August 11, 2019

Report for E-design 344

by

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E-Design report # 1

Declaration

By submitting this report electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualifcation.

Signature: ....
A. Muthua

August 11, 2019
Date: ....

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Nomenclature

Constants

g =	$9.81\,\mathrm{m/s^2}$

Variables

C	Capacitance	[F]
Q	Charge	[C]
i	Current	[A]
P	Power	[W]
R	Resistance	[Ω]
Θ	Thermal resistance	[°C/W]
V	Voltage	[V]

Abbreviations

BJT	Bipolar Junction Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
AC	Alternating Current
DC	Direct Current

Chapter 1

Power supply system design

1.1 System overview

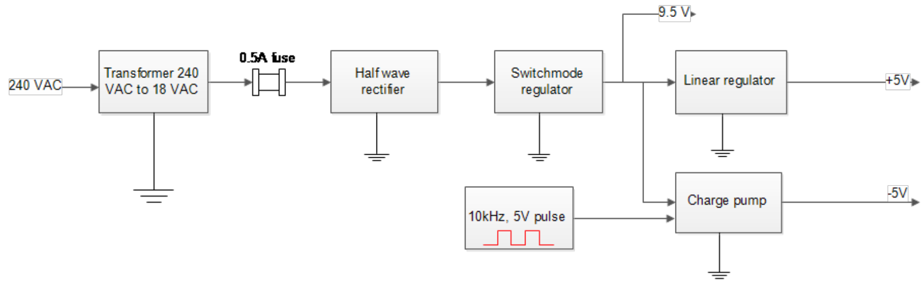


Figure 1.1: System diagram

1.2 Rationale

The 240 VAC to 18 VAC transformer was provided for this design, to avoid the risk associated with working directly with the mains supply voltage. As only a half wave rectifier is implemented in the design the AC return can be directly connect to the DC ground. The rectifier provides a positive voltage that is passed through two stages of regulation.

The switchmode regulator is connected to the rectifier as it is more efficient at higher input voltages [1]. However,it produces significant noise in its output which is unwanted in this device's application. So, the switchmode is adjusted to give an intermediate voltage that drives a linear regulator to give a 5 V supply, and a charge pump scheme to supply −5 V.This allows for minimal noise in the 5 V rail, and increases the efficiency of the charge pump scheme.

Chapter 2

Rectifier

2.1 Theory and related work

A basic half-wave rectifier consists of a diode in series with a sinusoidal input voltage. This allows only the positive cycle of the input to appear at the output. Adding a shunt/filter capacitor to the rectifier's output allows for current to flow continuously as the capacitor discharges during the cutoff period of the diode [2].

2.2 Design

Design rationale
For this design, the main consideration is that the capacitor is large enough to supply current to the rest of the circuit at the required voltage. This is calculated in Equation 2.1. However, the current flowing through the diode is also a concern as a 0.5 A fuse is installed in the design. So, it must be ensured that any transient charging currents are not large or sustained enough that the fuse blows. The 1N4007 diode used here has a peak reverse voltage of 700 V[3] which is more than sufficient.
Design calculations
Capacitor calculation:

$$\begin{aligned} dQ &= i \times dt = C(V_{pk} - V_{min}) \\ C &= \frac{200\,\mathrm{mA} \times 0.02}{18\sqrt{2} - 0.7 - 12} = 313.6\,\mu\mathrm{F} \end{aligned} \tag{2.1}$$

Ideally, a 330 μF capacitor would be used. However, due to the voltage rating of the available capacitors, two 220 μF capacitors were instead used.

Diode current[2]:

$$i_{D,peak} = i_{load}(1 + \pi\sqrt{\frac{2V_M}{V_r}}) = 200\,\text{mA} \times (1 + \pi\sqrt{\frac{2(18\sqrt{2} - 0.7)}{18\sqrt{2} - 0.7 - 12}}) \tag{2.2}$$
$$= 1.438\,\text{A}$$

This is higher than the fuse rating. However, the melting time of the fuse at this current is: $\frac{0.215}{1.438^2} = 104\,\text{ms}$[4]. This is much higher than the maximum positive cycle period of 10ms. Hence, it can be assumed to be safe enough.

