Analog Electronics

This lecture briefly reviews some basic circuit theory and describes some devices other than logic ICs that are useful in digital control applications.

After this lecture you should be able to design a transistor power switch including determining minimum V_{CE} or V_{DS}, minimum base current or V_{GS}, power dissipation, and maximum heat sink thermal resistance.

Most high-power actuators operate from AC power supplies. This lecture briefly describes devices and circuits that are used to control AC power sources.

After this lecture you should be able to analyze the operation of, and draw schematics for power control circuits using SCRs, diacs and triacs.

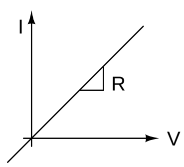
Basic Circuit Theory

- The sum of the voltages around any loop in a circuit is zero (*Kirchhoff's Voltage Law*).
- The sum of the currents into any node in a circuit is zero (*Kirchhoff's Current Law*).
- The voltage drop across a resistor is: $V = IR$, where I is the current and R is the resistance (*Ohm's Law*).
- The power dissipated in a circuit element is given by the equation $P = VI$.

Resistors

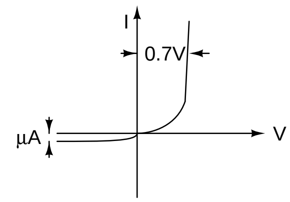
Resistors are one of the most common circuit elements. They limit current flows and provide voltage drops. The most important specification of a transistor is, of course, its resistance. Other important specifications for a resistor are power dissipation and tolerance.

The I-V characteristic of a resistor is:



Diodes

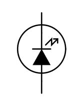
A diode is a two-terminal device that only allows a signficant amount of current to flow in one direction. When a silicon diode is forward biased the voltage across it is a maximum of about 0.7 V. The I-V characteristic of such a diode is:



LED's

Light Emitting Diodes (LED's) are devices with the same electrical characteristics as diodes, but they have the additional property that they generate light when forward-biased. They are often used for displays and can be arranged in multi-segment matrices to form numeric or (less often) alphanumeric displays. The forward-biased voltage drop is about 2 volts and typical supply currents are 2 to 10 mA. LED's can usually be driven from a 3- or 5-volt logic output if a current-limiting resistor is used.

The schematic symbol for an LED is:

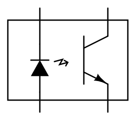


Phototransistor

A phototransistor (or photodiode) is a transistor where the collector-emitter current is controlled by the amount of light falling on a portion (the base) of the transistor. This allows the device to be controlled by a light source.

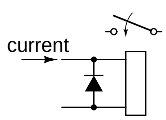
Optocouplers

An optocoupler is a device that combines an LED and a phototransistor in the same case. The LED shines on the phototransistor and turns on the phototransistor when the LED turned on. The advantage of an optocoupler is that the only coupling between the input (LED) and output stages is with light. The two stages are thus completely isolated and need not share a common reference voltage.



Relays

A relay is an electromechanical device consisting of an coil forming an electromagnet and one or more moving contacts. When current flows through the coil the magnetic force moves the contacts and closes or opens electric circuits. When the relay is driven by semiconductor devices a protection diode must be used to bypass the temporary reverse voltage pulse generated when the current is switched off.



In many power-control applications relays have been replaced by solid state devices such as transistors, optocouplers, SCRs and TRIACS (other types of solid-state control devices).

Operational Amplifiers

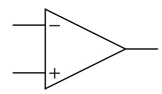
Operational amplifiers (op-amps for short) are a basic building block for many analog circuits. Op-amps are available as inexpensive integrated circuits, often with two or four amplifiers on the same chip. Op-amps are often used to interface between a digital controller and analog devices.

Properties of Ideal Op-Amps

An op-amp is a differential amplifier. That is, its output is proportional to the difference between two inputs. If the voltage at one terminal, the non-inverting input, is v_+ and the input at another input, the inverting input, is v_- then the output is equal to $v_{\text{out}} = A(v_+ - v_-)$ where A is the op-amp's gain.

