CDIO Project Report

Buck Converter

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**Group I:**

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Introduction

A **buck converter** (**step-down converter**) is a DC-to-DC power converter which steps down voltage (while stepping up current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) typically containing at least two semiconductors (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination.

Switching converters (such as buck converters) provide much greater power efficiency as DC-to-DC converters than linear regulators, which are simpler circuits that lower voltages by dissipating power as heat, but do not step up output current.

Buck converters can be highly efficient (often higher than 90%), making them useful for tasks such as converting a computer's main (bulk) supply voltage (often 12V) down to lower voltages needed by USB, DRAM and the CPU (1.8V or less).
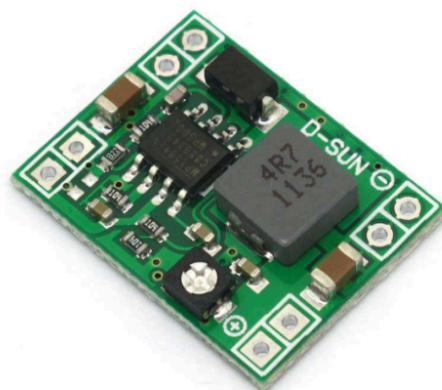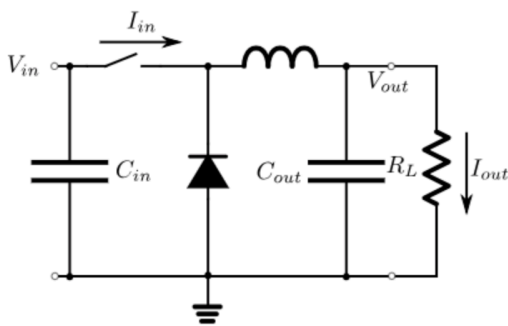
Working Principle

Buck Converter Operation

The buck converter circuit consists of the switching transistor, together with the flywheel circuit (Diode, Inductor and Capacitor). While the transistor is on, current is flowing through the load via the inductor L. The action of any inductor opposes changes in current flow and also acts as a store of energy. In this case the switching transistor output is prevented from increasing immediately to its peak value as the inductor stores energy taken from the increasing output; this stood energy is later released back into the circuit as a back e.m.f. as current from the switching transistor is rapidly switched off.

Transistor Switch 'on' Period

When the switching transistor is switched 'on', it is supplying the load with current. Initially current flow to the load is restricted as energy is also being stored in **L1**, therefore the current in the load and the change on **C1** builds up gradually during the 'on' period. Throughout the 'on' period, there will be a large positive voltage on **D1** cathode and so the diode will be reverse biased and therefore play no part in the action.
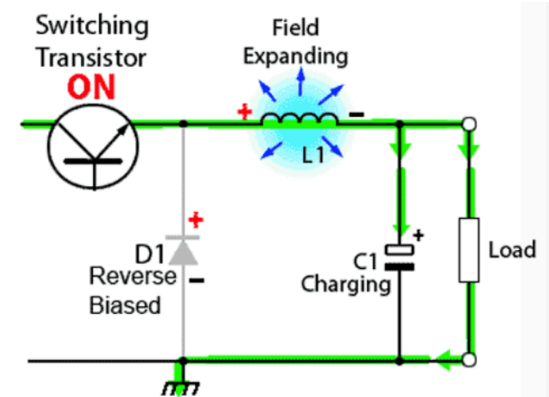
Transistor Switch 'off' Period

When the transistor switches off the energy stored in the magnetic field around **L1** is released back into the circuit. The voltage across the inductor (the back e.m.f.) is now in reverse polarity to the voltage across **L1** during the 'on' period, and sufficient stored energy is available in the collapsing magnetic field to keep current flowing for at least part of the time the transistor switch is open.
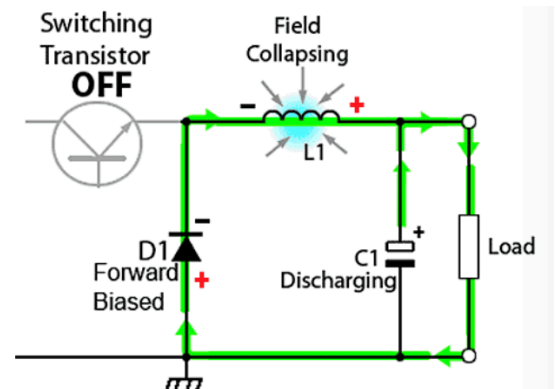
The back e.m.f. from **L1** now causes current to flow around the circuit via the load and **D1**, which is now forward biased. Once the inductor has returned a large part of its stored energy to the circuit and the load voltage begins to fall, the charge stored in **C1** becomes the main source of current, keeping current flowing through the load until the next 'on' period begins.

Continuous & Discontinuous Mode

Continuous Mode

A buck converter operates in continuous mode if the current through the inductor (I_L) never falls to zero during the commutation cycle.
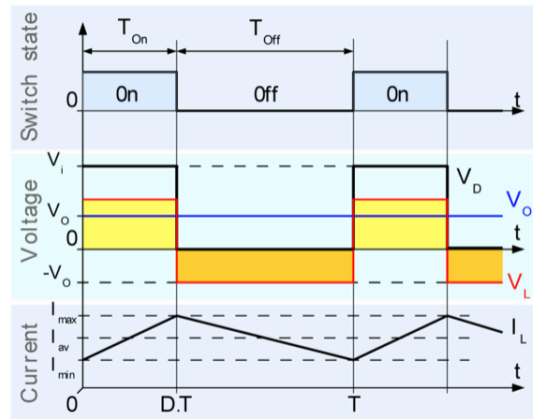
In this mode, the operating principle is described by:

- When the switch is closed, the voltage across the inductor is $V_L = V_i - V_o$. The current through the inductor rises linearly (in approximation, so long as the voltage drop is almost constant). As the diode is reverse-biased by the voltage source V, no current flows through it.
- When the switch is opened, the diode is forward biased. The voltage across the inductor is $V_L = -V_o$ (neglecting diode drop). Current I_L decreases.

