Report for E-design 344

by

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E-Design report # 1

July 2019

Declaration

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B. Fourie

Date: 2019/08/09 ....

Contents

Declaration **i**

Contents **ii**

List of Figures **iv**

List of Tables **v**

Nomenclature **vi**

1 Power supply system design **1**
- 1.1 System overview 1
- 1.2 Rationale 1

2 Rectifier **2**
- 2.1 Theory and related work 2
- 2.2 Design 2
- 2.3 Simulation 2
- 2.4 Measurements 3

3 Switchmode regulation **4**
- 3.1 Theory and related work 4
- 3.2 Design 4
- 3.3 Simulation 5
- 3.4 Measurements 6

4 Linear regulation **7**
- 4.1 Theory and related work 7
- 4.2 Design 7
- 4.3 Simulation 8
- 4.4 Measurements 8

5 Charge pump regulation **10**
5.1 Theory and related work 10
5.2 Design 10
5.3 Simulation 11
5.4 Measurements 12

6 System test results **13**

References **14**

Appendix A: Social contract **15**

Appendix B: Wiring safety check **16**

Appendix C: Screengrab of GitHub repo **17**

List of Figures

1.1 System diagram 1

2.1 Rectifier design with 24 V_{RMS} input 3
2.2 Rectifier Output Voltage Ripple 3

3.1 Circuit schematic of the 12V regulator 5
3.2 12V regulator tested with 18 V_{RMS} input 6
3.3 Measured 12V Regulator Output Voltage Plots 6

4.1 Circuit schematic of the 5V regulator 8
4.2 Measured 5V Regulated Output Voltage Plots 9

5.1 Circuit Schematic of the -5 V Regulator 11
5.2 Measured -5 V Regulator Output Voltage Plots 12

6.1 Full Power Supply Implementation 13

List of Tables

4.1 Table showing simulated power consumption of linear regulator. . . . 8

5.1 Table showing simulated voltage output of charge pump. 11

6.1 Table Showing Output Characteristics Of Power Supply Subcircuits. . 13

Nomenclature

Constants

Variables

P	Power	[W]
I	Current	[A]
V	Voltage	[V]
R	Resistance	[Ω]
F	Capacitance	[F]
H	Inductance	[H]
f	Frequency	[Hz]
η	Efficiency	[%]

Chapter 1

Power supply system design

1.1 System overview

A power regulation system for an AC power meter, compatible with both 24 VAC/18 VAC inputs and capable of supplying 200mA, was designed and can be seen in Fig. 1.1. The high voltage 240 VAC input to the transformer was stepped down to 24 VAC/18 VAC, with a 500 mA fuse for overcurrent protection. This output voltage was rectified to be used by the intermediary 12 VDC stage, which fed into the final regulators for the 5 VDC and −5 VDC rail voltages, which was implemented using a linear regulator and a charge pump respectively.

1.2 Rationale

In order to supply the voltages for the 5 VDC and −5 VDC power supplies the input had to be stepped down to 12 VDC to minimize power losses in the linear regulator, protect the biasing transistor for the change pump, and not to exceed any maximum voltages if a 24 VAC input was used.

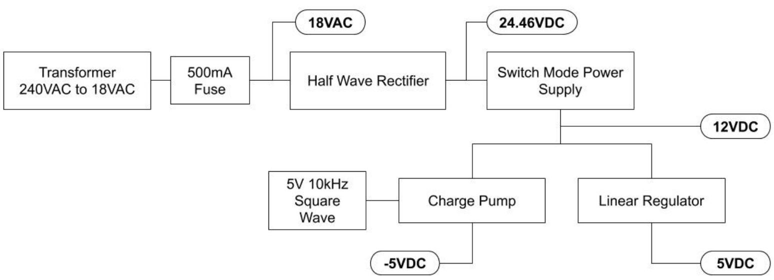


Figure 1.1: System diagram

Chapter 2

Rectifier

2.1 Theory and related work

The half wave rectifier was chosen for this design and can be seen in Figure 2.1, this was chosen as it is requires less diodes than a full wave rectifier, however since it only conducts every positive half cycle a bigger smoothing capacitor is required.

