ALL ABOUT Switching Power Supplies

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Part 2—The basics and theory of operation were covered in the earlier installment. Now, we will take a look at two regulator IC's and show how practical circuits can be designed around them.

WITH THE FOUNDATION GAINED IN THE earlier story, we can try our hands at circuit design. The equations are simple.

Design examples

This section will present four design examples: three flyback designs using the Fairchild μA78S40 and one push-pull design using Motorola's MC3520/3420. All four designs will be chosen using the most commonly encountered input/output values.

In the first two examples, we'll assume that you have a system with only one power supply that provides +5 volts. You want to power a circuit that contains op-amps. The op-amps require a ±15-volt supply at less than 150 mA; and the output ripple must be 20 mV or less. The first example shows how to obtain +15 volts from the 5-volt supply; the second example shows how to obtain −15 volts from the same 5-volt supply.

Table 1 shows all the design equations for the step-up, step-down and inverting configurations. First, refer to Fig. 1-a for the basic design concept. Figure 4 shows the actual circuit for a step-up flyback switching regulator. Assuming that the saturation voltage of the switch (V_s) is 0.5 volt and the voltage drop across the diode (V_D) is 1 volt, then the ratio of on-time to off-time is

$$t_{ON}/t_{OFF} = \frac{V_{OUT} + V_D - V_{IN}}{V_{IN} - V_S} = \frac{15 + 1 - 5}{5 - 0.5} = 2.44.$$

The peak input current is

$$2\ I_{OUT(MAX)} \times \frac{V_{OUT} + V_D - V_S}{V_{IN} - V_S}$$

$$= 2(0.150)\left(\frac{15 + 1 - 0.5}{5 - 0.5}\right)$$

$$= 1.03 \text{ amp.}$$

Next, we choose an operating frequency of, say, 9.71 kHz. If we choose a 30-μs off-time, then the on-time is 73.2 μs and C_T is 0.01 μF. A 75-ohm resistor is used in the driver circuit to provide about 53 mA of current to the base of the switch. The value of R_{SC} is calculated as 0.33 ohm. The average input current is 0.515 mA at full load; this provides an efficiency of 87%, calculated by the appropriate equation in Table 1. The output-capacitor value is $(I_{pk} - I_{OUT})^2/2\,I_{pk} \times t_{OFF}/V_{ripple} = (1.03 - 0.15)^2/2(1.03) \times (30 \times 10^{-6}/20 \times 10^{-6}) = 555\frac{1}{2}$ μF. Therefore, choose a value $\geq 555\frac{1}{2}$ μF. The value of the inductor is calculated as 450 μH by

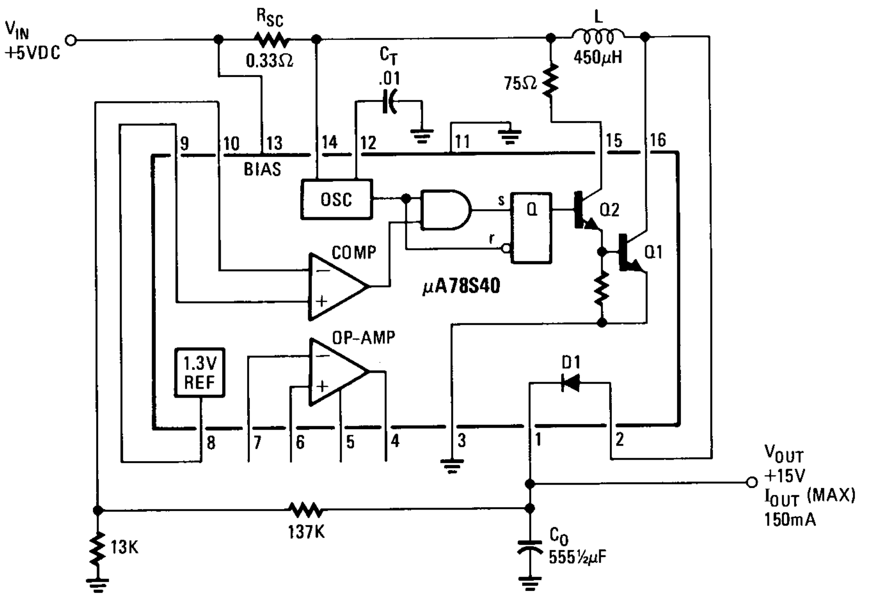

FIG. 4—STEP-UP SWITCHING REGULATOR provides +15 volts at 150 mA with 20 mV ripple from a +5 volt input.

