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EE321K ELECTRONICS LAB
DESIGN PROJECT RESULTS

DC STEP-UP SWITCHING POWER SUPPLY

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THE PROJECT

Design and build a DC step-up switching power supply that accepts a 10 VDC input from the lab power supply and provides a 25 VDC output with the following specifications.

Specifications: V_{out} (DC) = 25V
V_{in} (DC) = 10V
I_{out} (full load) = 100mA
Switching frequency = 30KHz
Output ripple ≤ 20mV_{pp} at full load

PREPARATION

We consulted several books on this subject, but most of the information we used came from Switching and Linear Power Supply, Power Converter Design by A. Pressman. This and the other texts we found discuss only designs using a transistor to provide the switching; we have used a MOSFET as recommended in the lab manual. The following circuit diagram comes from the Pressman text.

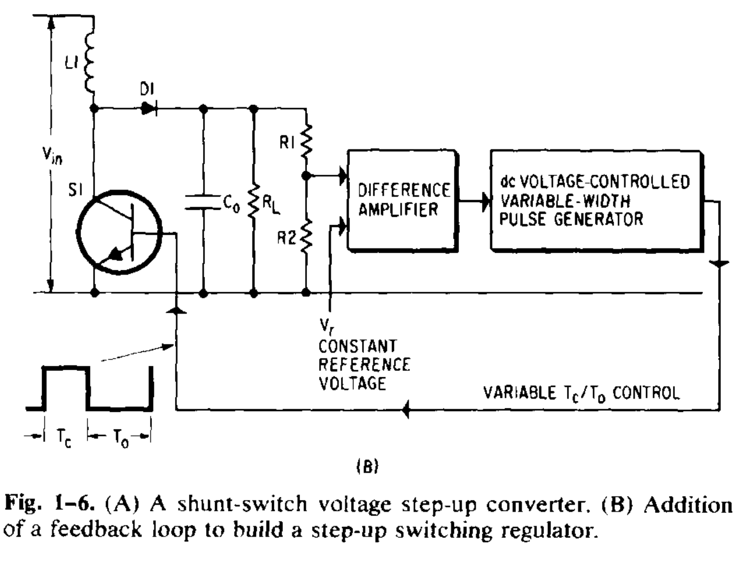
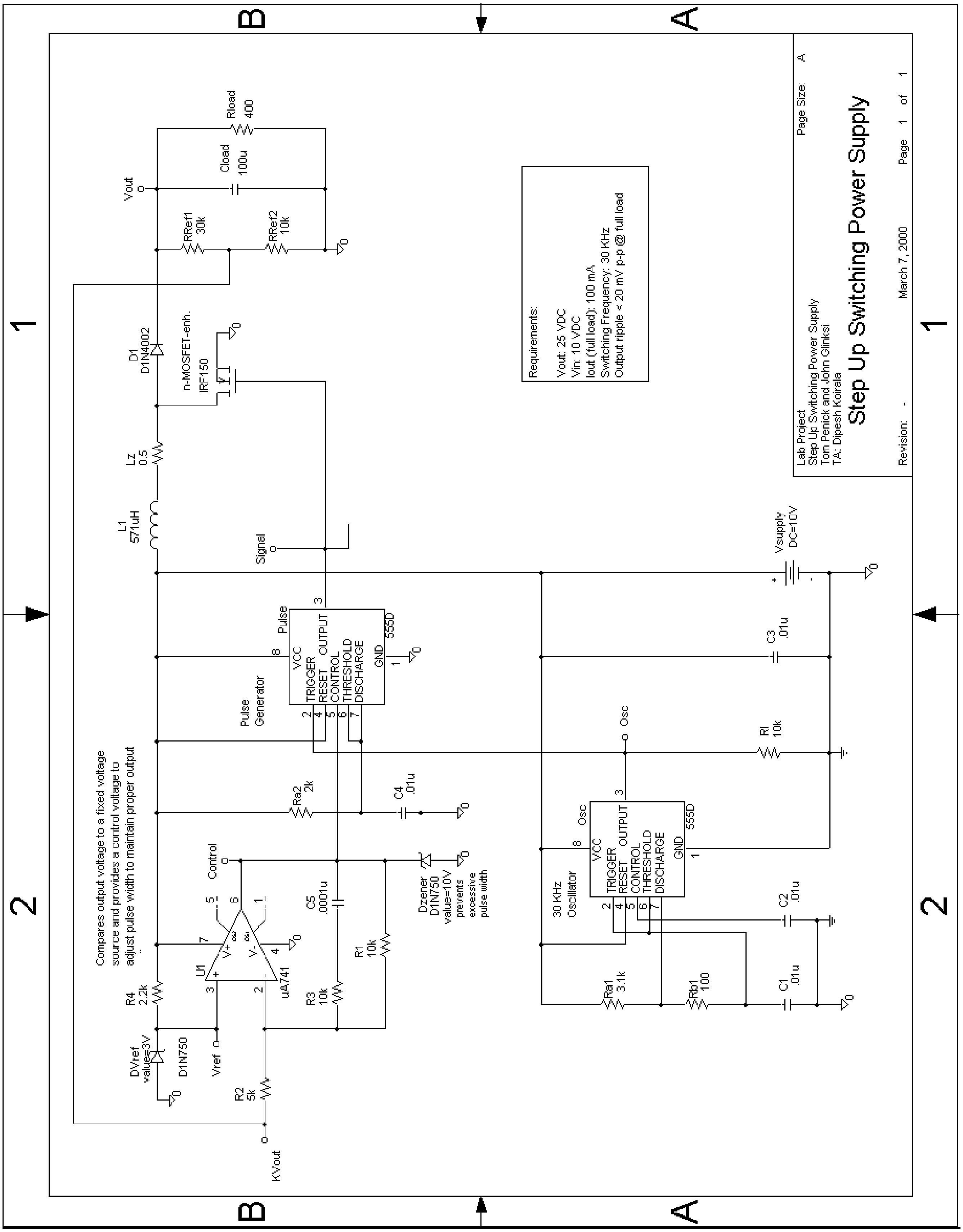


