PS-1 All-Discrete Power Supply

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Contents

Chapter 1

Theory of Operation

1.1 Summary

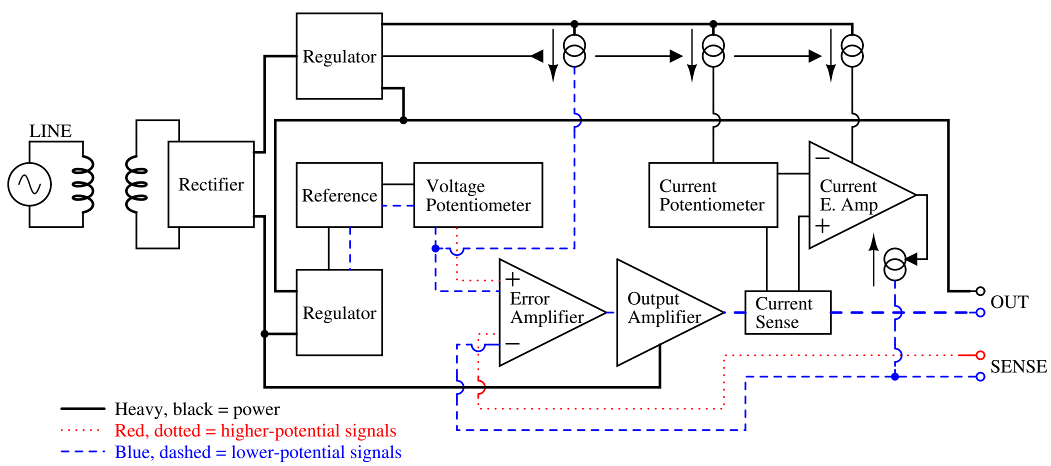

Figure 1.1: Block diagram.

Figure 1.1 is the block diagram of the entire power supply.

First, the line (mains) voltage feeds the primary winding of a transformer, giving approximately 28 VAC on the secondary. This is rectified and filtered to DC by diode bridge D2 and capacitor C2.

The current exiting the rectifier passes through a simple "regulator", consisting of just three diodes, to provide a pair of supply rails for biasing current sources. To maintain good line regulation, the remaining voltage feeds into a local regulator, giving a rail of approximately 32 V to power the control circuitry.

This regulated rail powers a Zener reference diode. This regulates the potential across the front-panel Voltage potentiometer, which is used to select an output set-point.

The voltage from this potentiometer, as a differential pair, feeds into the error amplifier, which compares it to the voltage sensed at the output, also as a differential pair. If the relative voltage between the output pairs is above that of the set-point, the output drive will be increased; if it is below, the output drive will be decreased. The output will thus settle to almost exactly the set-point.

After power leaves the output amplifier, it passes through a current sense resistor. This resistor sees a potential difference, by Ohm's Law, corresponding to the current flowing through it. A current sense amplifier compares this to a current limit set-point; if the current drawn begins to exceed the set level, the current sense amplifier will pull the negative sense line further negative. This causes the voltage amplifier to "see" too much potential on the output, and it decreases output drive.

1.2 Local Regulation

To maintain good line regulation, the circuitry of the power supply is itself powered by a local regulator.

