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# Step-Down Switching Regulator Design

Metropolia University of Applied Sciences

Bachelor of Engineering

Electronics

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## Abstract


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The goal of the thesis project was to design two different step-down switching regulators which would be measured for their line and load regulation. EMC measurement was also done for the PCBs since switching regulators are prone to produce interference.

First step was to choose IC regulators and do the calculations from their datasheets for the right components to get the wanted values for voltage and current of the load. Next the designs were done and tested on a breadboard to measure the output voltages with different line voltage and load resistance to see if the calculations and designs are correct. Then the designs were made on PCB and the measurements were repeated. The circuit boards were also EMC measured afterwards. The IC regulators chosen were LM78S40 and LM2575.

The regulators were tested, and both were working as they should. For EMC the ICs were measured for emission with the point of interest being the switching frequencies of the regulators. At the end it could be seen that there was a distinguishable difference in the operation of the IC regulators. LM78S40 had too much ripple and was causing some unexplainable interference, while LM2575 had no ripple at all, and its switching frequency was found.



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|---|---|
| Keywords: | electronics, regulator |

# Tiivistelmä

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Opinnäytetyön tavoitteena oli suunnitella kaksi hakkuriregulaattoria, joiden syöttö- ja kuormaregulaatiota mitattiin. Piirilevyille tehtiin myös EMC-mittaukset, koska hakkurit ovat alttiita aiheuttamaan häiriötä.

Ensiksi valittiin IC-regulaattorit ja niiden datalehtien pohjalta tehtiin laskut oikeita komponentteja varten, joilla saatiin halutut arvot kuormajännitteelle ja -virralle. Seuraavaksi suunnitelmat toteutettiin ja testattiin koekytkentälevyllä lähtöjännitteiden mittaamiseksi eri syöttöjännitteellä ja kuormalla, että nähtiin ovatko laskut ja suunnitelmat oikein. Sitten suunnitelmat toteutettiin piirilevylle ja mittaukset toistettiin. Piirilevyt myös EMC-mitattiin jälkeenpäin. Valitut IC-regulaattorit olivat LM78S40 ja LM2575.

Regulaattorit testattiin ja molemmat toimivat niin kuin piti. EMC:n osalta IC:t mitattiin emission kannalta, kiinnostuksen kohteena oli regulaattoreiden vaihtotaajuus. Lopulta voitiin nähdä, että IC-regulaattorien toiminnassa oli havaittava ero. LM78S40:ssä oli liikaa rippeliä ja se aiheutti selittämättömiä häiriöitä, kun taas LM2575:ssä ei ollut rippeliä ollenkaan ja sen vaihtotaajuus löytyi.



Avainsanat: elektroniikka, regulaattori

## Contents

## List of Abbreviations

| | |
|---|---|
| DC: | Direct current |
| EFT: | Electrical Fast Transient |
| EMC: | Electromagnetic compatibility |
| EMI: | Electromagnetic interference |
| ESD: | Electrostatic Discharge |
| EUT: | Equipment under test |
| IC: | Integrated circuit |
| LISN: | Line Impedance Stabilization Network |
| NSA: | Normalised Site Attenuation |
| OATS: | Open Area Test Site |
| PCB: | Printed circuit board |
| PK: | Peak |
| QP: | Quasi-Peak |
| RBW: | Resolution Bandwidth |

# 1 Introduction

With power supplies there is often a need to increase or decrease the magnitude of DC voltage. For this purpose, a DC-to-DC converter called voltage regulator is used to maintain nearly constant output voltage even when input voltage or load current changes. The two most commonly used voltage regulators are linear regulators and switching regulators.

The goal of this thesis project was to design two switching regulators with step-down configuration using IC switching regulators, which were measured with different input voltages and load currents. EMC measurements were conducted after completion of the designs. The first regulator LM78S40 Universal Switching Regulator was used as a step-down switching regulator. The second regulator was LM2575 Step-Down Switching Voltage Regulator which can only be used in step-down configuration.

After completion of the switching regulator designs it could be seen how the line and load regulations affect the operation of the designed PCBs, and the interference produced from the circuits.

# 2 EMC

When electronic circuits for different purposes operate close to each other, they can affect one another. Electromagnetic interference (EMI) is a major problem in circuit design. As the circuitry has become smaller, more circuits and components are placed closer to each other, which increases the probability of interference. [1.] Switching devices, which are turned on and off, are based on a modulation technique to adjust output voltage and/or frequency. As a drawback, a high level of EMI is generated. [2.]

## 2.1 Noise and Interference

Electrical signal that is other than the desired signal in a circuit is called noise. This does not mean the distortion products produced due to nonlinearities. Although they are undesirable, they are not considered noise unless they are coupled into another part of the circuit. This means that a signal from another part of a circuit can be considered to be noise if coupled to some other part of the circuit.

Common noise sources are

- intrinsic noise sources like thermal and shot noise
- man-made noise sources
- noise caused by natural disturbances like lightning.

Interference is the undesirable effect of noise. Interference is an improper operation of a circuit caused by noise. Unlike noise, interference can be eliminated. Noise can still be reduced to such magnitude, that it causes no interference. [1.]

## 2.2 EMC Tests and Measurements

EMC tests and measurements are performed to certify the compliance of a product in related standards. For EMC tests and measurements there are three major components of EUT:

- finding out related standards
- knowing operational status during tests and measurements
- understanding methods, measurement devices, and procedures of tests and measurements.

So, the EMC test and measurement procedure must be reliable, realizable, and repeatable. These issues are controlled via traceability.

One critical instrument for EMC measurements is a spectrum analyzer. Spectrum analyzer measures the magnitude of an input signal versus frequency within the frequency range of the instrument. Usually, it displays unprocessed signal information like voltage, period, power, sidebands, wave-shape, and frequency. It can be used to observe signal components like dominant frequency, power, distortion, bandwidth, harmonics, and other spectral components from the spectra of electrical signals, which are not easy to detect in time domain waveforms.

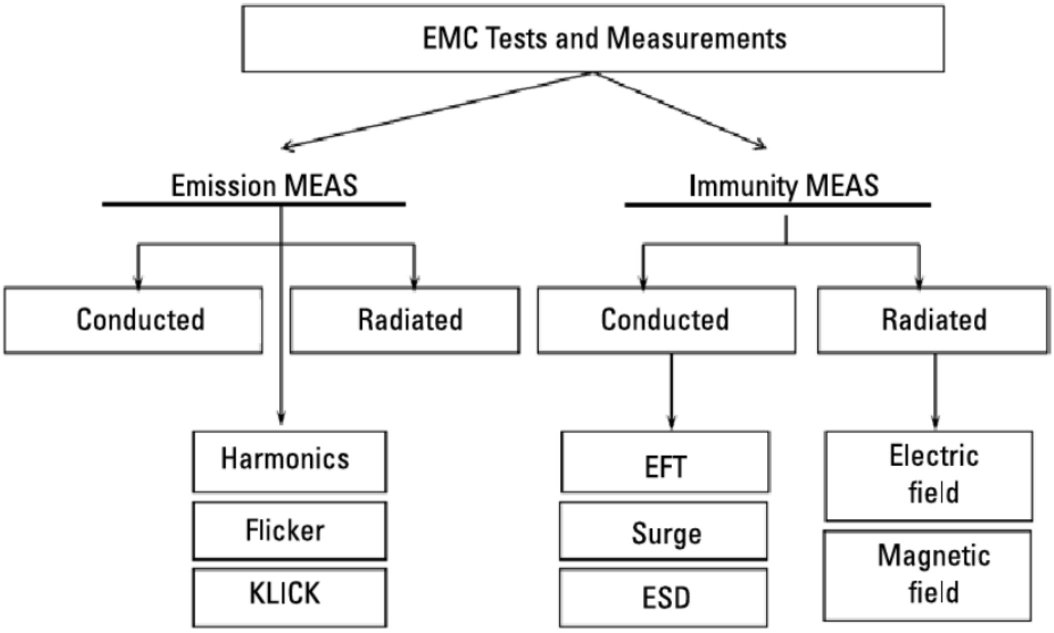



Figure 1. EMC Tests and Measurements. [3]

EMC tests and measurements can be seen in Figure 1. Emission is measured but immunity (or susceptibility) is tested. Emission has two parts of measurements: conducted emission (CE) and radiated emissions (RE). Addition to these, harmonics, flicker, and clicks are also measured. Immunity tests also have two parts: conducted immunity (CI) and radiated immunity (RI). [3.]

### 2.2.1 Emission Measurement

CE and RE measurements are performed in the frequency ranges from 150 kHz to 30 MHz and form 30 MHz to 6 GHz. The measurements performed under 30 MHz are the CE measurements and the results are given in dBµV versus frequency. These measurements are performed with 9 kHz RBW. Measurements with peak detector takes only 2 minutes, but it takes 100 minutes with quasi-peak detector. For this reason, there is no reason to perform QP detection if the values from the PK detection are below 6-10 dB the limit values.

Equipment Necessary for CE Measurements

| Equipment | Specification |
|---|---|
| EMI receiver | CISPR 16-1-1 compliant |
| LISN | 9 KHz-30 MHz, CISPR 16-1-2 |
| Coaxial cable | — |
| Reference ground plane | At least 2m by 2 m. |
| Shielded enclosure (optional) | Depends on the EUT dimension |
| RF mains filters (optional) | Broadband RF filter |
| Voltage probe (CISPR 16-1-2) | 9 KHz–30 MHz, high impedance |

Figure 2. Equipment Necessary for CE Measurements. [3]

CE measurements are performed form 150 kHz to 30 MHz with the equipment specified in Figure 2. The EUT and EMI receiver are connected to a LISN with an AC power supply. The measurements are performed under the specified EMC test standards for traceability.

RE measurements are made in an anechoic chamber or OATS with a QP detector in the frequency range from 30 MHz to 6 GHz. For reduced time, a PK detector may also be used instead of QP detector, but the QP detector will be used in case of dispute.

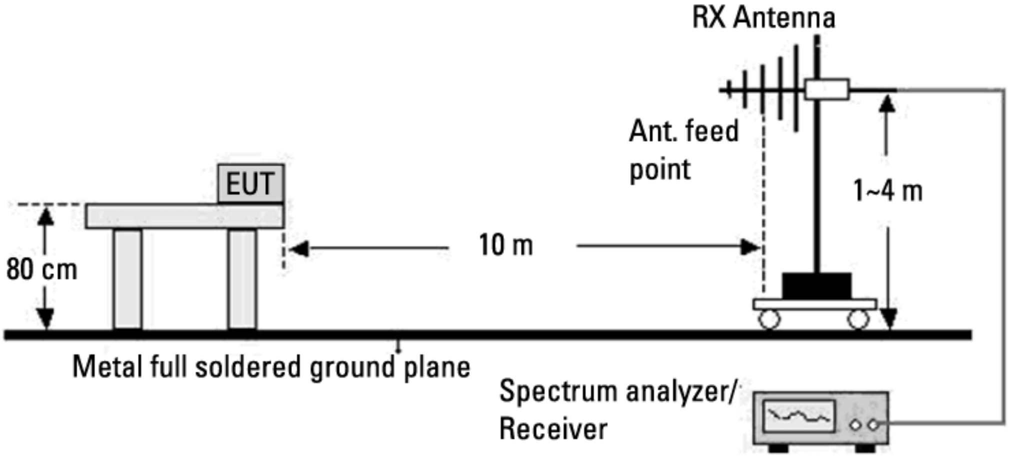



Figure 3. A typical RE measurement setup. [3]

The setup is typically built with the equipment seen in Figure 3 and specified with the related EMC test standards. RBW used during these measurements are 120 kHz, and 1 MHz is used above 1 GHz. The results are given as field strength in dBµ/V versus frequency. [3.]

### 2.2.2 Immunity/Susceptibility Tests

Immunity CI is tested below 80 MHz and RI tested above 80 MHz. Also, immunity against ESD, EFT/burst, surge, magnetic fields, and voltage dips are mandatory. Testing these are performed under high electric and magnetic fields, and they may be harmful for EMC test personnel. Tests for immunity are difficult, dangerous, and need expensive setups.

Conducted immunity tests are performed between 150 kHz and 80 MHz according to the related standard. The equipment for induced or conducted EM fields is checked under the typical operating conditions of the EUT. The EUT should be tested within the conditions which it will be used in.

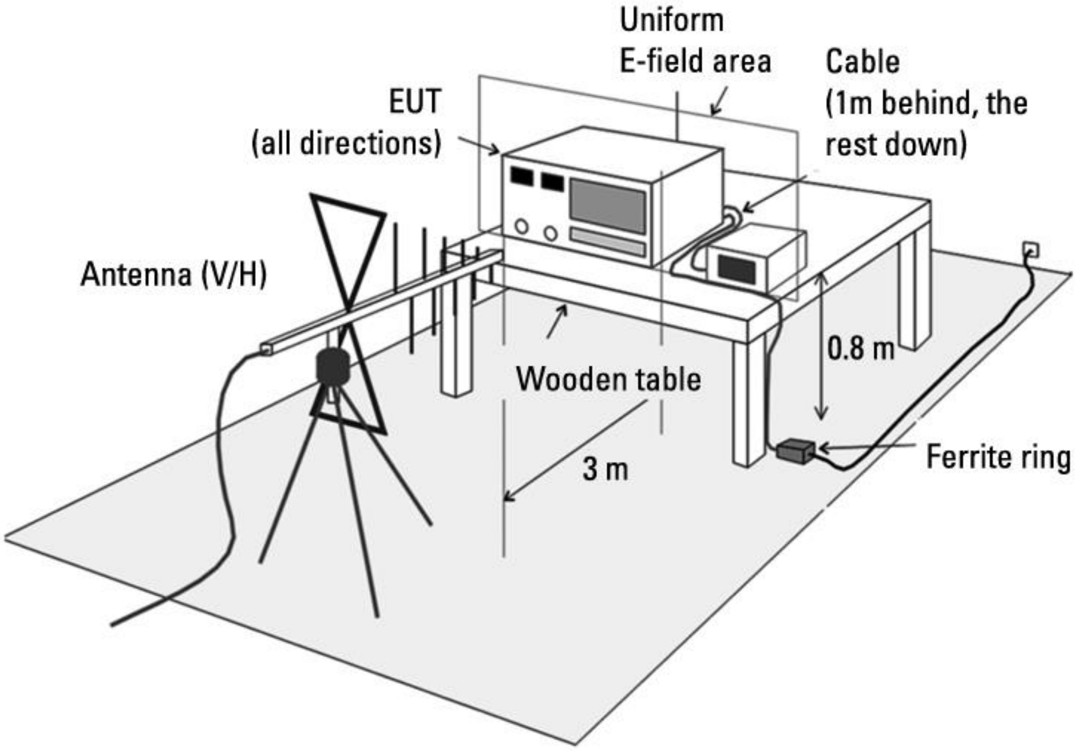



Figure 4. A typical RI test setup. [3]

Radiated immunity tests are performed with the typical RI test setup in Figure 4. RI tests are mandatory for most commercial products from 80 MHz to 1 GHz frequency. [3.]