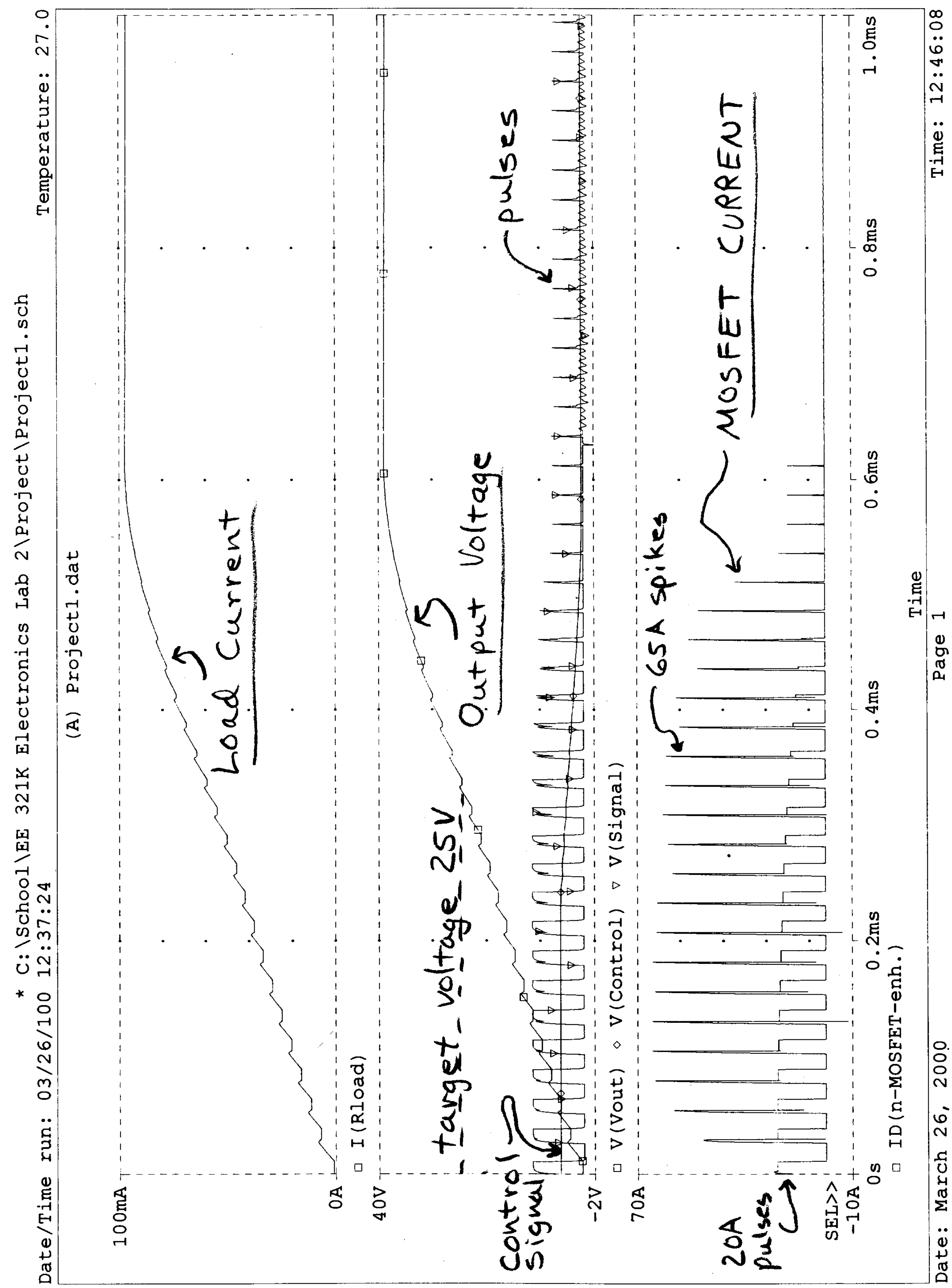
Fig. 1–6. (A) A shunt-switch voltage step-up converter. (B) Addition of a feedback loop to build a step-up switching regulator.

