Linear Voltage Regulator

Introduction

For most electronic equipment a DC power supply is preferred since, except for a start-up transient, the supply does not (ideally) 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 half- or more usually a full-wave rectified waveform. The supply is almost always a voltage supply as a practical matter; it is easier and less lossy to maintain a voltage supply in a standby condition rather than a current supply, and to operate it under varying load.

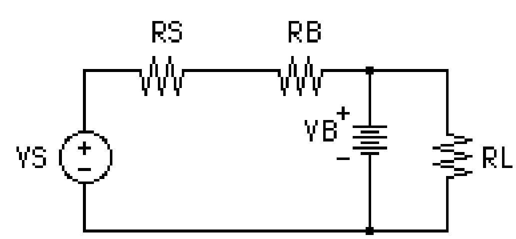
The unidirectional but varying rectified waveform is filtered in various ways to reduce the variation (the 'ripple' voltage) to an acceptable level. Nevertheless for many purposes the filtered supply voltage ripple variation often is unacceptably large, particularly within practical filtering limitations. 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 unregulated supply terminals and the load primarily to reduce this terminal voltage variation, but also to provide additional benefits.

Voltage rectification and filtering is discussed in a separate note. 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 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 implementation of the discrete circuit concepts, and do not differ in fundamental principle (or in basic circuit concepts) from their discrete counterparts. It is the interaction in the context of an associated introductory design project that makes the discrete voltage regulator of special instructional interest.

There are, broadly speaking, two types of electronic voltage regulator circuits, linear voltage regulators and 'switching' regulators. The distinction between different types of regulators lies basically in 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 <u>linear regulator</u> is considered.

Linear voltage regulators are divided further into 'shunt' and 'series' regulators; the distinction here is whether the regulator component which makes necessary corrections is placed in parallel with or in series with the load.

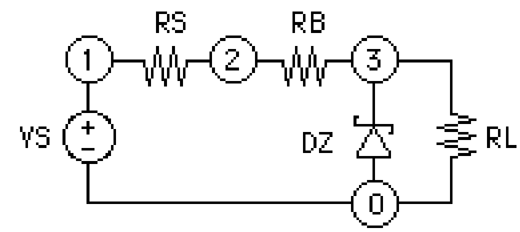
Zener Diode Shunt Regulator



The circuit drawn to the right illustrates what is perhaps the simplest voltage regulator. 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 <u>extended</u> supply is fixed by the properties of the (idealized) battery. <u>Load</u> regulation, changes in load current as RL varies, is accommodated by re-division of the supply current between the battery and the load. <u>Line</u> 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 in general the battery alone could not used as the regulated supply, since it is (ideally) inherently well regulated. Indeed this is what is done in appropriate circumstances, e.g., 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 that 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.

Although the Zener diode shunt regulation circuit was discussed earlier in connection with the introduction of the Zener diode, it bears an abbreviated repetition in the present context.



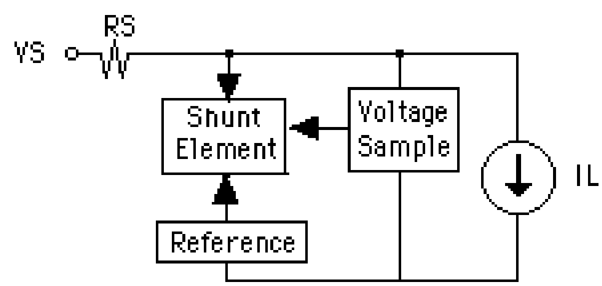
A Zener diode shunt regulator circuit is drawn to the right; as before VS and RS represent the Thevenin equivalent circuit for an unregulated power supply. Provided that the circuit conditions are such that the Zener diode operates in its breakdown region the voltage across the load resistance RL is 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; 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 noncritical applications.

Feedback Shunt Regulator

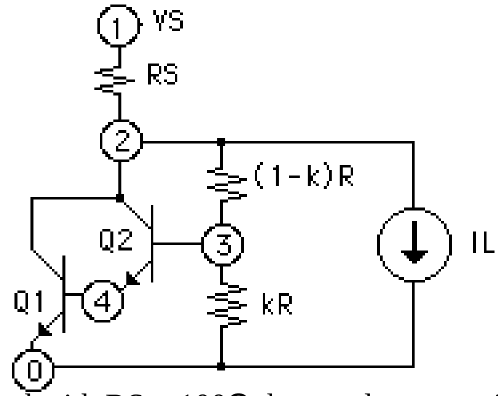
The Zener regulator is an 'open loop' system, i.e., the current distribution adjustment is inherent in the diode breakdown properties. A different view of the regulator pictures it as a feedback control system, i.e., sampling of the load voltage, comparison of this sample to a reference voltage as a 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 nearly constant emitter junction voltage drops. See the netlist below for specific 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, 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.

