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EELE317

February 19, 2025

Voltage Regulator Design Problem

Purpose

The system includes a step-down transformer, bridge rectifier, and Zener shunt regulator. The goal was to verify compliance with the given output voltage, ripple, and load specifications. The following specifications were expected to apply:

- Output Voltage : 5.2 V (+/- 10% over rated load)
- Output Voltage Ripple: <1% (< 52 mV pk-pk)
- Load Rating: 0 – 100 mA

Circuit Performance Specifications

	Output Voltage	Output Voltage Ripple	Load Rating
Required	4.68 V - 5.72 V	<1% (< 52 mV pk-pk)	0 – 100 mA
Simulated	5.2 V - 5.9 V	20 mV	5.9 µA – 102.9 mA
Measured	5.21 V – 5.54 V	40 mV	5.4 µA – 99.7 mA

Table 1: Specifications Comparison

Circuit Design

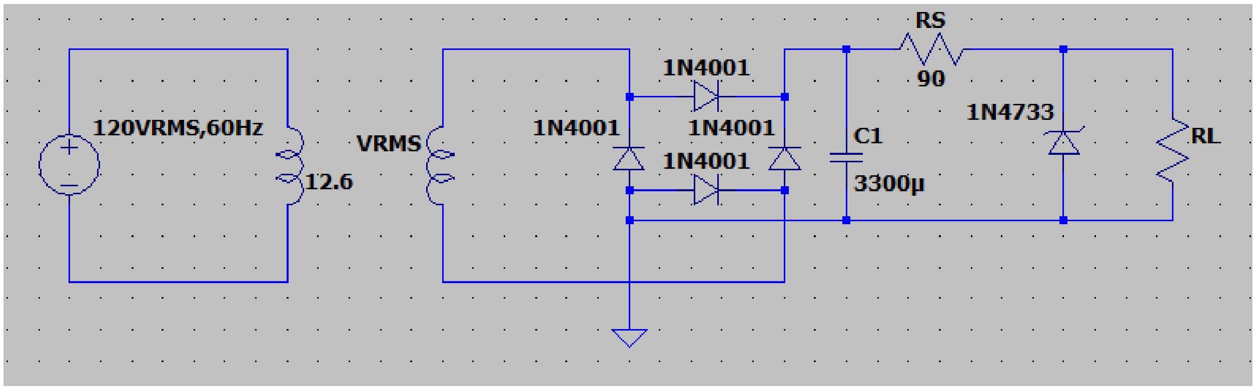

Figure 1: Circuit Schematic

120 V_{RMS}, 60 Hz to 12.6 V_{RMS}: A wall outlet providing power to a 12.6 V_{RMS} step-down transformer.

1N4001 Diodes: Rated PIV: 35 V, Peak Current Surge: 30 A

Peak Inverse Voltage applied: 16.4 V, Peak I_D applied: 9.408 A

1N4733 Zener: 5.1 V, 178 mA Maximum Current

Peak Current Applied: 141 mA

C1: 3300 µF, 50 V Rating

Peak Voltage over Capacitor: 17.8 V

R_S: 120 Ω, 1/4 W

Peak Current: 141 mA, Total Peak Power Per Resistor: 0.15 W

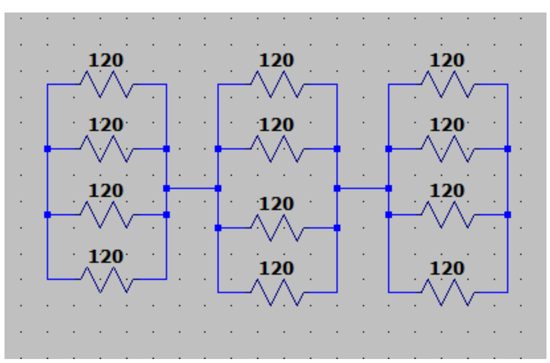

Figure 2: Full Layout of the R_S

Theory of Operation

The circuit will take a stepped-down 60 Hz 12.6V_{RMS} voltage from the wall and put it through a bridge rectifier, which will do a full wave rectification on the sine wave. The expected maximum voltage to go through the diodes in the bridge rectifier will be 17.8 V, and the current going through the diode is expected to peak at 9.408 A during start-up. The 1N4001 diodes will be able to handle these ratings in the bridge rectifier, as they are rated for 30 A peak surge. This line voltage will then be smoothed with a 3300 μF capacitor which will hold the voltage at a 700 mV ripple, with a 17.8 V peak and 17.1 V minimum. The 3300 μF capacitor is rated for 50 V, so the voltage applied over this capacitor will be safe. This will then go through a 90 Ω series resistor, which makes a peak current of 141 mA, with minimal fluctuations. With power considerations, the resistors are 1/4 W, so multiple resistors in parallel are needed to reduce the current going through each resistor. When using four in parallel, the power in the resistors is 0.15 W, which is under the power rating. The current from this is then directed to the Zener shunt, which is a Zener diode and load resistor in parallel. The 1N4733 Zener diode was used, which has a 5.1 V breakdown and can tolerate a maximum current of 178 mA. With a maximal load, the diode will be capable of handling the peak current of 141 mA. Additionally, with a breakdown voltage of 5.1 V, the Zener diode will regulate the circuit within the voltage range of 5.2 V +/- 10%. Due to the ripple from the capacitor, there will be about a 50 mV voltage ripple in the output after being regulated by the Zener.