We modeled the circuit in Pspice using 555 timer ICs for the 30KHz clock and the pulse width modulator. Interestingly, the Pspice result showed huge current spikes in the MOSFET and 20A pulses of current as the inductor begins to charge. This seems to result in an excess of charge in the inductor and an overvoltage in the output since the inductor has enough stored charge to drive the output past the target voltage by the time the modulation control reduces the pulse width in an attempt to regulate the output. At any rate, we didn't expect this to be as much of a problem in the actual circuit since the lab supply won't deliver these high current levels.

The Pspice circuit simulation does seem to work in principle. That is, the difference amplifier control voltage output drops as the output voltage of the step-up power supply rises to the target value, and the control voltage from the difference amplifier does modulate the pulse width which controls the on time for the MOSFET. However, in practice the difference amplifier was unsuitable since the output voltage is limited by the value of the reference voltage at the input and the output of the regulator did not react *aggressively* enough to small changes in it’s input. Thus the effects on voltage regulation were weak.



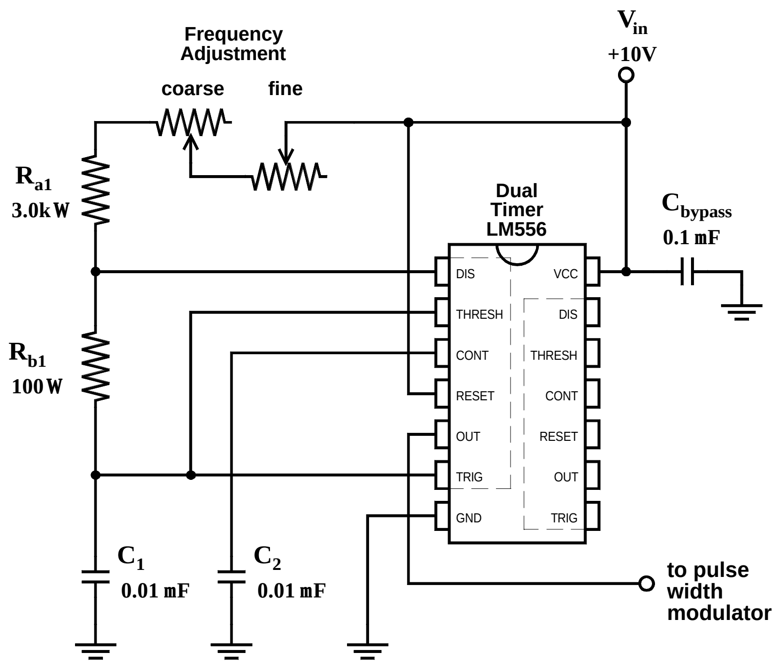
Pspice circuit diagram



Pspice results

OSCILLATOR

We used ½ of the 556 dual timer to create a 30 kHz square wave oscillator. It was found that a long duty cycle was needed so that the oscillator would not cut off the pulse from the pulse width modulator. A duty cycle of 98% was used.



Oscillator Circuit

Below is the formula relating component values to frequency. This turned out to be surprisingly inaccurate and our values had to be determined by trial and error.

Oscillation frequency:

$$f = \frac{1.46}{\left(R_{a1} + 2R_{b1}\right)C}$$

Duty cycle:

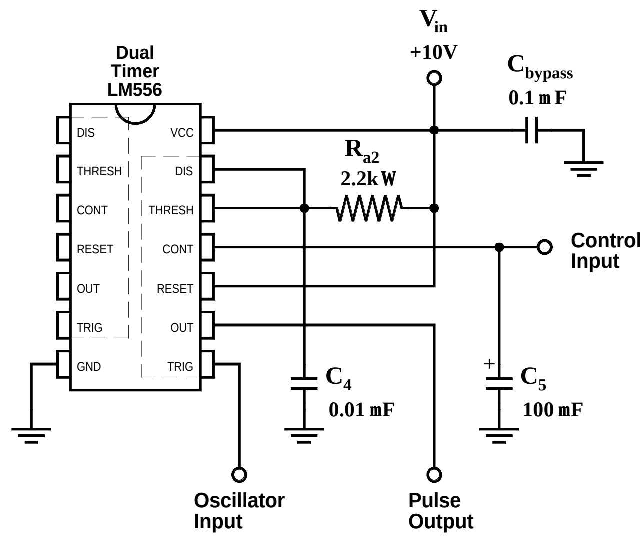
$$D = \frac{R_{b1}}{R_{a1} + 2R_{b1}}$$

PULSE WIDTH MODULATOR

We used the other half of the 556 dual timer to create the pulse width modulator.

The control input was found to float at about 2/3 V_{cc}. At this value we had wide pulses, but not a continuous pulse which would have caused a short at the voltage input. Using a pull-down type control made this a nice safety feature.

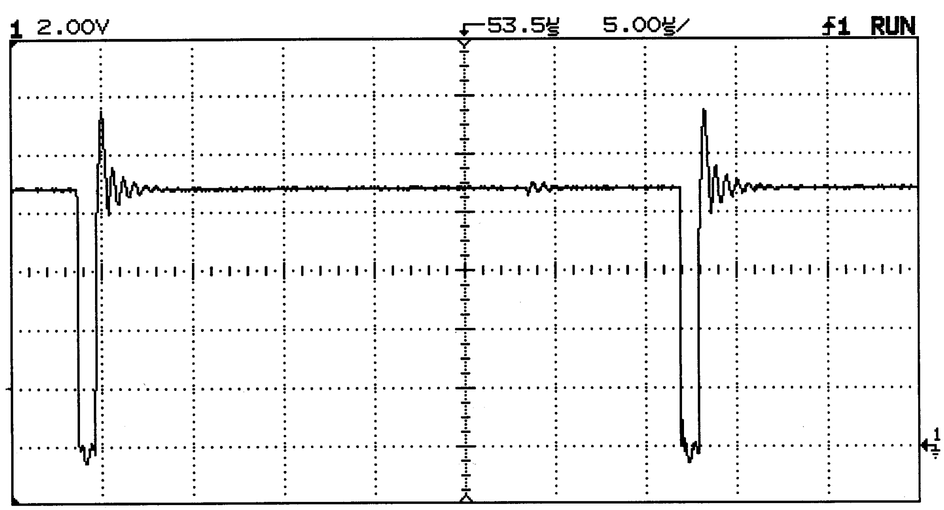
The capacitor C_5 serves to damp the controlling action to prevent overshoot.