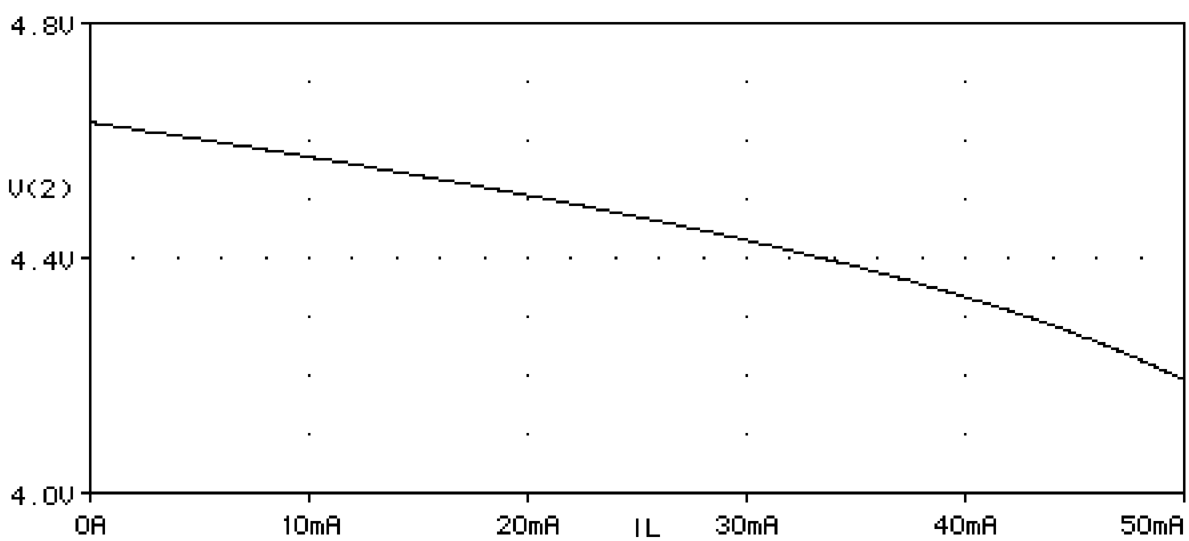


The illustrative regulator (netlist follows) is designed for a load voltage of (1.4)(3.3) = 4.6 volts from a 10 volt unregulated source. The voltage drop across RS then is 10-4.6 = 5.4 volts, and with RS = 100Ω the supply current is 54 ma. This provides an upper limit on the regulated load current, since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

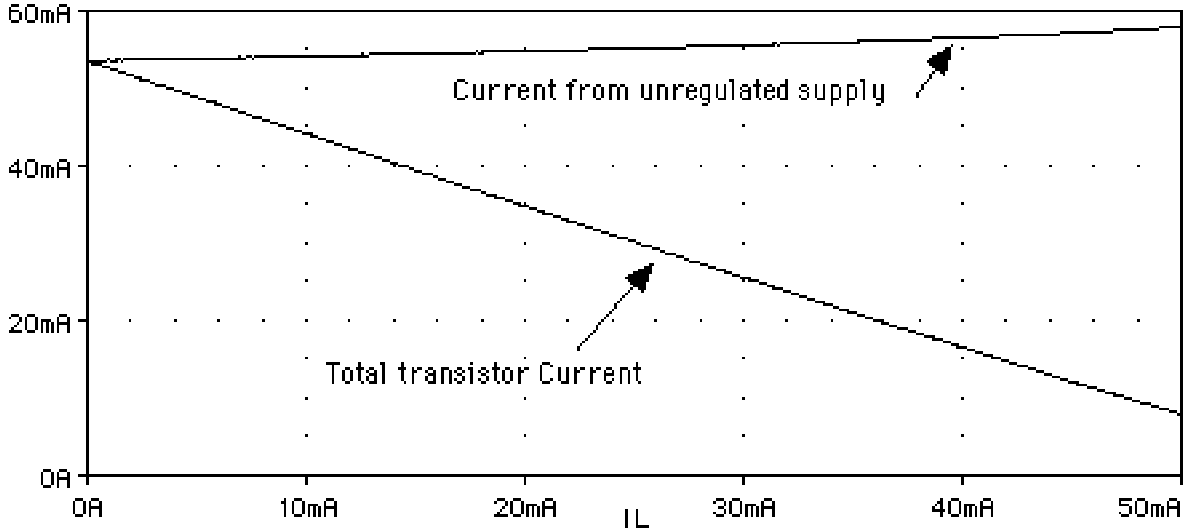
```
*Shunt Regulator
VS      1     0      DC     10
RS      1     2             100
Q2      2     3      4      Q2N3904
Q1      2     4      0      Q2N3904
RB1     2     3             22K
RB2     3     0             10K

IL      2     0      DC     1
.DC  IL       0      50m .1m
.LIB EVAL.LIB
.PROBE
.OP
.END
```

