SECTION 3
SWITCHING REGULATORS

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INTRODUCTION

Virtually all of today's electronic systems require some form of power conversion. The trend toward lower power, portable equipment has driven the technology and the requirement for converting power efficiently. Switchmode power converters, often referred to simply as "switchers", offer a versatile way of achieving this goal. Modern IC switching regulators are small, flexible, and allow either step-up (boost) or step-down (buck) operation.

When switcher functions are integrated and include a switch which is part of the basic power converter topology, these ICs are called “switching regulators”. When no switches are included in the IC, but the signal for driving an external switch is provided, it is called a “switching regulator controller”. Sometimes - usually for higher power levels - the control is not entirely integrated, but other functions to enhance the flexibility of the IC are included instead. In this case the device might be called a “controller” of sorts - perhaps a “feedback controller” if it just generates the feedback signal to the switch modulator. It is important to know what you are getting in your controller, and to know if your switching regulator is really a regulator or is it just the controller function.

Also, like switchmode power conversion, linear power conversion and charge pump technology offer both regulators and controllers. So within the field of power conversion, the terms “regulator” and “controller” can have wide meaning.

The most basic switcher topologies require only one transistor which is essentially used as a switch, one diode, one inductor, a capacitor across the output, and for practical but not fundamental reasons, another one across the input. A practical converter, however, requires several additional elements, such as a voltage reference, error amplifier, comparator, oscillator, and switch driver, and may also include optional features like current limiting and shutdown capability. Depending on the power level, modern IC switching regulators may integrate the entire converter except for the main magnetic element(s) (usually a single inductor) and the input/output capacitors. Often, a diode, the one which is an essential element of basic switcher topologies, cannot be integrated either. In any case, the complete power conversion for a switcher cannot be as integrated as a linear regulator, for example. The requirement of a magnetic element means that system designers are not inclined to think of switching regulators as simply “drop in” solutions. This presents the challenge to switching regulator manufacturers to provide careful design guidelines, commonly-used application circuits, and plenty of design assistance and product support. As the power levels increase, ICs tend to grow in complexity because it becomes more critical to optimize the control flexibility and precision. Also, since the switches begin to dominate the size of the die, it becomes more cost effective to remove them and integrate only the controller.

SWITCHING REGULATORS

The primary limitations of switching regulators as compared to linear regulators are their output noise, EMI/RFI emissions, and the proper selection of external support components. Although switching regulators do not necessarily require transformers, they do use inductors, and magnetic theory is not generally well understood. However, manufacturers of switching regulators generally offer applications support in this area by offering complete data sheets with recommended parts lists for the external inductor as well as capacitors and switching elements.

One unique advantage of switching regulators lies in their ability to convert a given supply voltage with a known voltage range to virtually any given desired output voltage, with no “first order” limitations on efficiency. This is true regardless of whether the output voltage is higher or lower than the input voltage - the same or the opposite polarity. Consider the basic components of a switcher, as stated above. The inductor and capacitor are, ideally, reactive elements which dissipate no power. The transistor is effectively, ideally, a switch in that it is either “on”, thus having no voltage dropped across it while current flows through it, or “off”, thus having no current flowing through it while there is voltage across it. Since either voltage or current are always zero, the power dissipation is zero, thus, ideally, the switch dissipates no power. Finally, there is the diode, which has a finite voltage drop while current flows through it, and thus dissipates *some* power. But even that can be substituted with a synchronized switch, called a “synchronous rectifier”, so that it ideally dissipates no power either.

Switchers also offer the advantage that, since they inherently require a magnetic element, it is often a simple matter to “tap” an extra winding onto that element and, often with just a diode and capacitor, generate a reasonably well regulated additional output. If more outputs are needed, more such taps can be used. Since the tap winding requires no electrical connection, it can be isolated from other circuitry, or made to “float” atop other voltages.

Of course, nothing is ideal, and everything has a price. Inductors have resistance, and their magnetic cores are not ideal either, so they dissipate power. Capacitors have resistance, and as current flows in and out of them, they dissipate power, too. Transistors, bipolar or field-effect, are not ideal switches, and have a voltage drop when they are turned on, plus they cannot be switched instantly, and thus dissipate power while they are turning on or off.

As we shall soon see, switchers create ripple currents in their input and output capacitors. Those ripple currents create voltage ripple and noise on the converter's input and output due to the resistance, inductance, and finite capacitance of the capacitors used. That is the *conducted* part of the noise. Then there are often ringing voltages in the converter, parasitic inductances in components and PCB traces, and an inductor which creates a magnetic field which it cannot perfectly contain within its core - all contributors to *radiated* noise. Noise is an inherent by-product of a switcher and must be controlled by proper component selection, PCB layout, and, if that is not sufficient, additional input or output filtering or shielding.

