ELEC2216

Advanced Electronic Systems

Contents

1   Power Supplies

1.1   What *is* power?

Power is the rate of disapation of energy. You can express power in terms of voltage and current using the chain rule.

$$P = \frac{dE}{dt}, \, V = \frac{dP}{dQ}, \, I = \frac{dQ}{dt}$$

$$P = I \cdot V = \frac{dP}{dQ} \cdot \frac{dQ}{dt} = \frac{dE}{dt}$$

Losses are often expressed in terms of power. Ohmic loss is the power lost though resistance.

$$P = I^2 R$$

This means that to decrease Ohmic loss you can increase the voltage while decreasing the current. This is easy to do for AC with a transformer, but harder to achieve for DC.

1.2   Quantifying Time-dependent Voltage

- Instantaneous value
- Peak value
- Peak to peak value
- Average value
- Effective value or RMS

1.2.1   Effective Voltage and Power

$$\text{At DC: } P = IV = \frac{V^2}{R}$$
$$\text{At AC: } P_{AV} = \frac{1}{T} \int_0^T \frac{v^2(t)}{R} dt$$

V_{RMS} is a voltage that will cause the same loss in a resistance R as a DC voltage V.

$$P_{AV} = \frac{V_{RMS}^2}{R} = \frac{1}{T} \int_0^T \frac{v^2(t)}{R} dt$$
$$\downarrow$$
$$V_{RMS} = \sqrt{\frac{1}{T} \int_0^T v^2(t) dt}$$

For a generic AC voltage $V_m \sin(\omega t)$ this solves to the following.

$$\begin{aligned}
V_{RMS} &= \frac{1}{2\pi} \int_0^{2\pi} V_m^2 \sin^2(\omega t) d(\omega t) \\
&= \frac{V_m^2}{4\pi} \int_0^{2\pi} (1 - \cos(\omega t)) d(\omega t) \\
V_{RMS} &= \frac{V_m}{2}
\end{aligned}$$

1.3 Transformers

Transformers convert AC voltages. This conversion is done in the ratio of turns in each coil: the turn ratio a.

$$a = \frac{n_1}{n_2} = \frac{v_1}{v_2}$$

1.4 Rectification

Rectification is the process of converting AC $\rightarrow$ DC voltages.

1.4.1 Half Wave Rectifier

In a half wave rectifier a diode is used to remove the negative part of the signal over a load
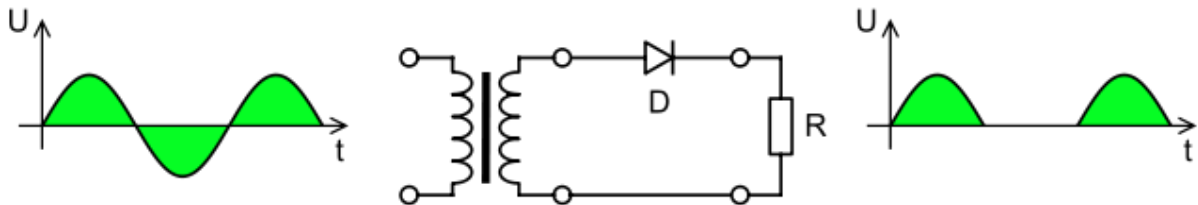

Figure 1: Circuit, input and output diagrams for a half-wave rectifier.

You can then put a capacitor across the output to smoothen the output waveform.

1.4.2 Full Wave Rectifier

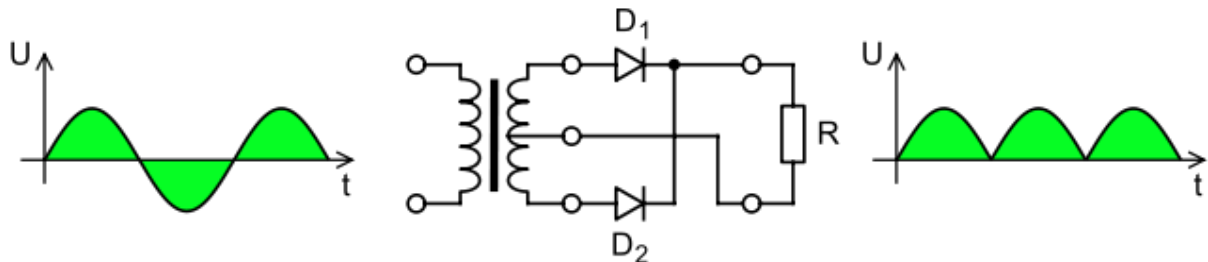Using a center tap on the transformer you can do full wave rectification.

Figure 2: Circuit, input and output diagrams for a full-wave rectifier.