The energy stored in inductor **L** is:

$$E = \frac{1}{2} L I_L^2$$

The rate of change of I_L can be calculated from:

$$V_L = L \frac{dI_L}{dt}$$

With V_L equal to $V_i - V_o$ during the on-state and to $-V_o$ during the off-state. Therefore, the increase in current during the on-state is given by:

$$\Delta I_{L_{on}} = \int_0^{t_{on}} \frac{V_L}{L} \, dt = \frac{(V_i - V_o)}{L} t_{on}, \; t_{on} = DT$$

where D is a scalar called the **duty cycle** with a value between 0 and 1.

Discontinuous Mode

In some cases, the amount of energy required by the load is too small. In this case, the current though the inductor falls to zero during part of the period. The only difference in the principle described in *continuous mode* is that the inductor is completely discharged at the end of the commutation cycle.
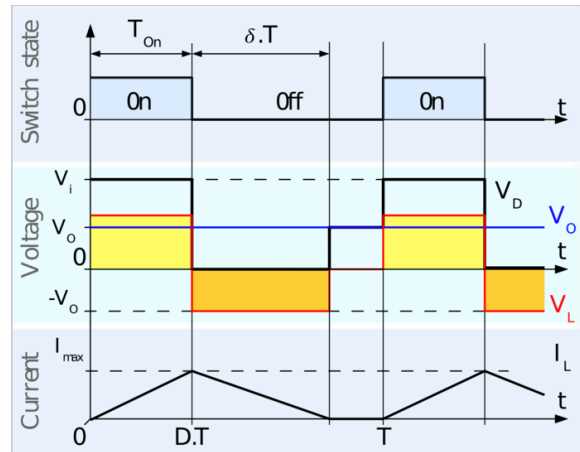
The inductor current falling below zero results in the discharging of the output capacitor during each cycle and therefore higher switching losses. A different control technique known as Pulse-frequency modulation can be used to minimize these losses.

Note!
Additional informations are excluded from this part of report because of the fact that designed buck converter works in continuous mode of operation.

Mathematical Formulas (Continuous Mode)

Peak inductor current	i_{pk}
Min inductor current	i_o
Ripple Current	$\Delta i \equiv \left(i_{pk} - i_o \right)$
Ripple Current Ratio to Average Current	$r \equiv \Delta i / i_{ave}$
Duty Cycle	$D \equiv T_{on} / T$
Switch On Time	$T_{on} = D / f$
Average and Load Current	$i_{ave} \equiv \Delta i / 2 \equiv i_{load}$
RMS Current for a Triangular Wave	$i_{rms} = \sqrt{i_o^2 + (\Delta i)^2 / 12}$

Increase in current during whole 'on' state:

$$\Delta I_L^+ = \frac{V_{in} - V_{out}}{L} t_{on} = \frac{V_{in} - V_{out}}{L} DT$$

Fall of current during whole 'off' state:

$$\Delta I_L^- = -\frac{V_{out}}{L} t_{off} = -\frac{V_{out}}{L} (1 - D)T$$
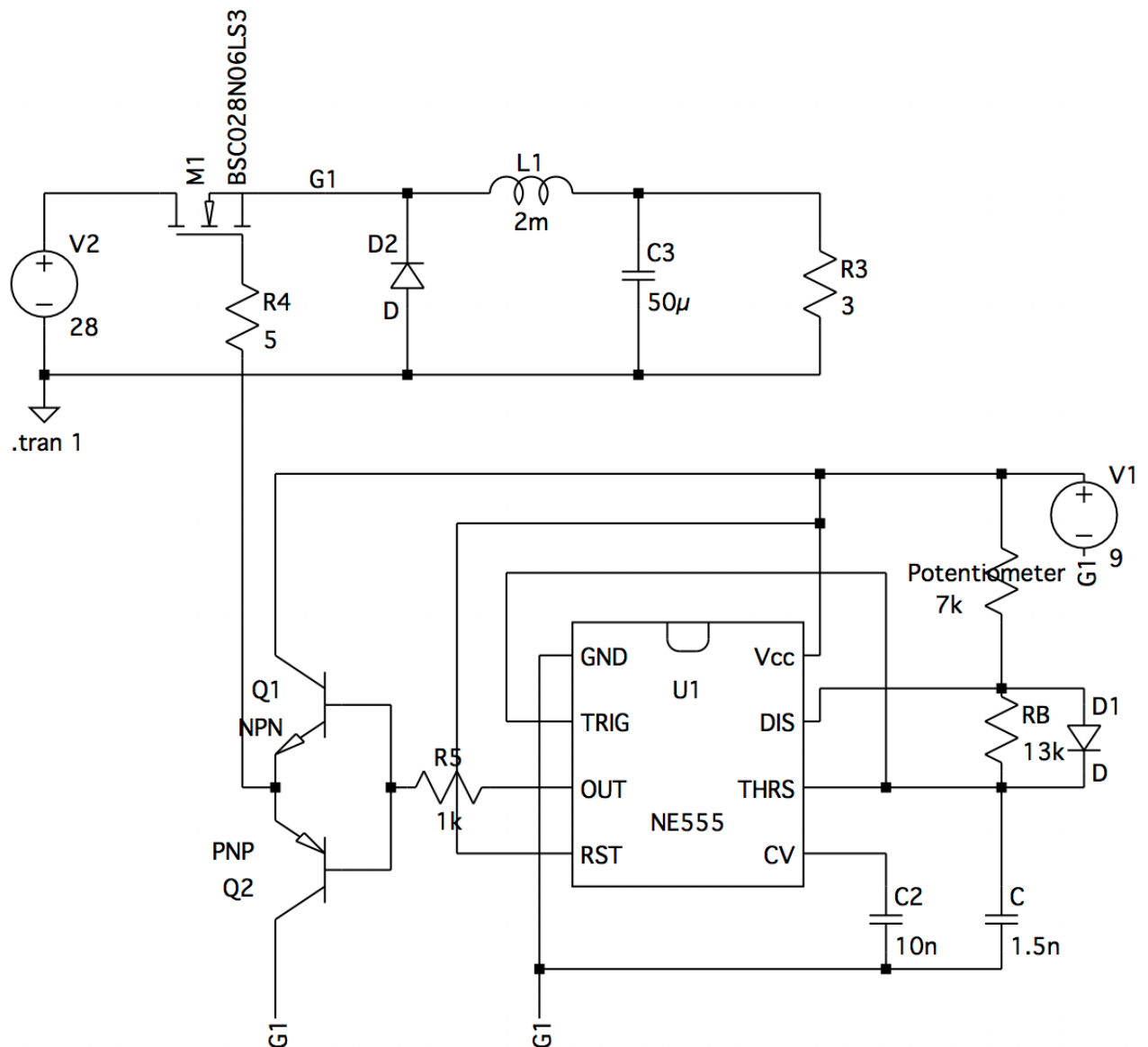
These two equations lead to the following condition:

$$\Delta I_L^+ + \Delta I_L^- = 0$$

$$\frac{V_{in} - V_{out}}{L} DT - \frac{V_{out}}{L} (1 - D)T = 0$$

$$V_{in} D - V_{out} = 0$$

$$V_{out} = V_{in} D$$

Therefore, the *Duty Cycle* can be calculated as:

$$D = \frac{V_{out}}{V_{in}}$$

Lt Spice Model Schematic

Buck Converter Parts:
- V2 - Voltage Source (Input)
- M1 - MOSFET
- D2 - Diode
- L1 - Inductor
- C3 - Capacitor
- R3 - Resistor (Load)
- R4 - Resistor

PWM Gate Unit Parts:
- NE555 - 555 Timer
- V1 - Voltage Source
- Potentiometer
- RB - Resistor
- D1 - Diode
- C - Capacitor
- C2 - Capacitor
- R5 - Resistor
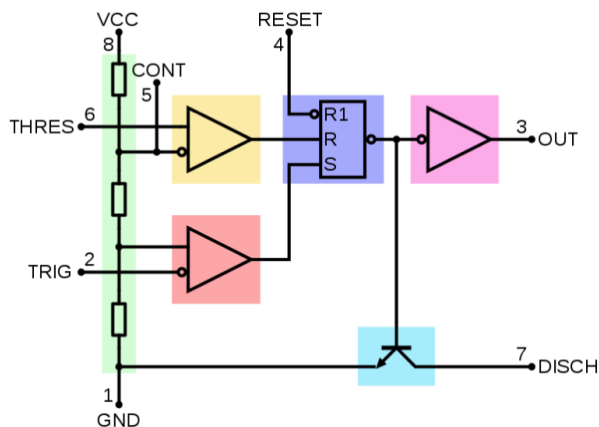- Q1 - NPN Transistor
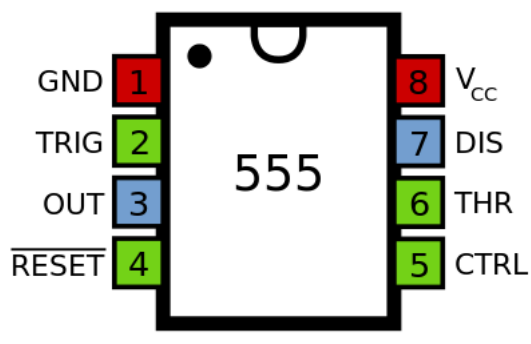- Q2 - PNP Transistor

PWM Parts Description

555 Timer

The **555 timer IC** is an integrated circuit (chip) used in a variety of timer, pulse generation, and oscillator applications. The 555 can be used to provide time delays, as an oscillator, and as a flip-flop element.
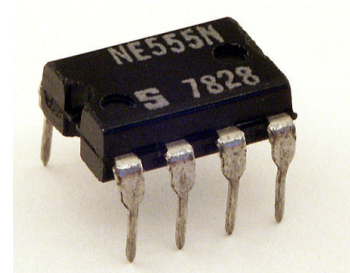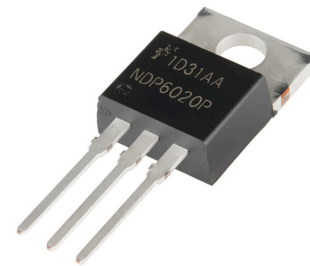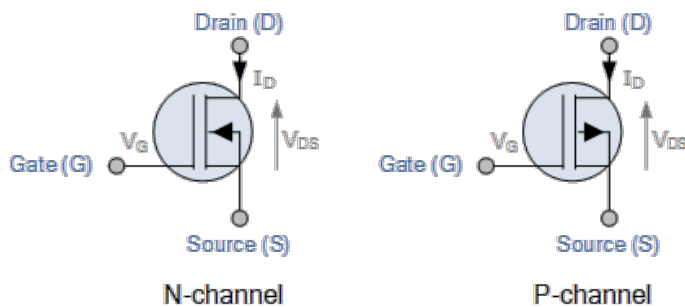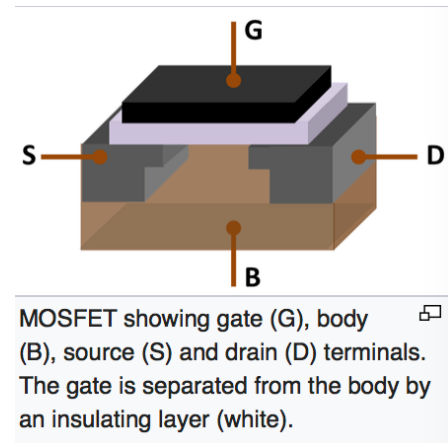
Internal Schematic

**Pinout of 555 single timer (8 pins)**

MOSFET

The **metal-oxide-semiconductor field-effect transistor** (**MOSFET**) is a type of field-effect transistor (FET), most commonly fabricated by the controlled oxidation of silicon. It has an insulated gate, whose voltage determines the conductivity of the device. This ability to change conductivity with the amount of applied voltage can be used for amplifying or switching electronic signals.

MOSFET showing gate (G), body (B), source (S) and drain (D) terminals. The gate is separated from the body by an insulating layer (white).

N-channel

P-channel

Gate Driver

Gate driver is a power amplifier that accepts a low-power input from a controlled IC and produces the appropriate high-current gate drive for a power MOSFET. A gate driver is used when a pulse-width modulation (PWM) controller cannot provide the output current required to drive the gate capacitance of the associated MOSFET.