Spice Simulation Results

The circuit was built and then simulated in LTSpice. A sinusoidal voltage supply was used instead of a transformer, and the Zener was modeled with an ideal diode and voltage supply.

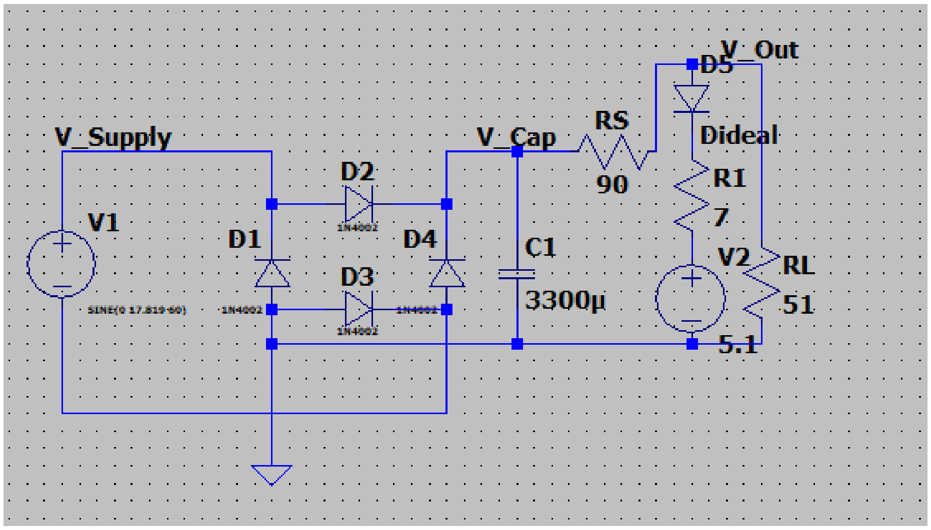

Figure 3: Circuit to be Analyzed in LTSpice

The voltage supply was rectified through the bridge rectifier with an expected voltage peak of 17.8 V. The 1N4001 Diodes all displayed the same current response, with a peak amperage of 1.57 A, with an initial current surge of 19.8 A. The 1N4001 can tolerate current surges of up to 30 A, so this current response was well within our accepted range.

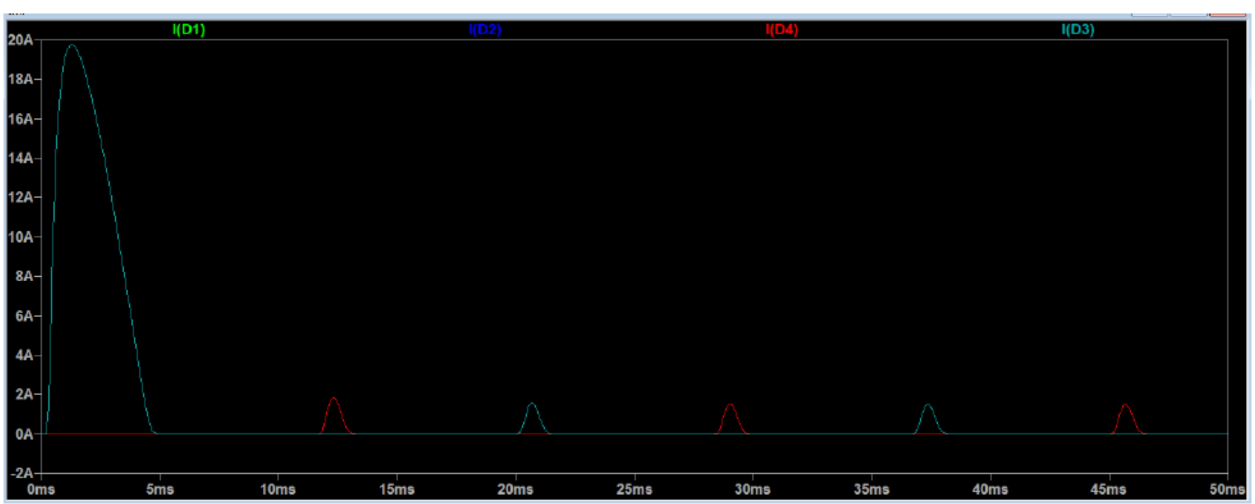

Figure 4: Current over the Diodes

The voltage over the 3300 μF capacitor causes a ripple of 16.0 V to 15.7 V. This is a 300mV ripple, which is below our calculated expected value. This difference in ripple calculation and peak voltage over the capacitor is from the lack of consideration of the voltage drop over the 1N4001 diodes. The smaller than expected voltage ripple is more desirable though, as it will result in an even smaller ripple on the output voltage.