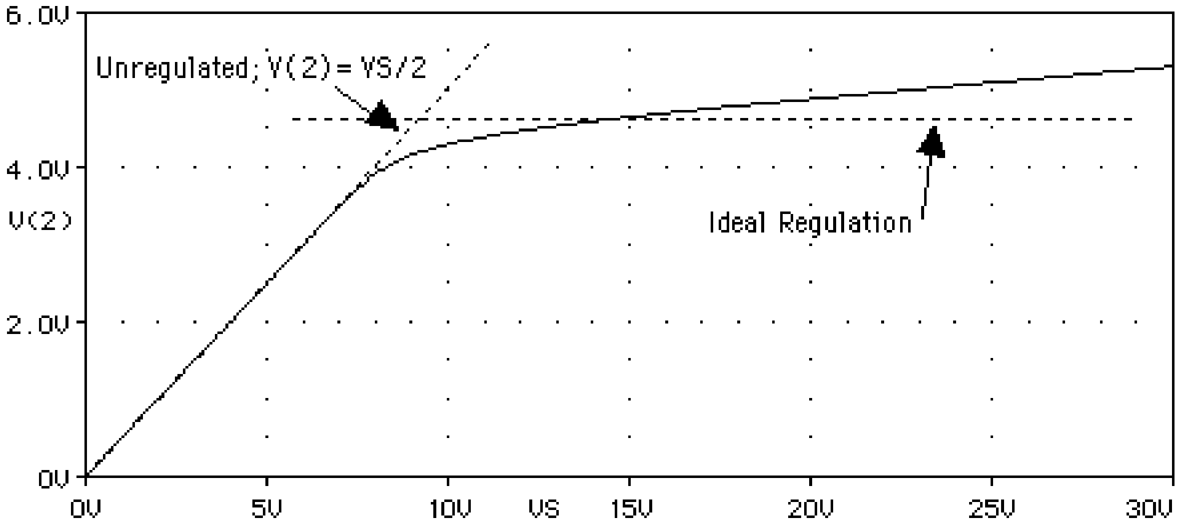
Absent the regulation a 50 ma current change through the 100Ω source resistance would result in a 5 volt line voltage change; the regulated change is an order of magnitude smaller.



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 = 100Ω.

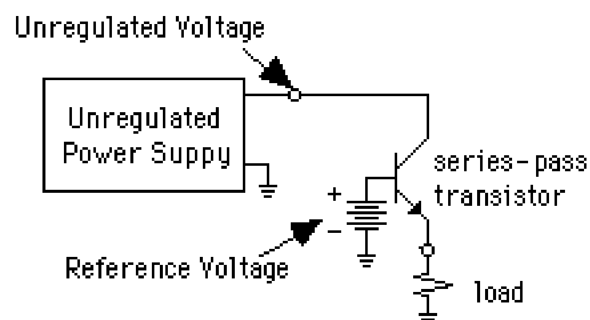


The regulated voltage is designed to be 4.6 volts with VS = 10 volts. The load resistance is 100Ω. A significant part of the load voltage change is associated with the Early Effect.

'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 is varied to adjust the load voltage.

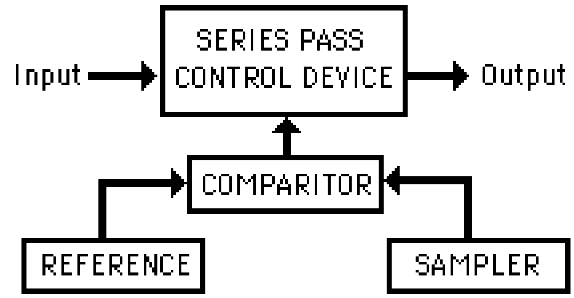
A simplified 'series' voltage regulator circuit is illustrated in the figure to the right. Basically the circuit configuration is that of a BJT emitter-follower, and circuit operation is interpreted conveniently as such at first . The unregulated supply provides the BJT collector voltage, and the battery, 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.

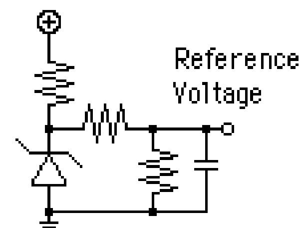
In order for the transistor to operate in normal mode the unregulated voltage reduced by the voltage drop across the internal resistance of the source <u>at maximum load current</u> must be large enough to keep the transistor from being saturated.

A generalized view of the series pass regulator circuit is illustrated by the functional block diagram drawn to the right. 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.



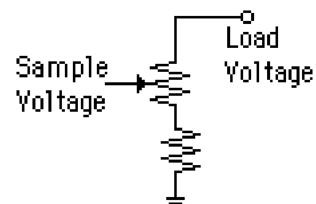
<u>Voltage Reference</u>:
A regulator is at best only as good as the voltage reference used to determine when a correction is necessary. In most applications it is awkward to use a battery as a reference. Integrated circuit regulators use sophisticated on-chip combinations of transistors and resistors 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 discrete version of an electronic reference as illustrated below.

It is essentially a Zener diode regulated voltage 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 voltage variations associated, for example, with rectifier ripple voltage.

