Linear Series Voltage Regulator

Introduction
For most electronic equipment a DC power supply is generally preferred since, except for a start-up transient, the supply ideally does not introduce any fiduciary timing dependence. However by and large electrical power is generated and distributed with a sinusoidal waveform. Thus a power supply typically begins with a rectifier to convert a sinusoidal input, e.g. 60 Hz for most U.S. consumer electronics, to a rectified waveform. The supply is almost always a voltage supply as a practical matter; it is generally easier and less lossy to maintain a voltage supply rather than a current supply in a standby condition, and to operate it under varying load.

The unidirectional but varying rectified waveform is filtered in various ways to reduce the variation (the 'ripple' voltage) to an acceptable level. Nevertheless for many purposes even the filtered supply voltage ripple variation often is unacceptably large, particularly within practical filtering limitations. Power line variations, for example, are passed on to the rectified output. Moreover the Thevenin equivalent circuit for the rectified and filtered power supply often involves a substantial 'internal' resistance, so that the terminal voltage of the supply varies with the amount of current drawn because of the voltage drop across this internal resistance. A 'voltage regulator' inserts additional electronics between the rectifier terminals and the load primarily to reduce this terminal voltage variation, but also to provide other associated benefits.

Voltage rectification and filtering is discussed elsewhere. The objective of this note is to provide an introduction to voltage regulator operation. The presentation will favor discrete element regulators for illustration, although in fact it is only infrequently that a monolithic integrated circuit regulator would not be preferable on both technical and economic grounds. It is simply pedagogical purpose that favors the discrete illustration. A regulator involves several subcircuits performing separate functions, which are coordinated to realize an overall purpose. Monolithic regulators are a sophisticated derivative of the discrete circuit concepts, and do not differ markedly either in fundamental principle or basic circuit concepts from their discrete counterparts. It is the system aspect that makes the discrete voltage regulator of special instructional interest in the context of an associated introductory design project.

There are broadly two types of electronic voltage regulator circuits, linear voltage regulators and 'switching' regulators. The distinction between different types of regulators lies basically in details of the means used to correct for unregulated voltage fluctuations. While the distinction is not terribly involved, it is nevertheless conveniently left until 'switching' regulators are considered in a separate note. In this note only the linear regulator is considered.

Linear voltage regulators are divided further into 'shunt' and 'series' regulators; the distinction here is whether the regulator component that makes the needed corrections is placed in parallel or in series with the load. The emphasis here is a series regulator, although an abbreviated illustration of shunt regulation is presented.

Zener Diode Shunt Regulator
Perhaps the simplest voltage regulator circuit is suggested by that drawn to the right. VS and RS represent the Thevenin equivalent of an unregulated power supply, feeding a load RL. To maintain the load voltage constant a battery (idealized) is placed across the load. The current supplied through VS is \((VS-VB)/(RS+RB)\), and is designed to be greater than the maximum value of the load current \(VL/RL\) over the rated range of operation. The terminal voltage of the extended supply is fixed by the properties of the (here idealized) battery. 'Load regulation', i.e. changes in load current as RL varies, is provided by division of the supply current between the battery and the load. 'Line regulation', i.e. changes in input voltage is accommodated by an increased voltage drop across RB. This circuit is an example of a shunt regulator; the circuit element making the regulation adjustment shunts the load.

One might well ask why the battery alone could not used as the regulated supply, since it is reasonably well regulated at least under light load. Indeed this is what is done in appropriate circumstances, e.g. for an electric watch or a small radio. However the shunt regulator configuration becomes more generally
applicable if the battery is replaced by a Zener diode operated in the reverse-breakdown region. For operation in that range the diode characteristic is approximated (PWL approximation) by a battery (Zener voltage) in series with a small resistance (Zener resistance). To the extent that resistance is small the circuit behavior approximates that of the battery regulator circuit.

A Zener shunt regulator circuit is drawn to the right; as before VS and RS represent the Thevenin equivalent circuit for an unregulated power supply. Provided that the circuit conditions are such that the Zener diode operates in its breakdown region the voltage across the load resistance RL is substantially constant. This requires a diode reverse-bias (load) voltage greater than the Zener breakdown 'knee' voltage, corresponding to a minimum diode current requirement. And also important of course, the Zener current must remain less than the maximum current rating of the diode.