Gate drivers may be implemented as dedicated ICs, discrete transistors, or transformers. They can also be integrated within a controller IC. Partitioning the gate drive function off the PWM controller allows the controller to run cooler and be more stable by eliminating the high peak currents and heat dissipation need to drive a power MOSFET at very high frequencies.
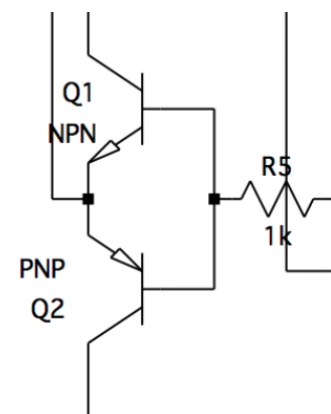
Simulation & Calculations (Lt Spice)

Buck Converter Values:
- Input Voltage (V_{in}) = 28 V
- Maximum Load Current ~1 A
- Choke Inductance (L1) = 2 mH
- Transistor Switching Frequency = 40 kHz
- Capacitance (C3) = 50 μF

PWM Values:
- Supplied Voltage = 9 V
- Main Capacitor (C) = 1.5 nF
- Second Capacitor (C2) = 10 nF
- Variable Frequency Regulator Potentiometer = 5-10 kΩ
- Fixed Frequency Regulator Resistor = 13 kΩ

Examples of Results for Buck Converter with Different Working Frequencies

I Case

Potentiometer = 10 kΩ
Working Frequency = 38 kHz
T_{on} = 13.46 μs
V_{out} = 13.2 V
V_{in} = 28.0 V
D = 0.4714
$I_{inductor}$ = 4.34 - 4.43 A
$I_{capacitor}$ = (-50) - (+50) mA
I_{load} = 4.4 A (steady state)

II Case

Potentiometer = 7 kΩ
Working Frequency = 44 kHz
T_{on} = 9.68 μs
V_{out} = 10.8 V
V_{in} = 28.0 V
D = 0.3857
$I_{inductor}$ = 3.54 - 3.62 A
$I_{capacitor}$ = (-40) - (+40) mA
I_{load} = 3.6 A (steady state)

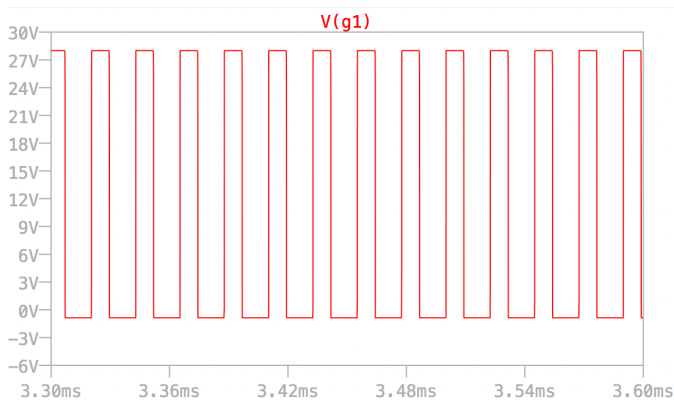## Maximum / Minimum Duty Cycle & Efficiency

Minimum Duty Cycle:
Potentiometer = 5 kΩ
Working Frequency = 20 kHz
T_{on} = 6.66 μs
T_{off} = 13.39 μs
V_{out} = 8.6 V
V_{in} = 28.0 V
Duty Cycle = 30.7%

Maximum Duty Cycle:
Potentiometer = 10 kΩ
Working Frequency =
T_{on} = 12.67 μs
T_{off} = 13.29 μs
V_{out} = 13.17 V
V_{in} = 28.0
Duty Cycle = 47.0 %

PWM Waveform Example (44 kHz Working Frequency)

Upper triangular waveform indicates T_{on} (switch is closed).
Straight-down waveform indicates T_{off} (switch is opened).
Summing up this time and taking the reciprocal gives *Working Frequency*.

Oscilloscope Measurements

Unfortunately during constructing designed buck converter, some mistakes were made and part of the assembled circuit does not work properly or were damaged.

Measurement of the PWM were possible, this is the result:

Notes:
1.Ripples in the switching frequency
2.Procedure of manipulating the PWM signal did not confirm the simulations from the Lt Spice

General Conclusion (Part I)

Due to lack of experience in electronic design, the assembled circuit did not confirm the predictions and simulations which were made during designing process.
Additionally, the designed circuit has very poor efficiency. The problems come from the fact that calculations and predictions were made incorrectly and have not been checked during designing process.

Ideal Circuit Schematic

Important Points:

- The ideal circuit should not consist of any sharp turns (90 degrees) as it will not cause any problem with reflections or high frequency signals. To prevent that, rounded connections can be used.
- Another problem is the length of the connections. Long connections will unnecessarily increase the inductance of the circuit. Therefore, connections as short as possible are preferable.
- It should be also noted that rounded connections are longer and harder to position than simple 45 degrees turns. The latter one is the perfect compromise in between these two problems and so the circuit connections should mainly be made in that way.
- Sometimes, connecting two elements is not possible with a simple connection on PCB. In those cases, a wire on top of the PCB can be used. If in between two elements there is a resistor connecting them, it is possible to use the resistance instead of a wire.
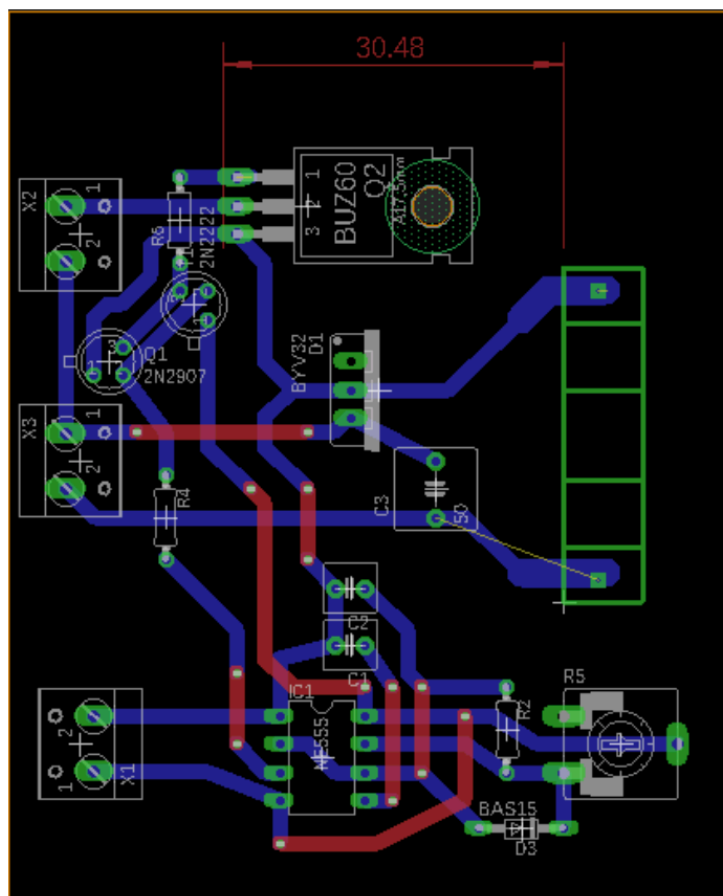
Schematic Representation of The Test Circuit
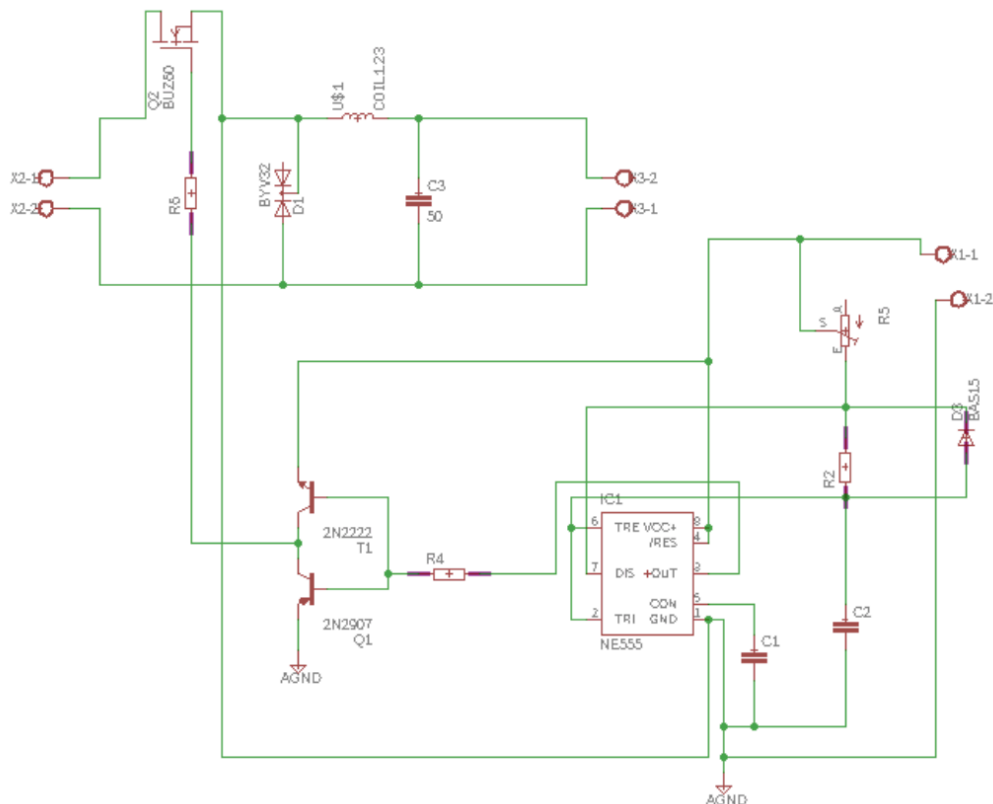
List of Materials

Amount	Name	Name on the schematic	Value	Price of single element
3	screw terminals	X1-1; X1-2	-	$0,08
		X2-1; X2-2		
		X3-1; X3-1		
1	555 timer	NE555	-	$0,3
1	coil prepared by the WG_3 group	U$1 COIL123	-	-
2	transistors (type:Mosfet)	2N2222 T1	-	$0,19
		2N2907 Q1		
2	diodes	BYV32 D1	-	$0,34
		D3 BAS15		
3	capacitors	C1	10n F	$0,19
		C2	1.5n F	$0.01
		C3	50μ F	$0.08
7	electric wires	-	-	$0.34
5	resistances	R6	5 Ω	$0,08
		R4	1000 Ω	$0,13
		R5	5-10 Ω	$0,08
		R2	13000 Ω	$0,95

PCB Layout

Etching Process

General Description

Etching is a "subtractive" method used for the production of printed circuit boards: acid is used to remove unwanted copper from a prefabricated laminate. This is done by applying a temporary mask that protects parts of the laminate from the acid and leaves the desired copper layer untouched.

Different machines and chemicals can be used for etching, which will affect the comfort, duration and quality of the result.

Two acid types that can be used for etching are ferric chloride (Eisen-3-Chlorid) and Sodium Persulfate (Natriumpersulfat-Feinätzkristall).

To improve the quality of etching, it is recommended to use machines that control temperature and constantly keeps the fluids in motion.

Photo-Resistive Laminates

The mask is printed on a transparent paper or foil, exposed and developed on the laminate with a UV lamp.

The laminates have a coating that is sensitive to light - by shining a light on them, an image of the design can be transfer to be created onto the board. Where light strikes the board, the coating weakens and creates an area of copper that will be dissolved away by the etching acid.

Steps to follow:

1. Export PCB Layout from EAGLE, and if preferable enhance the graphic
2. Print the file in highest resolution, first on white paper, then on a transparent paper of foil.
3. When printing on foil, use either a special toner or a toner dissolver spray to heighten the density and get the print tone overall even.
4. Peel the protective blue film off the laminate and place it in the imaging frame copper side down, on top of the transparent film.
5. Close the lid of the imaging frame, set the timer for 4 minutes and press the knob to start the exposure.
6. Once the imaging process finishes, place the board in the development tank for 1-2 minutes and shake it once in a while.
7. Place the board in the rinse tank containing distilled water for a few seconds.