# 3 Voltage Regulators

## 3.1 Voltage Regulation

Voltage regulation is the DC-to-DC conversion which is usually a part of a power supply. The common categories for these are linear regulators and switching regulators. The two common linear regulator types are series and shunt. Three common switching regulators are step-down, step-up, and inverting.

### 3.1.1 Line Regulation

A regulator is what maintains the output of a power supply's voltage nearly constant. Line regulation can be defined as a change in percentage of output voltage for a given change in the input voltage as seen in Figure 5.

$$Line\ regulation = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}}\right) 100\ \% \quad (1)$$

It can also be expressed in units of %/V to express how many percent the output changes when the input voltage increases or decreases by 1 V. [4.]

$$Line\ regulation = \frac{\left(\frac{\Delta V_{OUT}}{V_{OUT}}\right) 100\ \%}{\Delta V_{IN}} \quad (2)$$

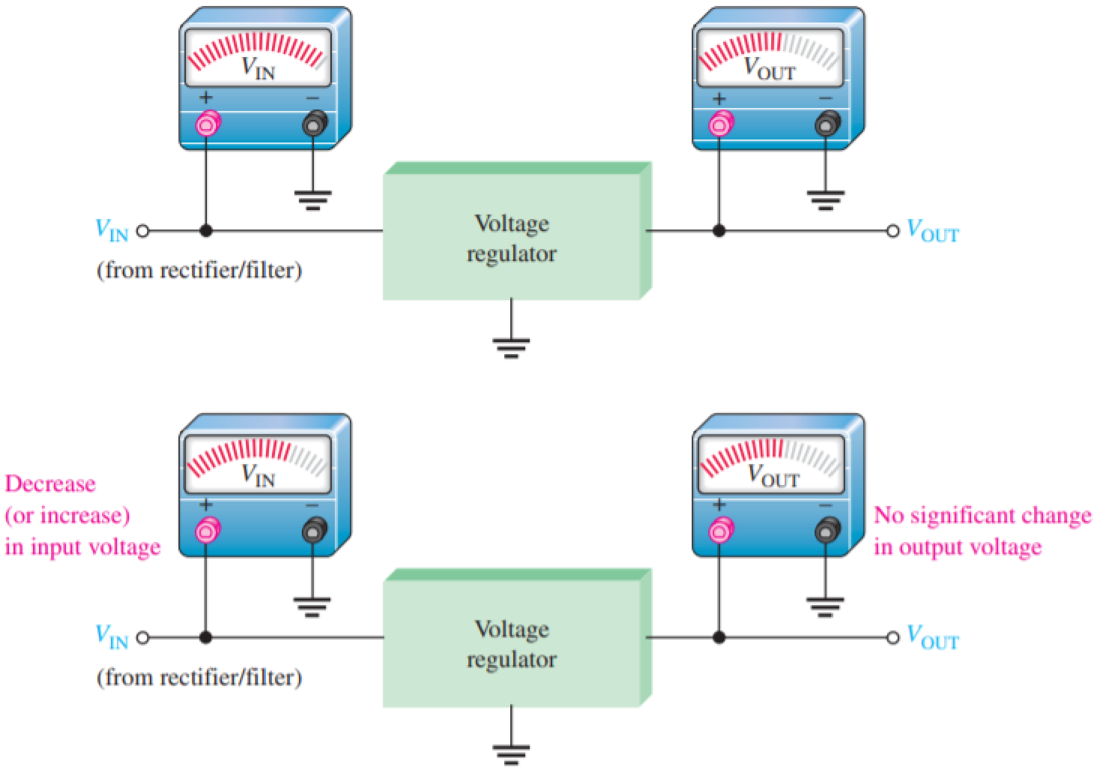



Figure 5. Line regulation. [4]

### 3.1.2 Load Regulation

Within certain limits, the output voltage does not change as the load resistance and current does, this can be seen in Figure 6.

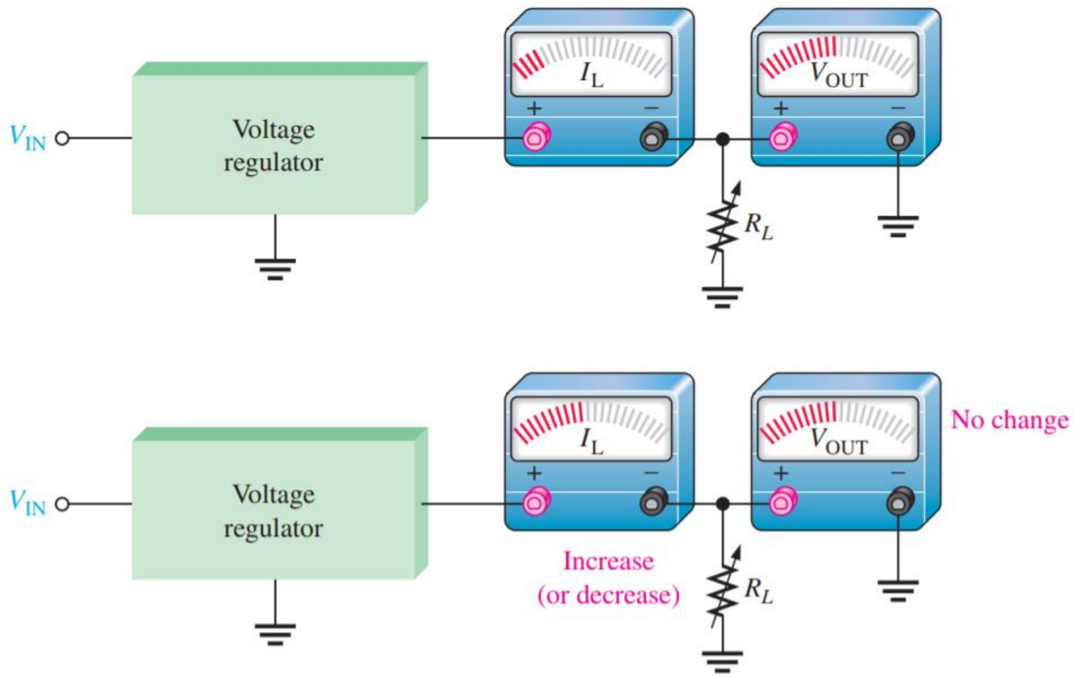



Figure 6. Load regulation. [4]

Load regulation can be expressed as percentage change in output voltage from no-load (NL) to full-load (FL).

$$Load\ regulation = \left(\frac{V_{NL}-V_{FL}}{V_{FL}}\right) 100\ \% \tag{3}$$

It can also be expressed as percentage change in output voltage for each mA change in load current. $Load\ regulation\ = 0.1\ \%/mA$ means that the output voltage changes 0.1 percent when the load current changes by 1 mA.

Sometimes the equivalent resistance of a power supply $R_{OUT}$ is given instead of load regulation. In this case the load regulation can be calculated from the Thevenin equivalent circuit for a power supply seen in Figure 7. [4.]

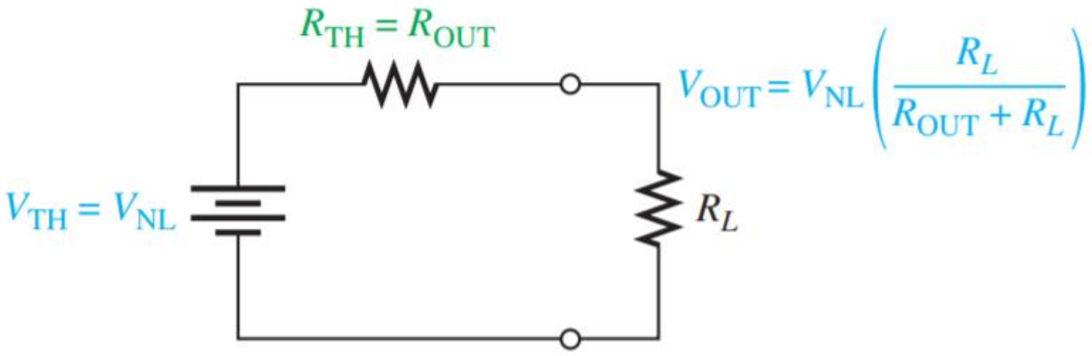



Figure 7. Thevenin equivalent circuit for a power supply with a load resistor. [4]

If R_FL equals the smallest-rated load resistance, the full-load output voltage is

$$V_{FL} = V_{NL}\left(\frac{R_{FL}}{R_{OUT} + R_{FL}}\right) \tag{4}$$

Equation for load regulation:

$$V_{NL} = V_{FL}\left(\frac{R_{OUT} + R_{FL}}{R_{FL}}\right) \tag{5}$$

$$Load\ regulation = \frac{V_{FL}\left(\frac{R_{OUT} + R_{FL}}{R_{FL}}\right) - V_{FL}}{\mathrm{V_{FL}}} * 100\ \% = \left(\frac{R_{OUT} + R_{FL}}{R_{FL}} - 1\right) 100\ \% \tag{6}$$

$$Load\ regulation = \left(\frac{R_{OUT}}{R_{FL}}\right) 100\ \% \tag{7}$$

## 3.2 Linear Regulators

### 3.2.1 Series

A basic op-amp series regulator uses transistor $Q_1$ as a control element, resistors $R_2$ and $R_3$ to voltage divide a sample circuit, Zener diode $D_1$ holds the reference voltage and op-amp compares the output and reference voltages (error detector) as shown in Figure 8.

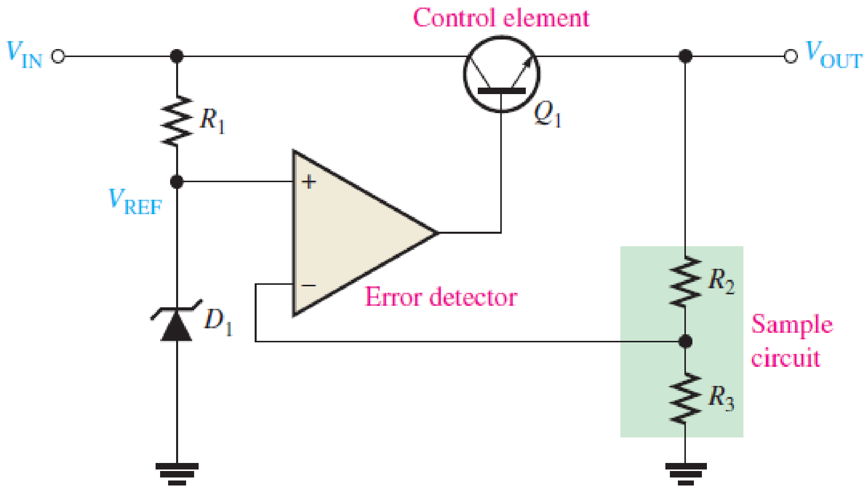



Figure 8. Op-amp series regulator. [4]

The regulating action to keep the output constant can be seen in Figure 9. If the output voltage tries to decrease because of a decrease in input voltage or resistive load, or an increase of load current, a proportional voltage decrease is applied to the op-amp's inverting input by the voltage divider. The error voltage is the small difference voltage that is developed across the op-amp's inputs, since the Zener diode holds close to constant reference voltage. The occurred difference is amplified, and the op-amp's feedback voltage $V_B$ increases. Because of this the output voltage also increases since the $V_B$ is applied to the base of $Q_1$. The output voltage increases until the op-amp's inverting input's voltage equals again the reference voltage. This keeps the output voltage nearly constant in the case it attempts to decrease.

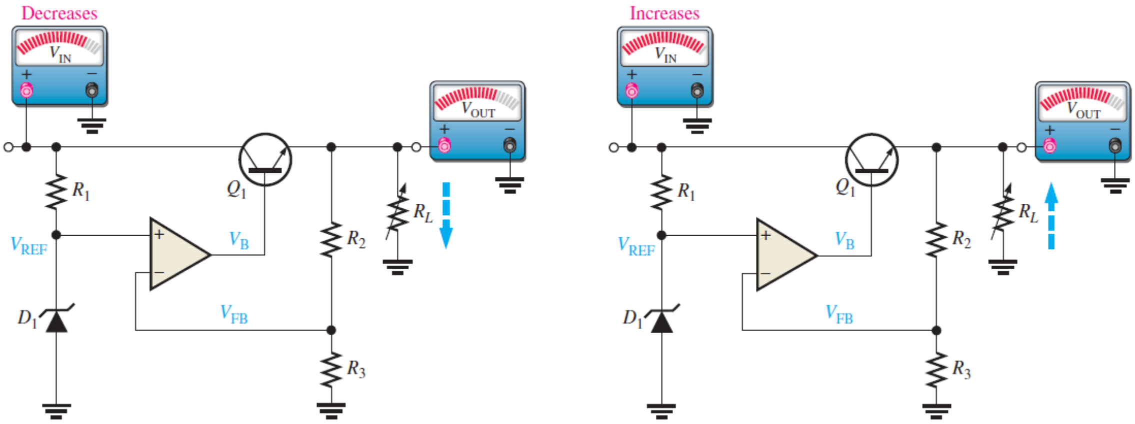



Figure 9. Series regulator action to keep the output voltage constant. [4]

In the case when the output voltage tries to increase, the opposite action occurs. The op-amp is connected as a noninverting amplifier where the reference voltage is the noninverting terminal, and the voltage divider forms the negative feedback circuit. [4.]

### 3.2.2 Shunt

In the case of linear shunt regulator, the control element (transistor) is parallel with the load seen in Figure 10. The operation varies from the series regulator for the regulation action is achieved by controlling the current through the transistor. [4.]

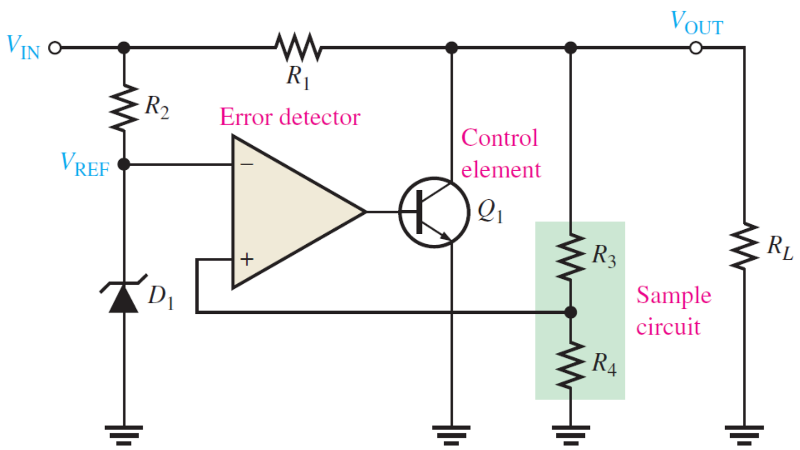



Figure 10. Op-amp shunt regulator. [4]

The response for the change in input voltage is illustrated in Figure 11. If the output voltage tries to decrease, the decrease is sensed by the sample circuit and applied to the op-amp's noninverting input. The resulting difference voltage reduces the voltage from the op-amp's output, which is connected to the base of the transistor $Q_1$, and this causes the collector voltage $V_C$ to increase, causing the collector current (shunt current) to decrease. The decrease in output voltage is compensated by the increase in $V_C$, and this keeps the output voltage nearly constant. The opposite action occurs if the output tries to increase. [4.]