INTEGRATED CIRCUIT SWITCHING REGULATORS

- **Advantages:**
  - **High Efficiency**
  - **Small**
  - **Flexible - Step-Up (Boost), Step-Down (Buck), etc.**

- **Disadvantages**
  - **Noisy (EMI, RFI, Peak-to-Peak Ripple)**
  - **Require External Components (L's, C's)**
  - **Designs Can Be Tricky**
  - **Higher Total Cost Than Linear Regulators**

- **"Regulators" vs. "Controllers"**

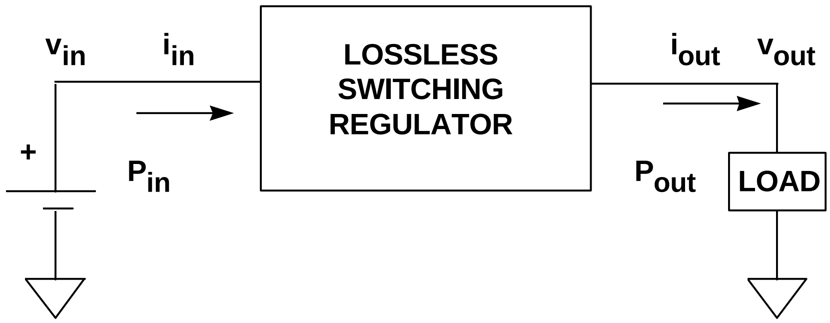
Figure 3.1

Though switchers can be designed to accommodate a range of input/output conditions, it is generally more costly in non-isolated systems to accommodate a requirement for both voltage step-up and step-down. So generally it is preferable to limit the input/output ranges such that one or the other case can exist, but not both, and then a simpler converter design can be chosen.

The concerns of minimizing power dissipation and noise as well as the design complexity and power converter versatility set forth the limitations and challenges for designing switchers, whether with regulators or controllers.

The ideal switching regulator shown in Figure 3.2 performs a voltage conversion and input/output energy transfer without loss of power by the use of purely reactive components. Although an actual switching regulator does have internal losses, efficiencies can be quite high, generally greater than 80 to 90%. Conservation of energy applies, so the input power equals the output power. This says that in step-down (buck) designs, the input current is lower than the output current. On the other hand, in step-up (boost) designs, the input current is greater than the output current. Input currents can therefore be quite high in boost applications, and this should be kept in mind, especially when generating high output voltages from batteries.

THE IDEAL SWITCHING REGULATOR



- $P_{in} = P_{out}$
- Efficiency = P_{out} / P_{in} = 100%
- $v_{in} \bullet i_{in} = v_{out} \bullet i_{out}$
- $\frac{v_{out}}{v_{in}} = \frac{i_{in}}{i_{out}}$
- **Energy Must be Conserved!**

Figure 3.2

Design engineers unfamiliar with IC switching regulators are sometimes confused by what exactly these devices can do for them. Figure 3.3 summarizes what to expect from a typical IC switching regulator. It should be emphasized that these are typical specifications, and can vary widely, but serve to illustrate some general characteristics.

Input voltages may range from 0.8 to beyond 30V, depending on the breakdown voltage of the IC process. Most regulators are available in several output voltage options, 12V, 5V, 3.3V, and 3V are the most common, and some regulators allow the output voltage to be set using external resistors. Output current varies widely, but regulators with internal switches have inherent current handling limitations that controllers (with external switches) do not. Output line and load regulation is typically about 50mV. The output ripple voltage is highly dependent upon the external output capacitor, but with care, can be limited to between 20mV and 100mV peak-to-peak. This ripple is at the switching frequency, which can range from 20kHz to 1MHz. There are also high frequency components in the output current of a switching regulator, but these can be minimized with proper external filtering, layout, and grounding. Efficiency can also vary widely, with up to 95% sometimes being achievable.

WHAT TO EXPECT FROM A SWITCHING REGULATOR IC

- **Input Voltage Range: 0.8V to 30V**
- **Output Voltage:**
  - **"Standard": 12V, 5V, 3.3V, 3V**
  - **"Specialized": VID Programmable for Microprocessors**
  - **(Some are Adjustable)**
- **Output Current**
  - **Up to 1.5A, Using Internal Switches of a Regulator**
  - **No Inherent Limitations Using External Switches with a Controller**
- **Output Line / Load Regulation: 50mV, typical**
- **Output Voltage Ripple (peak-peak) :**
  20mV - 100mV @ Switching Frequency
- **Switching Frequency: 20kHz - 1MHz**
- **Efficiency: Up to 95%**

Figure 3.3

POPULAR APPLICATIONS OF SWITCHING REGULATORS

For equipment which is powered by an AC source, the conversion from AC to DC is generally accomplished with a switcher, except for low-power applications where size and efficiency concerns are outweighed by cost. Then the power conversion may be done with just an AC transformer, some diodes, a capacitor, and a linear regulator. The size issue quickly brings switchers back into the picture as the preferable conversion method as power levels rise up to 10 watts and beyond. Off-line power conversion is heavily dominated by switchers in most modern electronic equipment.

Many modern high-power off-line power supply systems use the distributed approach by employing a switcher to generate an intermediate DC voltage which is then distributed to any number of DC/DC converters which can be located near to their respective loads (see Figure 3.4). Although there is the obvious redundancy of converting the power twice, distribution offers some advantages. Since such systems require isolation from the line voltage, only the first converter requires the isolation; all cascaded converters need not be isolated, or at least not to the degree of isolation that the first converter requires. The intermediate DC voltage is usually regulated to less than 60 volts in order to minimize the isolation requirement for the cascaded converters. Its regulation is not critical since it is not a direct output. Since it is typically higher than any of the switching regulator output voltages, the distribution current is substantially less than the sum of the output currents, thereby reducing I^2R losses in the system power distribution wiring. This also allows the use of a smaller energy storage capacitor on the intermediate DC supply output. (Recall that the energy stored in a capacitor is $½CV^2$).

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