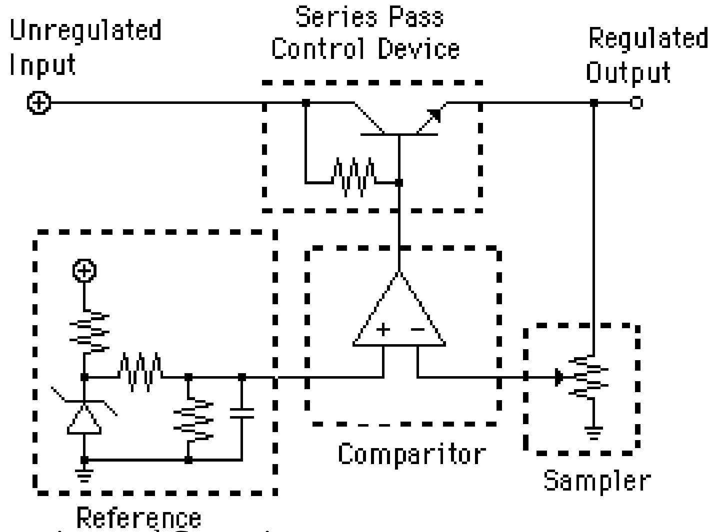


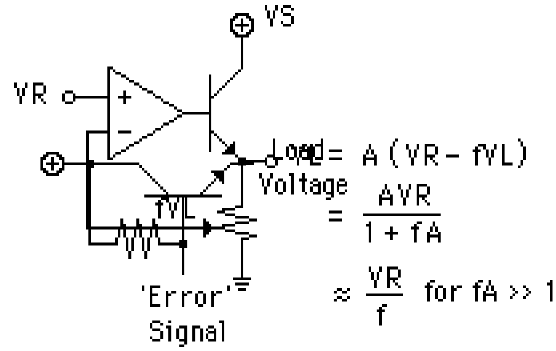
<u>Sampling</u>:
In the simple regulator circuit the reference (battery) voltage is compared directly to the output voltage by the emitter junction, implying that the reference voltage and the output voltage have to be (nearly) equal. On the other hand the regulator could be used to regulate a sample (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 illustrative 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. Since the largest sampling fraction of the potentiometer is 1, it follows that the <u>smallest</u> 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 comparison operation in the simplified regulator illustrated earlier is performed by the emitter junction of the transistor. 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.

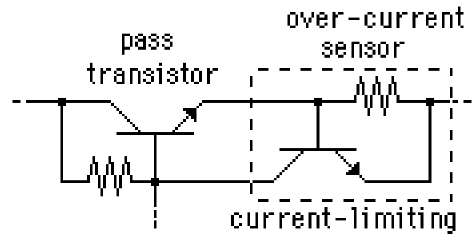
The same transistor that is used for the comparison function in the previous simplified regulator also provides the correction in that circuit. Separating these functions, as in the comparitor, better enables a separate optimization of each function rather than a compromise choice.
A 'series pass' transistor, 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. A Darlington pair may be used for greater control sensitivity.

Overall 'Series-Pass' Voltage Regulator
The circuit diagram drawn below 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 comparitor. 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 right. 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).

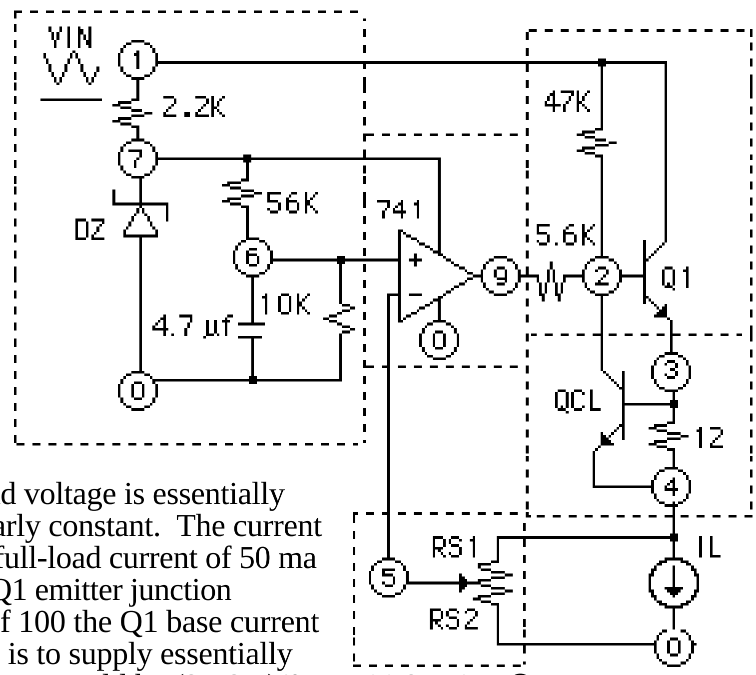
Current Limiting
Accidents happen. With power supplies, for example, it is not uncommon for the supply to be accidentally short-circuited because of a load failure. An output short-circuit defeats the regulating

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. One type of current-limiting circuit is illustrated by the circuit drawn below, left.



The current from the pass transistor emitter is passed through a small current-sensing resistor placed in series with the load, and 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' at 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).

Illustrative 'Series Pass' Illustration I
A representative series-pass regulator circuit is drawn below; various subsystems are enclosed by dotted lines. This is a 'first-pass' regulator design to provide a regulated voltage variable between (roughly) 2 and 12 volts, a maximum load current of about 50ma, a 25v unregulated DC supply is assumed.



On the left a Zener regulator is used to provide both the reference voltage for the regulator and a single-rail supply voltage for the OpAmp. For reasons to be described a 15v diode-breakdown voltage is used. With a nominal unregulated DC input voltage of 25 v the Zener diode current is approximately (25-15)/2.2 = 4.55 ma. The reference voltage for the regulator then is about (10/66)15=2.27v.