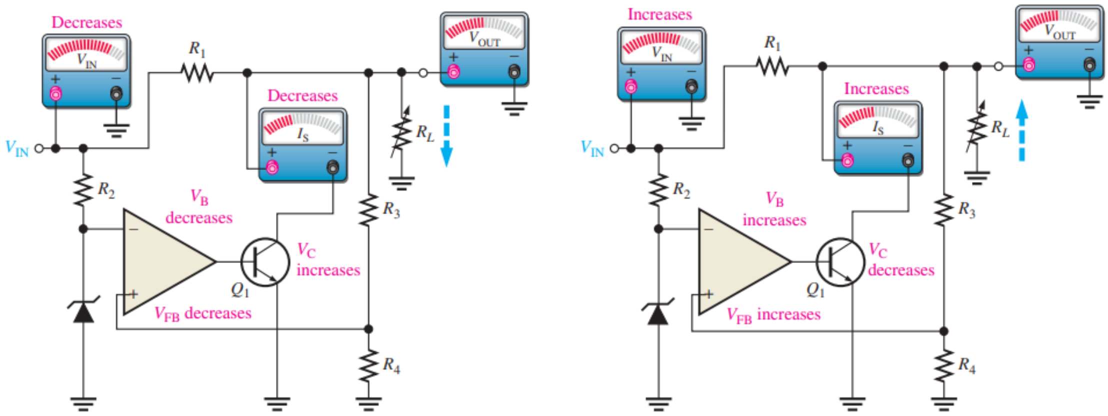



Figure 11. Responses for the change in input voltage. [4]

## 3.3 Switching Regulators

The problem with the linear regulators is decrease in voltage, which is virtually seen as power loss, degraded efficiency, and heat. Switching regulator takes power from the voltage source only the needed amount and reassembles it. In every cycle, it takes only the needed amount of energy for the load. For this action the efficiency of 90 % or more is possible.

The current to the transistor is switched on and off. The switch (transistor) is closed for the time $t_{on} < T$, where the period is $T = \frac{1}{f}$, which is also the sum of the on-time and the off-time $T = t_{on} + t_{off}$. The duty cycle of switching regulator is $D = \frac{t_{on}}{T}$. [5.]

### 3.3.1 Step-Down

In the step-down configuration (also known as buck converter) seen in Figure 12, the output voltage is always less than the input voltage.

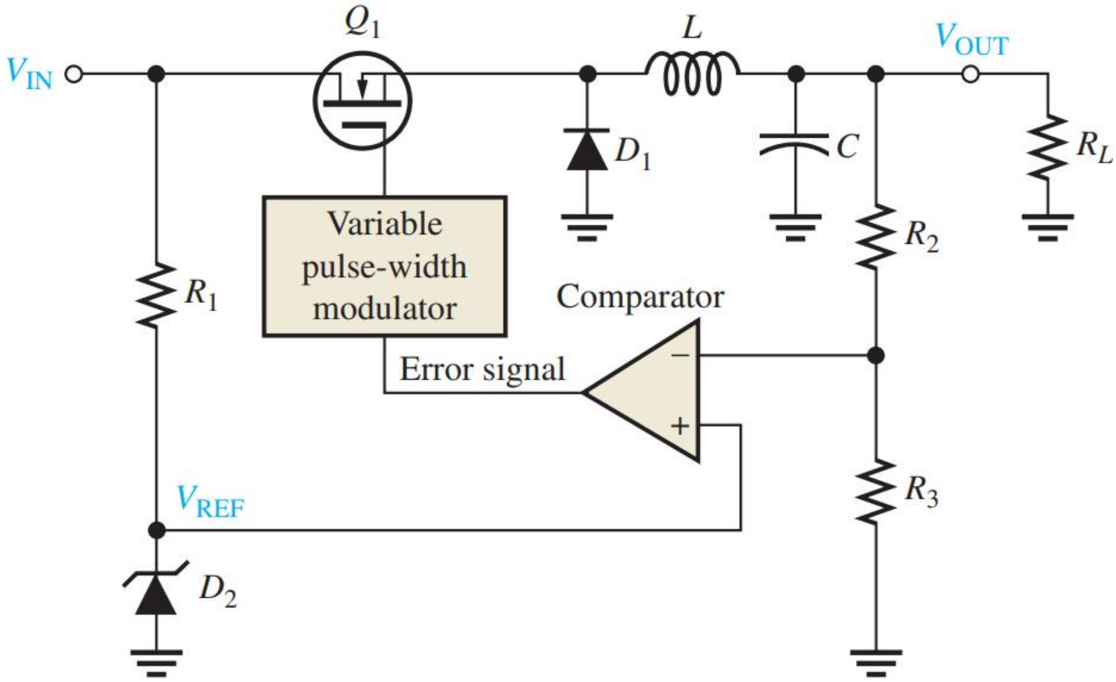
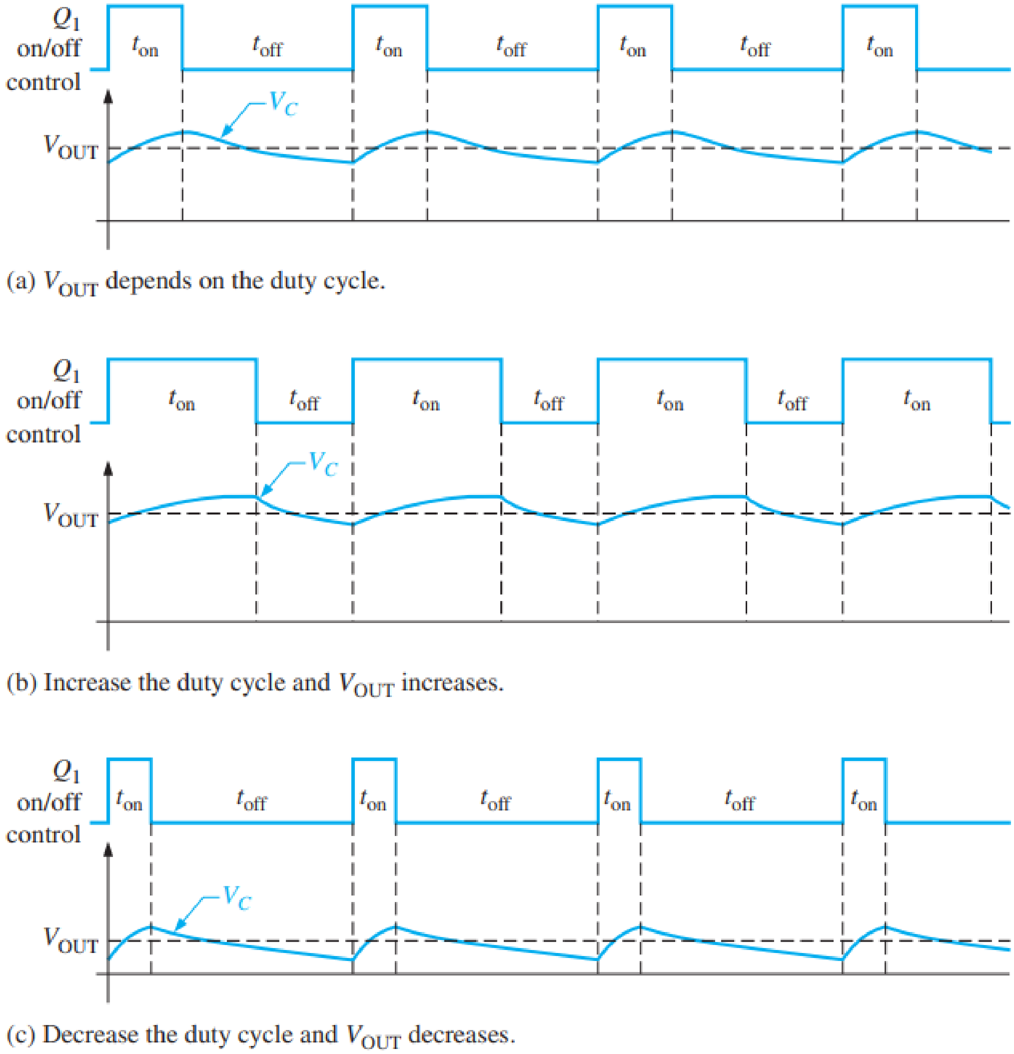



Figure 12. A step-down switching regulator. [4]

A MOSFET switching transistor $Q_1$ is used as the switch, which is controlled by the feedback to control the on-off time. When the switch is closed, the diode is off, and the inductor starts to store energy. The magnetic field collapses when the switch opens, which keeps the current nearly constant in the load. The load current is provided through the diode $D_1$ and the LC filter keeps the current and voltage constant.

The duty cycle, seen in waveforms in Figure 13, is based on the regulator’s load requirement. The capacitor charges during the on-time and discharges during the off-time. The increase in $t_{on}$ is relative to $t_{off}$, thus increasing the charge of the capacitor and increasing the output voltage. The fluctuations of the output voltage are smoothed by the inductor.




(a) $V_{OUT}$ depends on the duty cycle.

(b) Increase the duty cycle and $V_{OUT}$ increases.

(c) Decrease the duty cycle and $V_{OUT}$ decreases.

Figure 13. Switching regulator waveforms. [4]

The output is ideally

$$V_{OUT} = \left(\frac{t_{on}}{T}\right) V_{IN} \tag{8}$$

If the $V_{OUT}$ tries to decrease, the $t_{on}$ will increase, and an additional charge of the capacitor offsets the decrease. In the case $V_{OUT}$ tries to increase $t_{on}$ decreases, and the capacitor discharge enough to offset the increase. [4.]

### 3.3.2 Step-Up

In step-up switching regulator (also known as boost converter) illustrated in Figure 14, the transistor $Q_1$ operates as a switch to the ground. As the transistor turns on, a voltage equal to input voltage is induced across the inductor. During the on-time, inductor voltage decreases from its initial maximum and the diode $D_1$ is reverse-biased. The inductor voltage becomes smaller the longer $Q_1$ is on, and the capacitor discharges only an extremely small amount through the load.

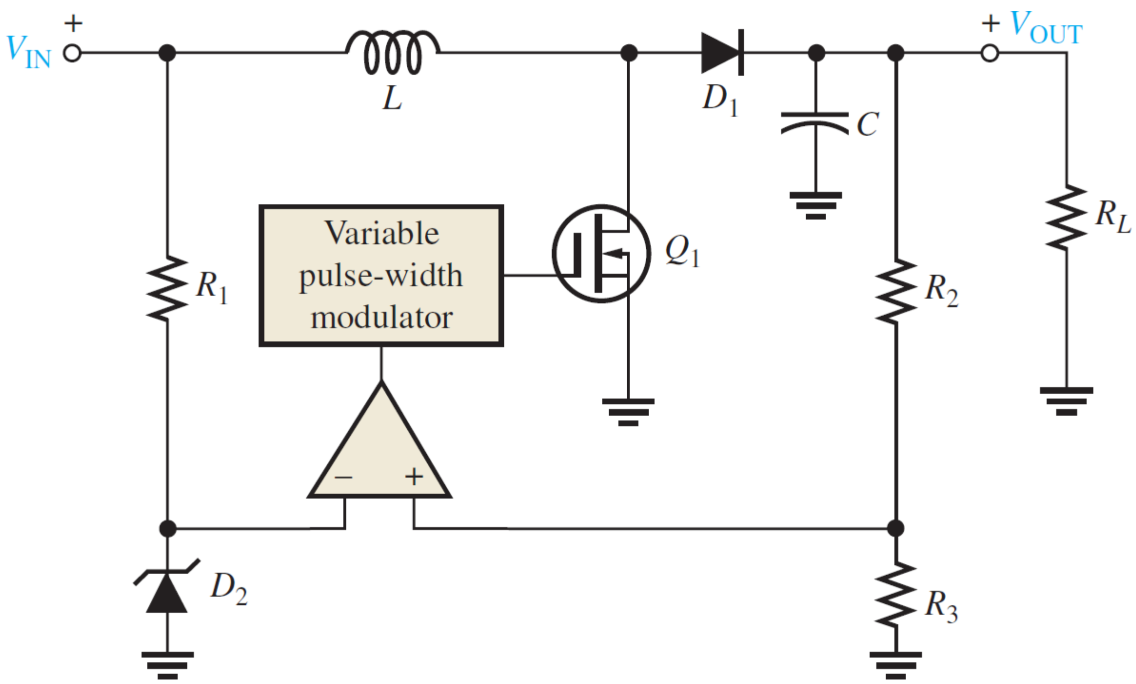



Figure 14. Step-up switching regulator. [4]

During the off-time, the inductor voltage reverses polarity, and makes $D_1$ forward-biased, allowing the capacitor to charge. Thus, the output voltage can be larger than input voltage, since the capacitor charge is added to the input voltage induced across the inductor. The output voltage is dependent on the magnetic field action of the inductor, which is determined by $t_{on}$, and the charging of the capacitor, that is determined by $t_{off}$.

Voltage regulation is achieved by the change in on-time, which is related to the change in line and load regulation, that determine the output voltage. If the output voltage $V_{OUT}$ tries to increase, $t_{on}$ decreases, which results the decrease in the charge amount of the capacitor. If the $V_{OUT}$ tries to decrease, $t_{on}$ increases and the charge amount of the capacitor in increases. This regulating action keeps the $V_{OUT}$ nearly constant. [4.]

### 3.3.3 Voltage-Inverter

An inverting switching regulator (as known as buck-boost converter) inverts the polarity of the output voltage, seen in Figure 15.

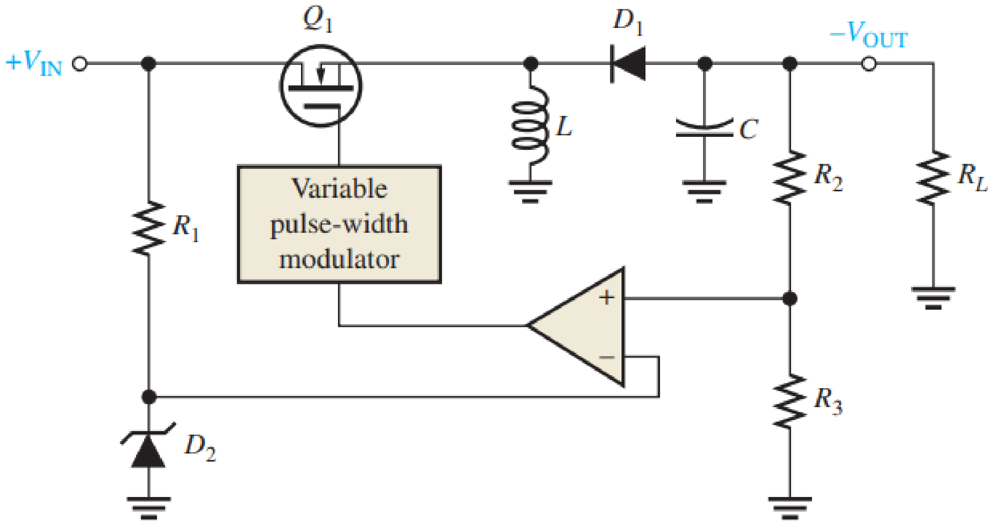



Figure 15. Inverting switching regulator. [4]

Transistor $Q_1$ turned on, the magnetic field of the inductor rapidly expands. The diode $D_1$ is reverse-biased while $Q_1$ is on and the inductor voltage decreases from its maximum. $Q_1$ turned off, the magnetic field collapses and the polarity of the inductor reverses. The on-off action of $Q_1$ produces a repetitive charging and discharging, and the LC filter smooths the voltage. As with the step-up regulator, the output voltage is determined by the on-time. Less on-time, the greater the output voltage. [4.]