Circuit diagram

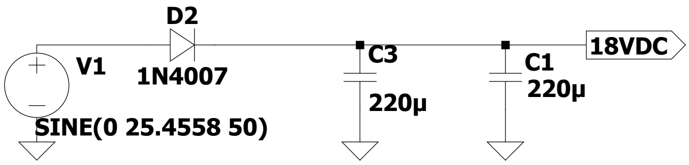
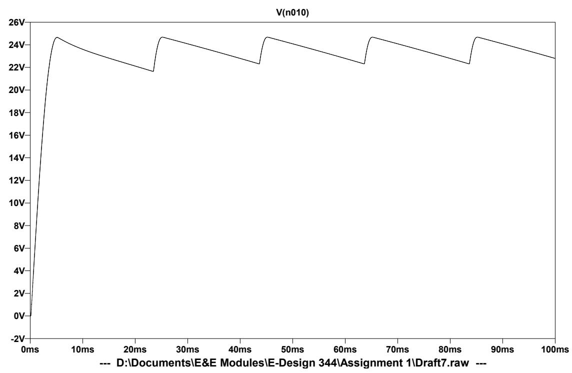
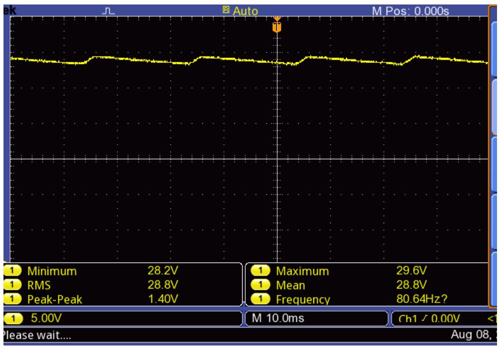


Figure 2.1: Half wave rectifier circuit

2.3 Simulation



(a) Simulated rectifier output.



(b) Measured rectifier output.

Figure 2.2: Rectifier simulated and measured output

2.4 Measurements

Chapter 3

Switchmode regulation

3.1 Theory and related work

Switchmode regulators operate by rapidly switching an energy storage device on and off. The duty cycle and frequency of the switch sets how much charge is transferred to the load. This, in turn determines the output voltage of the regulator. These regulators can be used to step down(buck) or step up(boost) a given input voltage. The series storage device is usually either fully conducting or switched off, thus, the regulator tends to dissipate almost no power. This gives it quite a high efficiency. Due to the switching operation of the regulator, it produces a significant ripple voltage at its output. However, it is a much better choice if the input voltage is much higher than the output voltage [1].

3.2 Design

Design rationale
As explained in Section 1.2, the switchmode regulator is used to give an intermediate voltage of that is then passed through the linear regulator designed in Section 4.2. This intermediate voltage is also used to power the charge pump scheme in Section 5.2. The intermediate voltage is chosen as 9.5 V as shown to be sufficient in Section 5.2.

In terms of the design of the regulator, the device's datasheet provides a sufficient circuit that is implemented in the design [5].The components listed below and shown in Figure 3.1 are all chosen based of [5], which provides the appropriate values to use for a wide reange of applications.

- A low ESR capacitor is required at the input pin to prevent large voltage transients from appearing, and to provide the instantaneous current required each time the switch turns on.

- A feedforward capacitor adds lead compensation to the feedback loop and increases the phase margin for better loop stability.
- An output capacitor is required to filter the output and provide regulator loop stability. Low impedance/ ESR capacitors designed for switching regulator applications must be used.
- Buck(step-down) regulators require a diode to provide a return path for the inductor current when the switch turns off. Because of their very fast switching speed and low forward voltage drop, Schottky diodes provide the best performance.
- An inductor at the output is used to store energy such that current continuously flows, even when the regulator is "switched off". An inductor of 330 μH is suggested, but a smaller inductor is already provided. So, it is used as it will provide just as much or more continuous current.
- Resistors, R1 and R2 in Figure 3.1, are used to adjust the output voltage as shown in Equation 3.1.