1.4.3 Bridge Rectifier

A bridge rectifier doesn't require a center tap on the transformer, and has half the current though the diodes, but has twice the voltage drop though the resistors.
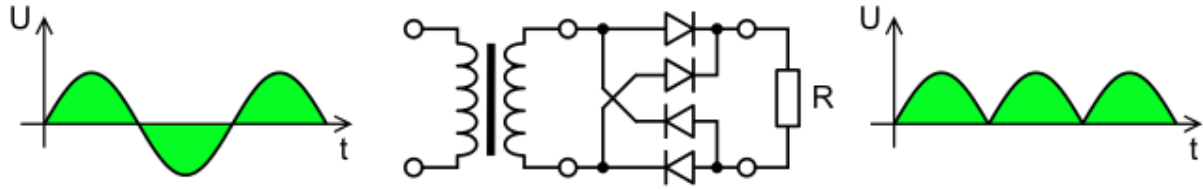

Figure 3: Circuit, input and output diagrams for a bridge rectifier.

1.5 Quantifying and Calculating Ripple Voltage

Ripple voltage is the deviation from the ideal DC voltage at the output. The voltage decay from the maximum voltage can be expressed as the following:

$$v_0(t) = v_p e^{-\frac{t}{RC}}$$

Then using the fact that for small t, $e^{-x} \approx 1 - x$:

$$v_{min} = v_p \left(1 - \frac{t}{RC} \right)$$

Then if $RC >> T$:

$$v_r \approx \frac{v_p T}{RC}$$

What capacitance is required for a less then 5% ripple in a Half Wave Rectifier over a load of 16kΩ?

$$v_r = \frac{v_p T}{RC}$$
$$\frac{v_r}{v_p} = \frac{T}{RC}$$
$$\frac{T}{RC} = 5\%$$
$$C = \frac{T}{0.05 \cdot R} = 25\mu F$$

From the above example you can see that a larger capacitance gives a smaller ripple. But large capacitors get expensive. It might be worth trying a regulator...

1.6   Regulators

- Line Regulation - keeping a constant output voltage with a varying input voltage.

- Load Regulation - keeping a constant output voltage with a varying output load.

- Ripple Rejection

1.6.1   Quantifying Power Supply Efficiency

- Quiescent Current is the current used by the supply at idle.

- Efficiency, P_{out}/P_{in}, is normally a large percentage.

1.6.2   Linear vs Switching Regulators

Table 1: Tabulated differences between Linear and Switching regulators.

Linear	Switching
Operates in linear region	Operates as a switch
Simple	Complex
Inefficient	Efficient

Additionally to the table above:

- Linear regulators are stable, resulting in a small v_r, but are step-down only.

- Switching regulators are more flexible then linear ones are they can be both boost (step-up) and buck (step-down) or boost-buck, however, they produce a lot of noise due to their switching nature.

1.7   Types of Linear Regulator

1.7.1   Series Regulator

A series regulator is (shock) placed in series with the voltage source. It has three pins, v_{in}, v_{out} and GND.
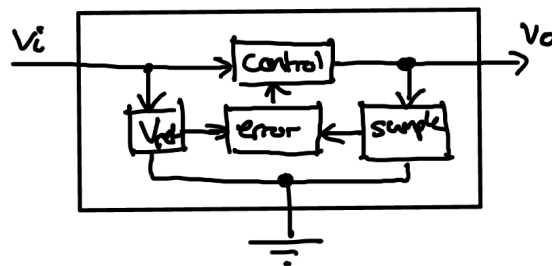

Figure 4: Block diagram for a series linear regulator.

Inside the regulator are four main components.

- v_{ref}, a voltage reference, normally a Zener diode.

- An error block, which is physically an op-amp.

- A sample stage, which is just a voltage divider.

- A Control element, physically a transistor.

1.7.2 Shunt Regulator

A shunt regulator is similar to a series regulator but is placed in parallel with the load.
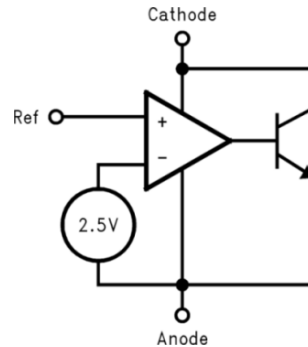

Figure 5: Schematic of TI's LM431 shunt voltage regulator.

1.8 Heat Flow in Linear Regulators

In a linear regulator dropping from 8V to 3V with a current of 1A, how much power must be dissipated in the regulator?

$$P = IV$$
$$P = 1 \cdot (8 - 5)$$
$$P = 3\text{W}$$

As shown in the above example a lot of power, and therefore heat, is generated in a linear regulator. To remove this heat from the board we use a heat sink.

The maximum temperature a silicon semiconductor will work at is roughly 150 to 200 °C.

1.9 Modeling Heat Flow

$$\Delta T = P_j \theta$$

Where:

ΔT is the temperature difference.

P_j is the power dissipated at the junction.

θ is the thermal resistance, in kelvin per watt, $\frac{K}{W}$.