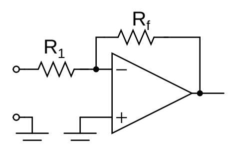
An ideal op-amp has two important properties: (1) nearly-infinite gain (A typically $> 10^5$) and (2) nearly-infinite input impedance. The consequence of the first property is that in normal operation the difference between the input pins must be very small and is usually assumed to be zero. The effect of the second property is that we can assume that there is zero current into the input terminals of the op-amp. These two properties make it easy to analyze op-amp circuits.

The symbol used in schematic diagrams for an op-amp is:



Inverting Amplifier

The following circuit is an amplifier with gain given by the ratio $-R_f/R_1$.



We can derive this result using the ideal op-amp properties. Since the sum of currents flowing into the inverting input must be zero, the currents through the two resistors must be equal and opposite. Since the difference in voltage between the input pins must be zero, the inverting pin must also be at ground level (0 V) and so we can compute these currents and from this obtain the amplifier's gain:

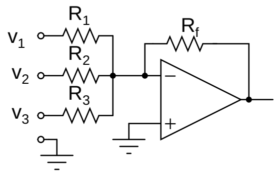
$$V_{\text{out}}/R_f = -V_{\text{in}}/R_1 \tag{1}$$

$$V_{\text{out}}/V_{\text{in}} = -R_f/R_1 \tag{2}$$

Summing Amplifier

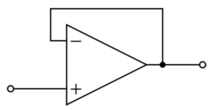
If we add additional input branches we can repeat the analysis and find that the following circuit sums up the input voltages so that

$$V_{\text{out}} = -\frac{1}{R_f}(R_1 v_1 + R_2 v_2 + R_3 v_3) \tag{3}$$



Voltage Follower

The following circuit can be used as a buffer between two parts of a circuit because it has very high input impedance (so that it doesn't load the driving circuit) and a low output impedance (so that it's output voltage doesn't vary as a function of the output current).



Practical Considerations

Op-amps must usually be supplied with both positive and negative power supplies (typically ± 12 or ± 15 volts). The output voltage must be kept several volts less than these voltages (e.g. ± 10V) for the op-amp to operate properly.

Typical op-amps can only supply very limited amounts of power (100 mW or so) although (expensive) high-power devices are available.

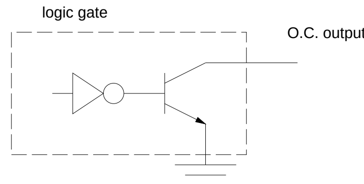
Op-amps are also limited in their frequency response (how quickly their outputs can respond to changes in the input). Typical op-amps are limited to frequencies under about 100 kHz although higher-frequency devices are also available.

Transistor Switches

In many applications it is sufficient for the controller to switch a DC output on or off. Some output devices (e.g. LED's) only require a few milliamps at low DC voltages and can be driven directly by the output of a logic gate. However, often more power is required than can be supplied by an ordinary logic gate.

Open Collector Outputs

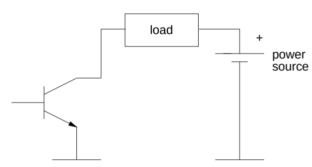
The simplest way to switch small amounts of power is to use a logic gate with an open-collector output. The outputs of these devices are the collector terminals of transistors whose emitters are connected to ground. Open collector outputs can thus "sink" an externally-supplied voltage to ground. Depending on the device and the logic family (e.g. a 74LS06), these can control up to 30 volts and sink 100–300 mA.



MOSFET and Bipolar Transistor Power Switches

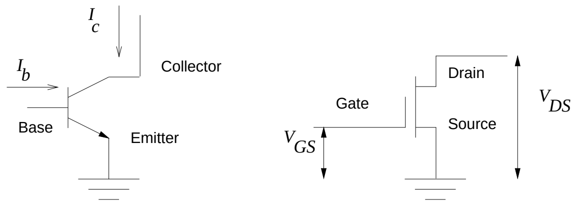
When larger currents need to be switched, a bipolar or MOSFET power-switching transistor can be used.

When used as an amplifier, a bipolar transistor is operated over a range of base currents for which the collector–emitter current is approximately proportional to the base–emitter current. When used as switches the transistors are biased so that they are either fully on or fully off. The discussions below show typical specifications for two medium-power switching transistors, a common bipolar NPN device (2N3055) and an n-channel enhancement-mode MOSFET (RFP15N06L).