TABLE I—DESIGN EQUATIONS for flyback switching-regulator configurations.

Characteristic	Step-up	Step-down	Inverting
$I_{IN(AVG)}$ maximum load	$\frac{I_{pk}/2}{2}$	$\frac{I_{pk}}{2} \times \frac{V_{OUT}+V_D}{V_{IN}-V_S+V_D}$	$\frac{I_{pk}}{2} \times \frac{\lvert V_{OUT}\rvert + V_D}{V_{IN}+\lvert V_{OUT}\rvert+V_D-V_S}$
Efficiency	$\frac{V_{IN}-V_S}{V_{IN}} \times \frac{V_{OUT}}{V_{OUT}+V_D-V_S}$	$\frac{V_{IN}-V_S+V_D}{V_{IN}} \times \frac{V_{OUT}}{V_{OUT}+V_D}$	$\frac{V_{IN}-V_{OUT}}{V_{IN}} \times \frac{\lvert V_{OUT}\rvert}{\lvert V_{OUT}\rvert + V_D}$
C_o	$\frac{(I_{pk} - I_{OUT})^2 \times t_{off}}{2\ I_{pk} \times V_{ripple}}$	$\frac{I_{pk} \times (t_{on} + t_{off})}{8\ V_{ripple}}$	$\frac{(I_{pk}-I_{OUT})^2 \times t_{off}}{2\ I_{pk} \times V_{ripple}}$
C_T	$45 \times 10^{-5}\ t_{off}\ (\mu s)$	$45 \times 10^{-5}\ t_{off}\ (\mu s)$	$45 \times 10^{-5}\ t_{off}\ (\mu s)$
L	$\frac{V_{OUT}+V_D-V_{IN}}{I_{pk}} \times t_{off}$	$\frac{V_{OUT}+V_D}{I_{pk}} \times t_{off}$	$\frac{\lvert V_{OUT}\rvert + V_D}{I_{pk}} \times t_{off}$
R_{SC}	$0.33\ V/I_{pk}$	$0.33\ V/I_{pk}$	$0.33\ V/I_{pk}$
t_{off}	$\frac{I_{pk} \times L}{V_{OUT} + V_D - V_{IN}}$	$\frac{I_{pk} \times L}{V_{OUT} + V_D}$	$\frac{I_{pk} \times L}{\lvert V_{OUT}\rvert + V_D}$
$\frac{t_{on}}{t_{off}}$	$\frac{V_{OUT}+V_D-V_{IN}}{V_{IN}-V_S}$	$\frac{V_{OUT}+V_D}{V_{IN}-V_S-V_{OUT}}$	$\frac{\lvert V_{OUT}\rvert+V_D}{V_{IN}-V_S}$
I_{pk}	$2\ I_{OUT(max)} \times \frac{V_{OUT}+V_D-V_S}{V_{IN}-V_S}$	$2\ I_{OUT(max)}$	$2\ I_{OUT(max)} \times \frac{V_{IN}+\lvert V_{OUT}\rvert+V_D-V_S}{V_{IN}-V_S}$

the appropriate equation. Finally the values of resistors R1 and R2 are chosen to obtain the desired output voltage. (Since the output voltage is 15 volts, let's choose the sum of R1 and R2 = 150K, so the current through the resistors is 100 μA. The voltage divider must divide by Ohm's law the 15-volt output down to 1.3 volts, the same as the reference voltage.) By Ohm's law R1 = 137K and R2 = 13K.