Design calculations
Feedback resistors/ Adjusting voltage output [5]:

$$\begin{aligned} V_{out} &= (1 + \frac{R_1}{R_2})V_{ref} \\ R_1 &= R_2(\frac{V_{out}}{V_{ref}} - 1) = 1k(\frac{9.5}{1.23} - 1) \\ &= 6.724\,\mathrm{k}\Omega \end{aligned} \tag{3.1}$$

A 10 kΩ variable resistor is placed at R_1 and set to give the required output voltage.
Circuit diagram

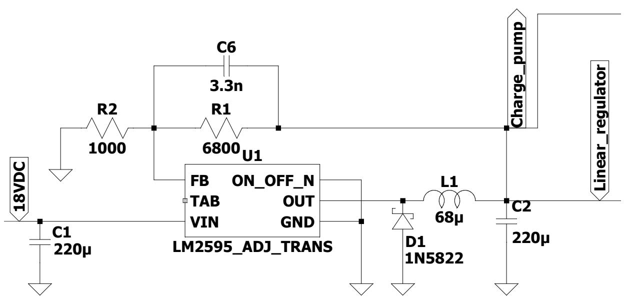


Figure 3.1: Switchmode regulator circuit.

3.3 Simulation

A plot of the LTSpice switchmode regulator simulation is given in Figure 3.2.

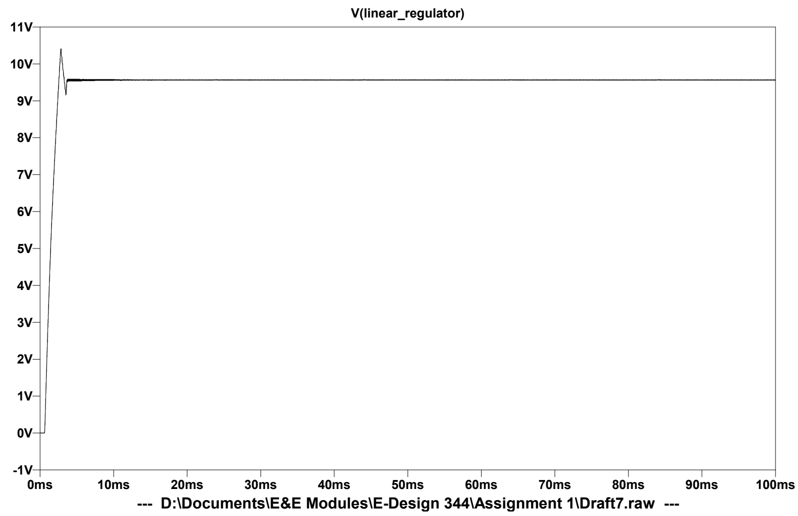


Figure 3.2: Simulated switchmode output.

3.4 Measurements

The measured output voltage from the switchmode is given in Figure 3.4.

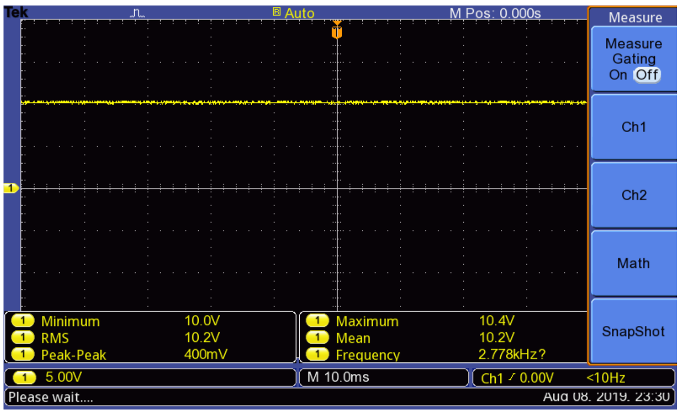


Figure 3.3: Switchmode output voltage

Figure 3.4: Switchmode measured output

Chapter 4

Linear regulation

4.1 Theory and related work

Linear regulators behave like variable resistance devices, where the internal resistance is varied in order to maintain a constant output voltage. In reality, the variable resistance is provided by means of a transistor controlled by an amplifier feedback loop. They reject any input voltage ripple and are able to produce steady voltage outputs with very little noise. However, they are quite inefficient as they dissipate the difference between the input and output voltage as heat. Thus, they are a poor choice if the output voltage is much lower than the input voltage, as is the case in this design [1].