Maximum Voltage

In the off state no current flows through the transistor and the full supply voltage appears across the transistor. It is necessary to ensure that this voltage does not exceed the manufacturer's rating. In the case of the 2N3055 NPN transistor the maximum collector-to-emitter voltage is 60V and for the RFP15N06L MOSFET the drain-source breakdown voltage is also 60V. MOSFET devices are available with maximum ratings of V_{DS} of several hundred volts.

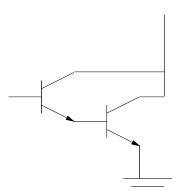


Switching the Transistor

In the on (saturated) state it is necessary to ensure that the base current (in the case of a bipolar transistor) or the gate voltage (in the case of a MOSFET) is sufficiently high to turn the transistor fully on. The manufacturer will specify the minimum current gain (50) for the NPN transistor (the ratio of collector to base current) from which the minimum base current can be computed or the gate-to-source threshold voltage (2V) that makes the MOSFET saturate.

Exercise 53: A 2N3055 is used as a switch and must control a current of 2A. What is the minimum required base current? What will happen if a lower base current is applied?

If the digital logic cannot supply sufficient current to the bipolar transistor or voltage to the MOSFET to saturate it, then additional circuitry (usually an additional transistor) will be required to drive the device. The configuration of two NPN transistors shown below is called a "Darlington pair."



Power Dissipation

When the transistor is turned on current will flow through the device and, since the transistor has a finite resistance, there will be a voltage drop and the transistor will consume some power. It is important to ensure that this power can be safely dissipated without causing the transistor to overheat and fail. The power dissipation will be the product of the current through the transistor and the voltage drop across it.

For an NPN transistor the manufacturer specifies the collector-to-emitter voltage when the transistor is fully on (0.4V) as well as a maximum collector current (10A). For a MOSFET the manufacturer specifies the drain-to-source resistance (0.14 Ω) and a maximum drain current (15A).

Exercise 54: A bipolar transistor with a maximum V_{BE} of 0.2 volts switches a current of 10 A. What is the power dissipated in the transistor when it is on? When it is off? If a MOSFET with an $R_{DS_{ON}}$ of 0.05 Ω is controlling a current of 5 A, What is the power dissipated in the transistor when it is on? When it is off?

The manufacturer also specifies a maximum junction temperature (200 C) and a maximum power dissipation (about 100W and about 30W for the two devices).

The junction temperature can be computed using the formula:

$$T_J = T_A + (\theta_{JC} + \theta_{CS} + \theta_{SA})P \qquad (4)$$

where T_J is the junction temperature, T_A is the ambient (air) temperature, θ_{JC} is the junction-to-case thermal resistance (in degrees/Watt) as given by the transistor manufacturer, θ_{CS} is the case-to-heatsink thermal resistance (depends on mounting method) and θ_{SA} is the heatsink-to-air thermal resistance as given by the heat sink manufacturer.

T_JC is on the order of 1 or 2 degrees per watt, T_SA ranges from 100 for simple clip-on heat sinks to less than 1 for large multi-fin models. T_CS is usually negligible.

Exercise 55: A transistor switch must dissipate 40 W. The maximum junction temperature is 200C. The transistor package has a thermal resistance of 1 degrees/W. The switch must operate over the temperature range of -40 to +40 C. How should you specify the heat sink?

Pulse Width Modulation

In some cases the controller must supply an actuator with a variable voltage. This can be done efficient by switching the output on and off at a high frequency (say, 50 kHz) and varying the duty cycle (the fraction of time that the voltage is on). For example, if the supply voltage was 12 volts and the output voltage had a 25% duty cycle the average output voltage would be 3 volts. The duty cycle can be varied by changing the pulse width if the frequency is constant (PWM) or by changing the frequency if the pulse width is constant.

Some loads (such as incandescent lighting or resistive heaters) can tolerate a time-varying supply voltage. But often it is necessary to smooth out (filter) the supplied voltage by using inductors and/or capacitors to store energy during 'on' period and release it during the 'off' period.

A microcomputer-based controller can implement a PWM analog output with a minimum of additional hardware since the only requirement is a standard binary (on/off) output.