Pulse Width Modulator Circuit

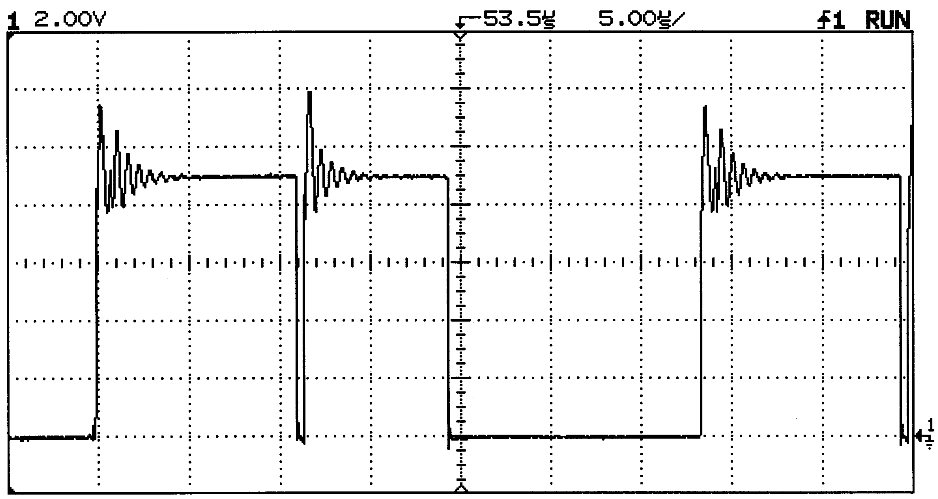
INITIAL TESTING

In the lab, we assembled and tested the 30KHz square wave oscillator and the pulse width modulator. We were able to check the frequency of the oscillator and found it to be somewhat different than what our calculations had predicted and made the necessary adjustments.



30KHz square wave oscillator output

We did observe a peculiar behavior of the pulse width generator. With an input signal of 3.36 volts, the pulse splits into two pulses. At lower and higher voltages, the problem disappears. This behavior persisted throughout most of the testing and we suspected that it might be a contributing factor in the noisy output that we were seeing. It was finally determined that this behavior only occurred when using 556 timer ICs made by Motorola (We tried five of them.) and was eliminated simply by using a 556 IC by a different manufacturer. (The 556 is a dual 555 timer.)



Splitting of the pulse from the pulse width modulator

COMPONENT SELECTION

Since we were working on a schedule and were concerned about possible delays due to damaging our supply of components, we looked for durable, overrated power components. We ordered components from Digi-Key Electronics and from All Electronics.

THE MOSFET

The function of the MOSFET transistor is to repeatedly charge the inductor by switching the input voltage through it at the rate of 30,000 times per second. Realizing that a failure of the controlling circuit could cause the MOSFET to remain closed, effectively shorting the power supply, we wanted to select a device that could handle high current. We chose the Fairchild NDP6060 n-channel MOSFET which is rated at 48 amps continuous at 25°C. The NDP6060 is designed for fast switching, low in-line power loss, and resistance to transients, and the documentation lists DC/DC conversion as one its applications. The transistor was purchased from Digi-Key.

THE INDUCTOR

The inductor must be sized so that it does not saturate at maximum output. Pressman’s book gives a formula for calculating the required value of the inductor.

$$L = \frac{\left(V_{\text{in}}\right)^2 \left(V_{\text{out}} - V_{\text{in}}\right)}{1.4 f \left(V_{\text{out}}\right)^2 I_{\text{out}}} = \frac{10^2 \left(25 - 10\right)^2}{1.4 \times 30{,}000 \times 25^2 \times 0.1} = 571\,\mu\text{H}$$

We used a J. W. Miller 5900-681, 680 μH, 1.0 amp choke, purchased from Digi-Key.