2.2 Design

Firstly a suitable output voltage, allowable output voltage ripple as well as a maximum load requirement had to be chosen. The maximum input voltage was chosen as $24\,\mathrm{V_{RMS}}$ and a ripple of 50% was chosen, it is worth noting that from [1] the voltage drop over the diode was found as $1\,\mathrm{V}$ which meant that the output voltage of the rectifier would always be $1\,\mathrm{V}$ less than the peak value of the sinusoidal input. As the $5\,\mathrm{V}$ power supply was designed to require no more than $100\,\mathrm{mA}$ and the $-5\,\mathrm{V}$ power supply no more than $150\,\mathrm{mA}$ a full load of $250\,\Omega$ was used. Referring to the 1N4007 diode datasheet it was confirmed that the full load current draw did not exceed the $1\,\mathrm{A}$ maximum forward current of the diode. Using Equation 2.1 from [2] the required capacitor was found to be $222.22\,\mathrm{\mu F}$, thus a $220\,\mathrm{\mu F}$ was chosen.

$$V_r = \frac{V_m}{fRC}. \tag{2.1}$$

2.3 Simulation

The rectifier circuit was simulated with both $24\,\mathrm{V_{RMS}}$ and $18\,\mathrm{V_{RMS}}$ inputs. With the voltage ripple given a $18\,\mathrm{V_{RMS}}$ input shown in Figure 2.2a. For a $24\,\mathrm{V_{RMS}}$

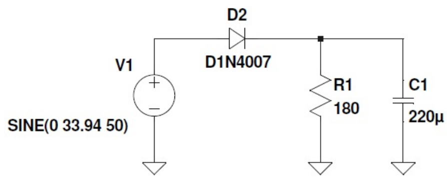
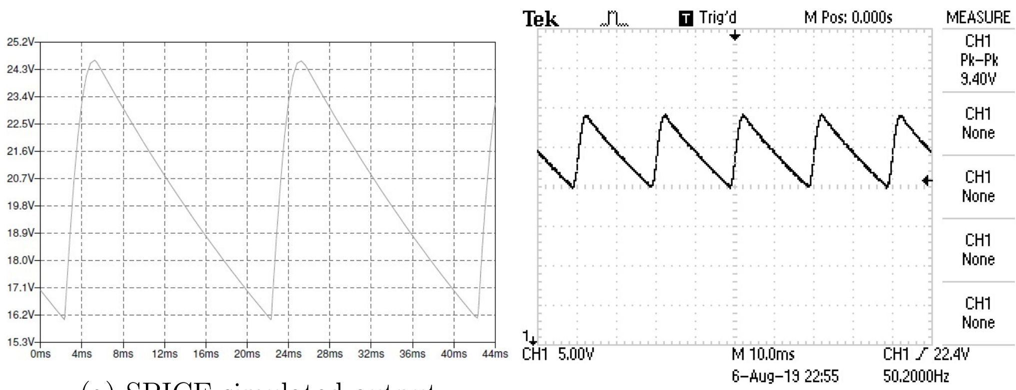


Figure 2.1: Rectifier design with $24\,\mathrm{V_{RMS}}$ input



(a) SPICE simulated output

(b) Output measured in laboratory

Figure 2.2: Rectifier Output Voltage Ripple. (a) Simulated output, (b) Measured output

input a ripple of 34.5% was reported, and for a $18\,\mathrm{V_{RMS}}$ input a ripple of 34.8% was reported, which was below the maximum ripple designed for.