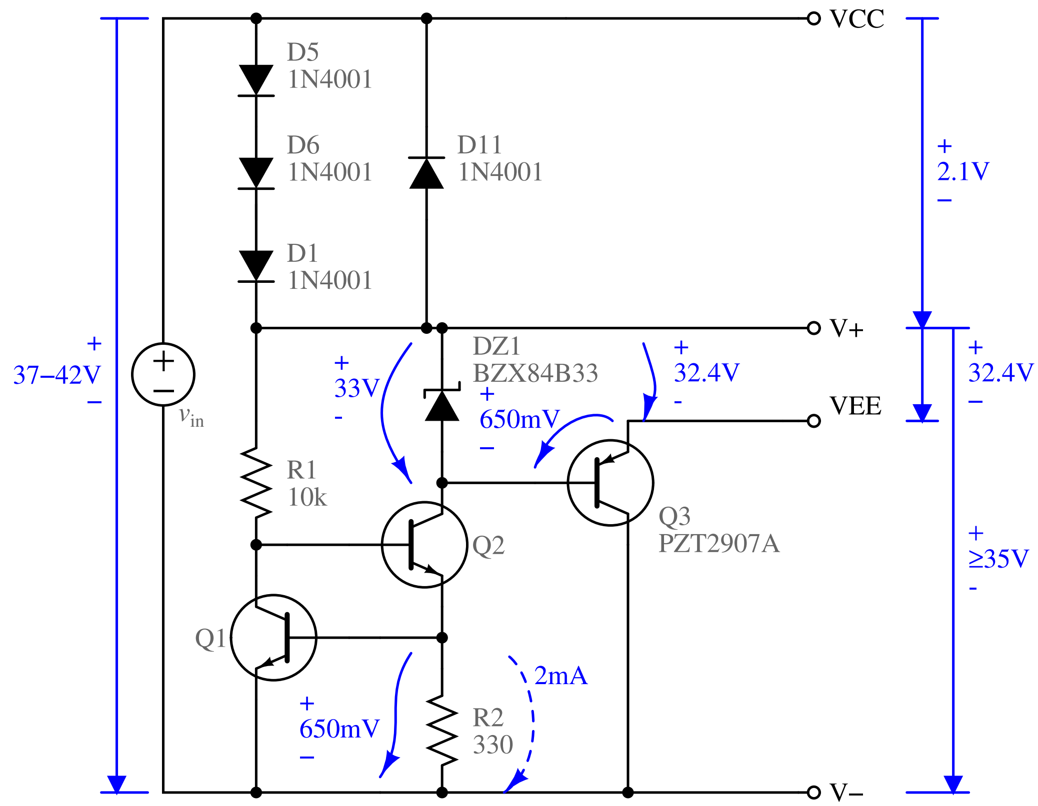

Figure 1.2: Local regulator sub-schematic

Note that unlike many electronic designs, this power supply uses a *positive ground* configuration. This means that rather than having a higher voltage rail regulated with respect to a lower rail, the lower rail is regulated to the higher one.

A small positive rail is required about 2 V above ground to provide extra headroom for the regulating circuits. The low current (500 mA) output means that it is reasonably efficient to achieve this by passing the positive supply input through a string of three diodes (0.7 V each, 2.1 V total), and using the voltage appearing at the negative end as 'ground', labeled V+ in the circuit diagrams. The voltage at the positive end is VCC.

This simple three-diode chain could barely be given the title "voltage regulator", but it is used for this purpose. Diode `D11`, connected backwards across the chain, protects the power supply if an external voltage is applied to it while it is shut down. This diode allows that external voltage to actually power the regulation circuitry, protecting it from damage by reverse voltages.

The VEE regulator is more complicated.

`Q1` and `Q2` act as a simple constant current source. Consider what will happen as the circuit starts up. The power switch will have just been flipped, and the rails, once all equal in voltage, begin to drift apart. `Q1` has `R2` pulling its base and emitter together, so it begins turned off, and we can ignore it. `Q2` has `R1` supplying it base current from V+, so it will turn on. As V+ climbs, so does the current flowing through `Q2`, and this same current flows through `R2`. Ohm's Law gives the voltage across this resistor as equal to the product of the current and the resistance. A typical transistor's threshold voltage is 650 mV. At this voltage, there is $\frac{\mathrm{V}}{\mathrm{R}} = \frac{650\ \mathrm{mV}}{330\ \Omega} = 1.97\ mA$ flowing. Because the threshold voltage has been reached between $\mathrm{Q1}$'s base and emitter, $\mathrm{Q1}$ begins to turn on, diverting away $\mathrm{Q2}$'s base current and limiting the output current. This feedback action causes the current drawn into `Q2` to settle at 1.97 mA.