THE RECTIFIER

The rectifier acts like a one-way valve to permit current to flow from the inductor into the capacitor but prevent backflow from the 25V output to the 10V input. The rectifier must operate at the 30 kHz clock frequency, have a low voltage drop, and be able to handle the voltage and current transients of the step up power supply. We chose a Schottky rectifier by International Rectifier. Rectifier 31DQ06 has an average forward current rating of 3.3 amps, a forward voltage drop of 0.38 V at 0.5 amps, and a maximum reverse voltage of 60V. It is designed for high-frequency operation and typical applications include switching power supplies. The Schottky rectifier was purchased from Digi-Key.

THE CAPACITOR

The capacitor must supply all of the load during the periods that the inductor is being charged. Pressman's book gives a formula for calculating the value of the capacitor needed to obtain the ripple voltage specification, where ΔV_0 is the ripple voltage.

$$C = \frac{I_{\text{out}} \left(V_{\text{out}} - V_{\text{in}}\right)}{f V_{\text{out}} \Delta V_0} = \frac{0.1\left(25 - 10\right)}{30{,}000 \times 25 \times 0.02} = 100\ \mu\text{F}$$

As it turned out, we had more trouble with voltage noise than with ripple voltage. This caused us to increase the value of the output capacitor to 1000 μF. Capacitors were purchased from All Electronics.

THE CIRCUIT BOARD

Since we were dealing with power components and an experimental design, we used solder-type circuit boards for experimentation and the final project. For the experimentation stage, we mounted power components on a circuit board and soldered terminal strips to the board to permit substitution of components and the connection of the control circuit. The experimental control circuit was assembled on a separate solderless proto board. The final circuit was soldered on a 4.2” × 5.4” copper-clad circuit board from All Electronics.

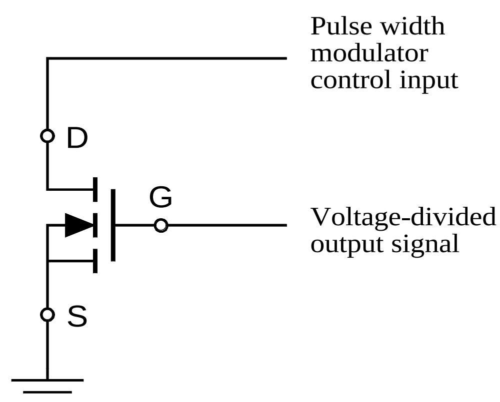
ACHIEVING VOLTAGE REGULATION

We need to regulate the output voltage at 25 VDC. Since the supply voltage is only 10 VDC, our regulator circuit must operate at voltages within this lower voltage range. We used a voltage divider on the output to obtain a voltage of about 6 VDC that varies in proportion to the 25 VDC output. A stable reference voltage is obtained from the supply voltage using a 6.2-volt zener diode. We need to compare these two voltages and send the appropriate control signal to the pulse width modulator that will cause the voltage-divided output voltage to match the reference voltage. The pulse width modulator accepts a control voltage signal with operation typically in the 3-7V range. The greater the control voltage, the more power will be delivered to the output. It is important that an upper limit be placed on this signal since a 100% duty cycle of the pulse width modulator would mean a short circuit on the supply voltage, i.e. the MOSFET is always on.

The difference amplifier, as seen in the first schematic, proved to be ineffective since its output voltage was limited to the value of the reference voltage and it did not respond with sufficient changes in output voltage to provide significant regulation.

It was found that the control input to the pulse width modulator floated at 2/3 VCC, a voltage value appropriate for maximum output power. If a regulator circuit was designed to pull down this voltage in order to exercise control, then there would be a built-in upper limit to the control voltage and it would not be necessary to worry about creating a short circuit at the input by applying an excessive control voltage.

With this in mind, we next tried using a MOSFET regulator. The voltage-divided output signal was connected to the gate so that when the output voltage went high, the gate would be high causing the MOSFET to conduct and pull the control input to ground as shown in the schematic below. This proved to be an effective regulator circuit as long as the load remained constant. But the output voltage did vary by a volt or two with different loads so we continued to search for a better solution.