The current-limiting circuitry shown on the right uses a 0.6/50 ≈ 12Ω current sensing resistor for a nominal 50 ma current limit.

Anticipating regulated operation, i.e., the load voltage is essentially fixed, the base voltage of Q1 also will be nearly constant. The current in the base feed resistor is a maximum for a full-load current of 50 ma with the minimum regulated voltage (plus a Q1 emitter junction voltage drop). For a (roughly) estimated ß of 100 the Q1 base current is approximately 0.5 ma, and if the amplifier is to supply essentially no current in this circumstance the base resistor would be (25-2.7)/0.5 = 44.6 ≈ 47KΩ.

Another extreme at the minimum regulated voltage occurs with zero load current, in which case the amplifier must sink essentially all the 0.5 ma. current through the base resistor The minimum amplifier output voltage will be about zero, so that a resistor of 2.7/0.5 ≈ 5.6KΩ is needed in series with the amplifier output.

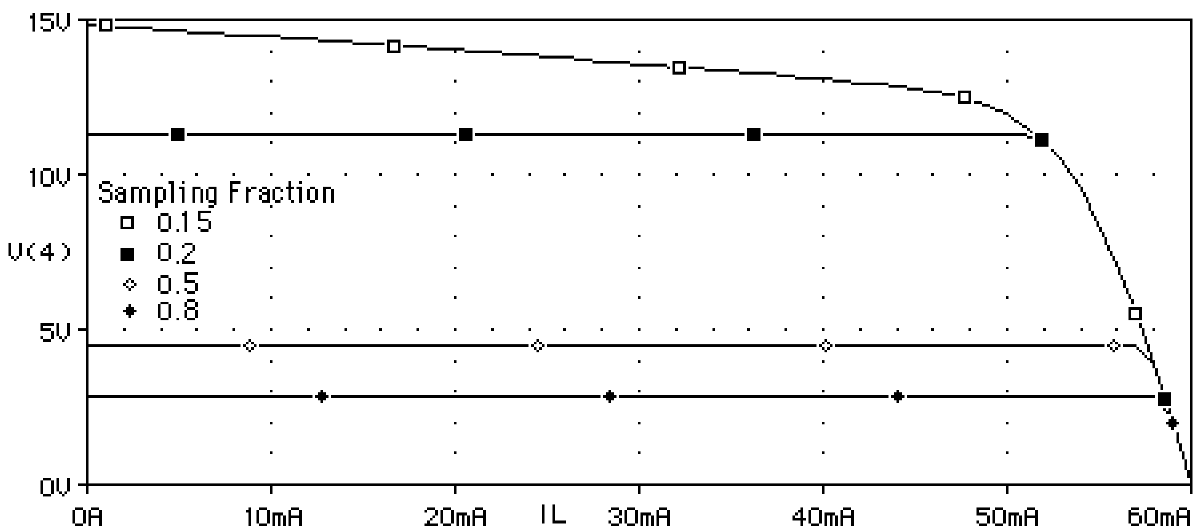
Yet another extreme occurs when the regulated load voltage is 12v; the current in the base resistor will be (25-12)/47 = 0.28 ma. Additional base current to enable a 50 ma full-load current, about (50/100)-0.28 =

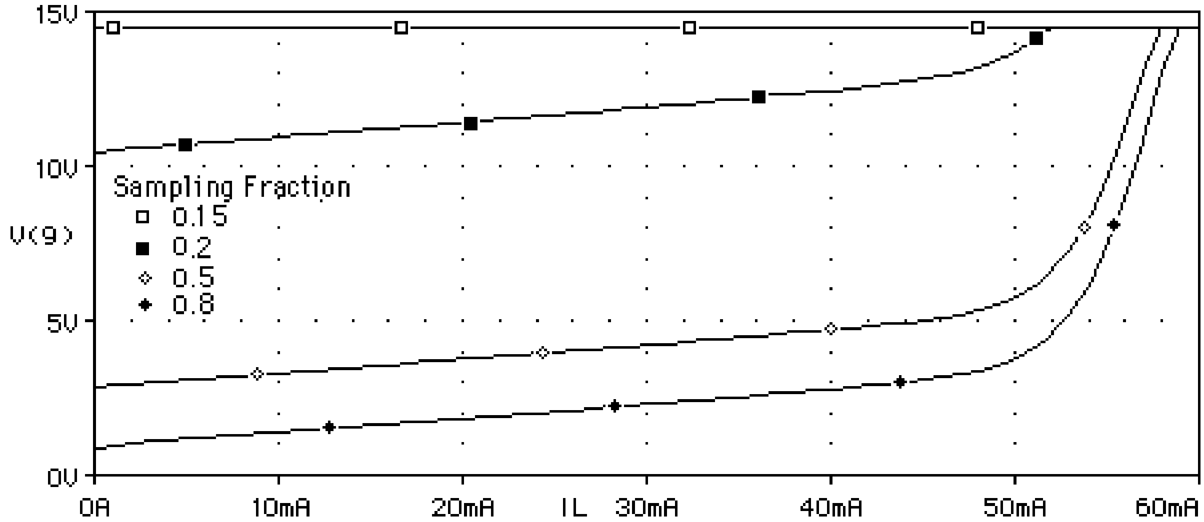
0.22 ma, must be provided by the opamp. This requires the opamp output voltage to be 12 + (0.22)(5.6) = 13.23 v. To avoid saturating the opamp an amplifier rail voltage of 15 v is used; this is the basis of the earlier Zener specification.