# 4 Calculations and Design

## 4.1 Calculations

The first thing to do was to examine the datasheet for the step-down configuration. LM78S40 or LM2575 could not be found in any simulation software, so both were first built on breadboard after the calculations of the right components. After finding that the circuit was working, it was measured first with different load resistances, and then with different input voltages.

### 4.1.1 LM78S40

LM78S40 in the step-down configuration is presented in Figure 16. The components had to be calculated with the given formulas in the datasheet [6]. The conditions for the thesis project calculations were input voltage 12 V, output voltage 5 V and maximum output current of 0.5 A.

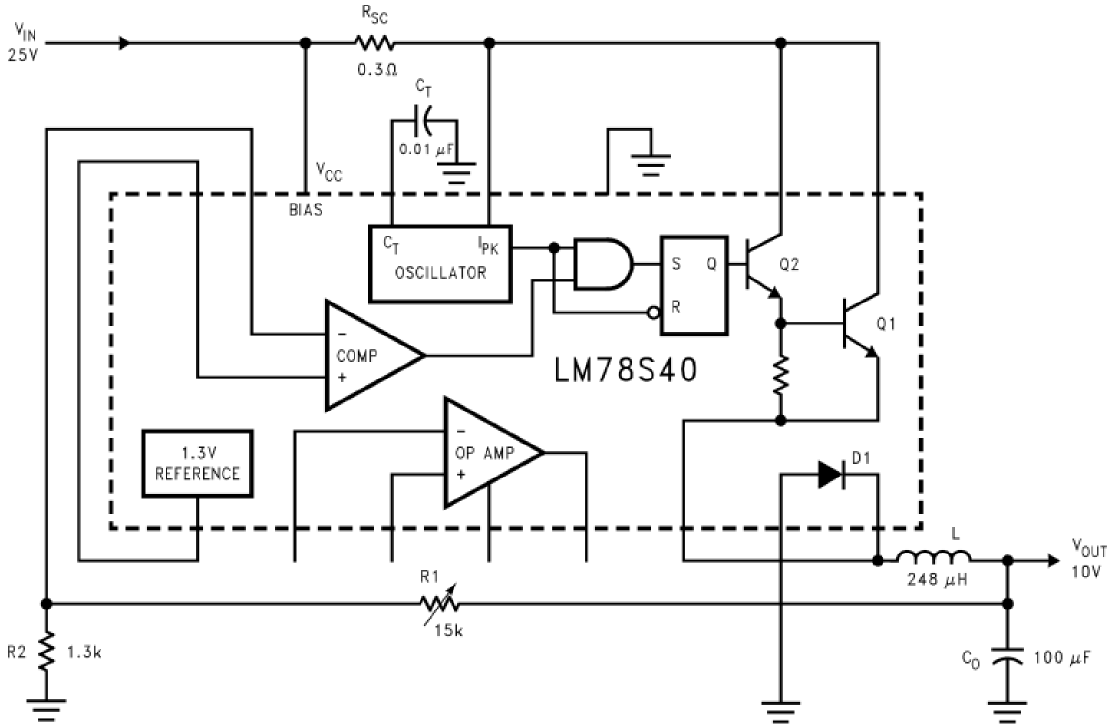



Figure 16. Step-Down configuration of LM78S40. [6]

Peak current:

$$I_{pk} = 2\, I_{out} = 1\ \mathrm{A} \tag{9}$$

Resistor for programming the current peak:

$$R_{sc} = \frac{0.33}{I_{pk}} = \ 0.33\ \Omega \tag{10}$$

Next, the ratio of rise and fall times was calculated:

$$\frac{t_{on}}{t_{off}} = \frac{\mathrm{V_{OUT}} + V_D}{\mathrm{V_{IN}} - V_{SAT} - V_{OUT}} \tag{11}$$

$$\frac{t_{on}}{t_{off}} = \frac{5 + 1{,}25}{12 - 1{,}1 - 5} = 1.1 \tag{12}$$

$$t_{on} = 1.1\ t_{off} \tag{13}$$

There were two design constraints:

$$t_{on}\ \geq\ 10\ \mu s;\ t_{off}\ \geq\ 10\ \mu s \tag{14}$$

$$(t_{on} +\ t_{off})\ \leq\ 50\ \mu s \tag{15}$$

Following these constraints, the value for $t_{off}$ was selected and $t_{on}$ was calculated:

$$t_{off} = 22\ \mathrm{\mu}s \tag{16}$$

$$t_{on} = 1{,}1 t_{off} = 24.2\ \mathrm{\mu}s \tag{17}$$

Calculations for $C_T$ and $L$:

$$C_T = (45 * 10^{-5}) t_{off} = 0.01\ \mathrm{\mu}F \tag{18}$$

$$L = \left(\frac{V_{OUT} + V_D}{I_{pk}}\right) t_{off} = 138\ \mu H \tag{19}$$

Inductor value was selected to be 150 µH for its availability.

Output capacitor was calculated from ripple requirements:

$$C_0 \geq \frac{I_{pk}(t_{on}+t_{off})}{8\ V_{RIPPLE}} = \frac{(1)(24.2+22)10^{-6}}{(8)(0.1)} = 58\ \mu F \tag{20}$$

Output capacitor value was selected to be 100 µF.

Assuming that the sampling network current is 1 mA, then:

$$R1 + R2 = 10\ k\Omega \tag{21}$$

$$R2 = (R1 + R2)\frac{V_{REF}}{V_{OUT}} = 10\ k\Omega \frac{1.3\ \text{V}}{5\ \text{V}} = 2.6\ k\Omega \tag{22}$$

For the R1 a 10 kΩ potentiometer was chosen so that the output voltage could be adjusted if necessary. [6.]

### 4.1.2 LM2575

Components for the simple step-down switching voltage regulator were calculated for input voltage 12 V, output voltage 5 V and output current 1 A. In Figure 17 shows a design for LM2575.

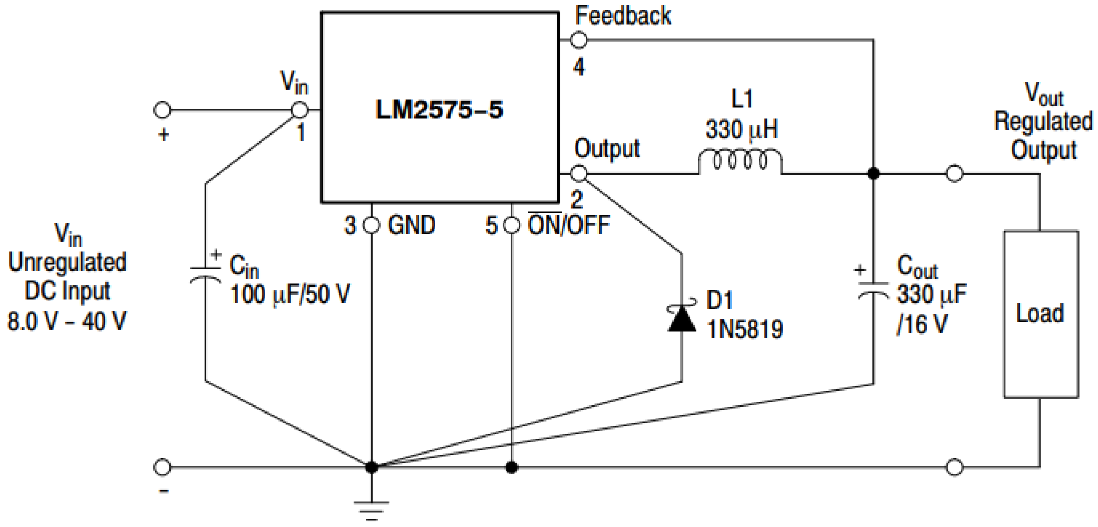



Figure 17. LM2575 with 5 V output. [7]

For inductor L1 selection, the “set” volts-second (E * T) had to be calculated. For this the fixed frequency of the internal oscillator is used. The frequency is 52 kHz.

$$E * T = (V_{IN} - V_{OUT}) * t_{on} \tag{23}$$

$$E * T = (V_{IN} - V_{OUT}) * \left(\frac{V_{OUT}}{V_{IN}}\right) * \left\{\frac{1000}{f_{osc}(in\ kHz)}\right\} [V * \mu s] \tag{24}$$

$$E * T = (12 - 5) * \left(\frac{5}{12}\right) * \left(\frac{1000}{52}\right) = 56\ [V * \mu s] \tag{25}$$

From inductor selection table provided by datasheet [7] in Figure 18, the intersection of 56 V*µs and 1 A corresponds to an inductor code of L220, which makes L1 value 220 µH. For this it was decided to use a suitable ferrite toroid. The 742701703 ferrite from Würth Elektronik was chosen and calculated by using an online ferrite toroid calculator [8].

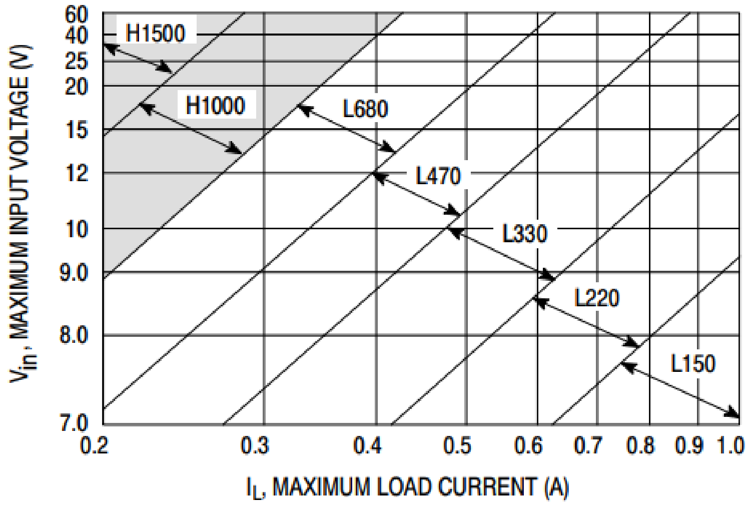



Figure 18. Inductor value selection guide. [7]

Output capacitor must meet the following requirement to meet stability requirements:

$$C_{OUT} \geq 7758 \frac{V_{IN(Max)}}{V_{OUT} * L1(\mu H)} (\mu F) \tag{26}$$

$$C_{OUT} \geq 39.8 \, \mu F \tag{27}$$

For acceptable output voltage ripple, output capacitor value was to be 220 µF.

The catch diode $D_1$ requires a current rating of at least $1{,}2 * I_{LOAD(Max)}$ and reverse voltage rating of at least $1{,}25 * V_{IN(Max)}$. The selected diode was SB540 Schottky.

For input capacitor 100 µF, 35 V aluminum electrolytic capacitor was selected. [7.]

## 4.2 Design

The next step was to design the PCB, which was made using PADS Logic and Layout. The circuit diagram was first made by using the Logic software from which it could be designed as PCB using the Layout software. Some of the components like LM78S40 could not be found in the software so they had to be designed using the datasheets. New components were made with PADS software also.

### 4.2.1 PADS Logic

The schematics were made with the PADS Logic software using the datasheets [6; 7] of the ICs. Most of the components could be found from the library which has a variety of different components. The components that are not found can also be made and added to the library. After choosing the right components, they were connected.

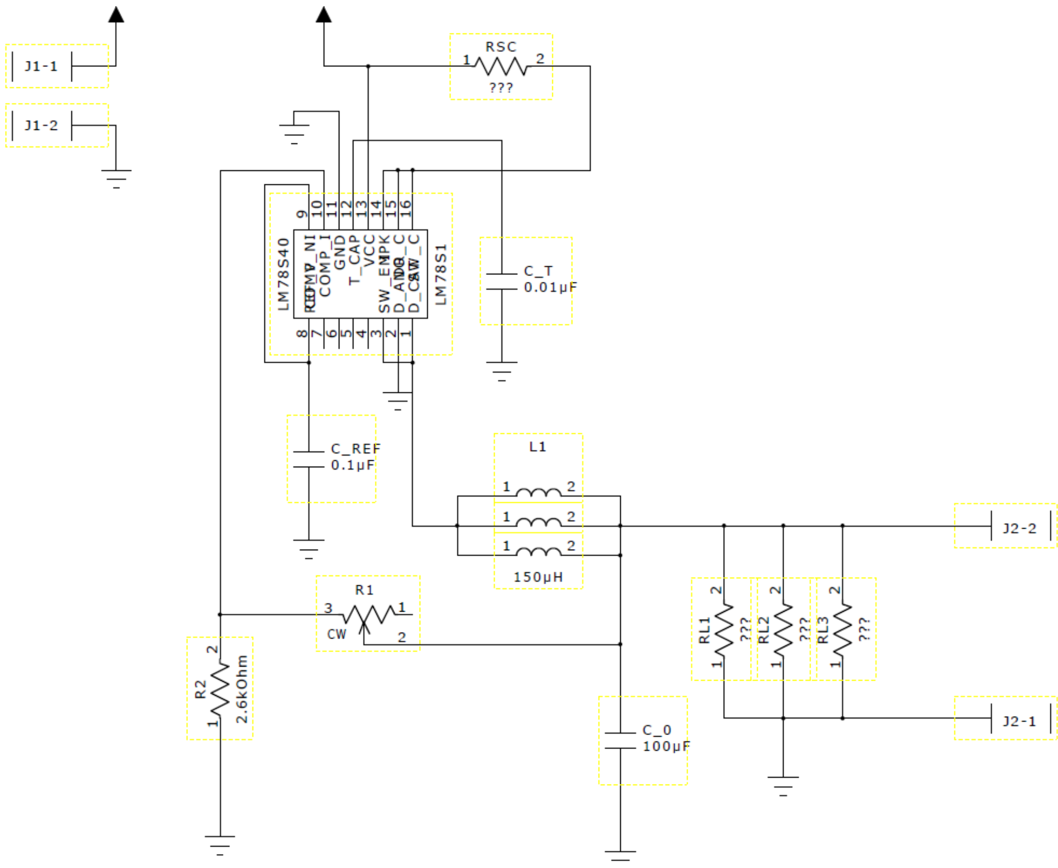



Figure 19. LM78S40 schematic.

Figure 19 shows the schematic with the calculated components for the step-down configuration of LM78S40. The part for LM78S40 could not be found from the library and was made by hand, also the connector part had to be made.