Both the nominal 650 mV threshold voltage and the 300 Ω resistance vary with temperature. The specified operating range of this power supply is from 5 °C to 45 °C. The transistor's threshold voltage loses about 2 mV for every 1 °C above a standard 25 °C room temperature. A typical A typical resistor might have a temperature coefficient of 200 ppm/°C, or more properly, 200 (μΩ/Ω)/°C, meaning its resistance changes by 200 μΩ for every 1 Ω of its nominal value per 1 °C above the standard 25 °C. This means that, assuming the threshold is indeed 650 mV at room temperature, the temperature-dependent current drawn is:

$$\text{Where } \Delta T = T - 25\ ^\circ C$$

$$I(\Delta T) = \frac{V(\Delta T)}{R(\Delta T)}$$

$$= \frac{650\ mV - (2\ mV/^\circ C)(\Delta T)}{(330\ \Omega)((200\ \mu\Omega/\Omega/^\circ C)(\Delta T) + 1)}$$

This has its maximum value at the minimum value of ΔT:

$$I(-20^\circ C) = \frac{690\ mV}{328.68\ \Omega} = 2.10\ mA$$

The error is $2.10\ mA - 1.97\ mA = 130\ \mu A$.

This 2 mA is drawn through DZ1, a BZX84-series, 2 %-tolerance, 33 V Zener diode, and this is precisely the current specified for the 2 % tolerance. The dynamic impedance (apparent output resistance at a specific bias point) of DZ1 is specified by the datasheet to be at worst 80 Ω, so the above 130 μA current error will cause a voltage error up to the product of the two values: $(130\ \mu A)(80\ \Omega) = 10.4\ mV$, or 0.03 % on top of the existing 2 % tolerance. Further error will be caused by DZ1's temperature coefficient, given as 800ppm/°C: 1.6 % in either direction over the specified range. Assuming the temperature change is not enough to affect the dynamic impedance, the errors can be added together, so the total non-trimmable voltage error is 1.6 % + 0.03 % = 1.63 %. (The 2 % is not considered because it is constant — a property of the individual diode — and can be adjusted with a trimmer).

The output voltage is buffered by Q3, a simple emitter-follower, which loses about 650 mV: from 33 V to 32.35 V. It will have a 2 mV/°C error just like Q1, contributing an additional 0.1 % error, for a grand total of 3.73 %. There will be a slight, additional error in this 650 mV caused by self-heating and by load current, but this error is nearly constant and will be calibrated away by the trimmers.

1.3 Voltage Reference

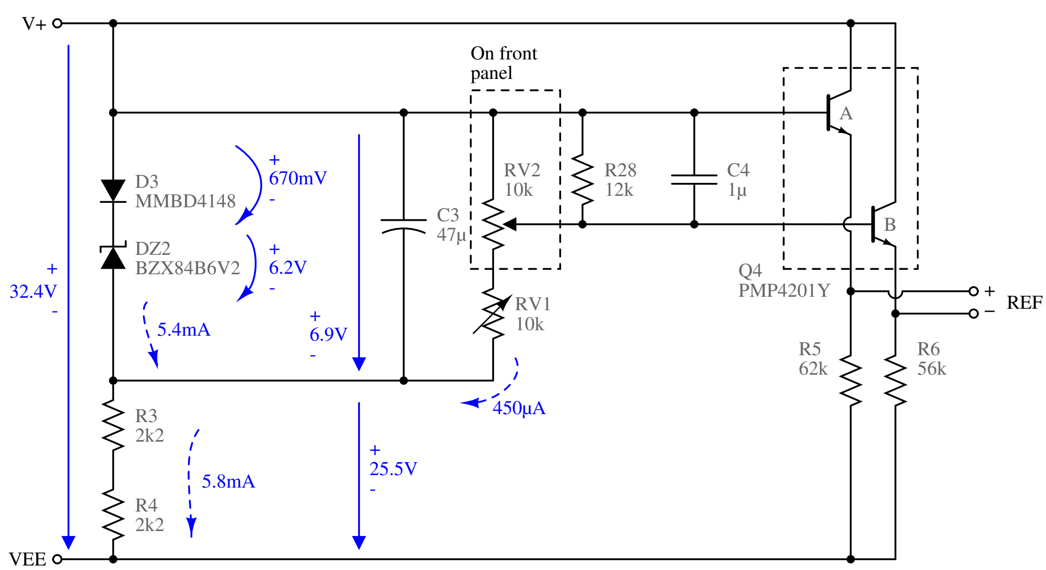

Figure 1.3: Voltage reference sub-schematic

To allow the power supply to output a fixed voltage, a voltage reference circuit is used. This is essentially a second regulator, and because it is run from the main regulator, the input power rejection compounds with that of the main regulator.

