DESIGN AND IMPLEMENTATION OF A SIMPLE, COMPACT FLYBACK EMULATOR

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Abstract

The aim of the project is to design and implement a 7Ah lead-acid battery emulator using a flyback dc-dc converter. The emulator uses a step-up coupled inductor to step up the input voltage of 5V to an average output of 12V. The designed emulator shows a high correlation of the discharge curves against an actual lead-acid battery. Furthermore, the emulator has a maximum current output of 0,25A and an efficiency of 68%. In future, it is recommended that a higher input voltage should be used and the coupled inductor should be changed to a step-down coupled inductor.

1. Introduction

Modelling is a key tool in engineering design and analysis, emulators are systems which model certain systems for the purpose of design testing or analysis. The purpose of this report is to convey the final design of a 7 Amp-hour lead-acid battery emulator using a flyback dc-dc converter implementation. The report details the problem analysis, final design implementation, performance analysis and the optimisation of the final prototype.

Section 1 shows a brief introduction. Section 2 shows the problem analysis of the project showing the breakdown of the problem for easier implementation and execution. Section 3 shows the final design implementation showing the design considerations and crucial decisions of the final prototype including the trade-offs and optimisations of the prototype. Lastly, in section 4, a performance analysis is shown showing the strengths, weaknesses as well as future recommendations of the final project.

2. Background and problem analysis

2.1 Background

In the engineering design process, it is critical to thoroughly test your prototype in order to analyse the performance and characteristics of the prototype and as such make improvements if necessary, this shows the iterative nature of the design process [1]. To test the prototype certain power sources are required for specific designs such as a lead-acid battery [2], however, this can become costly and energy inefficient as the process can span over a long period. Consequently, emulation becomes a key tool in the design process. An emulator is a component that models a certain system such as a lead-acid battery. An emulator will exhibit traits of the system albeit being more convenient to use for testing and more robust [3].

2.2 Requirements

There are several key requirements of the project.

- The emulator must be implemented using a flyback dc-dc converter.
- The emulator must exhibit traits of a 7 Ah lead-acid battery.
- The emulator must be implemented on a Veroboard.
- The control circuitry of the emulator must be implemented using either an ATmega 328p or PIC microcontroller.
- The emulator must be safe to use and user-friendly.

2.3 Assumptions

The emulator will not be subjected to exceedingly large loads which could compromise the integrity of the prototype. Secondly, the discharge time of an actual 7AH battery is long for a small load so the time will be scaled appropriately. Lastly, during testing, the input voltage will not be varied exceedingly as this will cause high voltage stress on certain components which could also compromise the integrity of the emulator.

2.4 Success criteria

The project will be deemed a success if it meets the following requirements:

- Output corrects load voltage, ranging from 12V when the battery is fully charged to 10V when the battery is empty by the control of the duty cycle.
- The emulator exhibits different discharge times for different loads.
- The emulator can cater for different input voltages by the control of the duty cycle.
- The emulator must be compact, durable, implemented on a Veroboard, safe to use, user-friendly and efficient.

2.5 Constraints

The project was constrained by the following.

- Only the provided equipment and components may be used.
- No single Integrated Circuit (IC) solutions may be used.

All other constraints are shown in the project brief [4].

3. Design

The aim of the design process is functionality, suitability to the user and efficiency. As such, all the components are calculated and obtained to align with the vision and the goal of the design. This is the governing concept that forms the foundation of the design process and eventually the final solution. To achieve this, the design process is broken up into smaller sub-systems, this does not only aid in time-management but also provides a level of abstraction which shows the dependency of each sub-system to the wholistic final product. Furthermore, this allows for each sub-system to be easily allocated to the appropriate team member which improves the quality output of each sub-system and thus the final product. See figure 1 below for the design breakdown and block diagram.

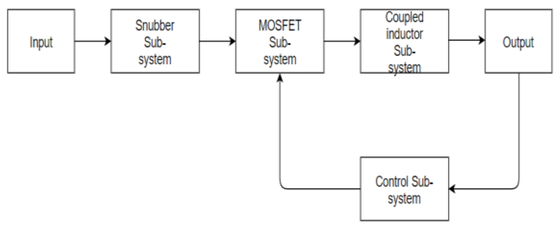


Figure 1: System block diagram

3.1 The Sub-systems

3.1.1 Coupled inductor subsystem

Aligning this sub-system with the core objectives and goals of the design which is functionality, suitability to the user and efficiency the initial design and the preliminary prototype was revised and modified.

