order to change the output voltage suitable for specific applications. All of the switching regulators topologies have been integrated into IC. For example the LT1074 is a buck regulator, MAX631 is a boost regulator and the LT1074 can be connected as a buck-boost regulator.

 Example 24-15 (page 946)