Etching

To get rid of all unwanted copper, given steps are recommended:

1. Put the board in the acid tank for about 20 minutes until the copper traces are completely etched.
2. Move the board into the rinse tank for a few seconds.
3. Dry the board with a cloth.
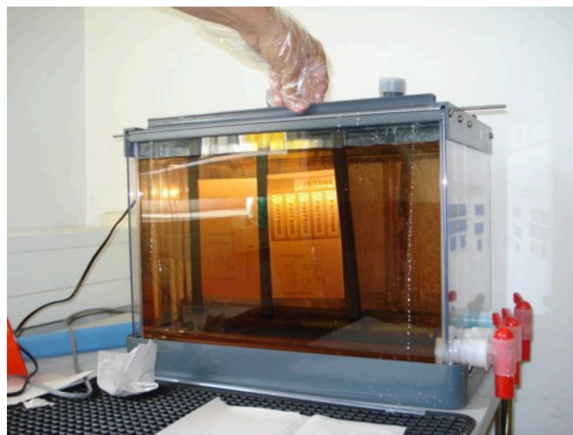
General Conclusion (Part II)

Finding the correct parts which parameters would match those required by the schematic proved to be more difficult that it seemed. Many parts were simply unavailable so there was a need to find similar ones.

Etching process was not perfect due to the stripes on the print of PCB layout, which was used for UV light. Because of that, copper paths were not perfect but it was fixed by creating paths out of solder. No other problems with etching were encountered.

Drilling holes in the PCB was also not difficult. The size of the drill as well as precision played a key role in this process. Too big drill or imprecise hole could damage the copper paths which would once again need to be fixed with solder.

After having soldered all the components, the resistance and current of each component were checked. Every part seemed to be working properly except the screw terminal of the load, which showed no connection with the rest of the circuit.

Magnetic Coil

E30/15/7 Ferroxcube
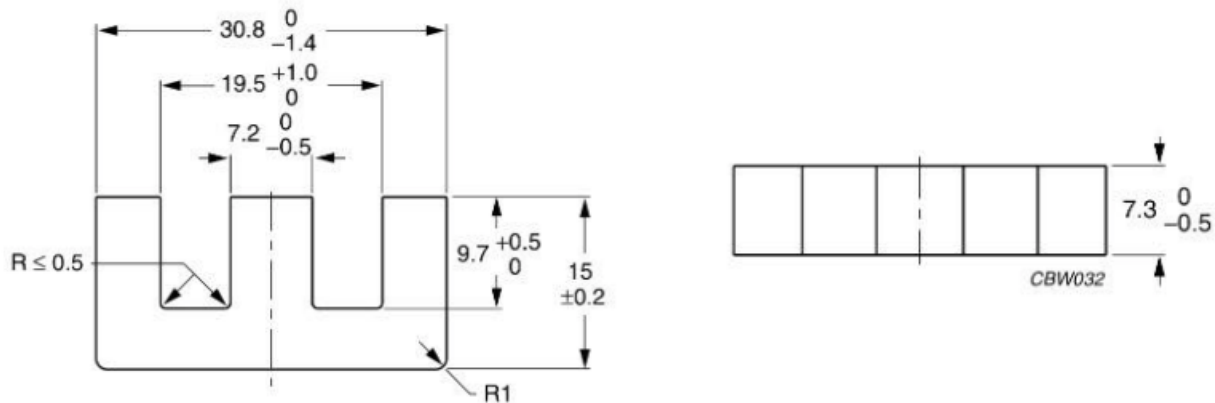
FEMM

Definition

Finite Element Method Magnetics (FEMM) is a finite element package for solving 2-D planar and axisymmetric problems in low frequency magnetics and electrostatics.

The package is composed of an interactive shell encompassing graphical pre- and post-processing; a mash generator; and various solvers. A powerful scripting language, Lua 4.0 is integrated with the program. There is no hard limit on problem size - maximum problem size is limited by the amount of available memory. Simulations are commonly performed with as many as a million elements, though simulations with then of thousands of elements are typical.

Steps to Follow

1. Tell the program what sort of problem is to be solved. It is necessary to select 'Problem' from the 'Menu'.
2. Draw the coil, add materials to the model, associating properties with block labels, creating boundary conditions.
3. Save the file. Generate the mesh, and by clicking on 'glasses' icon analysis results appear. (Checking values and properties is possible)
4. Additionally, FEMM can also plot values of the field along a user-defined contour.

