Linear Series Voltage Regulator NOTES

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.

Feedback Shunt Regulator
The Zener regulator is an 'open loop' system, i.e., the current distribution adjustment is inherent in the diode breakdown properties. A different view of the regulator pictures it as a feedback control system, i.e. sampling of the load voltage, comparison of this sample to a reference voltage as a measure of variance from the desired load voltage, and use of this difference signal to implement an appropriate correction. The block diagram to the right presents this approach.

Shunt regulator circuits generally are not as efficient as the series type discussed later, and with the availability of inexpensive monolithic series regulators are not much used. However to provide a certain degree of completeness the simplified shunt-control regulator circuit, drawn below, is used as an illustration.

The illustration uses bipolar transistors as the shunt-regulating element. Q1 actually carries most of the shunt current; Q2 is an emitter follower added to reduce the influence of drawing base current from the voltage sampling resistors. The reference voltage in this simplified circuit is provided by the sum of the almost constant emitter-junction voltage drops. See the netlist below for specific illustrative element values used.

RB1 and RB2 form a voltage divider (neglecting the Q2 base current for simplicity) to provide a sample of the output voltage. Because large changes in the transistor current (primarily Q1 current) involve only small emitter junction voltage changes the load voltage is maintained substantially constant at $2V_{BE}/k \approx 1.4/k$. If the load...
voltage increases for example, say because of a load current increase, the Q2 base voltage increases and causes an increase in transistor current, i.e. a reaction mitigating the load current increase.

The illustrative regulator (netlist to the right) is designed for a load voltage of \((1.4)(3.3) = 4.6\) volts from a 10 volt unregulated source. The voltage drop across RS then is \(10 - 4.6 = 5.4\) volts, and with \(RS = 100\, \Omega\) the supply current is 54 ma. This provides an upper limit on the regulated load current, since this fixed total current divides between the load and the transistors.

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*Shunt Regulator
VS 1 0 DC 10
RS 1 2 100
Q2 2 3 4 Q2N3904
Q1 2 4 0 Q2N3904
RB1 2 3 22K
RB2 3 0 10K
IL 2 0 DC 1
.DC IL 0 50m .1m
.LIB EVAL.LIB
.PROBE
.OP
.END
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Absent the regulation a 50 ma current change through the 100\,\Omega source resistance would result in a 5-volt line voltage change. As the following plot indicates the regulated change is an order of magnitude smaller.

In the following figure the current into the shunt regulating transistors (sum of the collector currents) is compared to the supply current, as the load current varies. The supply current is (approximately) constant reflecting the load voltage regulation. The transistor current decreases to provide an increased load current.

Finally the next figure shows the line regulation, i.e., the effect of supply voltage changes for a fixed load resistance \(RL = RS = 100\,\Omega\).
The regulated voltage is designed to be 4.6 volts with $V_S = 10$ volts. The load resistance is $100\,\Omega$. A significant part of the small load voltage change is associated with the transistor Early Effect.

'Series Pass' Regulator

For a shunt regulator a (more or less) fixed supply current is provided, and the load current is regulated by adjusting how much of this current is diverted from the load by the shunt-regulating element. A series regulator places the regulating element in series with the load, and it is the voltage across the regulating element that isvaried to adjust the load voltage.

A simplified 'series' voltage regulator circuit is illustrated in the figure to the left. Basically the circuit configuration is that of a BJT emitter-follower, and circuit operation is interpreted conveniently as such at first. The unregulated supply provides the BJT collector voltage, and the battery, which provides the reference voltage against which variation from a desired load voltage is measured, biases the BJT base.

The emitter voltage differs from the base voltage by the base-emitter junction voltage drop, and this is substantially constant, i.e. very small changes in junction voltage allow for large emitter current changes. Provided the transistor operates in normal mode changes in load current, i.e. load resistance, result in minimal load voltage changes. The voltage difference between the unregulated voltage and the regulated output is dropped across the transistor collector-base junction.

Note that the load current is supplied by the unregulated source; the battery provides only the much smaller transistor base current.

In order for the transistor to operate in normal mode the unregulated voltage reduced by the voltage drop across the internal resistance of the source at maximum load current must be large enough to keep the transistor from being saturated.

The functional block diagram drawn to the right illustrates a generalized view of the series pass regulator circuit. The REFERENCE block is a generalization of the function served by the battery, i.e. it is the criterion against which changes of the output voltage from the desired value are measured. A sample of the output voltage is compared to the reference, and the difference signal controls a correcting device.

A circuit implementation of this configuration is shown below.
**Voltage Reference:**
A regulator is at best only as good as the voltage reference used to determine when a correction is necessary. In most applications it is generally awkward to use a battery as a voltage reference. Integrated circuit regulators use sophisticated on-chip combinations of transistors and resistors to obtain precise temperature-compensated voltage references, and such references also are available as individual components. For purposes of illustration here however we describe briefly a simplified Zener diode regulated voltage reference source. The Zener supply generally would be taken from the unregulated supply voltage to avoid passing the Zener current through the series control device. The voltage divider serves a dual purpose. As a not so incidental matter the divider provides a reference voltage lower than the Zener voltage itself; as will become clear the reference voltage used for the comparison operation also generally will be the lowest voltage which can be regulated. In addition to this function the voltage divider accommodates a low-pass filter to reduce further voltage variations associated, for example, with rectifier ripple voltage feed-through.

