Line regulation is the relationship between a change in the input (line) voltage and the output voltage and is expressed in either percentage or absolute magnitude terms. It is not uncommon to find regulators with line regulation on the order of 0.01 percent. Such a regulator would exhibit an output swing of only 0.01 percent over the full range of the specified input voltage.

Load regulation is the relationship between a change in the load current and the output voltage and is also expressed as either a percentage or a magnitude. Regulators are available with load regulation on the order of 0.1 percent. This means that, over the full range of specified output current, the output voltage will not change by more than 0.1 percent.

Line and load regulation are not the only parameters affecting the DC output level of the regulator. These parameters characterize the voltage control element and feedback amplifier in the regulator. The operation of these components is only as good as the quality of the voltage reference and the applied feedback voltage. High-quality DC power supplies can deliver 1 percent DC accuracy, meaning that the reference and feedback resistor network have a combined tolerance better than 1 percent. A 3.3-V, 1 percent supply guarantees an output range from 3.267 to 3.333 V. Most digital systems use 5 percent supplies, because such accuracy is typically easy to achieve, and most commercial logic ICs are specified with V_{CC}/V_{DD} tolerances of no more than 5 percent. This is where the common 4.75- to 5.25-V operating range comes from when dealing with 5-V logic. Some logic ICs are specified with V_{CC}/V_{DD} tolerances of 10 percent, although fewer ICs are found with such loose ratings these days because of the ease with which 5 percent supplies are implemented. It is easier for a semiconductor manufacturer or an analog circuit designer to build a system with a tighter supply voltage requirement, because the components do not have to operate over a wider range of conditions. Specifying all ICs with 1 percent requirements would make the vendors' jobs easier, but it would also result in more expense and complexity at the system level. Five percent is a good compromise at the current state of technology.

Finally, ripple rejection is the ability of a regulator to block incoming ripple from feeding through to the output. It is the ratio of the input ripple magnitude to the output ripple magnitude and is usually expressed in decibels, because it is a large number for any effective regulator. Ripple rejection specifications of 50 to 80 dB are common. These specifications are often measured at 120 Hz, because this is the ripple frequency resulting from a rectified 60 Hz AC input in North America and other parts of the world. Ripple rejection gets worse with increasing frequency, making a 120 Hz specification worst case when compared to the 100-Hz ripple that would be observed from a rectified 50-Hz AC input in Europe or Asia.

17.2 THERMAL ANALYSIS

Before heading straight into a discussion of voltage regulation techniques, it is appropriate to briefly introduce thermal analysis in the context of electronic components. Some energy will be dissipated as heat during the process of converting an input voltage to an output voltage, regardless of the type of regulator. All or most of the power in a typical system passes through voltage regulators, making them a concentrated point of heating. Without performing a basic thermal analysis, a power regulation component may be inadequately sized and cooled and could fail in a potentially dangerous manner. Melting circuits, fires, and even small explosions can result from poorly designed regulators. A given component, for example, can be designed to safely dissipate 10 W without heating excessively, but a similar component could fail while dissipating only 1 W if proper thermal design practices are not followed.

Power regulation and thermal analysis are topics so intertwined that one cannot separate them and be assured of a reliable and safe system. The best, most efficient regulator is worthless if it is operated in a manner that causes it to overheat and fail.

Four characteristics apply to basic thermal analysis: power dissipation, maximum device operating temperature, thermal resistance to ambient air, and the ambient air temperature. First, the amount of power dissipated by a device must be determined through circuit analysis. Second, each component is rated at a maximum safe operating temperature. This is the temperature of the device itself, not of the surrounding environment. Resistors have ratings up to 100°C, 200°C, and higher. Capacitors typically have specified operating temperatures below 100°C. Semiconductors have ratings according to their intended function. Diodes can be rated as high as 200°C, while many logic ICs have ratings under 100°C. When dealing with semiconductors, the internal operating temperature is referred to as *junction temperature*, the temperature of the silicon itself.

Thermal resistance to ambient air is an important parameter. It defines the ease with which heat is conducted away from the component and out to the ambient environment. A higher thermal resistance results in more heat buildup. Thermal resistance is designated by either "R" or the Greek letter theta, θ, and is related to power and heat using an analog of Ohm's law: $\Delta T = \theta P$. θ is expressed in units of °C/W. In other words, a rise in temperature results from a quantity of power multiplied by the thermal resistance through which the power is flowing. If a component is provided with a highly conductive thermal path to the ambient environment, its θ is low and, consequently, its temperature rise is low for a given power level.

In the semiconductor context, two thermal specifications are common: θ_{JC} and θ_{JA}, the thermal resistance of junction-to-case and junction-to-ambient, respectively. Semiconductors are often specified with at least one of these parameters, and sometimes both. If neither parameter is specified, the manufacturer will specify a maximum power dissipation at a particular ambient temperature along with derating information for each degree rise over the specified temperature. θ_{JA} is specified when the component is intended to be used free of any heat sink. Therefore, the component has a certain natural thermal resistance from the silicon to the surrounding air. θ_{JC} is specified when the component may be used with a heat sink, because a heat sink effectively becomes part of the package, or case, and enables an overall θ_{JA} calculation.

Finally, the ambient air temperature establishes a starting temperature for the thermal analysis. If the maximum ambient air temperature is 40°C, a component will definitely not run any cooler than 40°C. The higher the ambient temperature, the less headroom there is for heating before a component reaches its maximum operating temperature.

Thermal analysis for passive components and semiconductors is theoretically the same, but the former is usually less of a concern in practice. In a digital system, the passive components that tend to dissipate substantial power are resistors and chokes. Resistors and chokes are available in a wide range of packages and materials, depending on the intended application. They can be found with ratings of milliwatts or hundreds of watts. Resistors and chokes also have fairly wide operating temperatures. In most cases, therefore, the thermal analysis of a resistor consists of first determining the power that it will dissipate and then picking a device that is rated for some multiple of that calculated value. A common rule of thumb is two to three times the calculated power dissipation. One can be more conservative if desired.

Semiconductors are a different story, because their operating temperature ranges are lower, and they are small parts that can handle large quantities of power. As such, the power density of a semiconductor can be very high. Lots of power and high thermal resistance resulting from small physical dimensions can cause lots of trouble very quickly.

The thermal analysis of a semiconductor begins by establishing the maximum operating conditions: power dissipation, P_D, and ambient temperature, T_A. This allows an initial calculation of the junction temperature: $T_J = T_A + \theta_{JA} P_D$. If this initial result is less than the component's rated operating temperature, the analysis shows no problem. It is important to be realistic about the maximum T_A and P_D. A device that barely functions on a cool day may fail dramatically on a hot day when T_A and, consequently, T_J are higher.