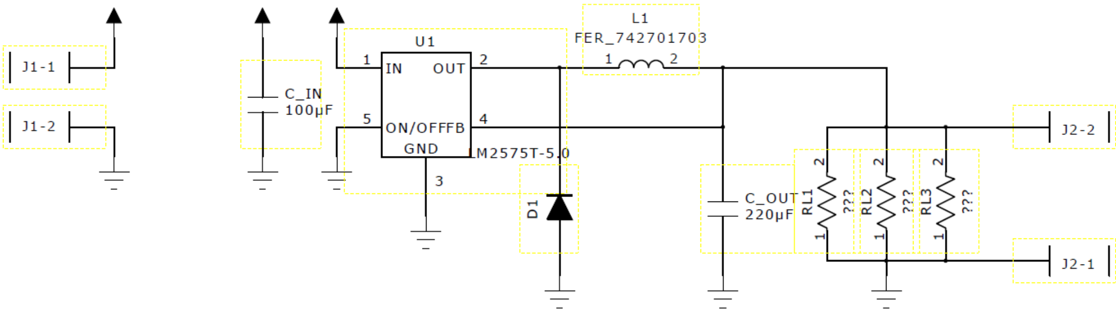



Figure 20. LM2575 schematic.

In Figure 20 it can be seen clearly that the design for LM2575 was much simpler than for the LM78S40. The IC could be found from the library of the software and the same connectors were used as in the previous design. Still the part for the ferrite had to be made.

Both of the designs have an option to put three resistors parallel for wider options for load resistance, and just in case if the output current is too much for the resistors. For this same reason LM78S40 also has an option to put three inductors parallel.

### 4.2.2 PADS Layout

The logic and layout software are connected, so connecting the components was done with PADS Layout. The layouts are shown in Figure 21 for LM78S40, and in Figure 22 for LM2575. The nets are connected to each other with copper lines.

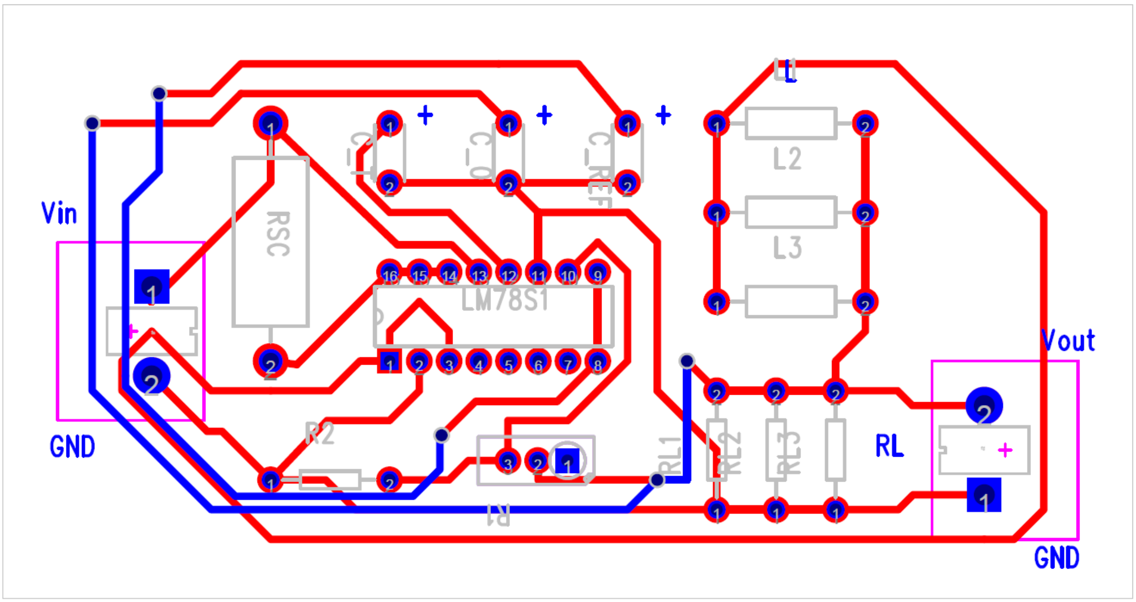



Figure 21. LM78S40 layout.

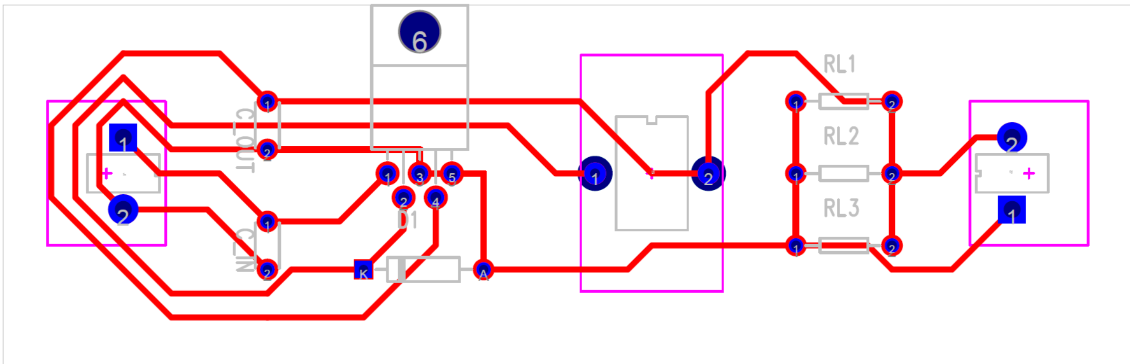



Figure 22. LM2575 layout.

For both circuits the components were designed to be put on top side and soldered through to the bottom side. The red copper lines are the connections on the bottom side and the blue ones are on the top side.

# 5 Measurements and Results

## 5.1 Voltage Measurement Process

For both cases the output voltage was measured with load resistance from 1k Ω down to 11.75 Ω with input voltage of 12 V. The output was also measured with input voltage from 8 V to 30 V with 470 Ω load resistance.

Both ICs were tested first on breadboard and then on PCB. The output voltages were measured with both oscilloscope and multimeter. Voltage ripple and duty cycle were also measured with the oscilloscope.

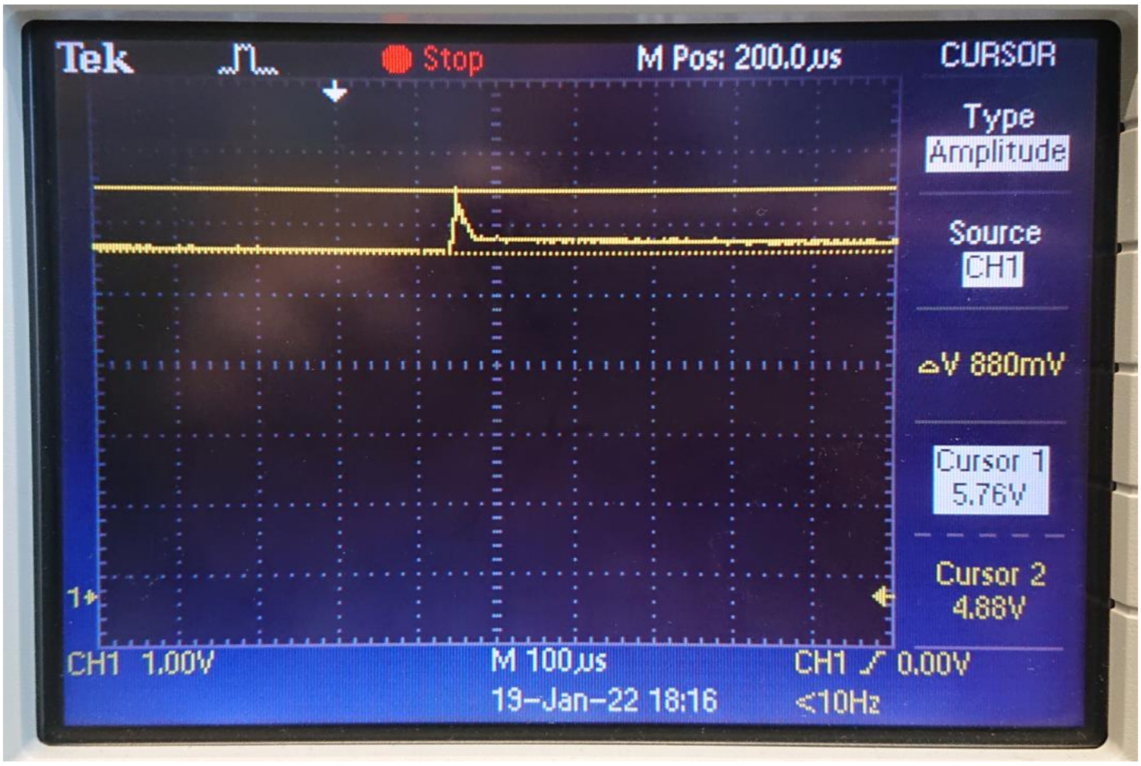



Figure 23. Voltage ripple measurement from the oscilloscope from LM78S40.

In Figure 23 the voltage ripple is measured from peak-to-peak using cursors, the ripple value for this measurement is 880 mV.


Figure 24. Duty cycle measurement using cursors from LM78S40.

A duty cycle is measured in Figure 24 using cursors the time between peaks. In this case the duty cycle is 4 ms.

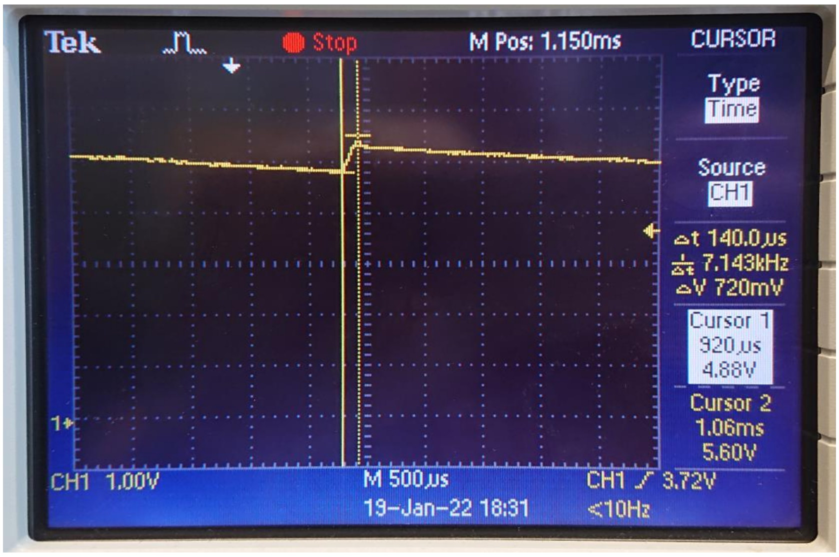



Figure 25. On-time measurement using cursors from LM78S40.

The on-time was measured as seen in Figure 25 from the time when the waveform is increasing. The time between cursors was 140 µs in this measurement.

## 5.2 Results

### 5.2.1 LM78S40

On the breadboard two 3.9 kΩ resistors in series were used for R1 (since the calculated value would have been 7.4 kΩ), so unlike with the PCB, the output voltage was not adjusted with a 10 kΩ potentiometer to 5.0 V in the beginning and was little less. For the breadboard measurements it was more important to see that the IC was working properly.

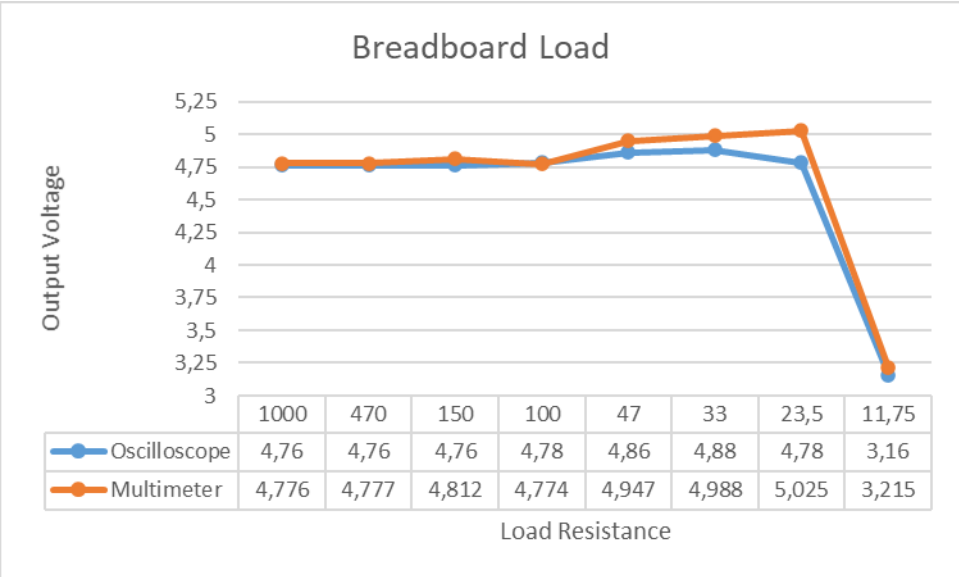



Figure 26. Breadboard output voltage with different load resistances.

In Figure 26 it can be seen that the regulator is working properly until the lowest measured load resistance value of 11.75 Ω.

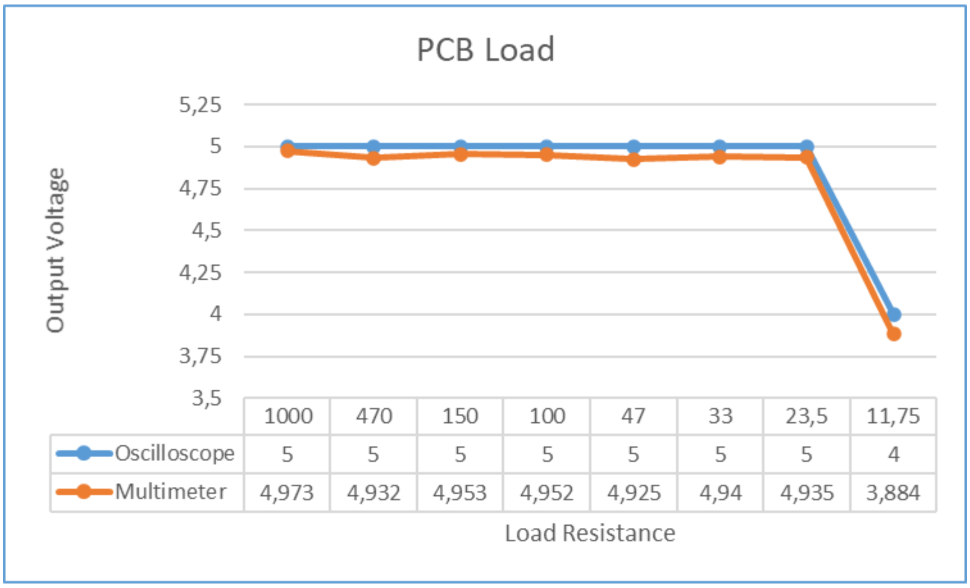



Figure 27. PCB output voltage with different load resistances.

The same result could be seen from Figure 27, so with both breadboard and PCB the output voltage is quite unaffected with the load resistance until the drop with the last measured value.

$$Load\ regulation = \left(\frac{V_{NL}-V_{FL}}{V_{FL}}\right) 100\ \% = \left(\frac{4.973-3.884}{3.884}\right) 100\ \% = 28\ \% \qquad (28)$$

$$Load\ regulation = \left(\frac{4.973-4.935}{4.935}\right) 100\ \% = 0.77\ \% \qquad (29)$$

The load regulation from the PCB is 28 % and with the lowest resistance value and with the second lowest 0.77 %. From this it can be seen that the regulator is working properly within certain limits.