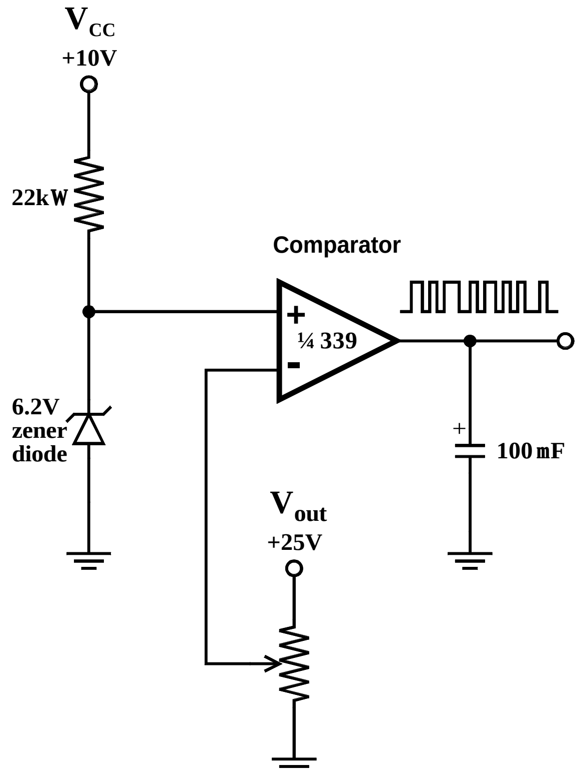


MOSFET Regulator

The MOSFET regulator did not employ a voltage reference but relied on its own gate characteristics and the appropriately divided signal from the power supply circuit output. We wanted to *compare* the divided output signal to a stable voltage reference. As we looked at various components we came across the *comparator*, an IC with which we were unfamiliar. But the name sounded promising, so we investigated the device.

The comparator is a combination analog/digital device in that it accepts analog inputs and provides a digital output. It has a negative and a positive input and an output. The voltages at the two inputs are compared and when the voltage at the negative input exceeds the voltage at the positive input, the output goes low. We used a LM339 quad voltage comparator, employing only one of the four comparators on the chip. The remaining inputs and outputs are grounded.

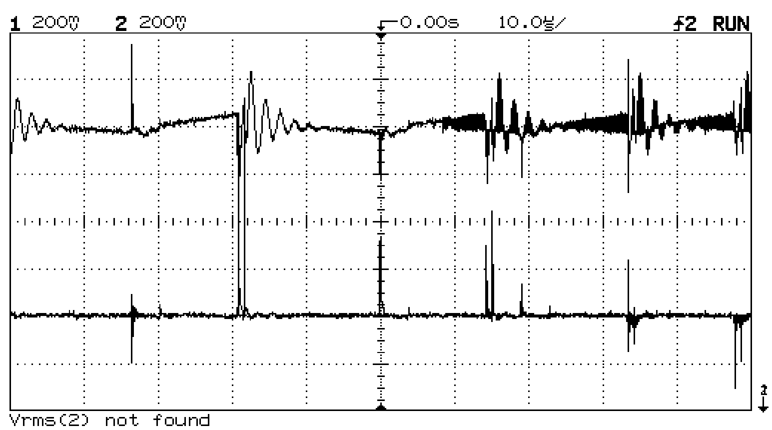
Using a zener diode, we applied a 6.2V reference signal to the positive input and connected the voltage-divided output signal to the negative input. When the voltage at the negative input exceeds the reference voltage, the output sinks to ground, otherwise the output floats. We connected the output of the comparator directly to the control input of the pulse width modulator. A 100 microfarad capacitor was added between this connection and ground to average the output of the comparator. The comparator proved to be an effective regulator with a maximum output voltage variation of 0.04V over a load range from 10% to 100% of the specified load rating.