The second supply will provide the same 150-mA output current, from +5-volt input and the ripple on the output will be 20 mV. In this case, the output voltage will be −15. Figure 1-c shows the basic circuit configuration. The actual circuit is shown in Fig. 5. An external catch diode and a PNP transistor are required, since no pin on the IC can see a voltage more negative than the ground pin 11. The timing ratio is

$$\frac{(\lvert V_{OUT}\rvert + V_D)}{V_{IN} - V_S} = \frac{(\lvert -15\rvert + 1.0)}{5 - 0.5}$$

$$= 3.56.$$

Once again, we choose a 0.01-μf value for C_T and t_{off} = 30 μs; t_{on} = 106 μs and the operating frequency is about 7.4 kHz. The peak current is

$$2\ I_{OUT(MAX)} \times \frac{V_{IN} + \lvert V_{OUT}\rvert\ V_D - V_S}{V_{IN} - V_S}$$

$$= 2(0.150)\left(\frac{5 + \lvert -15\rvert + 1.0 - 0.5}{5 - 0.5}\right)$$

$$= 1.37 \text{ amp.}$$

Therefore, R_{SC} = 0.33 ohm, and the inductor's value is

$$\frac{\lvert V_{OUT}\rvert + V_D}{I_{pk}} \times t_{off}$$

$$= \frac{\lvert -15\rvert + 1.0}{1.37} \times 30 \times 10^{-6}$$

$$= 350\ \mu H.$$

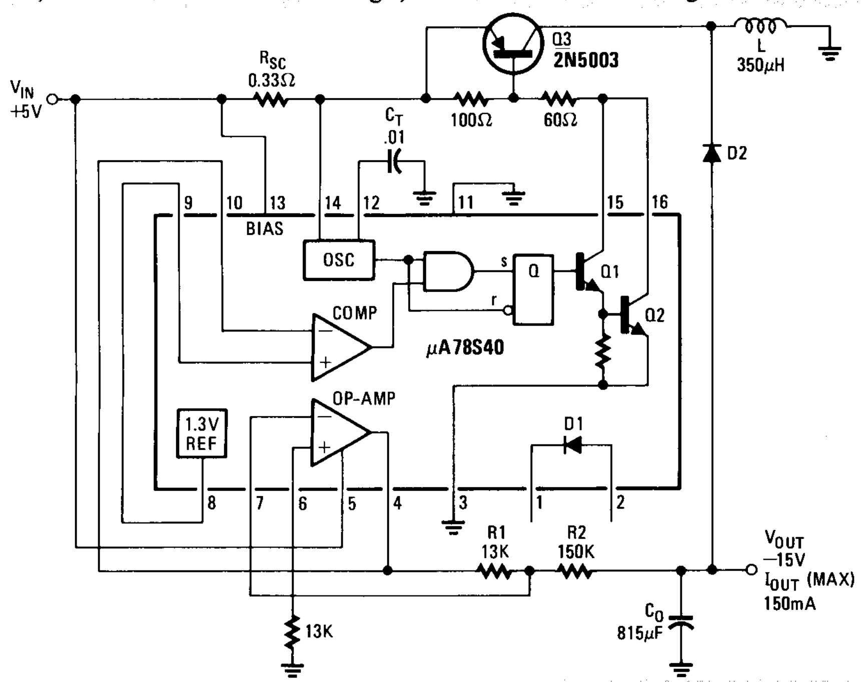

FIG. 5—INVERTING SWITCHING REGULATOR provides −15 volts at 150 mA with 20 mV output ripple from a +5 volt input. Efficiency is 84% at full load.