Zener diode DZ2, another BZX84-series 2 % reference diode, is combined with a standard MMBD4148 (surface-mount equivalent to the well known 1N4148) in a sort of compound diode. The reason for this is temperature coefficients:

Diode	Voltage at 5 mA bias	Temperature error, mV/°C (min)	(typ)	(max)
MMBD4148	670 mV		-2	
BZX84B6V2	6.2 V	0.4	2.3	2.7
Total	6.87V	-1.6	0.3	0.7

Note that temperature coefficient of standard silicon PN diodes like the 4148 is much more regular, so only a 'typical' value was given. This combination gives a compound diode with a typical variation of only 0.3 mV/°C, or 0.09 % over the full temperature range.

Because only a pair of resistors (a pair, rather than just one, to share heat, as they will get warm) is being used to supply current, there will be another contribution to the error from the variation in VEE, calculated above. VEE can have a drift-related (non-trimmable) error of up to 1.63 %. This translates to a variation in current through R3 and R4 of $(0.0163)(32.4\ \mathrm{V}-6.9\ \mathrm{V})/(4.4\ \mathrm{k\Omega}) = 94.5\ \mu\mathrm{A}$ in either direction. The dynamic impedance of the BZX84B6V2, listed in the datasheet, is no more than 10 Ω. The dynamic impedance of the MMBD4148 is about 20 Ω, which is not listed and must be measured from the "Forward Voltage vs. Forward Current" plot. This gives an error of up to $(94.5\ \mu\mathrm{A})(30\ \Omega) = 2.84\ \mathrm{mV}$ total, or 0.04 %. Assuming the two errors are not large enough to meaningfully affect each other, the total non-trimmable error of the primary reference is 0.13 %.

This reference voltage goes into front panel potentiometer RV2, and a section of the voltage is trimmed off by RV1 to compensate for aforementioned variations in parts. R28 ensures that if RV2's wiper becomes disconnected (a somewhat common failure mode in panel-type potentiometers), the output voltage defaults to zero. C4 provides extra filtering to remove any noise picked up by the cable running to the panel.

Q4 is a pair of NPN transistors, factory-selected to have nearly identical characteristics and mounted in one small package to ensure equal temperature. Each transistor is used to buffer one side of the reference voltage, and despite the approximately 650 mV drop, the relative voltage should still be equal because of the matched characteristics. Buffering is necessary because the error amplifier requires a known impedance of the input signals, but the impedance at the output of a potentiometer changes drastically over the range. The output impedance of an emitter follower is very low, and will be dominated by the resistors in the error amplifier.

R5 and R6 are selected to give as close to equal currents through each half of Q4 as possible, without using an active current source circuit. Using V+ as a reference ground for calculation, Q4A will always see 0 V on its base, and so its emitter will give -0.65 V. With VEE as -32.4 V, R5 will see 31.75 V, drawing 512 µA. As the potentiometer is turned, the voltage at Q4B's base and emitter will change, ranging from -0.65 V at the emitter to -5.30 V. This gives a current range through R6 from 484 µA to 567 µA, centered at 525 µA.