The operating frequency of the whole system influences the size of the inductances. The frequency is decreased from 50 000 Hz on the preliminary prototype to 20 000 Hz. Operating at high frequencies does indeed decrease the size of the inductances which create a smaller inductor and decreases the winding losses as less wire is used however this creates even more consequential problems which affect the fundamental operation and functionality of the whole system.

One of the severe problems encountered on the preliminary prototype is inductive ringing during the high-frequency switching cycles. This inductive ringing creates high-voltage spikes on the inductor, this further causes overheating and overstressing of the sensitive components of the whole system such as the MOSFET and the diodes. Also, this inductive ringing creates a false output which compromises the sampling function of the microcontroller used for the control circuitry which leads to erroneous results. Therefore, to solve this a lower frequency of 20 000 Hz is chosen as the optimum frequency.

Once the operating frequency is determined the size of the primary inductance is calculated to be 115μH and the secondary inductance calculated to be 143μH. See the extended calculation on Appendix A.

3.1.2 Control sub-system

The algorithms devised uses the fundamental parameter of the battery which is capacity this simplifies the emulation process and improves the overall functionality of the design while being suitable to the user thus aligning to the key objectives and goals of the project.

As with actual batteries, the output of the emulator is maintained at 12.5 V at the start of the emulation process. This voltage represents a fully charged state of the battery which the charge of the battery is still maximum. Once this state is achieved the current drawn by the load is subsequently measured by the microcontroller. Measuring the current drawn by the load allows for the charge withdrawn to be easily calculated. As time elapses the charge drawn by the load is subtracted from the remaining charge of the battery until depletion. The time it takes for the battery to be depleted varies with the load as different loads draw different current. This is important because not only does it allow for the easy gauge of the state of the battery which controls the output voltage, but it also caters for the change of the load while the battery is discharging. Consequently, once a load is changed the emulation resumes at the remaining capacity of the battery which improves the quality of the output and emulation model accuracy.

As stated previously, the state of the battery determines the output voltage, therefore, at 50% charge, the output starts decreasing linearly until it reaches a minimum voltage of 10,5V when the battery is depleted. LED's indicate the state of the battery at these crucial stages.

The final prototype is designed to have a maximum load of 2,2Ω which draws a maximum current of 4,8A as explained in the preliminary report. This maximum current withdrawal results in the battery to be depleted in 1 hour which is long and is subsequently scaled down. The scaling becomes 1 sec corresponds to 10 hours as we are working with small loads. Therefore, the emulator has an added benefit of easy control of scaling the discharge times.

This control algorithm results in highly accurate output parameters which are shown in the test results section.

3.1. 3 Snubber and MOSFET sub-systems

The main protection sub-system of the MOSFET is the snubber circuit, this circuit minimises the high-voltage spikes on the coupled inductor due to the high-frequency switching. The snubber circuit is a combination of a diode in series with a 11V Zener diode. The Zener diode is operated in the breakdown region to maintain 11V at the terminals. However, this creates high-voltage stress on the diode which is prone to failure. An alternative solution is proposed in the future recommendations section.

3. 2 Design optimisations

3.2.1 Parasitic effects and optimisation

To reduce parasitic effects and thus optimise the design certain components are implemented. Firstly, a 0,1μF capacitor is used to decouple the source, this is to compensate for the inductive properties of the wires. Secondly, a composite output capacitor of 100μF is used to compensate for the parasitic inductance and resistance of a single electrolytic capacitor.

Furthermore, to improve the electromagnetic compatibility of the design shorter wires are used, common current paths are prevented and to improve the accuracy of the microcontroller and reduce electric field interference, measurements are taken at stable points of the output rather than fast switching edges.

Lastly, aligning with the design objectives of suitability the emulator uses an input voltage of 5V, this is chosen to easily integrate the microcontroller thus enabling the microcontroller and the emulator to be implemented on the same platform. This optimisation greatly increases the quality output and the performance of the design, this is shown in the testing and evaluation sub-section.

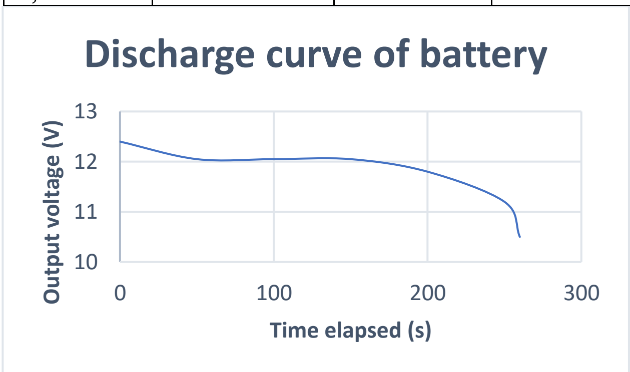
4. Results and Critical analysis

4.1 Test results

The final prototype is tested, and a summary of the results is shown below. See Appendix B for extended testing results and plots.