A netlist for a PSpice computation follows. Computations are performed for several sampling fractions over the specified range of load currents.

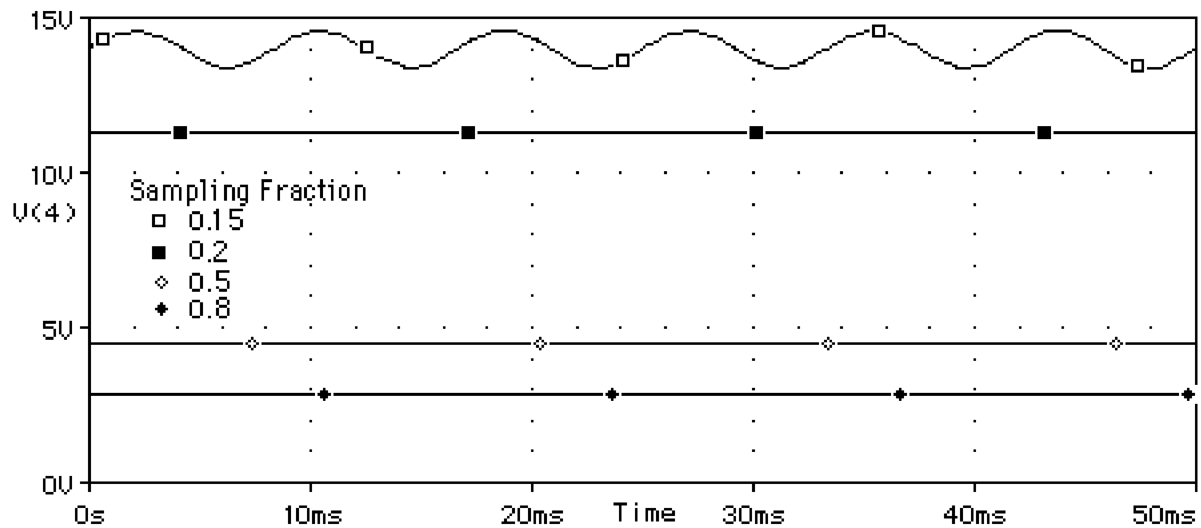
```
Series Pass Regulator Example
VIN     1   0    SIN(25, 5, 120)
Q1      1   2    3       Q2N3904
RPASS   1   2            47K
RCL     3   4            12
QCL     2   3    4       Q2N3904
IL      4   0    DC      20M
.PARAM WIPER= 0.4
RS1     4   5            {10K*(1-WIPER)}
RS2     5   0            {10K*WIPER}
XAMPX6      5    7 0 9   UA741
RAMP    9   2            5.6K
DZ            0     7        DX2
.MODEL DX2 AKO:D1N750 D(BV = 15)
RREF         1     7        2.2K
RZ1        7   6            56K
RZ2        6   0            10K
CZ         6   0            4.7U
.STEP PARAM WIPER LIST .15 .2 .5 .8
.DC        IL  0      60M    1M
.TRAN  0.1M   0.05
.LIB EVAL.LIB
.PROBE
.OP
.END
```

The load regulation curves for several sampling fractions are plotted next. Note that regulation has failed for a sampling fraction of 0.15; this would correspond to a load voltage of about 2.27/0.15 ≈ 15v. The amplifier however saturates at about this voltage (even with zero load current). This behavior is shown in the next plot of <u>amplifier</u> output voltage vs. load current. Note the rapid increase in this voltage as the current-limiting is initiated; the amplifier output voltage increases (until saturation occurs) in an attempt to compensate.



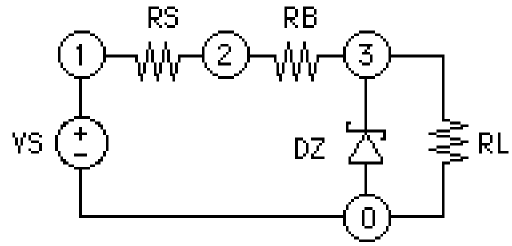


The input voltage used for the computation includes a (quite large) sinusoidal component simulating power supply ripple. The ripple is in effect a line voltage variation, and the regulating action should smooth the variation. A transient computation is plotted below to illustrate the smoothing action. Note the 'ripple' for a sampling fraction of 0.15, i.e., absent the regulating action.