1.4 Voltage Error Amplifier

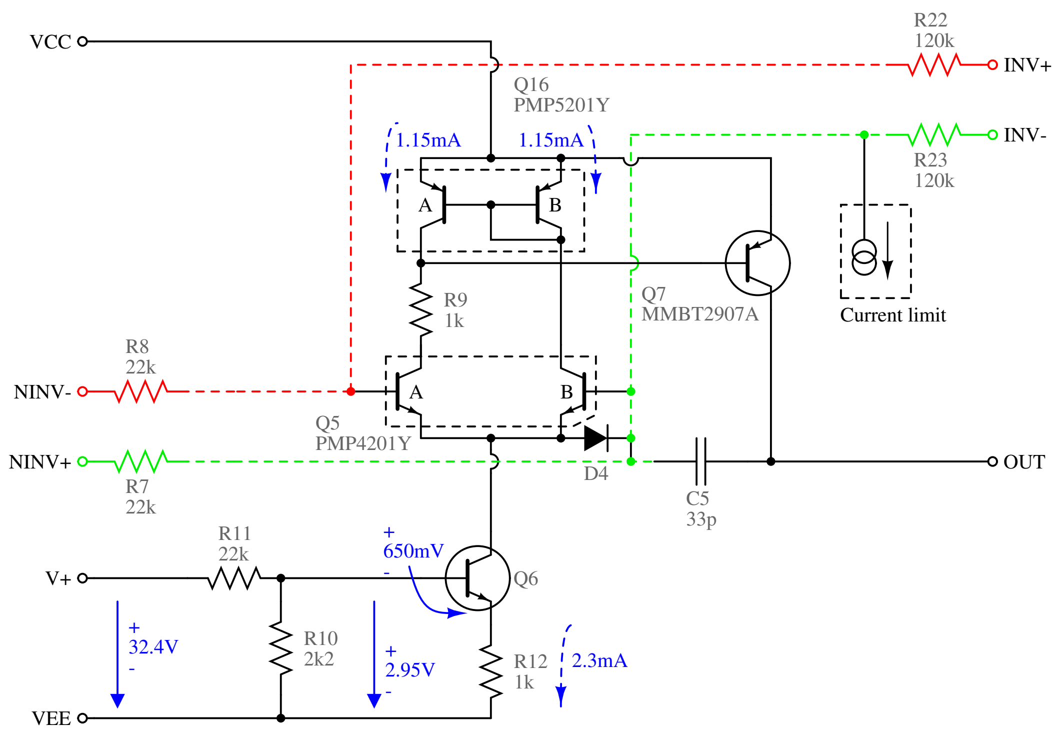

Figure 1.4: Voltage error amplifier sub-schematic

An error amplifier is a circuit which compares a reference level to the actual output, adjusting the output driver according to the amount of error present. This is done simply by subtracting the output level from the reference level, amplifying the difference by a large amount, and using this directly to control the output.

The error amplifier shown above is based on a transistor arrangement called a "long-tailed pair" or "differential pair" (Fig. 1.5). This is the heart of most differential circuits, including the operational amplifier.

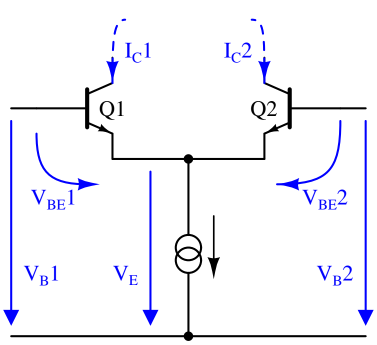

Figure 1.5: Long-tailed pair

I will spare you the mathematics of fully analyzing the long-tailed pair, because it is very easy to explain without numbers. Imagine the saturated case. This is where the two input voltages, $V_{BE}1$ and $V_{BE}2$, are vastly different, so the output is as large as it possibly can be. Suppose $V_{BE}2$ is significantly greater than $V_{BE}1$. The voltage at the emitters, V_E, must be one B-E drop less than $V_{BE}2$. This is because if it were any lower, Q2's B-E diode would be forward biased, and would begin to conduct. So Q2 will be conducting, with $I_C2 > 0$, and Q1 will not conduct, with $I_C1 = 0$, because its B-E diodes will not be forward biased. Therefore, the current draw into the transistors is determined by which of the two voltages is larger. This is a comparator.

If V_B1 and V_B2 are very close, both transistors will conduct, with the one having a larger V_{BE} conducting more. V_E will be determined by both base voltages, and since V_{BE} is just $V_B - V_E$, the current into each transistor will be determined by the *relative* voltage between the bases. This is a proper differential amplifier.

The voltage error amplifier must be a *precision* amplifier. A matched pair, Q5, is used, to make sure the gains and threshold voltages on each side are the same. Still, there is more variation that must be corrected.

First, if the two transistors draw significantly different currents, their gains and thresholds change. `Q16` is another matched pair, acting as a current mirror. `Q16B` is diode-connected, so that current may be drawn through it, and `Q16A` is transistor-connected to the same V_{BE}, so that it will pass the same current. This stabilizes the current difference between the two, and `Q6`, a simple current source, stabilizes the total current.

An error amplifier must have extremely high gain in order to be precise. This is because its operation *depends* on a small error being present. Higher gain means it will be sensitive to a smaller error. `Q7` is connected as a simple common-emitter amplifier to provide voltage gain to the output.