Table 1: Summary of parameters

Max current(A)	Max load (Ω)	Inductive spikes (V)	Efficiency
0,25	50	17	68



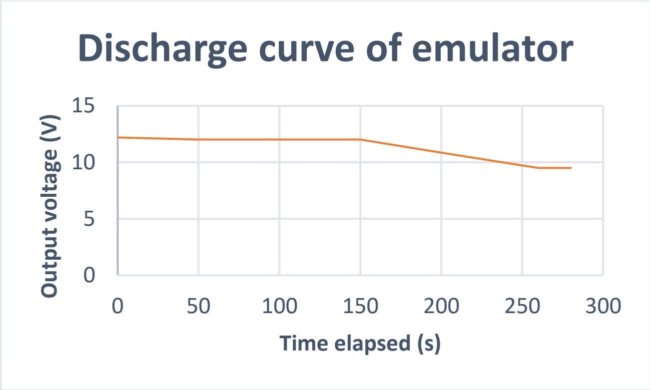


Figure 2: Discharge characteristics of the emulator compared to actual lead-acid battery for one load

4.2 Critical analysis and discussion

The control circuitry is performing as predicted. At the start of the emulation process the microcontroller can maintain an output voltage of 12,5V as stipulated in the design phase by the varying of the duty cycle as seen in Appendix B. Furthermore, the duty cycle that is needed to maintain 12,5V at the terminal of the emulator varies with the load, this allows for the easy use and adaptability of the emulator to various loads thus making it more robust and re-usable. This also shows that the ADC function of the microcontroller is operating as expected as the output voltage is sampled accurately in order to vary the duty cycle in compensation of the load. However, due to the sensitive nature of the ADC function of the microcontroller, a trade-off was made between efficiency and simplicity when designing the intermediary circuit between the actual output voltage of the emulator and the feedback loop back to the microcontroller as the microcontroller can only sample voltage below 5V. As such, a voltage divider circuit is implemented to step the voltage down to below 5V instead of an op-amp circuit with a low gain, however, this voltage divider circuit creates inefficiencies as the resistors dissipate power.

As seen in figure 2 above the discharge curves of the emulator and the actual 7Ah lead-acid battery show high correlation which show that the emulation procedure and algorithm devised performs adequately with a deviation voltage of 1V. However, as seen for the figure this correlation breaks down at the knee-point of the discharge graphs. This is due to the modelling of the emulation process when designing the emulation algorithm. For simplicity, the discharge behaviour is modelled as a linear decrease after the knee-point, however, this shows that the model needs to be revisited and modified as this creates inaccuracies in the emulation discharge behaviour.

As shown in table 1 above the emulator can handle a maximum load of 50Ω and a corresponding maximum current of 0,25A. This contradicts the design which predicted a maximum load of 2,2Ω and a maximum current of 4,69A. Similarly, here a trade-off between a highly accurate output current and a compact, suitable design of the system was made. This low output current is mainly because of the low input voltage, because energy cannot be transformed so due to the low input voltage of 5V while the emulator has an output voltage of 12,5V this means the current has to, therefore, be decreased to compensate for the rise of the voltage. However, this input voltage is chosen so that the microcontroller can easily be integrated into the whole system thus achieving a compact design.

Lastly, the snubber circuit does not perform as predicted as the inductive spike voltages are 17V which are still high, this causes the efficiency of the emulator to be greatly decreased. Furthermore, this creates stress on the sensitive components such as the MOSFET, this leads to the MOSFET to excessively overheat which creates false switching, therefore, propagates down the system to create false outputs. This therefore leads to the MOSFET being implemented with large heat-sinks to compensate for the overheating which in turn compromises the compact nature of the design.

The design does meet the goals and objectives of the project including the success criteria, therefore in that regard is a success. However, various improvements can be implemented in achieving a more efficient and final solution.