Simulation

The inductor made of Ferrite (3C90) as a base, and 18 AWG Copper wires with 56 turns as a coil shows this results:
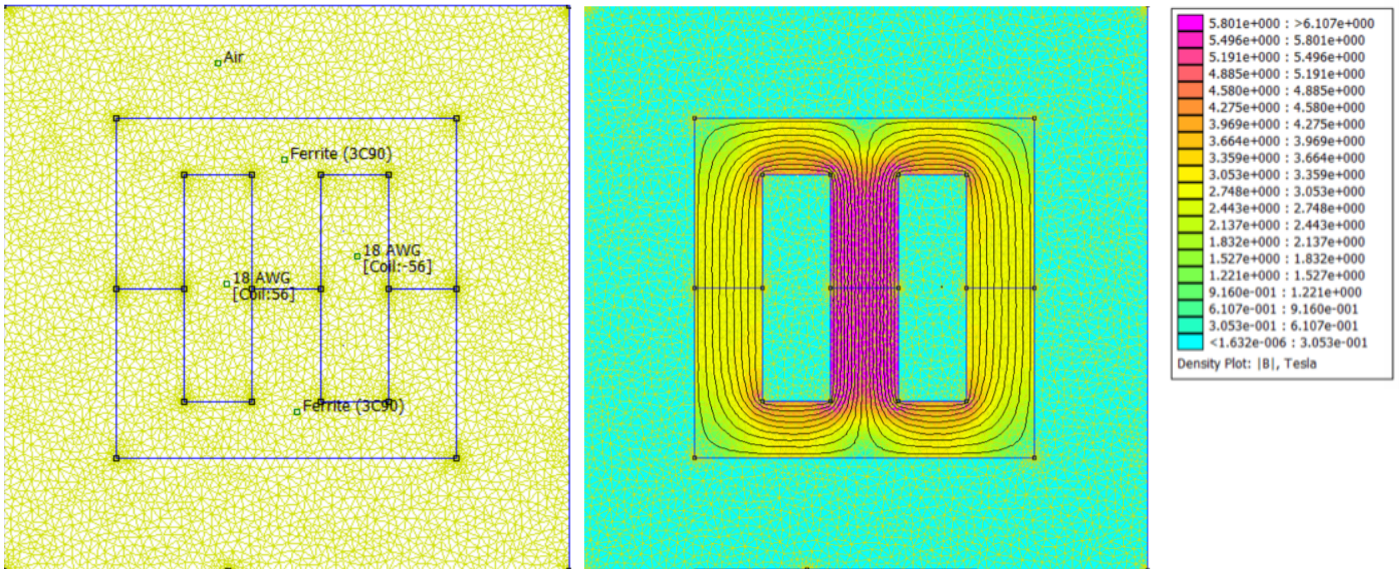
Circuit Properties Values Obtained After Simulation
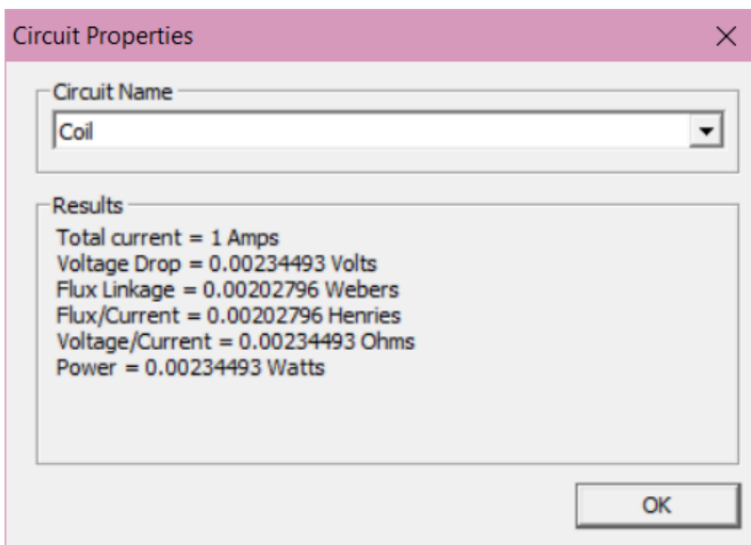
Inductor Measurement

Methods of Measuring Inductance of the Inductor
- Measuring the inductance using a resistor (used in this project)
- Measuring inductance on a voltage current slope
- Measuring inductance using a capacitor and resistor

Steps to Follow:
- Connect the coil in series with a resistor with known resistance
- Input the current into the circuit
- Observe the input voltage and the voltage in the wire where the inductor and resistor meets
- Adjust the frequency so that junction voltage (where the inductor and resistor met) was half of the input voltage
- Find the frequency of the current (kHz)
- Calculate the inductance using formula: $L = \dfrac{\sqrt{3}R}{2\pi f}$

Coil "Coating"

3-D Model of 'coating' for the coil prepared in Autodesk 123d program.

Autodesk 123D Design
123D Design is a 3-D modeling software designed primarily for creating 3-D print projects.
Autodesk 123D Design offers possibility to quickly create precise and makable objects using smart tools that allow to start with simple shapes.

Features and Highlights
- Support for opening, inserting and saving meshes in STL and OBJ formats
- Perform Combine, Subtract and Intersect operations between meshes and solids
- Option for Combining objects on STL export in order to support printers that read first body only
- Import SVG files and use them as sketches or as simple extrusions
- Drop selected objects to the grid with a simple key (F10)
- Option for defining snapping increments for different operations
- 3-D Print sends model to Meshmixer for processing before 3-D printing