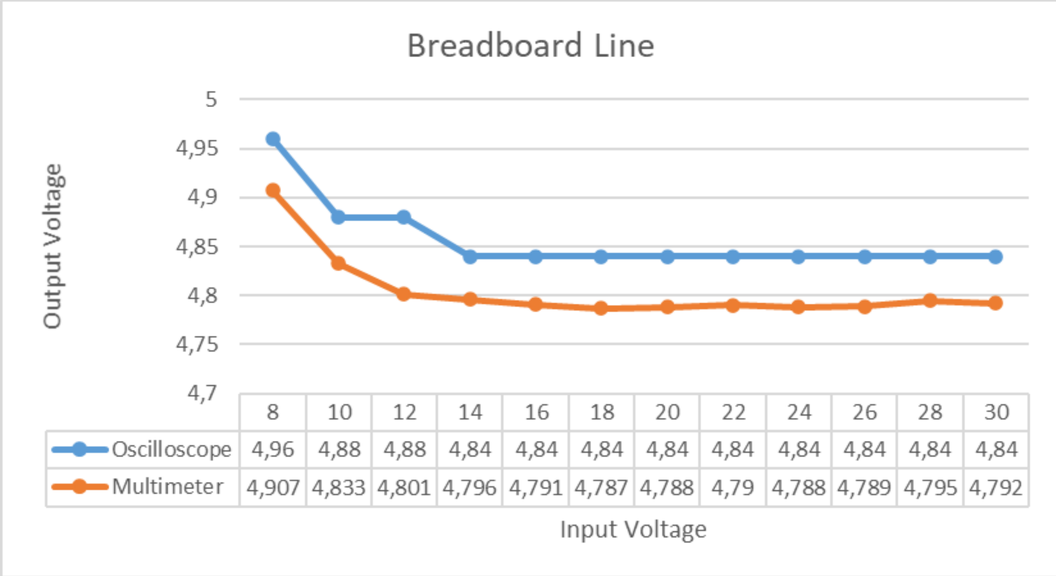



Figure 28. Breadboard output voltage with different input voltage value.

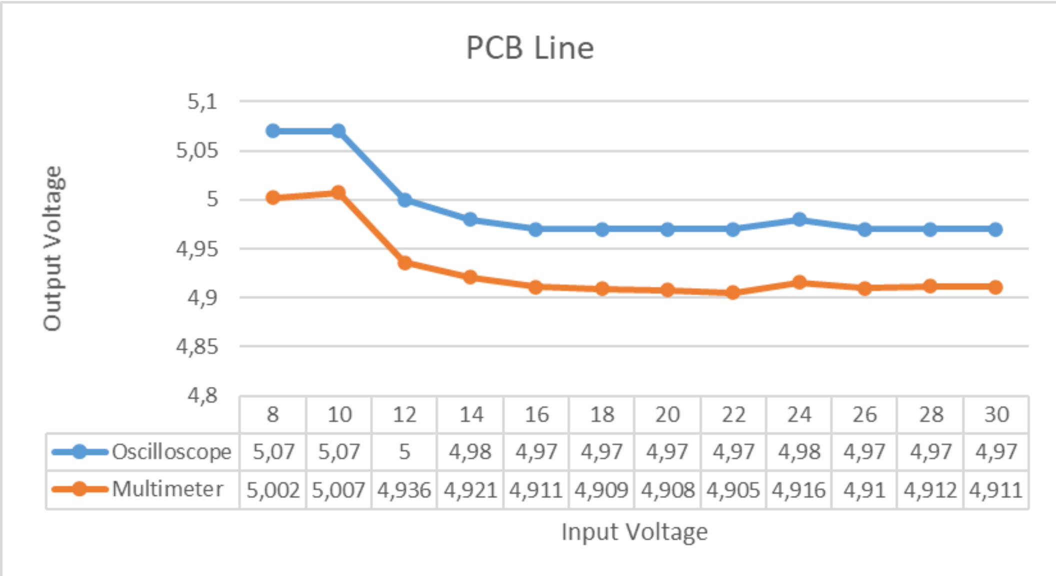



Figure 29. PCB output voltage with different input voltage value.

From Figure 28 and Figure 29 it can be seen that there seems to be no real change in output voltage with the change in input voltage.

$$Line\ regulation = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}}\right) 100\ \% \quad (30)$$

$$Line\ regulation = \left(\frac{0.10}{22}\right) 100\ \% = 0.45\ \% \qquad (31)$$

Line regulation from the PCB is 0.45 %.

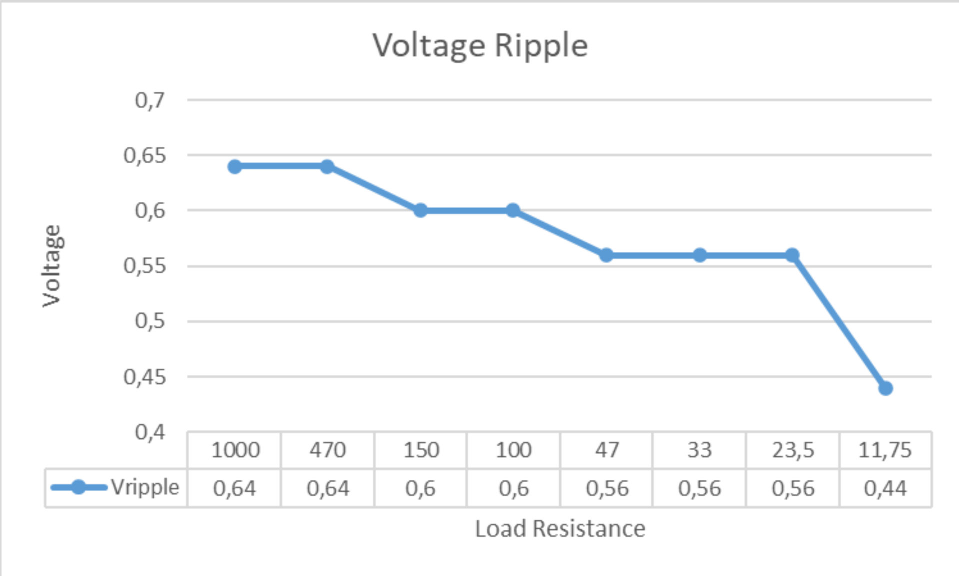



Figure 30. Ripple from the PCB with load resistance change.

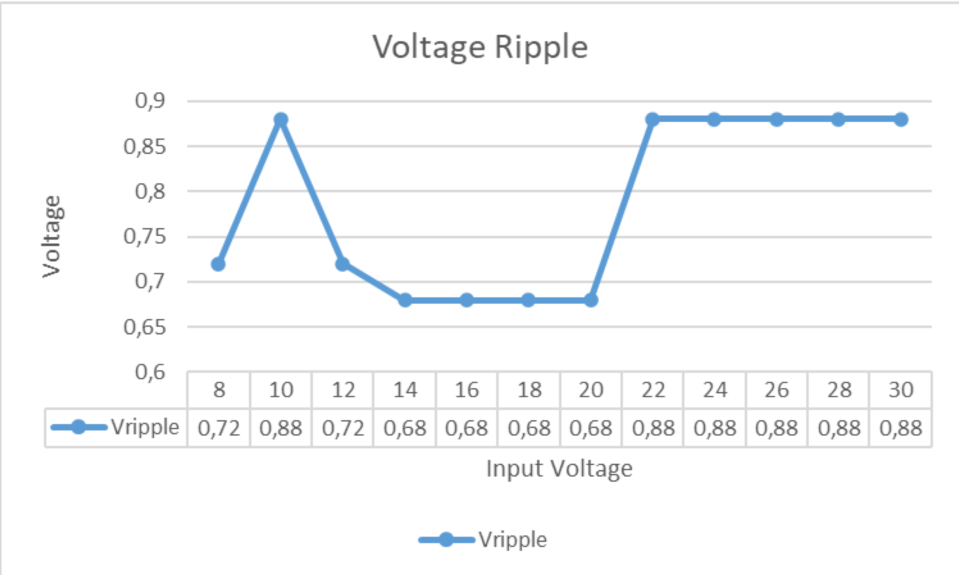
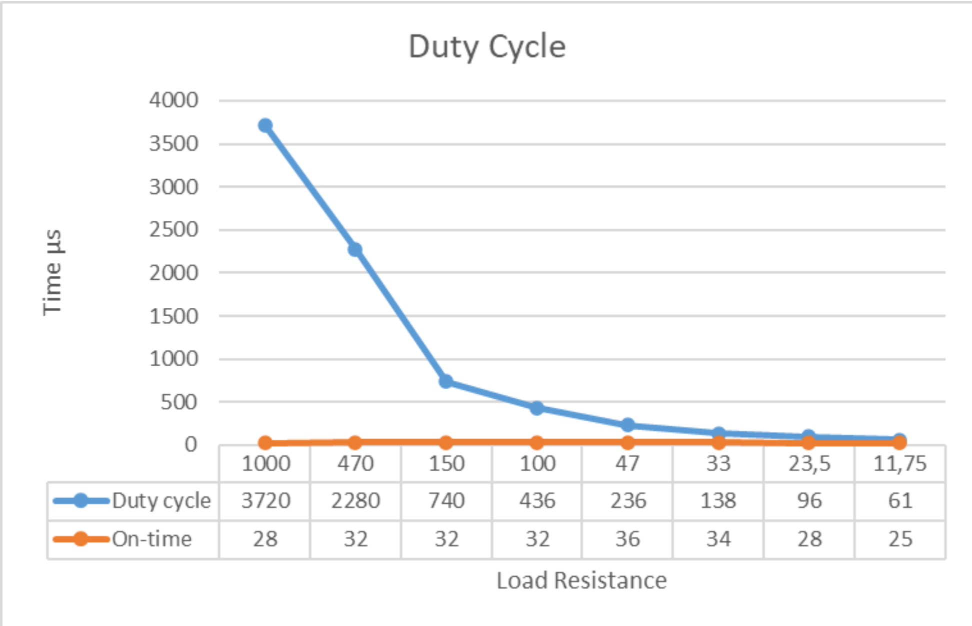



Figure 31. Ripple from the PCB with input voltage change.

As it can be seen in Figure 30 and Figure 31, there is quite a lot of ripple voltage. Still otherwise the circuit was working as it should, but the voltage should be filtered if put in use.




| | 1000 | 470 | 150 | 100 | 47 | 33 | 23,5 | 11,75 |
|---|---|---|---|---|---|---|---|---|
| Duty cycle | 3720 | 2280 | 740 | 436 | 236 | 138 | 96 | 61 |
| On-time | 28 | 32 | 32 | 32 | 36 | 34 | 28 | 25 |

Figure 32. Duty Cycle change and on-time with different load resistance.

The duty cycle decreases with the decrease on load resistance, but the on-time seems to stay quite the same in Figure 32. This is since the increase in output current $I_O$.

$$D \approx \frac{I_{IN}}{I_O} \qquad (32)$$

But $t_{on}$ still stays nearly the same since the output voltage also does

$$t_{on} = \frac{V_{OUT}}{V_{IN}} T \qquad (33)$$

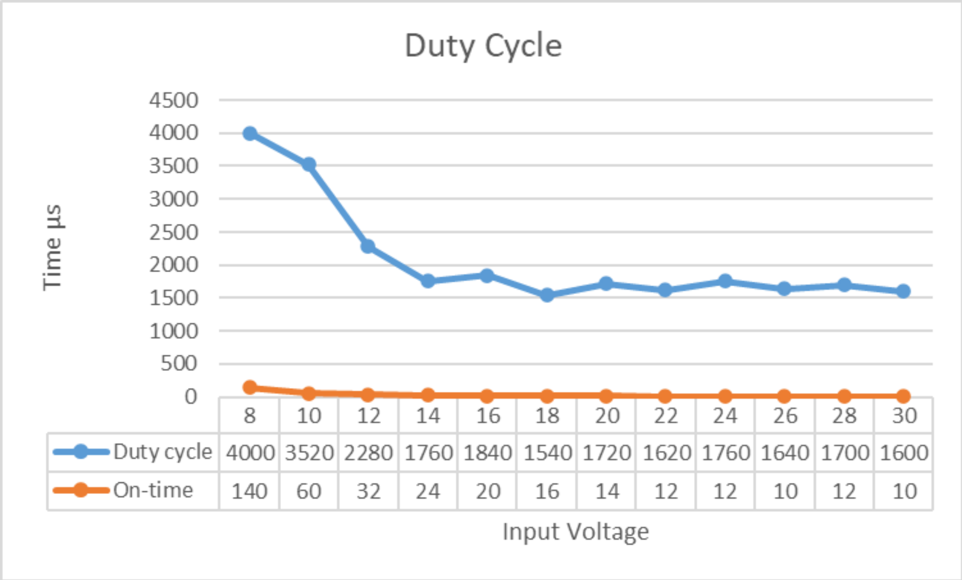



Figure 33. Duty cycle and on-time change with different input voltage.

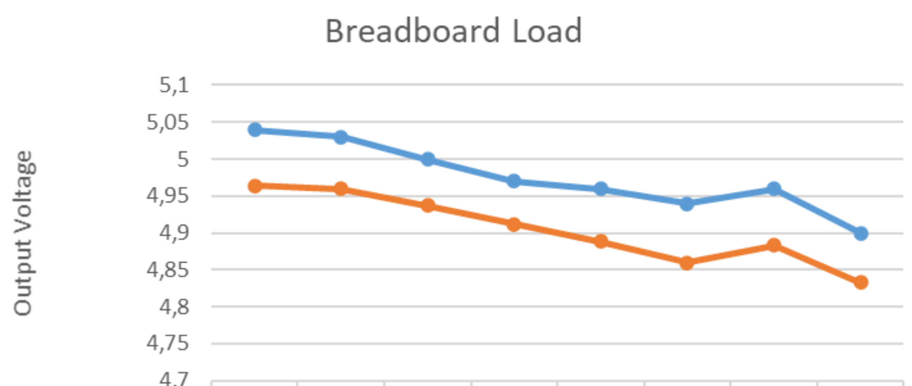
As seen in Figure 33 the change in input voltage does not seem to affect the duty cycle and $t_{on}$ that much after 14 V. The duty cycle should decrease due to the increase in $V_{IN}$.

$$D \approx \frac{V_{OUT}}{V_{IN}} \tag{34}$$

The signal was not that stable when the input voltage was increased, so the measurements with cursors might not have been quite accurate.