2.4 Measurements

The circuit was then built and the output was measured with a full load of $250\,\Omega$. This output voltage was then measured against an input voltage of both $18\,\mathrm{V_{RMS}}$ and $24\,\mathrm{V_{RMS}}$. The ripple given a $18\,\mathrm{V_{RMS}}$ input can be seen in Figure 2.2b. Given both inputs a maximum ripple of only 36.9% was reported, which was far below the maximum ripple designed for. This allowed for a continuous current supply to all of the subcircuits and did not exceed the minimum voltage requirements of the switch mode power supply. These measurements agreed with the results that were obtained in SPICE and confirmed the design of the regulator.

Chapter 3

Switchmode regulation

3.1 Theory and related work

A buck converter was implemented to decrease the input voltage to an intermediary voltage usable by the final regulation stage. The buck converter works by charging up an inductor, which by Faraday's Law builds up an opposing voltage, and at the same time stores energy in the form of a magnetic field. If the voltage supplied to the inductor is removed it will reverse the polarity of its voltage and will supply the load with the energy stored in its magnetic field. Through this constant switching between the on and off state the converter is able to decrease the voltage from the input to the output at very high efficiency [3].

3.2 Design

A LM2595 was implemented to control the switching frequency of the switch mode power supply in order to supply an adjustable output of 12 VDC, the design is shown in Figure 3.1. The series buck regulator in the adjustable output configuration was chosen for the design so that the output could be fine tuned using a potentiometer. The input voltage ranges for the switch mode power supply was chosen as 24.46 V to 33.94 V, with a maximum load current chosen as 250 mA, this was much less than the maximum input voltage of 45 V that the regulator is rated for. From the datasheet under these circumstances the regulator operates at roughly 78% efficiency [4].
In order to set the output voltage Equation 3.1 had to be used to choose a ratio of R_1 to R_2 to supply the correct output voltage, R_1 was chosen as $1\,\text{k}\Omega$, and V_{ref} was given as 1.23 V, this gave $R_2 = 8.756\,\text{k}\Omega$. Following this a 68 µH inductor was chosen following the datasheet. Next a output capacitor C_{out} with a low Equivalent Series Resistance (ESR), smaller than 330 µF had to be chosen.

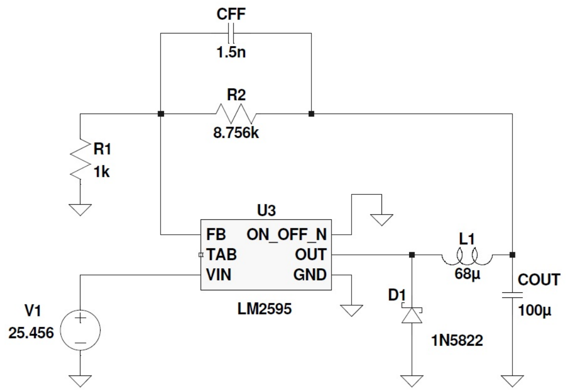


Figure 3.1: Circuit schematic of the 12V regulator

A 100 µF capacitor was chosen, however since this capacitor did not have a low ESR a decoupling capacitor had to be placed in parallel with it to remove any ripple voltage due to switching of the regulator. It is worth noting that this capacitor had to have a voltage rating 1.5 times larger than the 12V output voltage. The same procedure had to be applied for the input bypass capacitor, which was chosen as a 220 µF capacitor rated for 50 V to prevent any large transients from appearing on the input.
As an output voltage larger than 10V was chosen for this design a 1.5 nF ceramic compensation capacitor needed to be added in parallel with R_2 to provide the necessary stability. Finally a flyback diode D_1 needed to be added in parallel with the inductor to eliminate any voltage spikes during switching [5]. This diode needed to be a fast recovery Schottky diode with a maximum current rating of 1.3 times larger than the load current, and an input voltage 1.25 times larger than the maximum input voltage, for this purpose a 1N5822 was chosen.

$$V_{out} = V_{ref}(1 + \frac{R_2}{R_1}) \tag{3.1}$$

3.3 Simulation

After the circuit was designed it was simulated in SPICE to determine if it was designed for the correct output voltage, as well as to determine if it could supply the required full load voltage. Referring to Figure 3.4 it can be seen that the resistor value chosen to output 12 V, caused the regulator to output 11.9625 V with a 4 mV peak to peak oscillation at 150 kHz under full load conditions. These oscillations correspond to the internal switching frequency of the regulator.