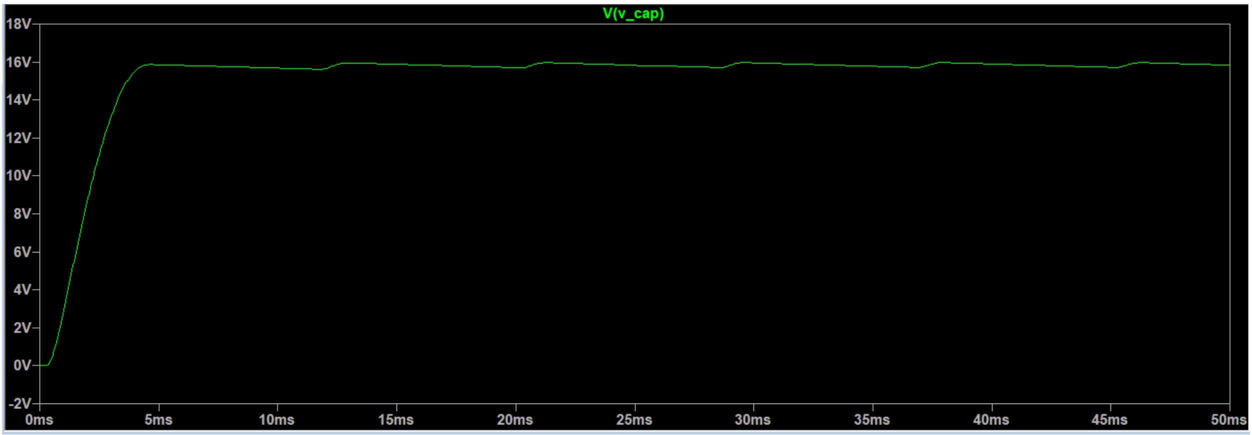

Figure 5: Voltage over the Capacitor

When the smoothed voltage goes through the series resistor, there is a peak current of 119 mA and the ripple causes the current to drop to 116 mA. With a 90 Ω resistor, the power going over the resistor would be significantly larger than what a 1/4 W resistor can handle, making it necessary to split the resistor into parallel resistors. The current being supplied is less than expected, due to calculations being done with the assumption of no voltage over the diodes whilst being on. The decrease in current will still be within range to supply sufficient current to allow for regulation across the desired load range.

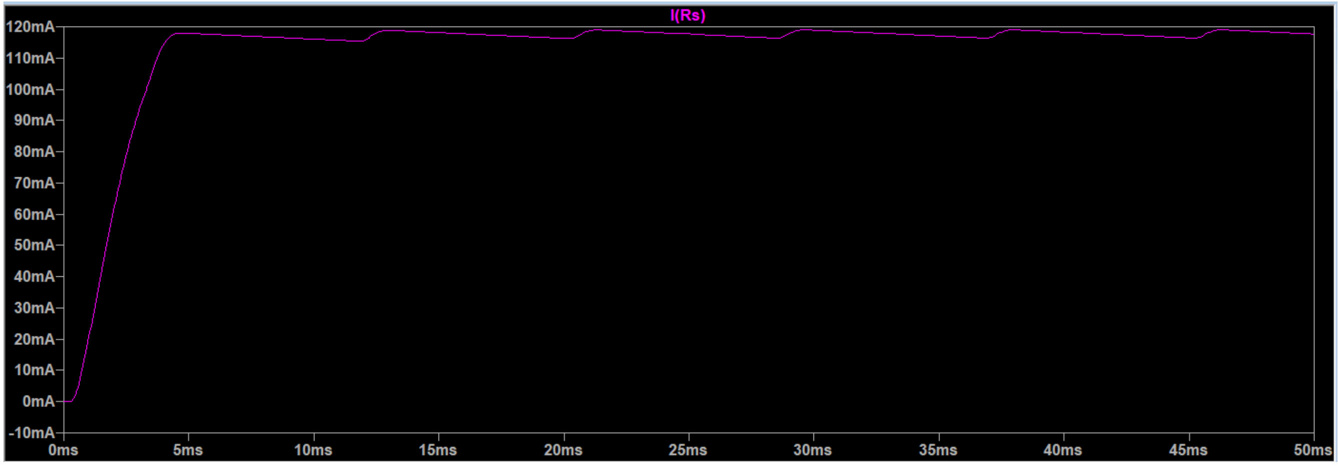

Figure 6: Current over the 90 Ω Series Resistor

Lastly, the Zener regulates the voltage over different loads. When simulated with a minimal load of 51 Ω, a small current over the 1N4733 was confirmed. This current verifies that the Zener was still properly behaving as a voltage regulator despite the minimal load. Below a load of about 50 Ω, the Zener's current drops to a negligible amount, which reveals the circuit's minimum load limitation.

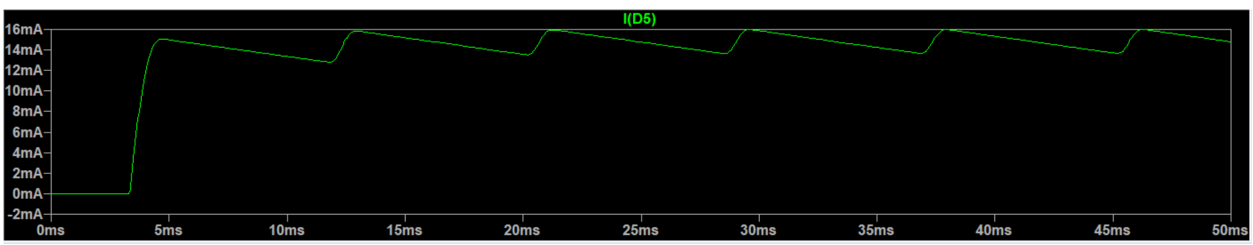

Figure 7: Current over the Zener at 51 Ω

Over a large load of 1 MΩ, and, as the load is increased, the Zener's current approaches the same current as the series resistor's current. This emphasizes the Zener's ability to regulate at high loads. Additionally, it reveals that the maximum current flowing through the Zener will be 119mA, which is below the maximum rated current for the 1N4733.