4.2 Design

Design rationale As explained in Section 1.2, the linear regulator is used to remove the noise produced by the switch-mode regulator. For efficient working of the linear regulator, the input voltage should not be too high. The maximum such voltage is calculated in Equation 4.1 below.

The input and output capacitors are taken from the device datasheet [6]. The input capacitor is not included in the design since the input pin is connected to the output of the switch-mode regulator, that already has a 220 μF capacitor. This is much larger than the 330 nF specified. A 100 nF output capacitor is included to improve the transient response.
Design calculations

Input voltage:

$$
\begin{aligned}
P_{dissipated,max} &= V_{in,max}I_{in} - V_{out}I_{load} \\
P_{dissipated,max} &= \frac{T_{J,max} - T_{air}}{\Theta_{JA}} \\
&= \frac{150 - 25}{150} = 833.33\,\text{mW}
\end{aligned}
$$

$$
\begin{aligned}
V_{in,max} &= \frac{P_{dissipated,max} + V_{out}I_{load}}{I_{load} + I_Q} \\
&= \frac{0.8333 + (5 \times 100m)}{100m + 2m} \qquad (4.1) \\
&= 13.072\,\text{V}
\end{aligned}
$$

A 9.5 V input is chosen as it meets the above requirement as well as that of the charge pump in Section 5.2.

Circuit diagram

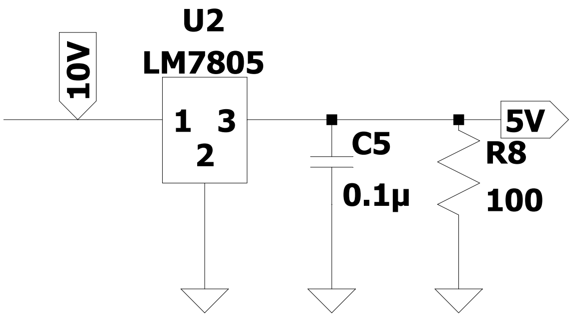


Figure 4.1: Linear regulator circuit.

4.3 Simulation

A plot of the LTSpice linear regulation simulation is given in Figure 4.2.

4.4 Measurements

A plot of the measured output voltage from the linear rectifier is given in Figure 4.3. This contains both the DC voltage level (Figure 4.3a) as well as the noise levels under AC coupling (Figure 4.3b).