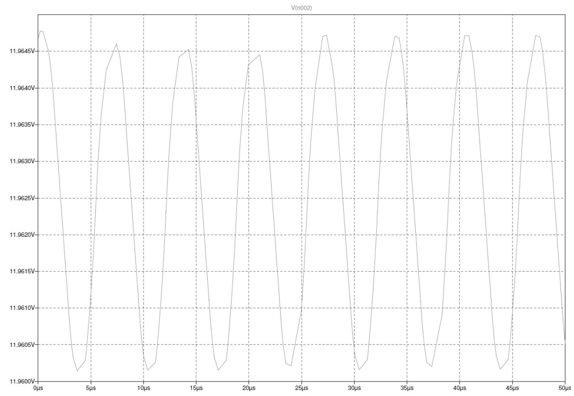
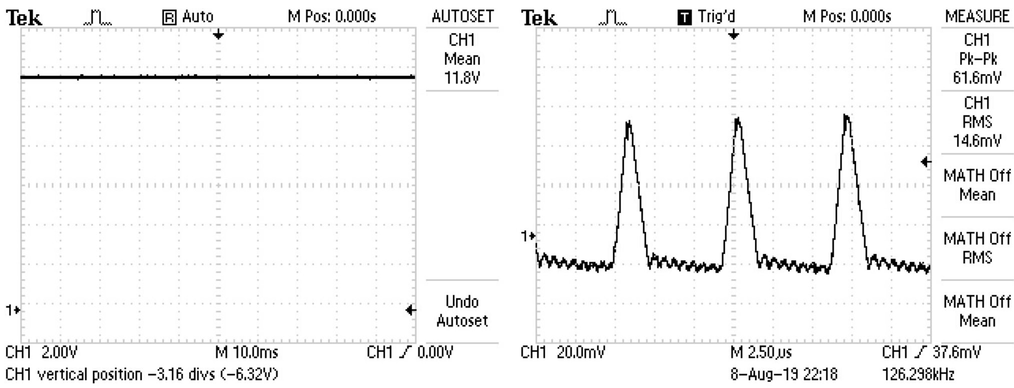


Figure 3.2: 12V regulator tested with 18 V_{RMS} input



(a) Buck converter output

(b) Noise characteristics

Figure 3.3: Measured 12V Regulator Output Voltage Plots. (a) reading showing output voltage, (b) output noise of the regulator

3.4 Measurements

After the circuit was built the output was measured and plotted using an oscilloscope as can be seen in Figure 3.3. Using a potentiometer to adjust the resistance of R_2 the output voltage was obtained as 11.8 V. The noise from the 12 V regulator was found as 61.8 mV, which was substantially higher than the result obtained in SPICE, however there were no noise level requirements for the design of the intermediary voltage supply and thus it had no negative effects on the design of the system.

Chapter 4

Linear regulation

4.1 Theory and related work

A linear regulator is a device that uses a closed feedback loop to continuously adjust a voltage divider network to maintain a constant output voltage. The main drawback of this regulation topology is that efficiency is limited as the difference between the input and output voltage is dissipated as heat.