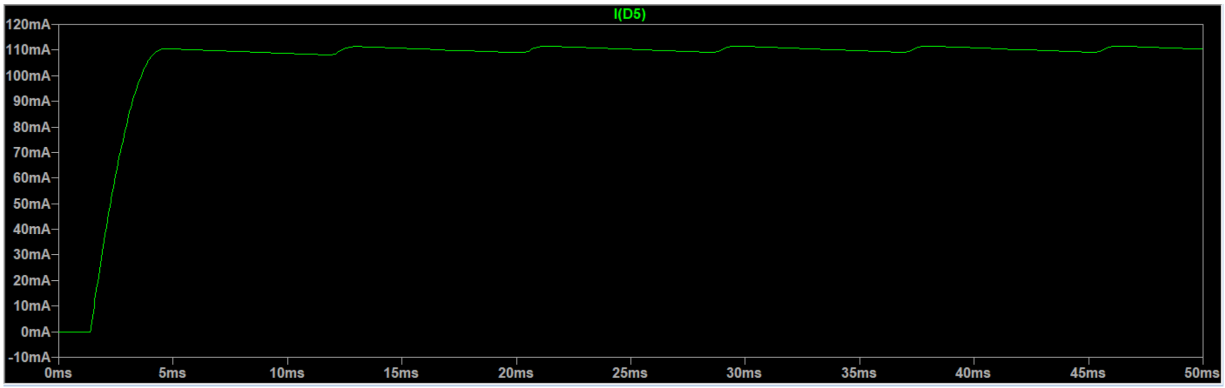

Figure 8: Current over the Zener at 1 MΩs

The voltage output at a load of 51 Ω was peak at 5.25 V, with a 20 mV ripple, with a maximum current of 102.9 mA. These values were as desired, with proper regulation occurring as the current maxed out close to 100 mA, and the voltage within our expected regulation range was produced.

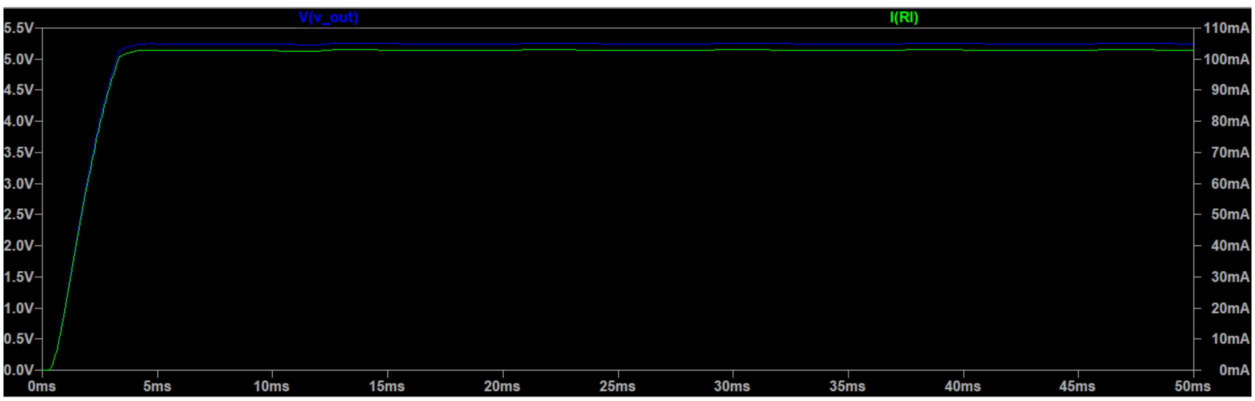

Figure 9: Voltage and Current over the 51 Ω Resistor

The voltage output at a load of 1 MΩ was peak at 5.91 V, with a 5 mV ripple, with a maximum current of 5.9 μA. These values were close to desired, with regulation occurring as the current approached zero and the voltage was close to the expected regulation range. Due to the modeling of the Zener diode, it is expected that the regulation effect was less than expected.

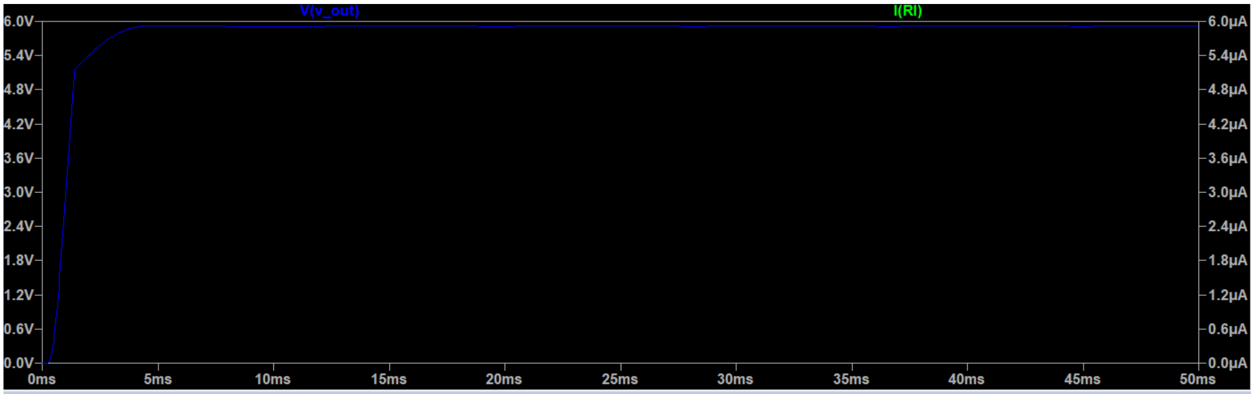

Figure 10: Voltage and Current over the 1 MΩ Resistor

Measured Circuit Performance

The circuit was then built on a breadboard and the actual performance was analyzed. First, the output voltage and load current were measured by using a digital multimeter. DCV and DCi settings on the multimeter were used to measure the values. Different loads were used to develop a response over different loads. The following table was developed with those values:

Load Resistor	Load Current	DC Voltage Output
51 Ω	99.7 mA	5.207 V
1 kΩ	5.5 mA	5.3 V
220 kΩ	25.3 µA	5.43 V
1 MΩ	5.4 µA	5.54 V

Table 2: Load Resistor, Load Current, and Output Voltage

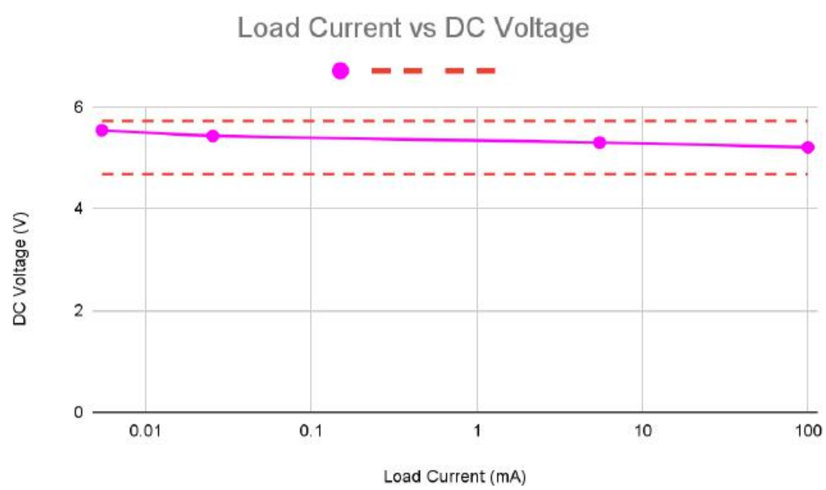

Figure 11: Output Voltage vs Load Current with design limit lines

The DC voltage of the load range was within the specified range of 5.2 +/-10%, and the current was also in the desired range. The voltage varying over the load range could be explained by the effects of the Zener's nonlinear breakdown, so more current over the Zener would cause a slight increase in the expected voltage.

Additionally, the output voltage ripple was measured by using an oscilloscope probe. When the output voltage was measured with both maximal and minimal load attached, the ripple was displayed to be 40mV, which was within the required specifications.

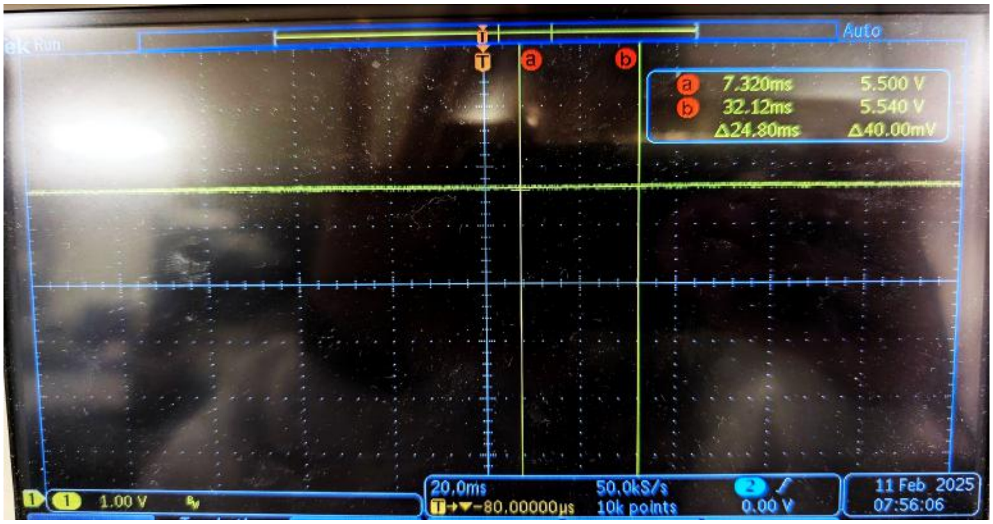

Figure 12: Voltage Output Ripple Oscilloscope Trace for 1 MΩ Load

To determine the supply regulation for the output circuit, a 1N4001 diode was put into series with the bridge rectifier. This resulted in a half wave, which an oscilloscope probe on the output could be used to monitor the voltage. Once the wave reached 4.6 V, the voltage output began to get regulated towards the desired 5.2 V. At no load, there was a 73.9% change in output over a 77% change in line voltage. At full load, there was a 21% change in output over a 77% change in line voltage. At lower loads, the range at which the Zener consistently regulated voltage was narrower, while the regulation was widened at full loads. As the Zener would get maximal amounts of current at a larger load, the regulation being more prevalent would be an expected behavior.

To verify that the diodes were operating within their expected current range, a 1.5 Ω resistor was put into series with the 1N4001 diode in the bridge rectifier. Two oscilloscope probes were then put over this resistor, and the math function was used to determine the voltage over the resistor. With a peak voltage over 1.1 V, the current on the diodes regularly peaked at 740 mA. This value was safe for the 1N4001 diodes to operate in.