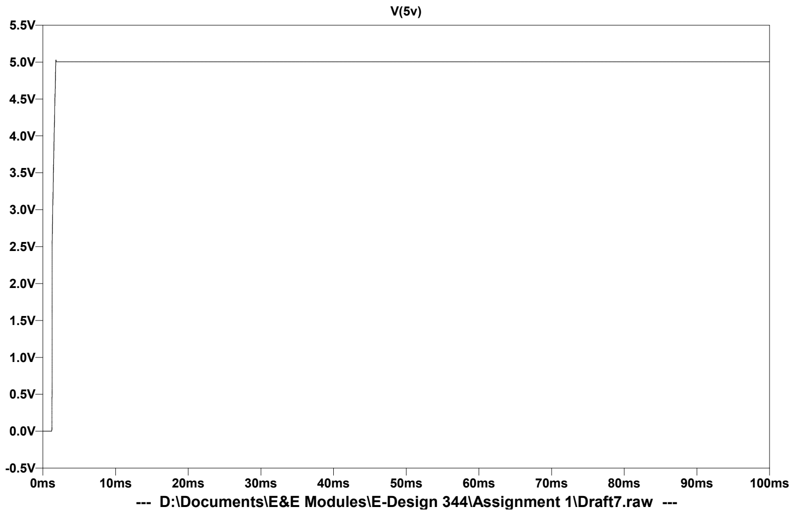
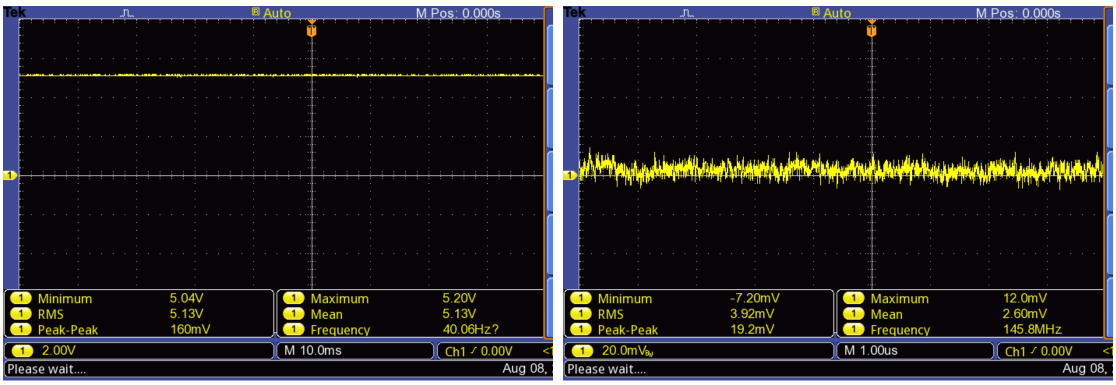


Figure 4.2: Simulated +5V output.



(a) +5V output voltage (b) +5V noise levels.

Figure 4.3: +5V measured output

Chapter 5

Charge pump regulation

5.1 Theory and related work

A charge pump is an electronic circuit that converts a supply voltage to a DC output voltage that is several times higher. Unlike the other traditional DC-DC converters, which employ inductors, charge pumps are only made of capacitors and switches (implemented by diodes or MOSFETs) [7]. The arrangement of these switches, allows for the charge pump to be used as a voltage doubler (or multiplier with extra stages) or as a voltage inverter [8].

5.2 Design

Design rationale As standard diodes are to be used as the switches in the design, the diode voltage drops have to be accounted for [8]. This means that the 5 V amplitude clock cannot be connected directly into the charge pump scheme if a $-5\,\mathrm{V}$ output is to be achieved. Thus, an amplifier stage is implemented to boost the clock to a sufficiently high amplitude.

This is achieved using one of the provided BJTs. In order to provide isolation to the amplifier stage, a pair of BJTs are connected between the amplifier and the charge pump. These are set to alternatively switch on and off, thus providing a path for current to flow during charging and discharging of the charge pump's flying capacitor without affecting the operation of the amplifier. To achieve this alternate switching, the amplifier is designed to be inverting and its output connected to the first of the transistors. The second switching transistor is then connected to the input clock to finalise the transistor switching scheme.

The amplifying transistor is designed to be in saturation or cutoff, to maximise its output [2]. The switching transistors only had a base resistor, as this helped to increase the efficiency of the charge pump. All the resistors were adjusted in simulation such that the charge pump could supply enough current to its load. Reducing the size of the resistors helped achieve this.

The arrangement of the capacitors and diodes was obtained from [8]. The capacitors should be large enough to store the charge lost to the load each cycle, but not so large that they cannot fully charge up. From Figure 5.1, C4 should be larger than C7 as it has to supply charge to the load, as well as charge up capacitor C7 when it discharges. C7 has to be large enough to avoid a significant ripple appearing at the output.

To provide some load regulation to the charge pump, a Zener diode is connected to its output [2]. This clips the output at $-5\,\mathrm{V}$ irregardless of the load connected. Since the charge pump is designed for a maximum load of $25\,\mathrm{mA}$, there is no risk of exceeding the power rating of the Zener. Finally, a filter is connected to the output of the charge pump. This helps remove the $10\,\mathrm{kHz}$ noise induced by the clock, as well as any $150\,\mathrm{kHz}$ noise from the switchmode regulator.