The average input current is 534 mA; the efficiency is 84% at full load. The output ripple is set at 20 mV by the output capacitor; its value is

$$\frac{(I_{pk} - I_{OUT})^2 \times t_{off}}{2\ I_{pk} \times V_{ripple}}$$

$$= \frac{(1.37 - 0.150)^2 \times 30 \times 10^{-6}}{2\ (1.37) \times 20 \times 10^{-6}}$$

$$= 815\ \mu F.$$

Since the op-amp's common-mode range includes ground, the internal op-amp can be used to invert the output voltage in order to compare it with the 1.3-volt reference. The gain of the op-amp circuit is $V_{OUT} = (-R_1/R_2)\ V_{IN}$; if R_1 = 13K, R_2 = 150K, and V_{IN} (output voltage of the regulator) = −15 volts, then V_{OUT} is about 1.3 volts. This is equal to the reference voltage; therefore, any voltage greater than −15 at the output will cause the comparator to change states, thus shutting off the switch.

For our third example, let's assume that you have a relay circuit that uses a 28-volt power supply. Let's assume further that you wish to add some TTL logic to allow your computer to read the status of these relays. The TTL requires a +5-volt supply; the voltage difference, $V_{OUT} - V_{IN}$, is too great for a linear three-terminal regulator to operate anywhere near efficient. Thus, we choose a switching regulator. Figure 1-b shows the basic step-down circuit. Let's assume that a 35-mV ripple is required and the maximum output current needed is 400 mA. Figure 6 shows the circuit required to meet these requirements.

For this circuit, the on-to-off-time ratio is given by:

$$t_{on}/t_{off} = \frac{V_{OUT} + V_D}{V_{IN} - V_S - V_{OUT}}$$

$$= \frac{5 + 1.0}{24 - 0.5 - 5} = 0.324.$$

If again we let C_T = 0.01 and t_{off} = 30 μs, then t_{on} is equal to 9.7 μs (the frequency is 25.2 kHz). The peak current is equal to twice the maximum output current, or 800 mA; the inductor's value then is 220 μH. Feedback resistors R1 and R2 set the output-voltage level. The feedback current should be set at 100 μA; therefore since R2 has a 1.3-volt drop when the output voltage is 5, the resistance must be 13,000 ohms. Also, at the same output voltage and feedback current, the other resistor must have a 3.7-volt drop across it; the resistance then is 37,000 ohms. Output capacitor C0 should have a value greater than 113 μF; efficiency under full load is 85%.

Since most transformer-coupled designs are of the push-pull variety as shown in Fig. 2 and Fig 3-b, we'll use this configuration as our final example.

The Motorola MC3520/3420 comprises the heart of this application (see Fig. 7). An external resistor and capacitor set the operating frequency ($f_o = 0.55/R_{ext}C_{ext}$); if R_{ext} = 11,000 ohms, and C_{ext} = 0.005 μF, then the oscillator frequency is 10 kHz. Care must be exercised in designing a push-pull power supply to insure that both transistors are never saturated simultaneously. The dead-time (the time when both transistors are shut off in order to prevent such simultaneous saturation) is a function of the oscillator frequency and the voltage applied to pin 7.

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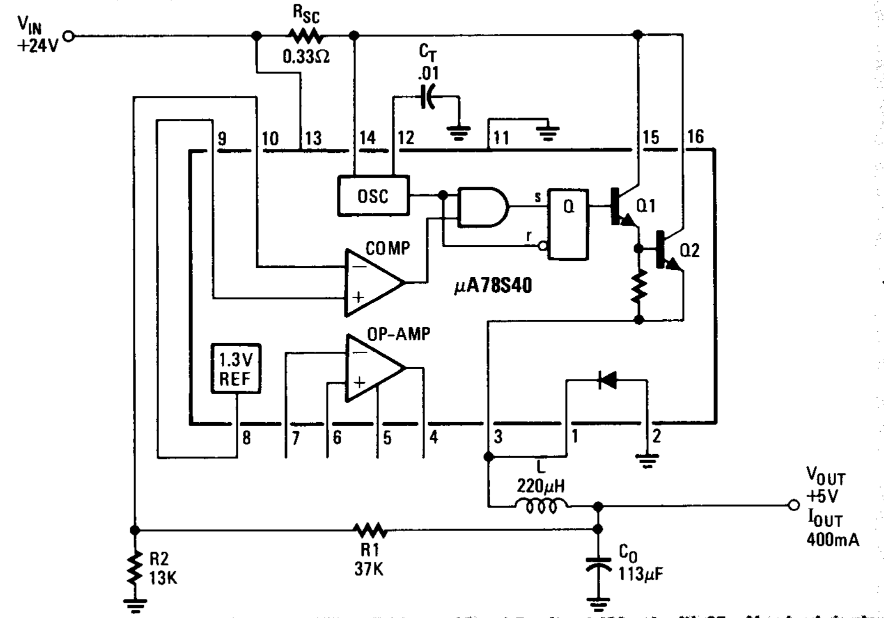