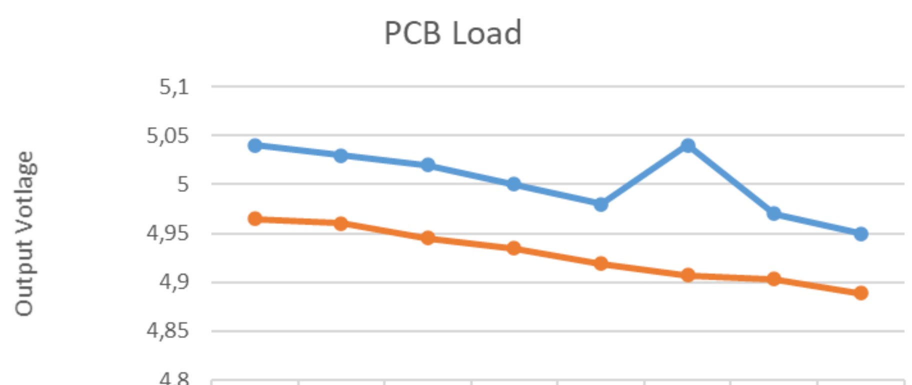
### 5.2.2 LM2575

For the second IC, the measurements were easier since there was no ripple at all. The output voltage was just stable DC voltage. This could be due that the LM2575 is made to work as a step-down switching regulator and is not as dependent on the external components as LM78S40 is.




| | 1000 | 470 | 150 | 100 | 47 | 33 | 23,5 | 11,75 |
|---|---|---|---|---|---|---|---|---|
| Oscilloscope | 5,04 | 5,03 | 5 | 4,97 | 4,96 | 4,94 | 4,96 | 4,9 |
| Multimeter | 4,964 | 4,96 | 4,937 | 4,912 | 4,888 | 4,86 | 4,883 | 4,833 |

Figure 34. Output voltage with different load resistances on breadboard.




| | 1000 | 470 | 150 | 100 | 47 | 33 | 23,5 | 11,75 |
|---|---|---|---|---|---|---|---|---|
| Oscilloscope | 5,04 | 5,03 | 5,02 | 5 | 4,98 | 5,04 | 4,97 | 4,95 |
| Multimeter | 4,965 | 4,96 | 4,945 | 4,935 | 4,919 | 4,907 | 4,903 | 4,889 |

Figure 35. Output voltage with different load resistances on PCB.

From Figure 34 and Figure 35 it can be seen that there was not any real difference between the output voltages on breadboard or PCB. Load regulation from the multimeter values from PCB:

$$Load\ regulation = \left(\frac{4.965-4.889}{4.889}\right) 100\ \% = 1.55\ \% \quad (35)$$

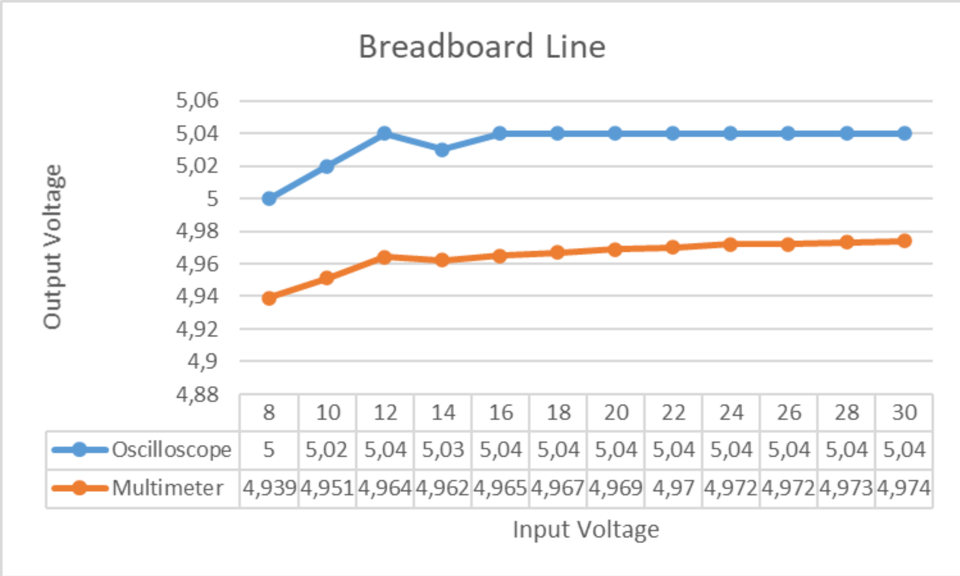



Figure 36. Output voltage change on breadboard with different input voltages.

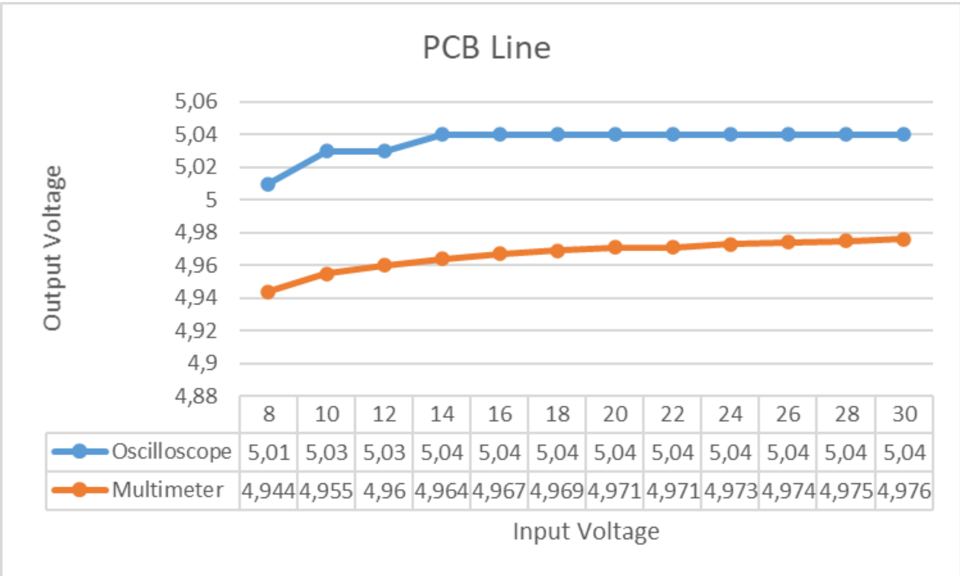



Figure 37. Output voltage change on PCB with different input voltages.

From Figure 36 and Figure 37 it can be seen that there is no real change in output voltage with input voltage change either. Line regulation from the multimeter values from PCB:

$$Line\ regulation = \left(\frac{4.976 - 4.944}{22}\right) 100\ \% = 0.15\ \% \tag{36}$$

## 5.3 EMC

### 5.3.1 Detectus AB EMC-Scanner

First the EMC was measured with Detectus AB EMC-Scanner seen in Figure 38, which is a patented scanner for measuring the emission from PCBs, components, cables, and products. [9.] The system scanned the circuit with a spectrum analyzer using a HP11941A near field probe which was connected to X-Y-Z robot. There was also a computer with custom software for controlling the robot and collecting data from the spectrum analyzer.

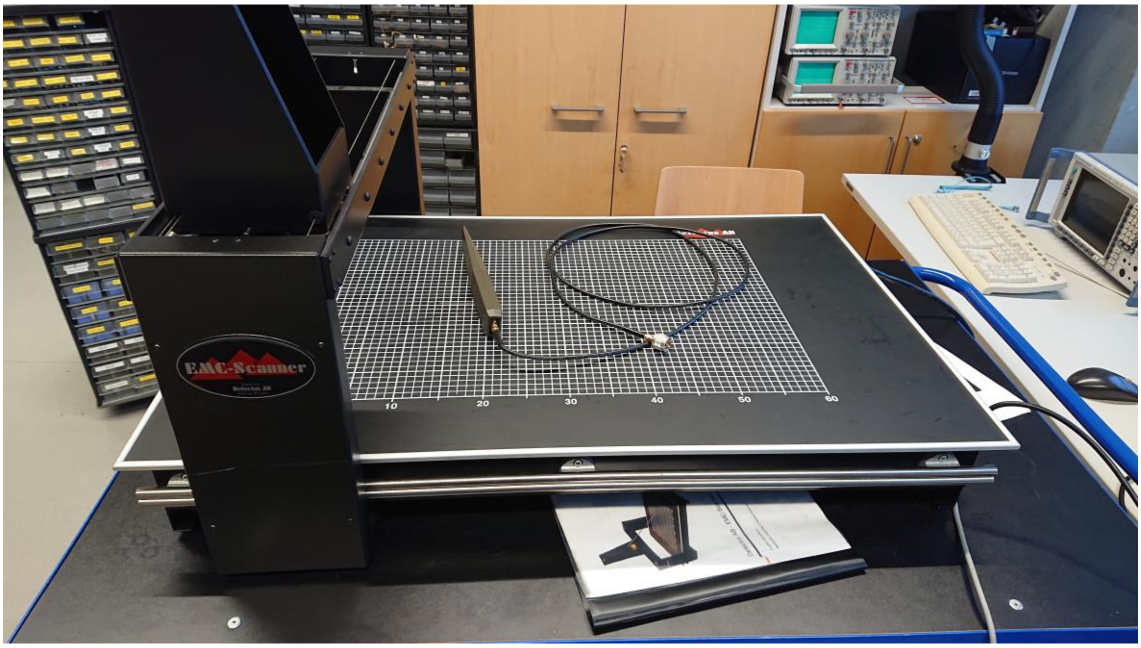



Figure 38. Detectus AB EMC-Scanner.

In this case the point of interest was to see if the frequency of the switching regulator could be found.  The peaks were gotten with the Pre-Scan function of the software.

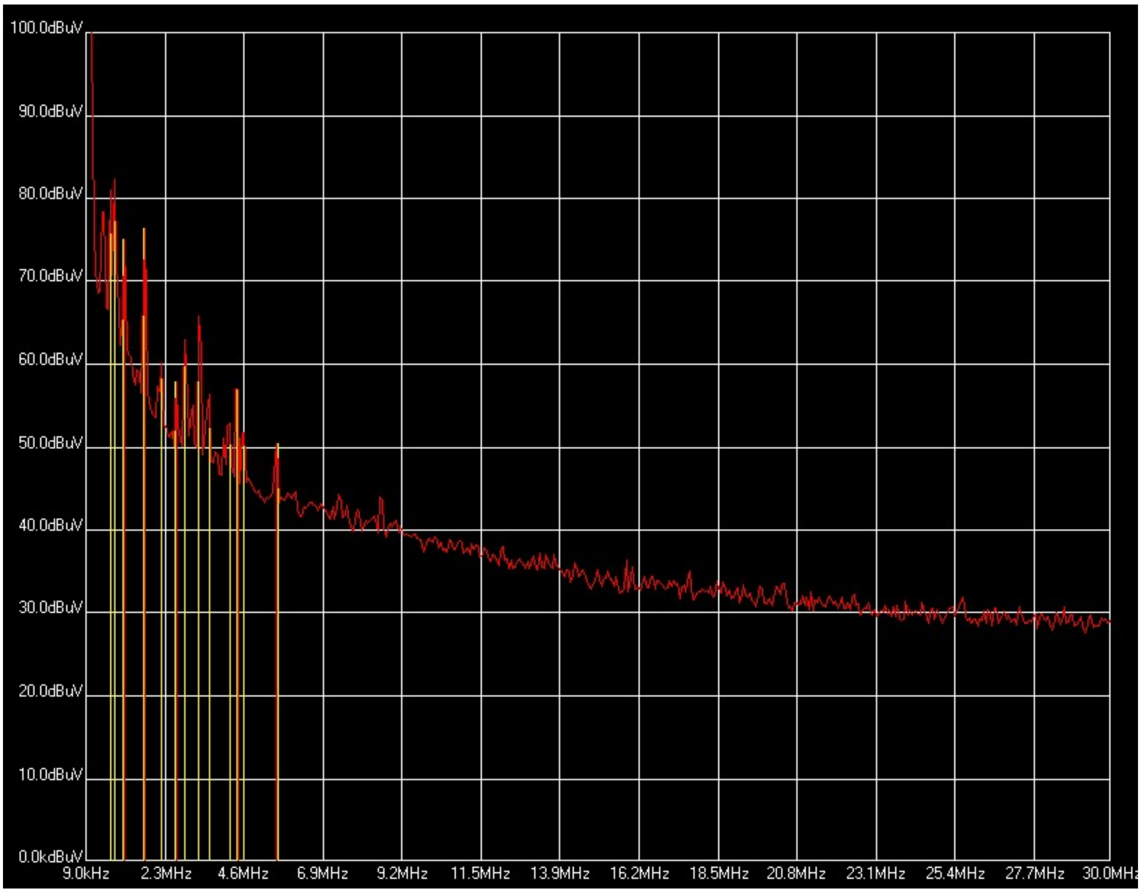



Figure 39. LM78S40 Pre-Scan Spectrum.

The spectrum was measured from 9 kHz to 30 MHz. The peaks in Figure 39 are so many that they are quite hard to make out from the spectrum, but the scanner also gave the details on a table from which the peaks can be easily read.

Table 1. Peaks of LM78S40 Pre-Scan Spectrum.

| **Peaks:** | |
|---|---|
| 840.0kHz | 82.28dBuV |
| 720.0kHz | 81.05dBuV |
| 1.7MHz | 76.43dBuV |
| 1.1MHz | 75.03dBuV |
| 3.3MHz | 65.76dBuV |
| 2.9MHz | 63.04dBuV |
| 4.4MHz | 56.85dBuV |
| 2.2MHz | 60.22dBuV |
| 3.6MHz | 56.39dBuV |
| 2.6MHz | 57.86dBuV |
| 4.2MHz | 52.96dBuV |
| 5.6MHz | 50.38dBuV |
| 4.6MHz | 51.77dBuV |

It can be read from Table 1 that LM78S40 has quite many disturbing peaks, but none as low that it could have been caused by the switching regulator. The peak at the lowest frequency measured is at 840 kHz, but the switching frequency is between 100 Hz and 100 kHz.

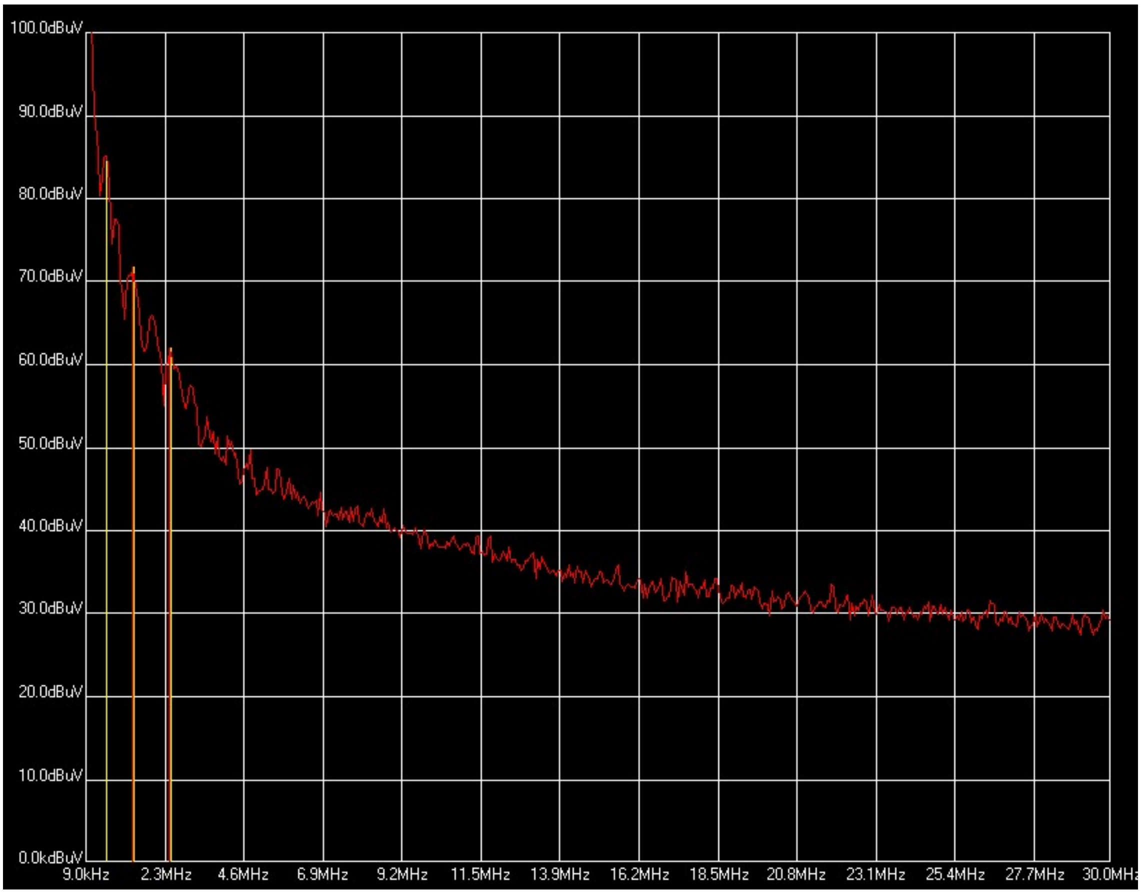



Figure 40. LM2575 Pre-Scan Spectrum.