Design calculations
Efficiency:

$$\begin{aligned} P_{supplied} &= \frac{V_{load}^2}{R_{load}} = \frac{(-5.24)^2}{330} = 83.2\,\mathrm{mW} \\ P_{delivered} &= V_{supply} \times i_{supply} = 10.2 \times 0.08 = 816\,\mathrm{mW} \\ Efficiency, \eta &= \frac{P_{delivered}}{P_{supplied}} \\ \eta &= \frac{0.0832}{0.816} = 10.196\% \end{aligned}$$

The efficiency of the charge pump is extremely low. This can be attributed to power losses throught the Zener diode. Ideally, voltage regulation would be achieved by changing the duty cycle of the clock [9], but since that was not possible here all the excess current that the charge pump produces is dumped into the Zener. Thus, the charge pump's efficiency becomes poorer the lower its load is.

Circuit diagram
The circuit diagram implemented for the charge pump is given in Figure 5.1.

5.3 Simulation

5.4 Measurements

The measured DC voltage level (Figure 5.3a) as well as the noise levels under AC coupling (Figure 5.3b) is shown.

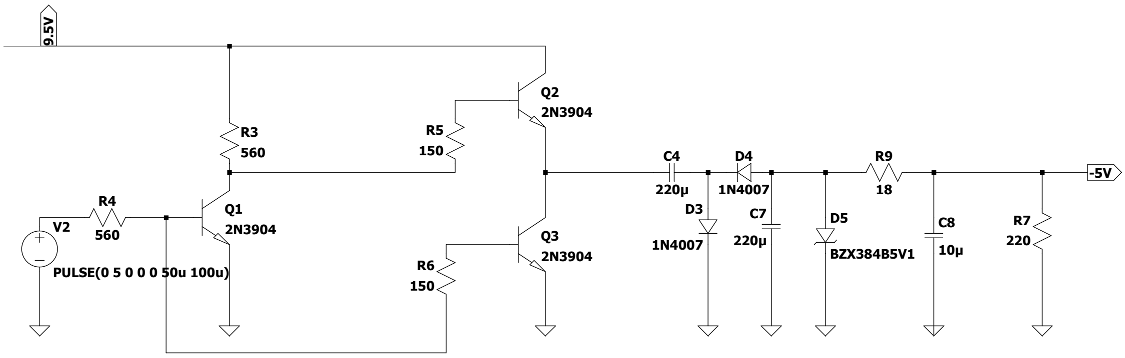


Figure 5.1: Charge pump circuit.

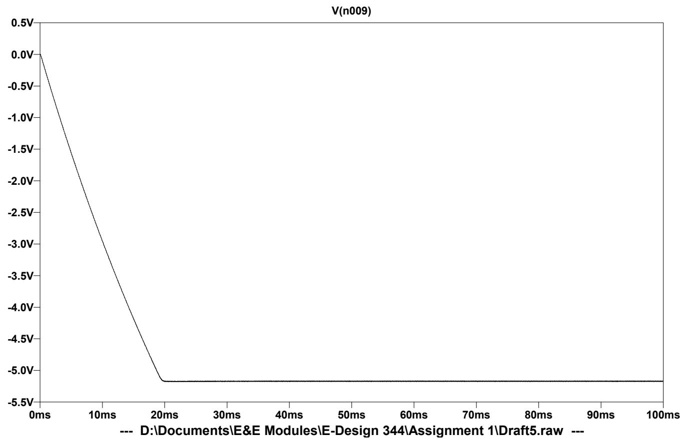
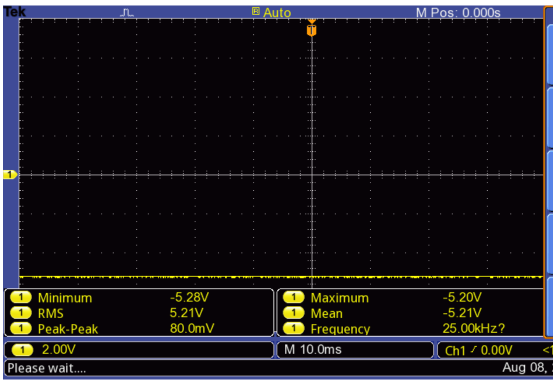
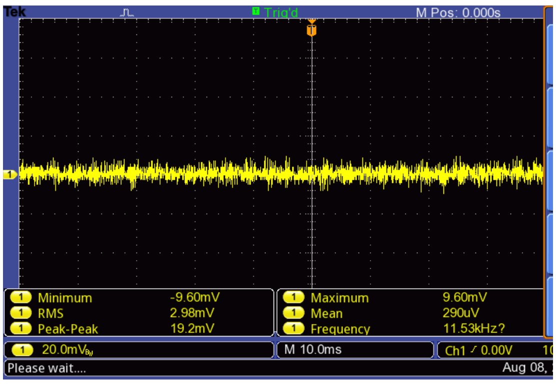