Pulse width modulation is also relatively efficient. Since the switching devices are either fully off (no current) or on (no voltage drop), little power is consumed by this type of control device.

The are some disadvantages to using PWM. One is that the output signal will contain a "ripple" component at the switching frequency. Another is the additional complexity of the software that must control the PWM output signal's frequency and duty cycle.

AC Control Electronics

We have seen how bipolar transistors and MOSFETs can be used to control actuators that operate on DC voltages. Other devices, SCRs and Triacs, are used to control actuators (e.g. motors) that operate on AC power and to convert AC to DC for high-power applications.

SCRs

Control of high-power AC equipment is typically done using devices called silicon controlled rectifiers (SCRs). The SCR is the most common of a class of devices called *thyristors*.

An SCR is similar to a diode in that it conducts current only in one direction (anode to cathode). However, the SCR has an additional gate terminal. Like a bipolar transistor, a small current must flow from the gate to the cathode for the SCR to conduct ("fire"). However, unlike a transistor, the SCR will continue to conduct as long as there is current in the anode-cathode circuit even if the gate current is removed. The SCR will "turn off" when the current in the anode-cathode circuit drops below a minimum value.

Some typical SCR specifications are the maximum on- and off-state voltages and currents, minimum turn-on and turn-off gate current and turn-on time. SCRs are available in ratings up to several thousand volts and amps.

Although SCRs are typically used with AC voltages, they can also be used to control DC supplies because they are cheaper and more efficient than transistors. In this case the SCR can be turned off by using a switch to short across ("commutate") the SCR.

Half- and Full-Wave Rectifiers

Rectifier circuits uses diodes to convert AC into time-varying DC. A half-wave rectifier conducts only during half of the cycle, while a full-wave rectifier conducts during the whole cycle. If a center-tapped transformer is available two diodes are sufficient, otherwise four diodes are required.

SCR for Voltage Control

Instead of using diodes in the above circuit, we can use SCRs. By varying the fraction of time into the cycle before the SCR is turned on, we can vary the fraction of the AC cycle which appears on the output. This in turn affects the average value of the output. For many types of devices (e.g. lights, heating elements, some types of motors) a time-varying DC waveform is sufficient. For other applications the DC will have to be filtered.

In this case the SCRs will turn off by themselves when the gate current is turned off and the AC voltage reaches zero (twice per cycle).

Triacs

A *triac* is a device that behaves like two SCRs connected in parallel anode-to-cathode with one common gate. This arrangement allows current flow in both directions through the same device. By controlling the point in the waveform when the triac is turned on, it can also be used to control the average power delivered to the load.

A triac is often used with another device called a *diac* which conducts current (in either direction) when the voltage across it exceeds a certain threshold. By using an RC circuit to vary the phase of the voltage applied to the diac, it is possible to control the turn-on time of the triac within the cycle. This is how common light dimmers work.

Solid state Relays

A "solid-state relay" is a circuit that has the same purpose as a magnetically-operated relay. It allows a low-power circuit to turn a high-power circuit on and off.

The relay isolates the control circuit (usually low-voltage electronics) from the controlled circuit (usually high-voltage power devices) and prevents voltages from being transferred to the control circuits and causing damage.

The solid-state relay works similarly to the optoisolator that was described earlier. The control side uses an LED to turn a light-operated SCR or transistor (for DC) or triac (for AC) on and off. These solid-state relays are available as encapsulated modules with guaranteed minimum isolation between the input and controlled terminals.

Transistor Switching for Generating AC

By using transistors to switch a DC supply on and off it is possible to create a square wave. If this square wave drives a current through the primary of a transformer then we can obtain a higher (or lower) AC voltage at the secondary by using a transformer with an appropriate turns ratio. This is how "power inverters" are used to drive AC-powered devices from batteries.

We can also control the frequency of the AC waveform thus control the speeds of certain types of ("synchronous") AC motors.

3-phase circuits

While low-power loads (less than about 15 A at 120 VAC=1800kVA) can use the types of single-phase power control circuits described above, most high-power (e.g. more than 25 A at 240 VAC = 6 kVA) AC devices operate on 3-phase power. The principles and components required are the same but the control electronics must switch three phases instead of one.