**Sampling:**
In the simple regulator circuit the reference (battery) voltage is compared directly to the output voltage by the emitter junction, implying that the reference voltage and the output voltage have to be (nearly) equal. On the other hand the regulator could be used to regulate a sample (i.e. fraction) of the actual output voltage rather than the actual output voltage itself. If the sampling fraction is fixed regulation of the sample voltage effectively regulates the larger voltage as well. If the sampling fraction is adjustable then the output voltage of the regulated supply also is adjustable.

A straightforward sampling circuit is drawn to the left. Note again that the sample voltage is what will be compared to the reference, and it is the sample value the regulator will attempt to hold constant. In general the output voltage will be adjusted so that the sample voltage will be maintained nearly equal to the reference to which it is compared, and since the largest sampling fraction of the potentiometer is 1, it follows that the smallest voltage which can be regulated is the reference voltage.

Applying this same reasoning further it follows that the smallest sampling fraction corresponds to the largest output voltage which can be regulated. For one reason or another this maximum voltage is limited, for example it is clear that it must be less than the unregulated supply voltage in order for the regulator to function (i.e. not saturate the pass transistor). This is the purpose behind inserting the fixed resistor in series with the potentiometer in the sampling circuit; the resistance would be chosen so that the smallest sampling fraction (when the potentiometer wiper is at its lower stop) avoids an inadvertent loss of regulation.

**Comparison and Correction:**
The emitter junction of the transistor performs the comparison operation in the simplified regulator illustrated earlier. A more effective discrete comparitor is an OpAmp which buffers (i.e. presents a high input resistance to) the reference voltage, and amplifies the difference between the reference and sample voltages. The amplified 'error difference' voltage is used (as described below) to adjust the output voltage. Note that the error voltage is the change from the quiescent bias voltage.

The same transistor that is used for the comparison function in the previous simplified regulator also provides the correction in that circuit. Separating these functions, as in the comparitor, enables separate optimization of each function rather than a compromise choice.
A 'series pass' transistor, placed in series with the current path, is a common control arrangement. It functions as an emitter follower, with the load resistor completing the emitter circuit.

**Overall 'Series-Pass' Voltage Regulator**

The circuit diagram drawn above puts all the pieces together in a (simplified) representative discrete device series regulator configuration. Note that the collector-base resistor of the control device also is the collector resistor of the 'error' transistor in the comparator. The error signal is applied to the base input of the series-pass transistor. Adjusting the sampling potentiometer changes the quiescent setting of the pass transistor base voltage; thereafter fluctuations in the output voltage produce amplified corrective changes in the base voltage.

The relationship between the simple emitter follower as applied to voltage regulation and the expanded circuitry may be seen in the functional circuit diagram to the left. The difference between the voltage reference and a sample of the output voltage is applied to the emitter follower base through an amplifier; the phase of the amplified signal is such that it mitigates changes in the output voltage. This is a basic feedback control circuit for which the overall amplifier 'gain' is estimated as shown. Note that to the extent the 'loop gain' $fA >> 1$ the output voltage is a fixed multiple of the reference voltage. Note also that regulation is maintained largely independent of the source voltage (given unsaturated operation of the pass transistor within its ratings).

**Current Limiting**

Accidents happen. With power supplies, for example, it is not uncommon for the supply to be accidentally short-circuited because of a load failure. An output short-circuit defeats the regulating circuitry because the pass transistor attempts to increase the short-circuit voltage by increasing the output current, generally and quickly beyond allowable circuit limits. To avoid this extreme behavior current-limiting circuitry can be added which (ideally) is inactive in normal operation but becomes active when the current exceeds a preset set-point value. The circuit drawn below, left illustrates one type of current-limiting circuit.

The current from the pass transistor emitter is passed through a small current-sensing resistor placed in series with the load; the voltage drop across this resistor is monitored by the emitter junction of a transistor. When the voltage drop is large enough this latter transistor is turned on and diverts current from the pass transistor base, limiting the pass transistor emitter current. The higher the current sensed the more strongly the current-limiting transistor turns on and the more strongly base current to the pass-transistor base is diverted. Note that the current-sensing transistor itself does not have to handle high output currents; it 'works' with the considerably lower level of the base current of the pass transistor.

The principal constraint on the maximum current permitted is the allowable dissipation in the pass transistor. The largest power dissipation for the pass transistor occurs with maximum rated load current and the minimum rated output voltage (the voltage across the pass transistor is the difference between the supply voltage and the output voltage, and so is a maximum for the condition stated).