Figure 5.2: Simulated +5V output.



(a) -5V output voltage



(b) -5V noise levels.

Figure 5.3: -5V measured output

Chapter 6

System test results

Table 6.1: System test results.

	Expected value	Measured value
Rectifier	$\geq 12.0\,\mathrm{V}$	28.2 to 29.6V
Switchmode regulator	$\geq 9.0\,\mathrm{V}$	10.0 to 10.4V
Linear regulator	$5.0\,\mathrm{V}$	5.04 to 5.12V
Charge pump	$-5.0\,\mathrm{V}$	-5.20 to -5.28V
$5\,\mathrm{V}$ noise	$\leq 20.0\,\mathrm{mV}$	19.2 to 25.6mV
$-5\,\mathrm{V}$ noise	$\leq 20.0\,\mathrm{mV}$	19.2 to 60.0mV

Table 6.1 gives a summary of the measurements taken from the system. They were taken under a $50\,\mathrm{mA}$ load on the $5\,\mathrm{V}$ supply, and a $15\,\mathrm{mA}$ load on the $-5\,\mathrm{V}$ supply.

The rectifier and switchmode regulator performed well within the required specifications as shown. The linear regulator and charge pump were also able to achieve their DC specifications sufficiently. The noise levels on both, however was slightly higher than expected.Despite the use of a low pass filter, switching noise from the switchmode was still present at the charge pump output, especially when a load was connected. So, an improvement on the current setup, or even an additional filter at the switchmode output could be used to combat this. This second option may also help reduce the noise on the linear regulator to acceptable levels. It was also noted that the noise at the linear regulator rose by up to $5\,\mathrm{mV}$ when the charge pump was operating simultaneously. Thus, an alternative solution would be to limit the load that the charge pump needs to supply in future.

References

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[3] *1N4001-1N4007 1.0A STANDARD DIODE.* WTE Power Semiconductors, 2006.

[4] *Axial Lead and Cartridge Fuses, 5x20 mm > Fast-Acting > 217 Series.* Littelfuse Inc., October 2014.

[5] *LM2595 SIMPLE SWITCHER Power Converter 150-kHz 1-A Step-Down Voltage Regulator.* Texas Instruments, May 2016.

[6] *MC78LXXA / LM78LXXA 3-Terminal 0.1 A Positive Voltage Regulator.* Fairchild Semiconductors, March 2013.

[7] Palumbo, G. and Pappalard, D.: Charge pump circuits: An overview on design strategies and topologies. *IEEE CIRCUITS AND SYSTEMS MAGAZINE*, pp. 31–45, 2010. ISSN 1531-636X.

[8] Frenzel, L.: The charge-pump option to ldo and inductor-based regulators. 2016. Available at: `https://www.electronicdesign.com/power/charge-pump-option-ldo-and-inductor-based-regulators`

[9] 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

2019

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: 02/08/2019..............................

....

I, Alex Gituanja Muthua........................ 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: 02/08/2019................................

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

Appendix B: Wiring safety check

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E-design 344 Plug to fuse safety check

2019

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 Stefan Gerber

1

Appendix C: Screengrab of GitHub repo