From Figure 40 it can be seen that in the case of LM2575, there are only three peaks, which is much less than in the case of LM78S40.

Table 2. Peaks of LM2575 Pre-Scan Spectrum.

| **Peaks:** | |
|---|---|
| 600.0kHz | 85.11dBuV |
| 1.4MHz | 71.67dBuV |
| 2.5MHz | 61.95dBuV |

From Table 2 it can be read that the lowest peak is at 600 kHz. Since LM2575 has an internal oscillator with fixed frequency of 52 kHz, it could be seen that none of these peaks were made by the switching regulator.

From this it could be concluded that AB EMC-Scanner could not measure low enough frequencies to detect either of the switching regulators.

### 5.3.2 Near Field Probe Scan

As an addition, a scan with the same HP11941A near field probe was done by hand. The probe was connected to Agilent 4395A Network/Spectrum/Impedance Analyzer.

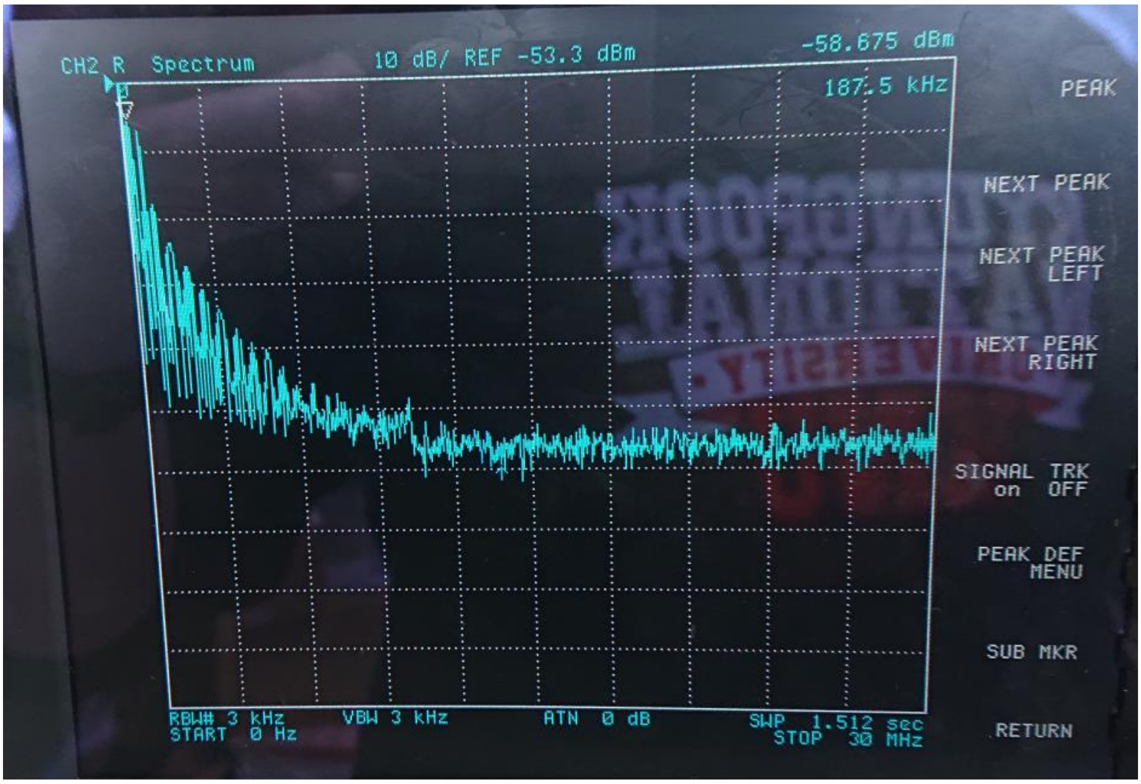



Figure 41. Spectrum of LM2575 to 30 MHz using near field probe.

This time LM2575 was measured first for it was thought easier to inspect comparing the results from the EMC-Scanner. The spectrum was measured from above the ferrite coil because after inspection it gave the most visible spectrum. All of the peaks seemed to be at the lower frequencies as can be seen in Figure 41.

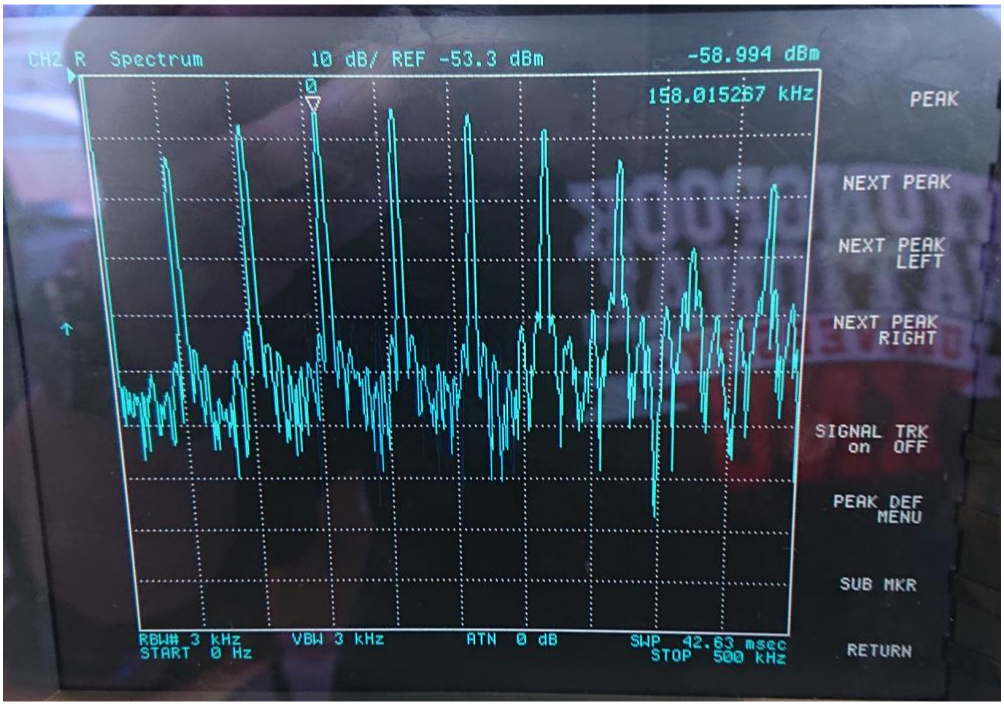



Figure 42. Spectrum of LM2575 to 500 kHz.

Taking a closer look at the lower frequencies seen in Figure 42, the highest peak seems to be at 158 kHz.

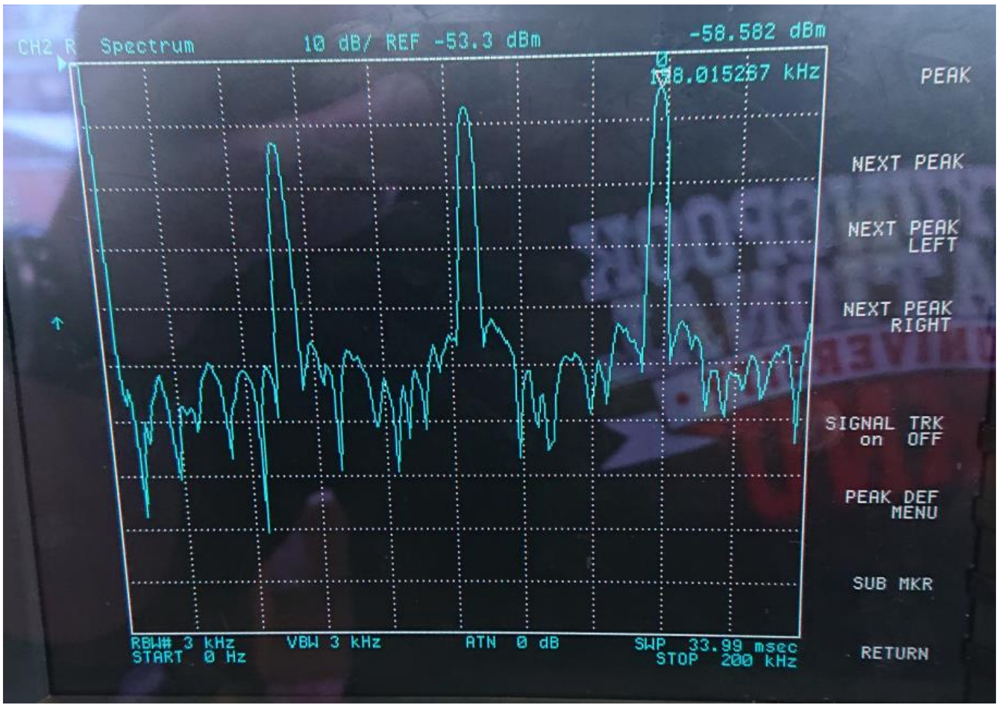



Figure 43. Spectrum of LM2575 to 200 kHz.

The first peak in Figure 43 is at -58.58 dBm @ 158 kHz, second at 60.77 dBm @ 105.3 kHz, and the third at -66.2 dBm @ 52.6 kHz, the resolution bandwidth RBW is about 52.7 kHz. Since the switching regulator's frequency is fixed at 52 kHz, it could be concluded that it was the third peak at -66.2 dBm @ 52.6 kHz. So unlike with the EMC-Scanner, it could be found with the same near field probe with hand.

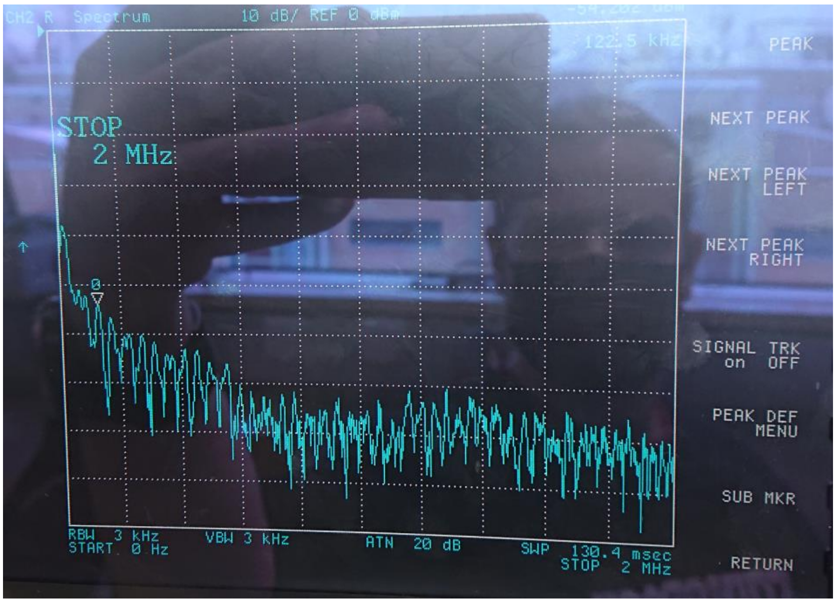



Figure 44. A spectrum of LM78S40.

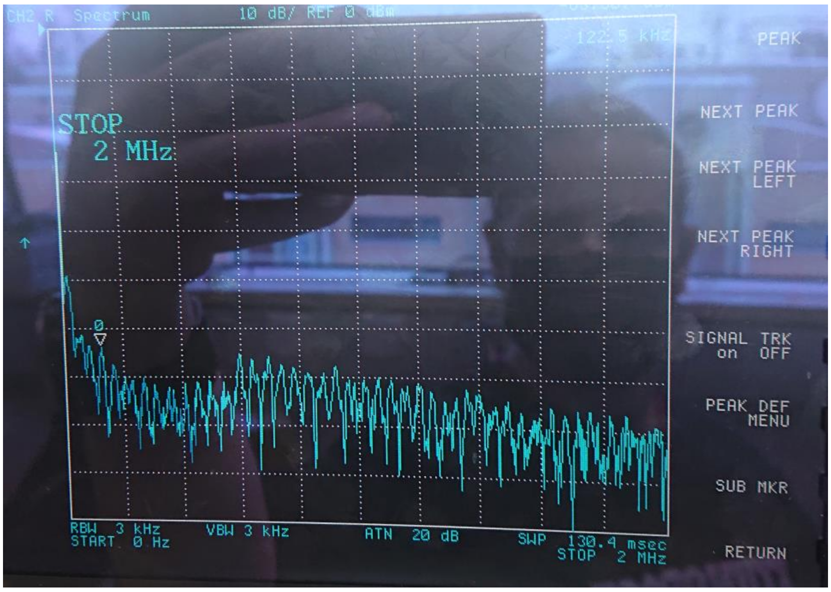



Figure 45. Another spectrum from LM78S40.

With LM78S40 the spectrum did not stay still. There was some unexplainable interference which made the spectrum unreadable. As it can be seen from the difference in Figure 44 and Figure 45, the spectrum jumping around. Still, in this case also the best spectrum could be read from above the coils.

# 6 Conclusion

The main goal of the thesis work was to make two properly working step-down switching regulators using integrated circuits. This goal was achieved with both ICs in case although the LM2575 was much more efficient than LM78S40. While working on this project the difference in integrated circuit switching regulators was seen clearly.

Both of the regulators had little difference while changing the line voltage and load resistance within certain limits. While the LM2575 had stable straight DC output voltage, the switching was visible with LM78S40, and because of the voltage ripple, the output should be filtered. This was the main difference seen working with the two ICs. LM2575 is designed to step-down to 5 V output voltage, when the LM78S40 is universal switching regulator that can be configured for step-up and inversion also and is more dependent on the external components.

The second goal was to see if the PCBs were emitting any interference since the switching regulators were used. While inspecting the frequency spectrum, results from LM78S40 were inconclusive, since it was causing some unexplainable interference, which made the measurement unsuccessful. From LM2575 on the other hand the switching frequency was found when using the near field probe by hand.

All in all, both of the step-down switching regulators were quite simple to design, and the work was a success with two working designs.

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