4.2 Design

For the purpose of this design a MC78L05 was chosen, since this regulator could handle up to 35 V input voltages it was compatible with the maximum 12 V output from the intermediary voltage stage. To ensure that the integrated chip could handle the required power requirements the necessary heat sink calculations needed to be completed.
Given these design requirements a 7 V difference was induced across the input and output of the regulator, and a maximum output current of 40 mA was chosen, which was less than the 100 mA current the regulator can supply. Furthermore under these conditions a power dissipation of 280 mW can be expected, which is much less than the 750 mW maximum power dissipation the regulator is designed for [6]. By applying Equation 4.1 from [7] and choosing an ambient temperature of 25 °C, the maximum induced temperature was found to be 67 °C, which is far below the maximum allowable operating temperature of 150 °C.

$$T_{max} = P_{max}(R_{\Theta_{JA}}) + T_A \tag{4.1}$$

Referring to Figure 4.1 the capacitor C1 had to be added to the circuit if the regulator was far away from the power supply filter and served the purpose of rejecting attenuation and specifically AC noise. The capacitor C3 was added to the

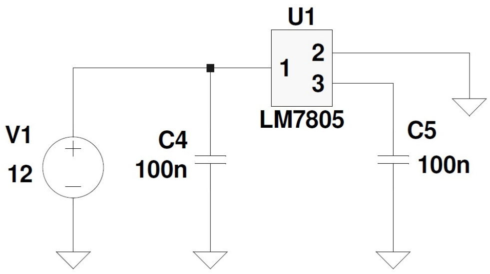


Figure 4.1: Circuit schematic of the 5V regulator

Table 4.1: Table showing simulated power consumption of linear regulator.

Load Resistance (Ω)	Output Voltage (V)	Power (mW)
No load	5.0028	60.80
1k	5.0028	95.72
470	5.0028	135.18
280	5.0028	185.70
Full load (125)	5.0028	340.8

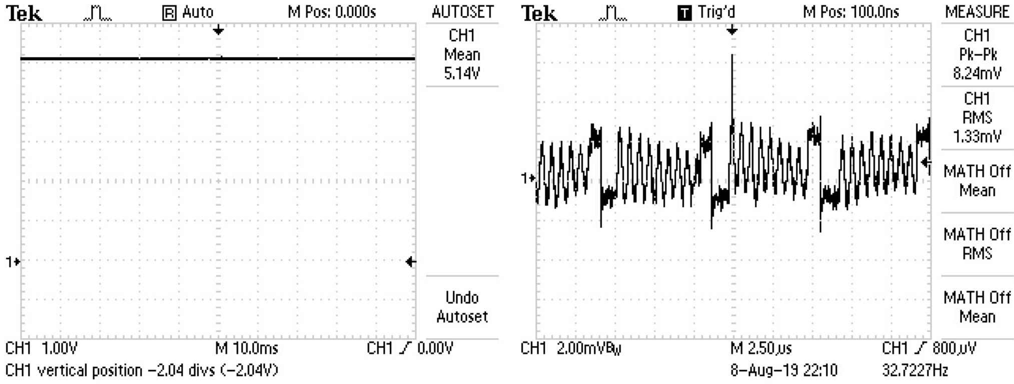
output of the regulator in order to improve stability and to improve the regulators transient response, both of these capacitors were chosen according to datasheet recommendations.

4.3 Simulation

In order to see if the designed circuit operated as required it was simulated in SPICE. The circuit was tested over a various range of load resistor values to see how much power was being consumed and to see if the output voltage remained stable.
These results were listed in Table 4.1, and as can be seen in the last column the power dissipated by the linear regulator was much higher than initially calculated. However this is not a problem as the maximum load requirements do not exceed the maximum power ratings of the linear regulator, and the regulator does not get hot enough to require a heat sink.