Normally the heat will flow though several boundaries. This requires you to equate several thermal resistances, for example the junction to case, θ_{jc} and case to ambient, θ_{ca}.

$$T_j - T_c = \theta_{jc} P_j$$
$$T_c - T_a = \theta_{ca} P_j$$
$$\downarrow$$
$$T_j = T_a + (\theta_{jc} + \theta_{ca}) P_j$$

This can be concidered a general form, so adding a heat sink on the case would lead to the following:

$$T_j = T_a + (\theta_{jc} + \theta_{cs} + \theta_{sa}) P_j$$

For a 3W transistor with the following thermal resistances, what is the junction temperature in a 25°C room?

$$\theta_{jc} \quad \text{of 5 K/W}$$

$$\theta_{cs} \quad \text{of 2 K/W}$$

$$\theta_{sa} \quad \text{of 10 K/W}$$

$$T_j = T_a + (\theta_{jc} + \theta_{cs} + \theta_{sa}) P_j$$
$$= 25 + (5 + 2 + 10) \times 3$$
$$= 25 + 17 \times 3$$
$$T_j = 76°C$$

---

2 Modeling a BJT at DC

2.1 What *is* a BJT?

2.1.1 The PN Junction

There are two types of semiconductor: p and n. p-type semiconductors have (positive) holes as their "free current carriers" whereas n-type semiconductors have (negative) electrons as their free current carriers.

A PN junction is formed when you place two pieces of n-type and p-type semiconductor together.

This PN junction is more classically known as a diode. Therefore the PN junction follows the diode equation.

$$I_d = I_s \left(e^{(qV/kT)} - 1 \right) \approx I_s \left(e^{(qV/kT)} \right) \tag{1}$$

2.1.2 The Bipolar Junction Transistor

A BJT is formed of three sections of alternating semiconductor. NPN transistors are looked at in the course, for PNP transistors just reverse the polarity of the equations.
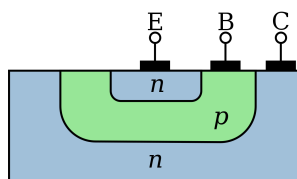

Figure 6: A realistic cross section of an NPN BJT.

BJT's have three connectors (emitter, base and collector) connected to each of the three sections of the transistor. In the connecting regions between each of the types of transistor there are depletion regions, like in the PN junction.

These depletion regions occur at the EBJ (**E**mmiter **B**ase **J**unction) and the CBJ (**C**ollector **B**ase **J**unction)
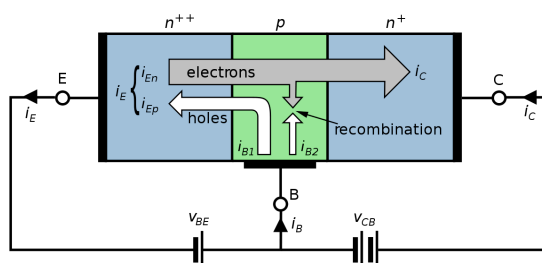
2.2 Bias Conditions

Figure 7: A biased BJT, annotated with arrows showing the direction of free current carriers in active mode.

When applying a voltage between the base and emitter (V_be) and the base and collector (V_bc) you get different characteristics.

Table 2: Characteristics of a BJT based on bias conditions.

	EBJ Bias	CBJ Bias
Cut-off	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

2.2.1 Current in a BJT for Active Mode

As shown in figure 2.2, some recombination occurs at the base. This is a proportional current loss, therefore the current in the collector can be expressed as:

$$I_C = \alpha I_E, \text{ where } \alpha < 1$$

The term α is called the common-base current gain. When you connect a load across the collector and ground you get the following output voltage:

$$v_o = RI_c = R\alpha I_E$$

Therefore, to get the largest output voltage we want to make alpha as close to 1 as possible. The amount of recombination is proportional to the number of holes (and therefore the doping level) in the base. As such, to get the maximum output voltage you must lightly dope the base.

Table 3: Notation for doping levels in a semiconductor material, all levels are relative to the other semiconductors in the system.

x^-	Lightly doped x-type semiconductor.
x^+	Heavily doped x-type semiconductor.
x^{++}	Very heavily doped x-type semiconductor.

2.3 Large Signal Equivalent

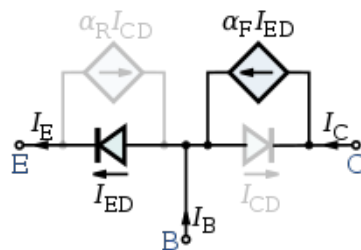For modeling a BJT at DC we use the "large signal equivalent" circuit.

Figure 8: The large signal model of a BJT, with areas not included for active mode grayed out.

So from out large signal equivalent and what we already have determined about the current characteristics at bias we can form the following equations.

$$I_E = I_s \left(e^{V_{BE}/v_T} \right)$$

$$I_C = \alpha I_E = \alpha I_s \left(e^{V_{BE}/v_T} \right)$$

$$I_B = I_E - I_C = (1 - \alpha) I_s \left(e^{V_{BE}/v_T} \right)$$

From this we can see that for high values of α ($\alpha \approx 1$) we get a very small base current I_B, giving us a larger collector current I_C.

2.4 The relationship between α and β

The current gain, β is the gain in current relating to the base and collector. It is normally on the order of 100.

$$\text{Common-base Gain, } \alpha = \frac{I_C}{I_E}$$

$$\text{Current Gain, } \beta = \frac{I_C}{I_B}$$

$$\downarrow$$

$$\alpha = \frac{\beta}{\beta + 1}, \ \beta = \frac{\alpha}{1 - \alpha}$$