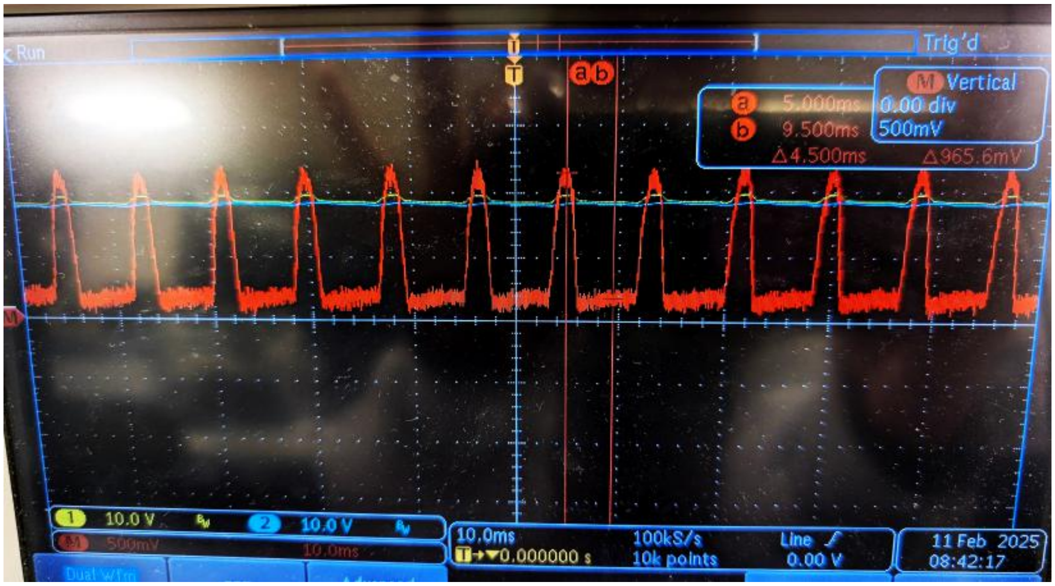

Figure 13: Voltage over a 1.5 Ω Resistor in Series with the 1N4001

Lastly, the circuit's power dissipation was analyzed by measuring current or voltage characteristics for the individual components of the circuit. The series resistor's voltage was 4.2 volts, as measured by an oscilloscope. The total power over R_S was therefore 1.764 W. Over each individual resistor the power dissipated would be 0.147 W. At the Zener diode, the datasheet's test impedance of 7 Ω and measured voltage over the Zener were used to determine a power dissipation of 3.85 W. The capacitor was found to have a dissipated power of 1.49 W by measuring the voltage change over time and multiplying it by the voltage over the capacitor and the capacitance. Lastly, the rectifier diodes were found to have a power dissipation of 10.5 µW. This small value came from the fact that when off, the diodes would have 20.9 V over it, and about 0.5µA current at the times the diodes were off. Additionally, it should be expected that there was minor power dissipation due to the connecting wires.

The power analysis reveals that the majority of power dissipation is from the Zener diode. As the Zener has to reduce the voltage and regulate it to about 5.2 V, it makes sense that it would dissipate the most power.

If using an 11.1 tap, the power dissipated would be less, as the peak voltage would be smaller, and the Zener diode would not need to dissipate as much energy. Meanwhile, the 22.2 tap would have significantly more power being dissipated on the Zener diode.

Conclusion

The circuit that was built was found to successfully meet the required specifications. To improve voltage regulation, a higher power zener could be used to ensure a more stable voltage output and a lower series resistor could increase the current for the zener to regulate. Power dissipation was a critical consideration throughout the design process, and multiple components had to be decided on based on the specifications for how much power the component could handle. Additionally, by approaching complex design problems by starting from the output, and then working backward to decide what was needed for the circuit, multiple components were chosen effectively, so that minimal changes needed to be made during the simulation of and building of the circuit.

Appendix

The following pages are attached:

- Written Design Process for HW7
- 1N4001
- 1N4733

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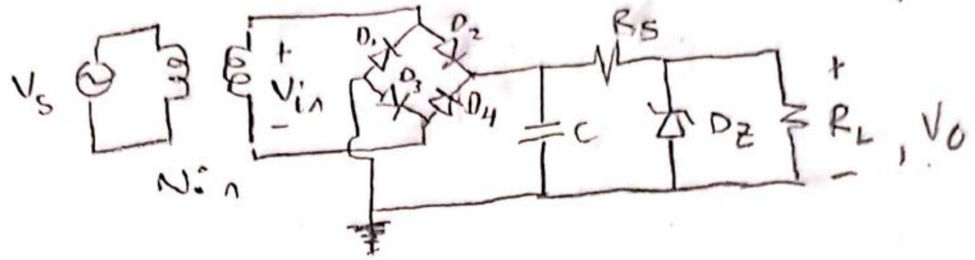
Design Process

1. The step-down power transformer, bridge rectifier, and zener shunt regulator:



2. For a load having 100 mA and no current, decide what current should be in the zener diode. The series resistor stays constant.

Zener Diode to be used:

$D_Z \rightarrow$ 1N4733 (5.1V, 1W)

$I_{Zt} = 49\,mA$, $V_{Zt} = 5.1V$, $r_Z = 7\Omega$

Max R_L & D_Z power: .8W

For R_L current of 0mA: ⇒ (min load rating)

Max current: 178 mA (80%)

$I_{DZ} \leq 142\,mA$

For R_L current of 100mA: ⇒ (max load rating)

$P_{RL} = (100mA)(5.1V) = 0.51\,W$

Zener still 5.1V, but more current flowing through R_L. To hold 5.1V, zener needs at least I_{Zt} current. But, max is 142 mA.

At 42 mA, $V_Z \approx 5.1V + (7\Omega)(42mA - 49mA) = 5.051$

V_0 needs to be 4.68V to 5.62V.