4.4 Measurements

The measured output voltage of the regulator was found to be 5.14 V under no load conditions, and 5.12 V under full load conditions supplying 40 mA as shown



(a) Linear regulator output (b) Noise characteristics

Figure 4.2: Measured 5V Regulated Output Voltage Plots. (a) reading showing output voltage, (b) output noise of the regulator

in Figure 4.2a. This was 2.8% higher than was designed for but still within a acceptable 5% tolerance. As can be seen in Figure 4.2b a noise level of less than 10 mV peak to peak was measured on the 5 V rail, which confirms that the regulator meets all the required specifications.
Furthermore from [6] it was found that the regulator had a maximum quiescent current of 5.5 mA, given this and a load of 120 Ω the expected efficiency of the regulator was calculated as 37.3% using Equation 4.2.

$$\eta = \frac{P_{out}}{P_{in}} \tag{4.2}$$

Chapter 5

Charge pump regulation

5.1 Theory and related work

A charge pump is a type of switching regulator that delivers power by alternatively charging and discharging capacitors and is specifically useful for supplying circuits with a low load current [8]. Charge pumps are more efficient than linear regulators as there are no heat losses and can produce an inverting output by connecting the output to ground.

5.2 Design

The design of the charge pump circuit and switching transistor implemented is shown in 1.1, here a maximum supply current of 5 mA was chosen.
The first step in designing the charge pump is deciding on a suitable charge tank capacitor C_1 that will ensure a continuous supply of current to the load. The larger the size of this capacitor the bigger the size of the maximum load. For the purpose of this design a 1 mF capacitor was chosen, and to remove any ripple voltages a 10 nF capacitor was placed in parallel with it. A secondary smaller capacitor C_2 had to be designed to discharge completely within the period of the 10 kHz pulse train to supply charge to the larger capacitor, here a low ESR 10 µF capacitor was chosen.
Since the square wave pulse train will be generated by an Arduino Beetle with a limited current supply an alternative current source had to be designed. For this purpose a common emitter configuration was chosen to provide a current gain to the output whilst providing no voltage gain, suitable collector and base resistors had to be designed such that the transistor could turn on and current could flow such as to charge up capacitor C_2.
A base resistor of 10 kΩ was chosen to minimize current losses through the tran-