Regulator Using Comparator

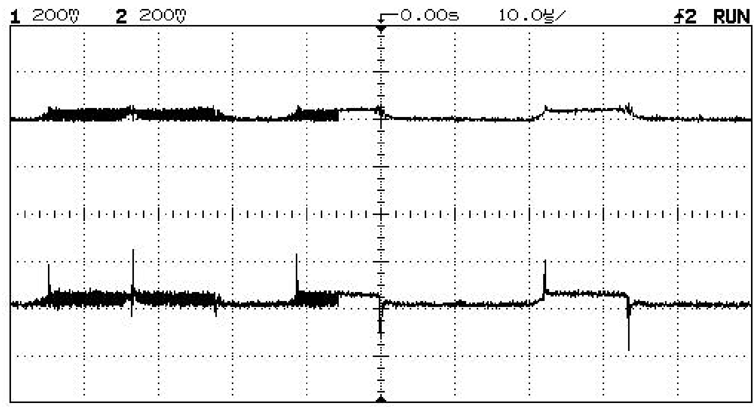
EXCESS NOISE

The final problem was reducing the noise seen in the output to within the 0.02 V_{pp} voltage ripple specification. In the oscilloscope trace at right, a voltage ripple can be seen at the input but not at the output. The noise at the output does not appear to be due to the ripple associated with the charging and discharging cycles of the inductor and capacitor, but a more random type of noise. Increasing the value of the output capacitor helped but it wasn't enough. Adding a capacitor to the input helped but that was not enough either. Since this was our initial experimental board, the wiring was rather messy so we rebuilt the circuit in a more orderly fashion.



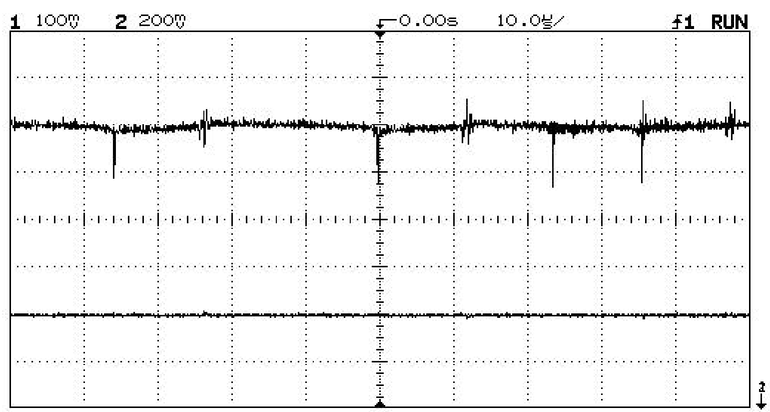
Input voltage (upper trace) and output voltage (lower trace) as seen on our experimental circuit board setup. Voltage ripples at the input appear to be associated with the 30 kHz clock frequency (period = 33.3 μs). Spikes at the output are more random with values up to about 1 V_{pp}.

We rearranged the components to shorten the interconnecting leads and separated the power components from the low-level signal components. We paid careful attention to the grounding and used separate leads from each component to a central point rather than making use of the grounding busses on the circuit board. We saw a definite improvement but output voltage spikes were still not within specifications.



Input voltage (upper trace) and output voltage (lower trace) before adding the 820 µH inductor and 470 µF capacitor at the output. Output noise appears to be about 400 mV_{pp}, substantially more than the 20 mV we are looking for.

Finally, borrowing an idea from another power supply schematic, we added an inductor in series just ahead of the output capacitor and added another capacitor in parallel ahead of the inductor. We had carefully used a central grounding location for all of our components, but found that it was necessary to separate the grounds of the two output capacitors by a length of wire. We still had noise at the main ground, but not at the final output ground. The schematic we saw used a 20 µH inductor, but all we had was an 820 µH inductor. It worked.



Input voltage (upper trace) and output voltage (lower trace) after adding the 820 µH inductor and 470 µF capacitor at the output. Output noise, which is on the 100 mV per division scale (the smallest scale available on this equipment for a 25-volt signal), is barely perceptible, less than 10 mV_{pp}, which is less than the 20 mV maximum specification.

FINAL CIRCUIT