FIG. 6—STEP-DOWN SWITCHING REGULATOR provides +5 volts at 400 mA with 35 mV output ripple from a +24 volt input.

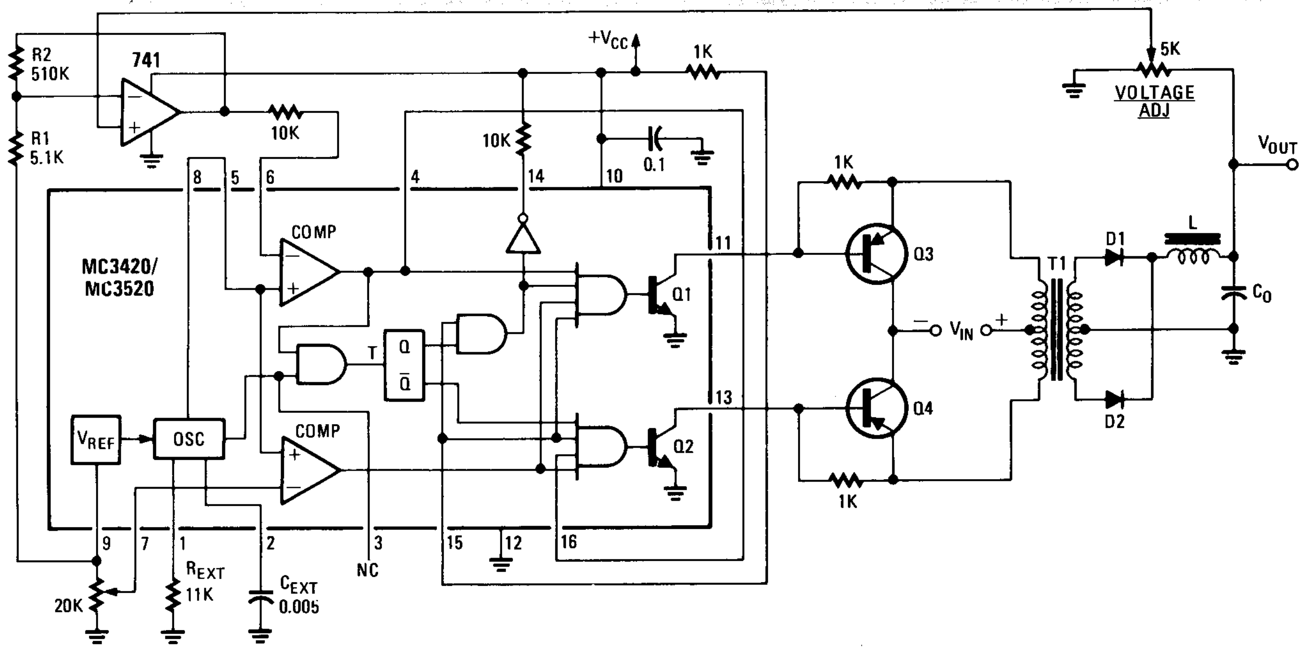

FIG. 7—PUSH-PULL SWITCHING REGULATOR using the MC3520/MC3420 IC from Motorola.