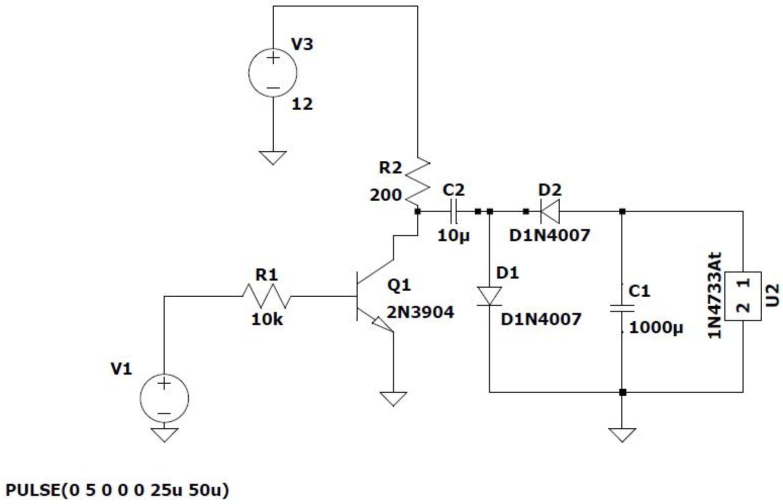


Figure 5.1: Circuit Schematic of the −5 V Regulator

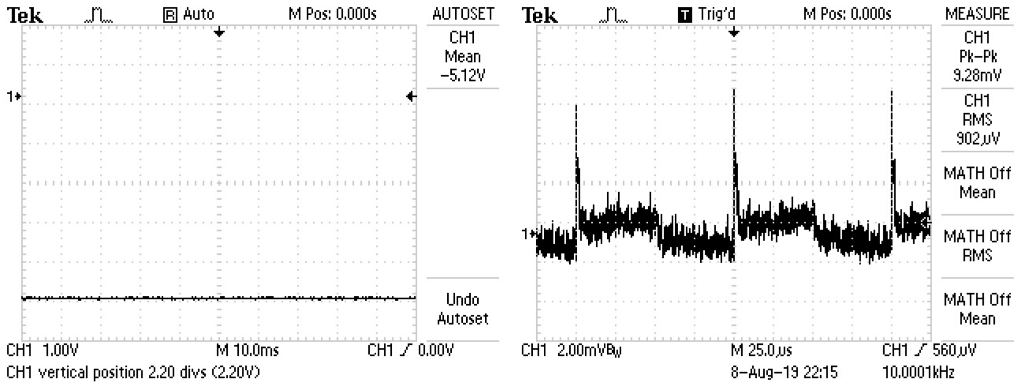
Table 5.1: Table showing simulated voltage output of charge pump.

Load Resistance (Ω)	Output Voltage (V))
No load	4.9989
10k	4.9959
4.7k	4.9923
1k	4.9575
470	4.4678

sistor, and collector resistor of 200 Ω was chosen to supply enough current to the −5 V rail and small enough to ensure that the 625 mW maximum power rating of the transistor would not be exceeded.

5.3 Simulation

After simulating the circuit in SPICE and testing it under various loads the output voltage was measured and tabulated in Table 5.1. It was found that a stable −5 V could be supplied by the regulator under load conditions not exceeding 5 mA, for load conditions exceeding this limit the supply voltage dropped drastically.
The theoretical efficiency of this charge pump circuitry was found by calculating the power dissipated in the load and summing all of the power into the charge pump and applying Equation 4.2. The regulator had an extremely low efficiency of 8.16% and a half Watt rated resistor had to be chosen for the collector resistor.



(a) Charge pump output (b) Noise characteristics

Figure 5.2: Measured −5 V Regulator Output Voltage Plots. (a) reading showing output voltage, (b) output noise of the regulator

5.4 Measurements

It was found that the charge pump supplied a stable −5.12 V output under no load conditions as can be seen in Sub figure 5.2a, with noise not exceeding 9.28 mV peak to peak as can be seen in Sub figure 5.2b. A 10 kΩ was applied to the output of the −5 V regulator and the output was measured using an oscilloscope, it was found that the output voltage level dropped to −4.76 V under a load drawing roughly 5 mA.
This result did not agree with what was obtained in SPICE, however it only deviated from the expected result by 5% which was within the expected tolerance. It was found that by increasing the voltage output of the switch mode power supply to 15 V increased the amount of current that the charge pump could supply at a −5 V output, however this increased power losses in the driver transistor circuitry.

Chapter 6

System test results

The power supply system was implemented successfully as can be seen in Figure 6.1, all of the sub circuits were tested under various circumstances and passed all of the design requirements, with all of the crucial system measurements tabulated in Table 6.1.

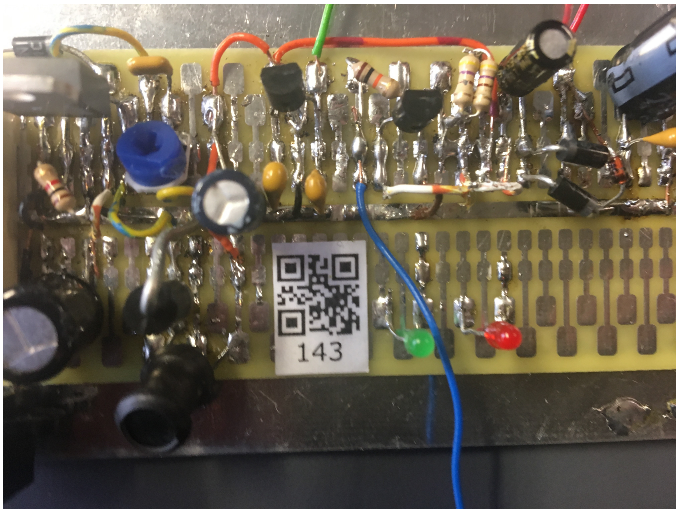


Figure 6.1: Full Power Supply Implementation

Table 6.1: Table Showing Output Characteristics Of Power Supply Subcircuits.