Coil "Coating" Design
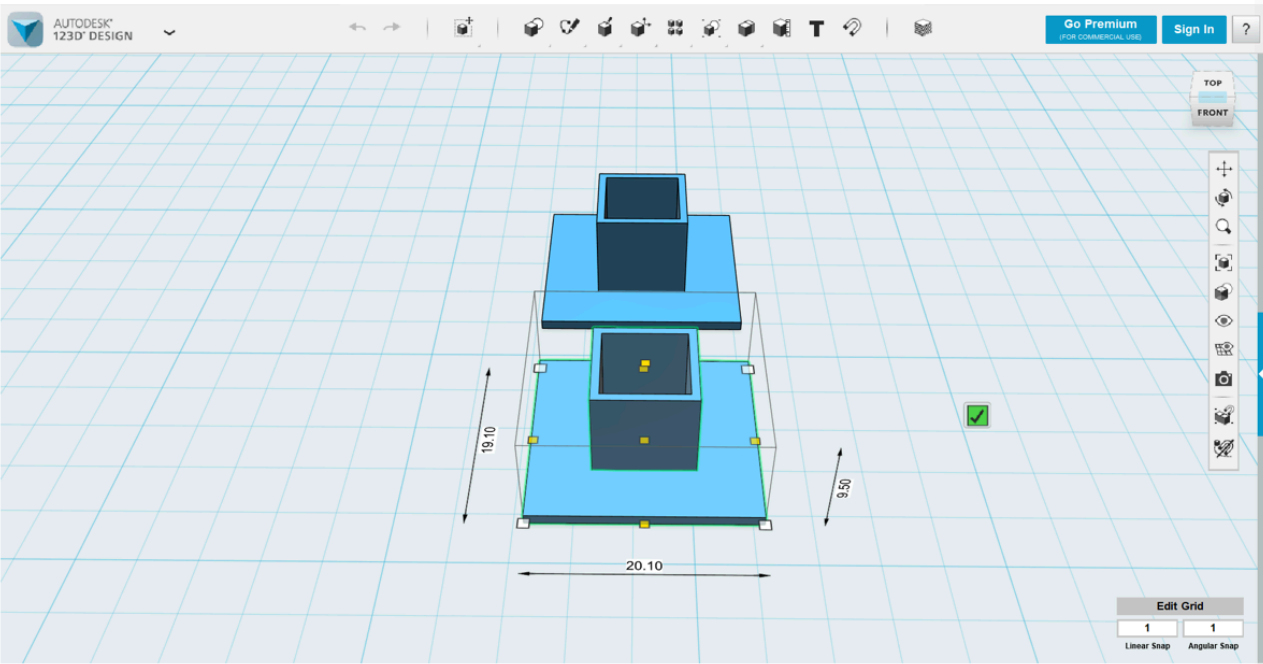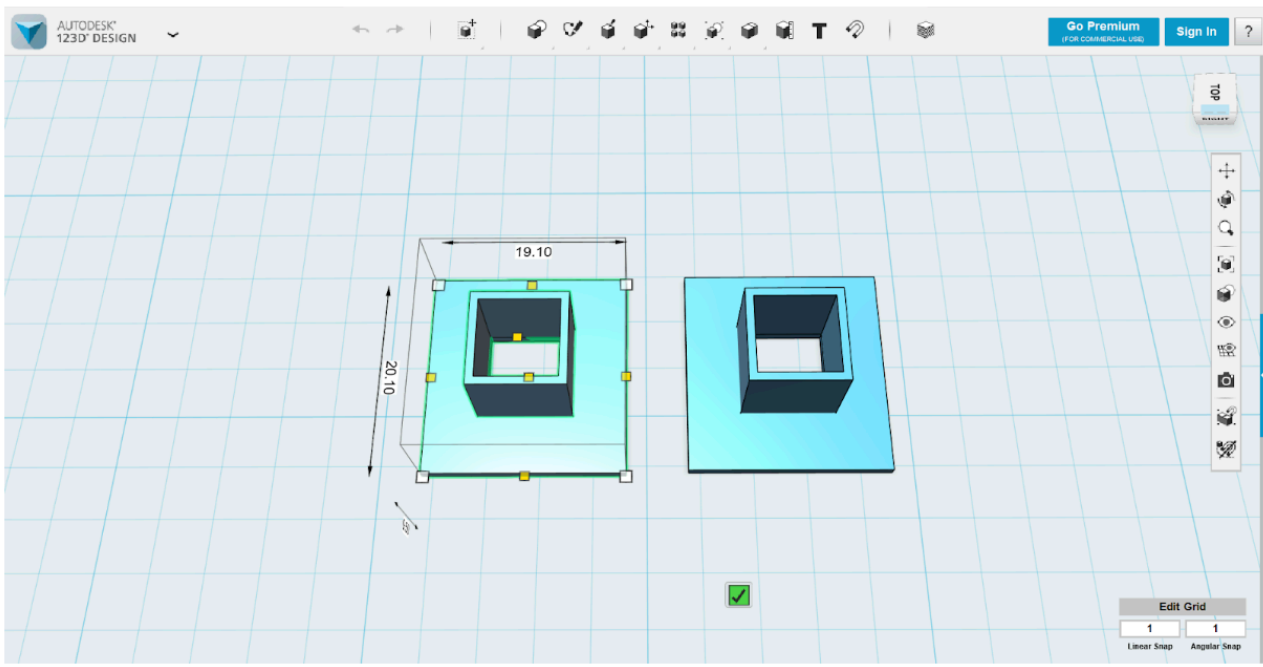
Calculations & Measurements

Task was to check parameters using simple circuit, that were made from our RC inductor, resistor and input (25V). We used software on PC and specialist measurement tools to check diagram of Voltage per time and after that, we have calculated and checked if we reached supposed parameters. We had some problem while checking, cause it showed up over 1000 times too small, but it showed up it was mistake in program, that we fixed easily. Still we had 17,5mH instead of planned 20mH, that were caused by inaccuracy of our copied data that we got from diagram.

We used common formula tau=L/R for LR Series Circuit and rule of 63% of max Voltage for calculating tau.
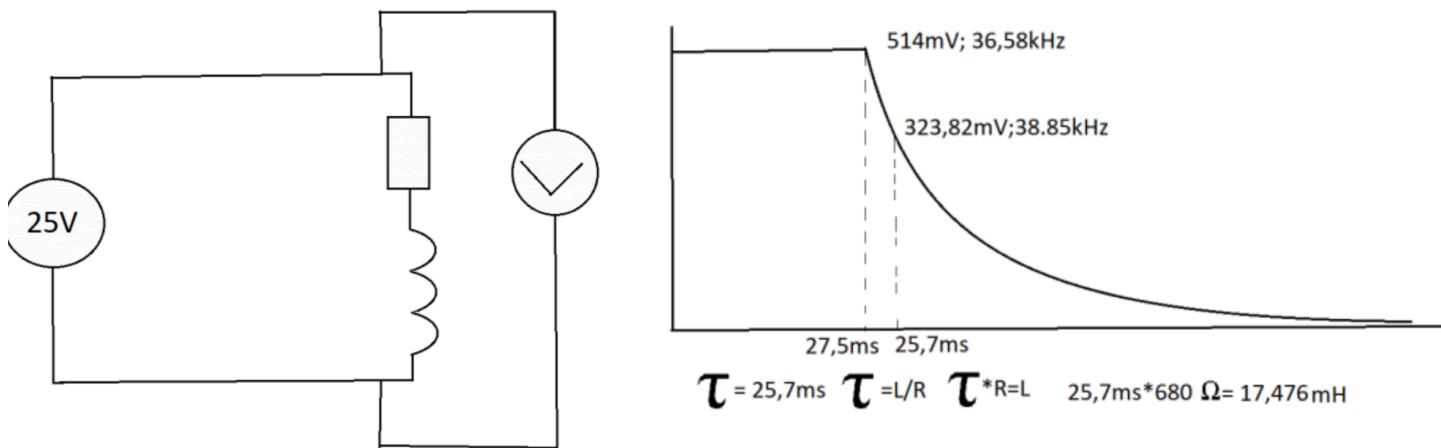
General Conclusion (Part III)

Due to lack of knowledge and experience, whole process of making magnetic coil was too difficult to obtain results, calculations and measurements needed to finish the project in 100%.
There are missing parts, which cannot be implement because of the fact that data was not saved, and missing informations are not possible to get back.