$\boxed{I_S = 135\,mA}$

ITEM # 77...

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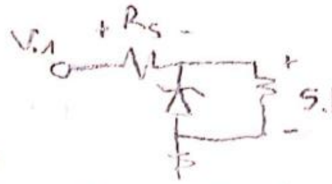
3. Using the 12.6 V_{RMS} step down transformer, choose R_S:



$$V_{max} = (12.6)(\sqrt{2})$$

$$R_S \approx \frac{V_{RS\,max}}{I_{S,\,expected}} = \frac{(12.6)(\sqrt{2}) - 5.1V}{135\,mA} = 94.21\,\Omega \qquad R_{min} = \frac{V_{RS\,max}}{142\,mA} = 89.57\,\Omega$$

V_{in} is a sinusoid, so it'll decrease slightly. This would require a smaller R_S to keep current. But, it needs to stay above R_{min}.

$$\boxed{90\,\Omega \quad (30\,\Omega \text{ in series } \times 3)}$$

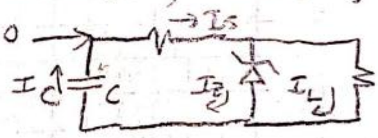
30Ω: Power $= I^2R = (0.15)^2(30\,\Omega) = 0.675\,W$ per resistor

↑ 1 W rating

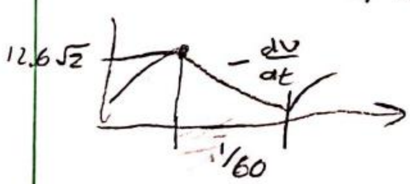
4. Capacitors: Using a 12.6 V_{RMS}, or V_{max} of 17.8 V.

Options: 330 μF, 470 μF, 1000 μF, 2200 μF

Capacitor current:



$$I_C \approx \frac{(12.6)(\sqrt{2}) - 5.1V}{90\,\Omega}$$



$$\Rightarrow I_C = I_S = 141\,mA$$

$$V_{in,\,rip} = \left(\frac{141\,mA}{C}\right)\left(\frac{1}{60}\right)$$

At V_{max}, $V_o \approx 5.1V + (7\,\Omega)(41\,mA - 49\,mA) = 5.044V$

R_L current of 100 mA & I_Z of 41 is worst case scenario for load.

V_{min} for 0.052 rip: $\frac{(5.044 \pm 0.052) - 5.1}{7} + 49\,mA = I_{in,\,min}$

$$I_{in,\,min} = 33.57\,mA$$

$$I_{S,\,min} = \frac{V_{min} - 5.1V}{90\,\Omega} = 100\,mA + I_{in,\,min}$$

$V_{min} = 17.121$, $V_{max} = 17.819$

V_{rip} due to capacitor must be under 0.698V

CamScanner

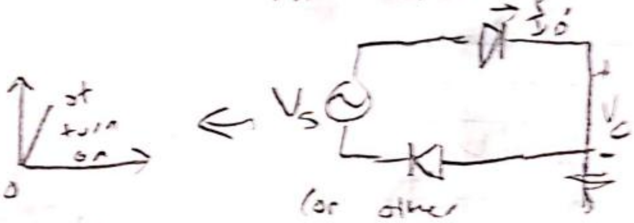
$V_{r,p}$: $0.698 \geq \left(\frac{141\,mA}{C}\right)\left(\frac{1}{60}\right)$

$C \geq 3366.8\,\mu F$

$\boxed{C = 4400\,\mu F \text{ (Two } 2200\,\mu F \text{ caps in parallel)}}$

5. The 1N4148 has a PIV of 100V and a current of 300mA.

At startup:



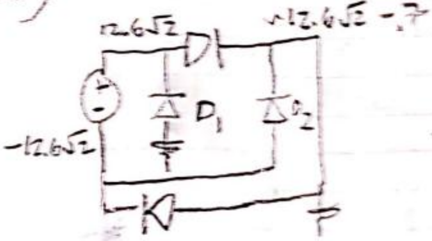
$12.6\sqrt{2}\sin(120\pi t)$

If turned on (at peak)

$\Rightarrow$ $I_D = C\frac{dV}{dt}$

$I_D = C\left(\frac{d}{dt}12.6\sqrt{2}\sin(120t)\right)\Big|_{t=0}$

$= 9.408$ A



$V_{D_1} \approx 17.8V$

$V_{D_2} \approx 17.8V$

PIV must be $> 17.8V$

The 1N4148 is not good for this application.

Instead, the 1N400X are good.

The 1N4002 will be used with $V_R = 100V$ and $I_{FSM} = 30A$.

6. The circuit was plotted on LT Spice.

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The output ripple: $5.238V - 5.216V =$
of 50Ω

$\boxed{22\,mV}$

The output ripple:
of ∞

$\boxed{\sim 0\,mV}$

capacitor's DC voltage: $\frac{15.59 + 15.9V}{2}$

$\boxed{15.7\,V}$

The diodes peak current stays under $I_{FSM} = 30\,A$, and the votage stays under 100V.

The resistor's current is where is expected, and the voltage is within range.