Power Supply	Output Voltage (V)	RMS Noise (mV)	Measured Noise (mV_{pp})
Switch Mode Power Supply	11.81	15.3	60.8
Linear Regulator	5.08	0.786	4.88
Charge Pump	-5.00	0.175	3.44

References

[1] *General Purpose Plastic Rectifier*. Vishay, 2011.

[2] Neaman, D.: Informal public transport in Sub-Saharan Africa as a vessel for novel Intelligent Transport Systems. In: *Microelectronics: Circuit (ITSC 2013)*, pp. 767–772. Oct 2013. ISSN 2153-0009.

[3] Gao, D.W.: Chapter 3 - Interfacing Between an ESS and a Microgrid. In: *Energy Storage for Sustainable Microgrid*, pp. 79–121. Jan 2015. ISBN 978-0-12-803374-6.

[4] *LM2595 SIMPLE SWITCHER*. Texas Instruments, 2013.

[5] Ravi: What is a flyback diode? 2019.
Available at: `https://www.electronicshub.org/flyback-diode-or-freewheeling-diode/`

[6] *3-Terminal 0.1 A Positive Voltage Regulator*. Fairchild Semiconductor, May 2002.

[7] Perold, W.: Topic: Heat sink notes. Class Lecture, 2019.

[8] Schweber, B.: What is a charge pump and why is it useful? (part 2). 2017.
Available at: `https://www.powerelectronictips.com/charge-pump-useful-part-2/`

Appendix A: Social contract

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E-design 344 Social Contract

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The purpose of this document is to establish commitment between the student and the organisers of E344. Beyond the commitment made here, it is not binding.

In the months preceeding the term, the lecturer (Thinus Booysen) and the Teaching Assistant (Stefan Gerber) spent countless hours to prepare for E344 to ensure that you get your money's worth and that you are enabled to learn from the module and demonstrate and be assessed on your skills. We commit to prepare the demis for the lab sessions, to set the tests and assessments fairly, to be reasonably available, and to provide feedback and support as best and fast we can. We will work hard to give you the best opportunity to learn from and pass analogue electronic design E344[1].

Signature: .... Date: 2 / 08. / 2019

....

I, ... have registered for E344 of my own volition with the intention to learn of and be assessed on the principals of analogue electronic design. Despite the potential publication of supplementary videos on specific topics, I acknowledge that I am expected to attend the lectures and lab sessions to make the most of these appointments and learning opportunities. Moreover, I realise I am expected to spend the additional requisite number of hours on E344 as specified in the yearbook.

I acknowledge that E344 is an important part of my journey to becoming a professional engineer, and that my conduct should be reflective thereof. This includes doing and submitting my own work, working hard, starting on time, and assimilating as much information as possible. It also includes showing respect towards the University's equipment, staff, and their time.

Signature: .... Date: 2/08/2019

[1] Find Stefan, Thinus, or one of the demis to sign this section

1

Appendix B: Wiring safety check

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E-design 344 Plug to fuse safety check

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Wire up the power plug to the high-voltage side of the transformer, the connectors and cable on the low-voltage side of the transformer, and the fuse. Get a demi sign off on the check list below. Include a scanned copy of the signed form as an appendix to your report.

- [x] Live and Neutral wires the right way around.
- [x] Wires tightenend properly.
- [x] Plug cover attached properly with screw.
- [x] No loose strands inside plug.
- [x] Cut 24V wire terminated safely.
- [x] Clear physical separation between the wires in the low-voltage side connectors
- [x] Fuseblock connected in in series immediately downstream from connector.

Signature .... Date: 26/07/2019

Name and surname Bradley Fourie

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Appendix C: Screengrab of GitHub repo