The unregulated voltage must be sufficiently greater than the (substantially constant) regulated voltage to assure proper diode operation. The difference voltage appears across the series combination of RS and RB) so that for a given value of RS+RB the maximum load current required plus the minimum 'keep alive' Zener current must be provided. The current supplied by the unregulated supply then divides between the diode and the load. The regulating action occurs because the Zener voltage remains substantially constant over a range of diode current, i.e., it provides a battery-like operation. When the load resistance is small, thus drawing a relatively higher load current the diode current is correspondingly smaller. Conversely when the load resistance is large, and so draws a relatively small current, the diode current is larger.

The effectiveness of this shunt regulator depends on and is limited by the (nearly) constant voltage Zener diode characteristic. It is simple, inexpensive, reliable, and useful generally in non-critical applications.

**Examples (from problem set)**

1) The Thevenin equivalent of a particular unregulated power supply is a voltage source VS, where 10v ≤ VS ≤ 12volts, and an internal resistance RS = 50Ω. Design a Zener diode shunt regulator (see circuit diagram) to provide a regulated 5 volt (nominal) output for 1KΩ ≤ RL ≤ 2.5KΩ Use a 1N5231 Zener diode with a Zener voltage of 5.1 volts @ 20 ma, and nominal 10Ω Zener resistance over the load current range.

**Answer**  
Assuming regulation is active the load current will vary between 5.1/1=5.1ma, and 5.1/2.5=2.04ma. Estimate a minimum 'keep-alive' Zener current of 20/10 = 2ma. This is the minimum current when the load current is a maximum. i.e., the source current must be at least 7.1ma. Similarly the maximum Zener current is 20 ma, and this occurs for minimum load current. Hence the maximum supply current can be no more than 22 ma.

The 'worst case' condition for the minimum source current occurs with VS= 10v, and is (10-5.1)/(RS+RB)≥ 7.1ma. The 'worst case' condition for the maximum source current occurs with VS= 12v, and is (12-5.1)/(RS+RB)≤ 22ma. These inequalities require 313.6Ω≤RS+RB ≤ 690Ω, and the specification of RS=50Ω then requires 263.4 ≤ RB ≤ 640. A nominal trial value of 470Ω was selected.

A netlist for and a plot of a PSpice computation follows. Model parameters for the 1N5231 Zener diode are noted for reference). Note the voltage scale of the plot.

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MODEL D1N5231
D(Is=1.004f Rs=.5875
  + Ikl=0 N=1 Xti=3 Eg=1.11 Cjo=160p
  + M=.5484 Vj=.75 Fc=.5 Isr=1.8n Nr=2
  + Bv=5.1 Ibv=27.721m Nbv=1.1779
  + Ibvl=1.1646m Nbvl=21.894 Tbv1=176.47u)
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2) In problem 1 the regulating action of your design assumes the Zener diode operates in the breakdown region. For a large enough load current the diode current is insufficient to maintain breakdown. Estimate this dropout current for your design, and compare with a PSPICE analysis.

**Answer**  The design makes RS+RB = 520Ω. Suppose VS = 12v. Then the source current while the diode is in breakdown is $\approx \frac{(12-5.1)}{0.52} = 13.27$ ma. Therefore when the load current is (approximately) 13 ma the Zener diode will be starved for current.

Similarly anticipate dropout for VS = 10v at about 9ma.
3) Add a sinusoidal voltage source in series with VS (1.5 volt amplitude, 120Hz) to simulate a substantial rectifier ripple voltage. Estimate the ripple across the load assuming a nominal $10\Omega$ Zener resistance and a $1\, \text{K}\Omega$ load resistance. Use PSPICE to obtain the load voltage transient response and compare to your estimate.

**Answer** Approximate the Zener diode (in breakdown) as a $10\Omega$ resistor in series with a 5.1V source. Apply superposition to relate the sinusoidal part of the output voltage to the sinusoidal input voltage:

$$\text{Output 'ripple'} \approx 1.5 \frac{10||1000}{520+10||1000}$$

$$= 28 \text{ mV peak}$$