MAXIMUM RATINGS

Rating	Symbol	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	Unit
†Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	50	100	200	400	600	800	1000	V
†Non−Repetitive Peak Reverse Voltage (halfwave, single phase, 60 Hz)	V_{RSM}	60	120	240	480	720	1000	1200	V
†RMS Reverse Voltage	$V_{R(RMS)}$	35	70	140	280	420	560	700	V
†Average Rectified Forward Current (single phase, resistive load, 60 Hz, $T_A = 75°C$)	I_O	1.0							A
†Non−Repetitive Peak Surge Current (surge applied at rated load conditions)	I_{FSM}	30 (for 1 cycle)							A
Operating and Storage Junction Temperature Range	T_J T_{stg}	−65 to +150							°C

Stresses exceeding those listed in the Maximum Ratings table may damage the device. If any of these limits are exceeded, device functionality should not be assumed, damage may occur and reliability may be affected.
†Indicates JEDEC Registered Data

THERMAL CHARACTERISTICS

Rating	Symbol	Max	Unit
Maximum Thermal Resistance, Junction−to−Ambient	$R_{\theta JA}$	Note 1	°C/W

ELECTRICAL CHARACTERISTICS†

Rating	Symbol	Typ	Max	Unit
Maximum Instantaneous Forward Voltage Drop, ($i_F = 1.0$ Amp, $T_J = 25°C$)	v_F	0.93	1.1	V
Maximum Full−Cycle Average Forward Voltage Drop, ($I_O = 1.0$ Amp, $T_L = 75°C$, 1 inch leads)	$V_{F(AV)}$	−	0.8	V
Maximum Reverse Current (rated DC voltage) ($T_J = 25°C$) ($T_J = 100°C$)	I_R	 0.05 1.0	 10 50	μA
Maximum Full−Cycle Average Reverse Current, ($I_O = 1.0$ Amp, $T_L = 75°C$, 1 inch leads)	$I_{R(AV)}$	−	30	μA

Product parametric performance is indicated in the Electrical Characteristics for the listed test conditions, unless otherwise noted. Product performance may not be indicated by the Electrical Characteristics if operated under different conditions.
†Indicates JEDEC Registered Data

1N4728 THRU 1N4764

ELECTRICAL CHARACTERISTICS

Ratings at 25°C ambient temperature unless otherwise specified.

Type	Nominal Zener voltage[3] at I_{ZT} V_Z V	Test current I_{ZT} mA	Maximum Zener impedance[1] Z_{ZT} at I_{ZT} Ω	Z_{ZK} Ω	at I_{ZK} mA	Maximum reverse leakage current I_R µA	at V_R V	Surge current at T_A = 25°C I_R mA	Maximum regulator current[2] I_{ZM} mA
1N4728	3.3	76	10	400	1.0	100	1	1380	276
1N4729	3.6	69	10	400	1.0	100	1	1260	252
1N4730	3.9	64	9	400	1.0	50	1	1190	234
1N4731	4.3	58	9	400	1.0	10	1	1070	217
1N4732	4.7	53	8	500	1.0	10	1	970	193
1N4733	5.1	49	7	550	1.0	10	1	890	178
1N4734	5.6	45	5	600	1.0	10	2	810	162
1N4735	6.2	41	2	700	1.0	10	3	730	146
1N4736	6.8	37	3.5	700	1.0	10	4	660	133
1N4737	7.5	34	4.0	700	0.5	10	5	605	121
1N4738	8.2	31	4.5	700	0.5	10	6	550	110
1N4739	9.1	28	5.0	700	0.5	10	7	500	100
1N4740	10	25	7	700	0.25	10	7.6	454	91
1N4741	11	23	8	700	0.25	5	8.4	414	83
1N4742	12	21	9	700	0.25	5	9.1	380	76
1N4743	13	19	10	700	0.25	5	9.9	344	69
1N4744	15	17	14	700	0.25	5	11.4	304	61
1N4745	16	15.5	16	700	0.25	5	12.2	285	57
1N4746	18	14	20	750	0.25	5	13.7	250	50
1N4747	20	12.5	22	750	0.25	5	15.2	225	45
1N4748	22	11.5	23	750	0.25	5	16.7	205	41
1N4749	24	10.5	25	750	0.25	5	18.2	190	38
1N4750	27	9.5	35	750	0.25	5	20.6	170	34
1N4751	30	8.5	40	1000	0.25	5	22.8	150	30
1N4752	33	7.5	45	1000	0.25	5	25.1	135	27
1N4753	36	7.0	50	1000	0.25	5	27.4	125	25
1N4754	39	6.5	60	1000	0.25	5	29.7	115	23
1N4755	43	6.0	70	1500	0.25	5	32.7	110	22
1N4756	47	5.5	80	1500	0.25	5	35.8	95	19
1N4757	51	5.0	95	1500	0.25	5	38.8	90	18
1N4758	56	4.5	110	2000	0.25	5	42.6	80	16
1N4759	62	4.0	125	2000	0.25	5	47.1	70	14
1N4760	68	3.7	150	2000	0.25	5	51.7	65	13
1N4761	75	3.3	175	2000	0.25	5	56.0	60	12
1N4762	82	3.0	200	3000	0.25	5	62.2	55	11
1N4763	91	2.8	250	3000	0.25	5	69.2	50	10
1N4764	100	2.5	350	3000	0.25	5	76.0	45	9

NOTES:

(1) The Zener impedance is derived from the 1KHz AC voltage which results when an AC current having an RMS value equal to 10% of the Zener current (I_{ZT} or I_{ZK}) is superimposed on I_{ZT} or I_{ZK}. Zener impedance is measured at two points to insure a sharp knee on the breakdown curve and to eliminate unstable units

(2) Valid provided that electrodes at a distance of 10mm from case are kept at ambient temperature

(3) Measured under thermal equilibrium and DC test conditions

GENERAL SEMICONDUCTOR®