PROBLEMS

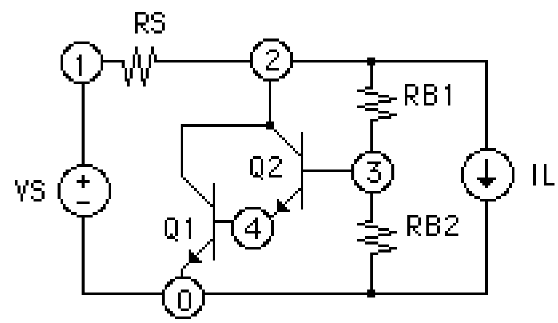
1) The Thevenin equivalent of a particular unregulated power supply is a voltage source VS, where 10v ≤ VS ≤ 12volts, and an internal resistance RS = 50Ω. Design a Zener diode shunt regulator (see circuit diagram) to provide a regulated 5 volt (nominal) output for 1KΩ ≤ RL ≤ 2.5KΩ. Use a 1N5231 Zener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



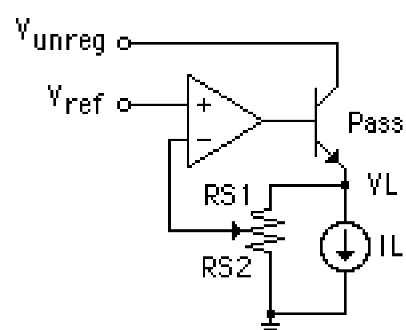
2) In problem 1 the regulating action of your design assumes the Zener diode operates in the breakdown region. For a large enough load current the diode current is insufficient to maintain breakdown. Estimate this dropout current for your design, and compare with a PSpice analysis.

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 10Ω Zener resistance and a 1 KΩ load resistance. Use PSpice to obtain the load voltage transient response and compare to your estimate.

4) The shunt regulator circuit discussed before is reproduced here for convenience (except that the load is shown as a DC current source). Given VS = 15 volt, RS = 1KΩ. Select element values (RB1, RB2) to provide a nominal load voltage = 6.5 VDC for load currents from 0 to about 10ma. Compare the designed regulation performance with that of a PSpice computation.

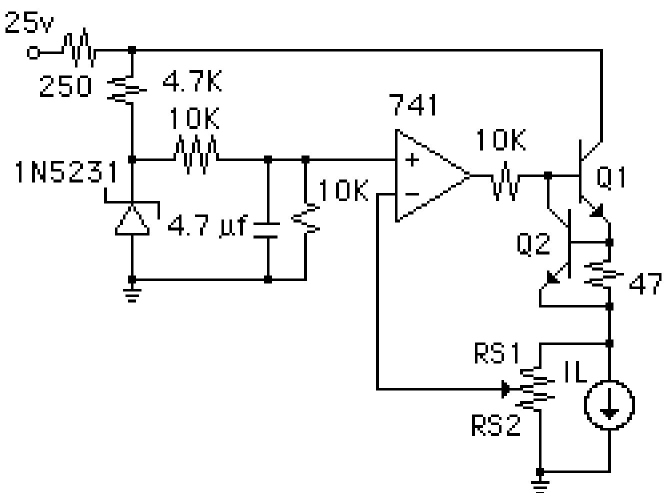


5) The accompanying (simplified) circuit diagram interprets the series-pass regulator as a feedback system. The (idealized) amplifier in the circuit below includes the transistor emitter junction in the feedback loop. Assuming a constant reference voltage the amplifier maintains a constant output voltage that is a multiple of the reference voltage (but not so large as to saturate the pass transistor or the amplifier).



Use a 741 opamp, a 2N3904 transistor, assume V_{unreg} = 25 volts, and a reference voltage of 2v. For a 10KΩ potentiometer evaluate the (idealized) regulator performance.