Feedback paths are colored in Figure 1.4. *Note: If you are reading a greyscale copy, the paths have been marked with dashed lines; the red path lies on top and runs through R8, and the green path lies underneath and runs through R7.* The red path is noninverting: if the voltage on that path is increased, the voltage on `Q7`'s collector (the output) will also increase. The green path is inverting. As an example of the corrective action of the circuit, if there is voltage loss in the positive output lead's resistance, the noninverting path will fall (as the positive output lead is connected to "INV+"), and "OUT", which drives the *negative* output lead, will fall in turn. The overall output voltage will increase, compensating for the drop in the positive lead.

`C5` exists to slow down the error amplifier. If the output drops too quickly, `C5` will begin to conduct, pulling down the inverting path, and therefore pulling the output back up. This is necessary for stability. Without it, the error amplifier can operate faster than the lag of the feedback system, causing it to "see" a delayed reading and leading to oscillation.

Both the current limiter and the thermal cutoff shut down the output by pulling the inverting path down (thus pulling the negative output up). If the path is pulled below the emitter voltage of `Q5`, `Q5B`'s B-E junction will be reverse biased, which can cause damage. `D4` limits this reverse bias to -0.7 V. Unfortunately, this provides a path for unlimited current (through `Q7` E-B, then through `Q5A` C-E, then through `D4`), so `R9` is installed to limit the current.

1.5 Current Error Amplifier

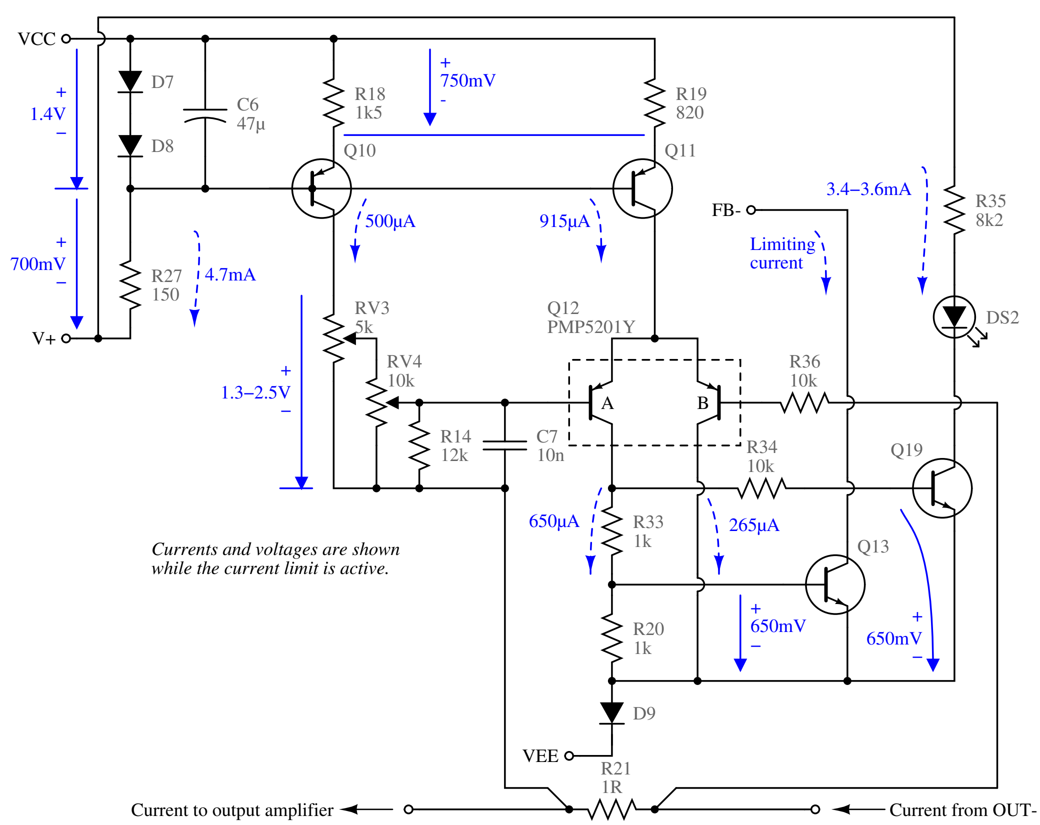

Figure 1.6: Current error amplifier sub-schematic