**'Series Pass' Illustration**

An illustrative series-pass regulator circuit is described below. This is a 'first-pass' regulator design to provide a regulated voltage with a maximum load current of about 30ma, a 20v unregulated DC supply with a 100Ω 'internal' resistance is assumed; the supply has a 120Hz sinusoidal 'ripple' of 2v peak.

The reference voltage is derived from a 15v Zener diode and is approximately $15(10/66) = 2.27v$; this is the minimum regulated voltage to be expected. For a maximum design regulated voltage of about 10v the set point of the potentiometer would be roughly 0.2. Assuming a ‘turn-on’ of the current limiting transistor at about 0.6v only a small base current siphoning is needed) a maximum current of about 15ma requires a sampling resistance of about $0.6/30 = 20Ω$; a value of 25Ω is used. The capacitor is chosen to filter a
nominal 120Hz ‘ripple’ frequency; the 4.7 µf capacitance corresponds to a reactance of about 280Ω compared to the 410kΩ resistances.

On anticipating regulated operation, keeping the load voltage essentially fixed, the base voltage of Q1 also will be nearly constant. For a (roughly) estimated β of 100 the Q1 base current for the full-load current of 30mA is approximately 0.3mA. A base resistance of about \((20 - 2.27 - 0.7)/0.3 = 56.77\) Ω is suggested. A value of 56kΩ is used so that for maximum load current and minimum load voltage Q1 bias current is provided through R1, and the amplifier itself supplies only a very small current. For higher load voltages the amplifier makes up any current shortfall through R1.

Another extreme occurs for the minimum regulated voltage occurs with zero load current: in this case the amplifier must sink essentially all of the 0.3 mA current from R1, diverting it from Q1. The minimum amplifier Q1 base voltage will be about \(2.27 + 0.7 = 2.97\)V. To operate the amplifier single-ended (minimum output voltage \(\geq 0\)) a resistor R3 of no more than \(2.97/0.3 = 10kΩ\) is needed inserted in series with the amplifier output to drop the excess voltage.

One other extreme circumstance to consider occurs with full-load current when the regulated load voltage is at the specified maximum of 10V; the current in the base resistor R1 will be \((20-10)/56 = 0.18\)mA. Additional Q1 base current required to enable a 0.3 mA full-load current, of about 0.12ma, must be provided by the amplifier. This requires the opamp output voltage to be \(10 + 0.7 + (0.2)(10) = 12.7\) V. To avoid saturating the opamp a positive amplifier rail voltage of 15V is used; this is in part the basis of the earlier Zener specification; the Zener reference is used to provide the positive supply of the amplifier. Note: the Zener model specifications for PSpice are revised.

These calculations are the basis for the following trial design.

![Circuit Diagram](image)

Note 1: The parameter SET is associated with the potentiometer R13. Values used are 0.1, 0.2, 0.3, and 1.0. The reference voltage is (as noted above) 2.27V, and the SET points correspond respectively to expected regulated voltages of 22.7, 11.35, 7.57, and 2.27V. Note however that the 22.7V exceeds the maximum voltage available, and regulation will fail.

Note 2: V4 is the VSIN part used to simulate a ripple voltage riding on the unregulated input. V14 is a DC source used for the line regulation computations.

Note 3: A resistance of 100Ω (value more or less arbitrarily chosen) is placed in series with the unregulated source to simulate the source Thevenin internal resistance.
Load regulation curves, i.e., load voltage vs. load current, are plotted next. Note that regulation fails when the Set point is 0.1; this calls for an output voltage of 22.7 volts and, as noted before, the supply cannot provide this voltage. The output voltage drops with increasing current, in part due to the $100\,\Omega$ 'internal' resistance of the source until current limiting sets in. The regulated voltages shown can be compared to the expected voltages for the associated potentiometer set point. For example the set point 0.2 corresponds to an expected regulated voltage of $2.27/0.2 = 11.35\,\text{v}$.

A somewhat enlarged scale is used for the curve below.
Line regulation curves, i.e., the variation of output voltage with changes in input voltage, are plotted below for a fixed 10ma load current and several potentiometer set-point values.

Regulation will not be active until Zener breakdown occurs; this occurs for an input voltage of roughly 17v (allowing for about a 2v drop across the 470Ω current limiting resistor for the Zener current). This 'start-up' voltage is more or less independent of the output voltage selected.

The pass transistor does not conduct until the input voltage is greater than about 0.7v + voltage drop across the 100Ω (about 1 volt for 10 ma current). After this threshold is reached but before the Zener diode breaks down the non-inverting input of the amplifier has a voltage applied which is (approx)

\[
\frac{10}{(0.47+56+10)} \times (V_{14} - 0.1k \times 10ma).
\]

Assuming a large amplifier gain this is essentially the voltage at the inverting input, and so is equal to (sampling fraction)\( \times V_{out} \). Hence until the 'normal' regulation occurs (= 17v for breakdown)

\[
V_{out} = 0.15 \times [V_{14} - 1] / \text{(sampling fraction)}.
\]

'Pre-regulation' plots are superimposed for sampling fractions of 0.1 and 1 respectively.