6) A regulator design based on the feedback configuration discussed above is drawn below. A PSpice netlist for the circuit is to the right. Identify the several subsystems of the regulator, and compute the circuit regulation behavior, i.e., the line regulation (load voltage vs V_{unreg} at a fixed load current) and the load regulation (load voltage vs load current for a fixed V_{unreg})




```
*Problem 6
VUN  1    0    DC     25
RUN  1    2           250
RZ   2    3           4.7K
DZ   0    3           D1N5231
RF1  3    4           10K
RF2  4    0           10K
CF   4    0           4.7U
X1   4 5  9 10 11     UA741
V+   9    0    DC     12
V-   10   0    DC     -12
RXX  11   6           10K
Q1   2    6    7      Q2N3904
RE1  7    8           47
Q2   6    7    8      Q2N3904
RS2  5    0           {WIPER*10K}
RS1  8    5           {(1-WIPER)*10K}
IL   8    0    DC     10M
.LIB EVAL.LIB
.PARAM WIPER = .4
.STEP PARAM WIPER .1 .5 .1
.DC  IL 0m 15m .1m  ;load regulation @ 25v
* .DC VUN  0 15  .5   ;line regulation @ 10m
.PROBE
.END
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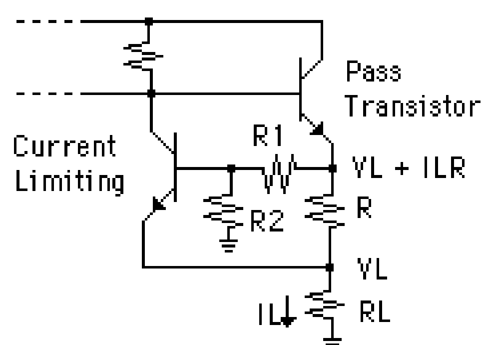
7) Re-analyze the regulator of problem 9 using a resistive load RL in place of the current source IL. To obtain a plot with resistance as the independent variable:

Define RL with RL N+ N- RMOD 1, and define RMOD by >.MODEL RMOD RES. Then to sweep use .DC RES RMOD(R) start end increment.

The sweep values actually are multipliers of the value assigned to RL, but since the value 1 was assigned they are equal to the resistance values.

8) A principal concern for series regulators is the power dissipated in the pass transistor; 'hard' current limiting to prevent excessive current was described earlier. However limiting sets in for approximately the same current at all regulated load voltages. But the voltage across the pass transistor is a maximum for <u>minimum</u> load voltage, and so a higher rated load current for a given power handling capability could be permitted for larger load voltages. The circuit to the right shows a modified limiting circuit that accomplishes this.

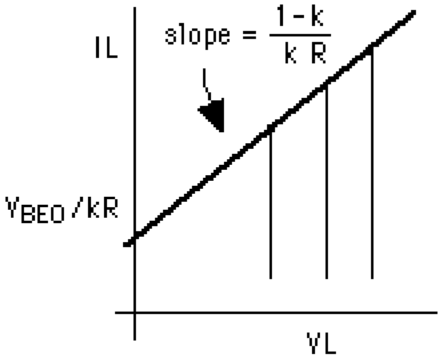


While the base is biased to a voltage less than the load voltage VL the emitter junction voltage V_{BE} of the (cutoff) current-limiting transistor is

$$V_{BE} = \left(\frac{VL + ILR}{R1 + R2}\right) R2 - VL$$

$$= kILR - (1-k)VL \quad \text{where } k \triangleq \frac{R2}{R1+R2} \le 1$$

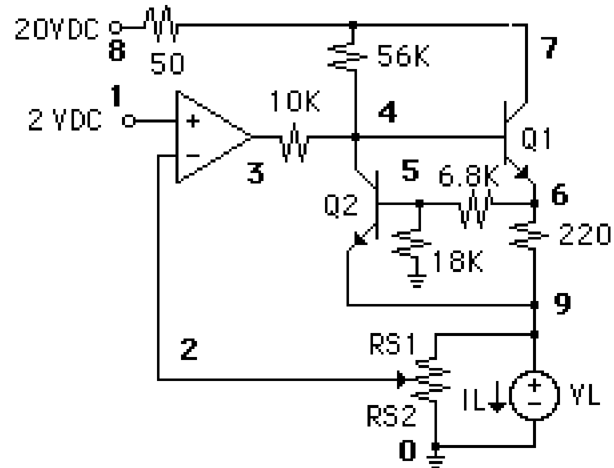
The voltage divider ratio k determines the relative influence of the load current and voltage in current limiting. Note that for a given load current V_{BE} is smaller the larger the load voltage, i.e., a larger load



current is needed to reach a given threshold. This expression should not be used to relate the load voltage to the load current. Rather VBE should be set to the (fixed) transistor threshold voltage VBE0, and the equation used to describe the locus of (VL, IL) coordinates for which the threshold is reached.

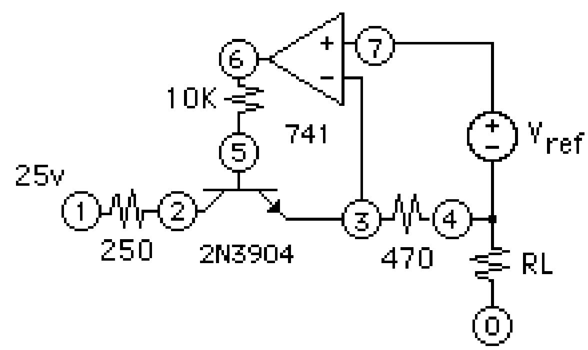
Regulation curves appear generally as indicated; the cutoff line is superimposed. V_{BE0} is the threshold junction voltage (≈ 0.6v), and the current intercept on the abscissa is V_{BE0}/kR.

The simplified series regulator circuit drawn to the right has been modified to apply 'foldback' current limiting. Compute and evaluate the foldback characteristics; compare to estimated behavior.



9) Design a series-pass regulator to provide a nominal -5 volts load voltage from a -15 volt unregulated supply.

10) For some purposes a current regulator is useful; the circuit diagram drawn to the right is a simplified current regulator. While the amplifier is active (not saturated) it adjusts the transistor emitter current so as to maintain a near-zero amplifier input voltage, i.e., Vref - 0.47 IL ≈ 0.



As RL is decreased the voltage at node 4 decreases (assuming constant current) and consequently V(3), and the amplifier output voltage also, must decrease. Eventually this voltage becomes less than V_{ref}, the minimum value required to maintain the current, and Q1 then rapidly cuts off.

Conversely, as RL is increased, V(3) rises, pulled up by the amplifier output. Eventually the amplifier saturates, V(3) sticks at about Vsat - 0.7, and the load current decreases as RL increases (~ 1/RL)

Perform a PSpice analysis to confirm the remarks made.