4. Future recommendations

To improve the output current of the emulator a high input voltage can be used, however, this leads to other parameters of the system to be modified as such to compensate. A higher input voltage will allow for the current to be adequate for the load requirements. Also, with a higher input voltage a step-down coupled inductor can be implemented, this not only does it allow for the voltage to be step-down from a high value to around 12,5V but it also means since it is a step-down inductor the output current will increase in compensation to the decrease in voltage. However, a higher input voltage will, therefore, mean, for the microcontroller to be implemented on the same platform, a voltage regulation sub-system must be implemented as the microcontroller works with a sensitive input voltage range which in turn increases the complexity of the whole system.

To improve the accuracy of the emulation discharge curve a more accurate model must be implemented. This model must relate the behaviour of the discharge curves of the battery at different levels of the charge states as this is how the battery discharges in real-life applications. A nearly depleted battery discharges differently from a nearly maximum charged battery.

Lastly, the efficiency of the emulator can be improved by using a low-pass RC filter snubber circuit rather than the implemented Zener diode snubber circuit. This circuit will filter the high-frequency voltage spikes on the inductor while increasing efficiency.

5. Conclusion

A design of 7Ah lead-acid battery emulator has been presented in the report. The emulator exhibits discharge curves with a high correlation to an actual lead- acid battery with a deviation voltage of 1V. The emulator shows an output maximum current of 0,25A. Lastly, future recommendation and improvements have been presented such as implementing a step-down inductor with a high input voltage. Nevertheless, the emulator meets the success criteria and objectives of the project, therefore, can be deemed a success.

References

[1] R. L. B. a. L. Nashelsky, Electronic devices and Circuit theory, Pearson.

[2] R. Erickson and M. Madigan, "Design of a Simple High-Power-Factor Rectifier Based on a Flyback Converter," 2014.

[3] S. Jian, D. Michell, M. Greuel, P. Krein and R. Bass, "Averaged modelling of PWM converters operating in discontinous mode," vol. 16, pp. 482-492, 2001.

[4] Electrical engineering design, ELEN 3017, Project brief 2019.

Appendix A

Below are the design parameters of the flyback emulator, once these parameters are obtained the components are calculated as shown below.

Design calculations

Lead acid battery parameters;

- Maximum output current I_{omax}= 4,2A
- Output voltage V_o=10,5V
- Minimum input voltage V_{inmin}=5V
- Maximum output voltage V_{imax}=20V
- Switching frequency f_{sw}=20 000hz

Turns ratio a = $(\frac{V_{inmim}-V_{on}}{V_o+V_{fw}})(\frac{D_{max}}{1-D_{max}})$=0,863   Where; V_{on}= On voltage of MOSFET, V_{fw}= Diode forward bias[1]

D_{max}= Duty cycle chosen to 50%

Secondary inductance L_{sec}= $\frac{(V_o+V_{fw})(1-D_{max})}{\Delta I * \mathrm{fsw}} = 143\ \mu H$ [1]

Where;

ΔI_s= Ripple current

Primary inductance L_{pri}= L_{sec}*a^2 = 115 µH [1]

Appendix B

To thoroughly test the performance characteristics of the emulator various measurements were taken as seen below for low loads and high loads. Furthermore, to test the validity the emulator characteristics are plotted against the characteristics of the lead-acid battery. Lastly, as evidence the actual oscilloscope measurement of the emulator is also shown

Type	Load characteristics	State of battery	Time elapsed (s)	Output voltage (V
Emulator	Load= 10 000Ω		0	12,6
	Current drawn = 1.20mA		50	11,3
	Time taken= 563 s		100	10
			150	10
			200	10
			250	10
			300	10
			350	10
			400	10
			450	10
			500	10
			550	9,25
			600	8,5
			650	8,5
Actual lead-acid battery	Load= 10 000Ω		0	13,1
	Current drawn = 1.22mA		10	13,1
	Time taken= 560 s		50	13
			95	11,1
			100	11
			105	10,9
			150	10,9
			350	10,9
			400	10,85
			450	10,8
			500	10,8
			550	10
			560	10
Emulator	Load= 5000Ω		0	12,2
	Current drawn = 2.5mA		50	12
	Time taken= 280 s		100	12
			150	12
			200	10,86
			250	9,73
			260	9,5
			280	9,5
Actual lead-acid battery	Load= 5000Ω		0	12,4
	Current drawn = 2.5mA		50	12,05
	Time taken= 280 s		100	12,05
			150	12,05
			200	11,8
			250	11,2
			260	10,5

Type	Load characteristics	State of battery	Time elapsed (s)	Output voltage (V
Emulator	Load= 50Ω		0	12,12
	Current drawn = 0.25A		3	12,12
	Time taken= 28 s		6	12,12
			9	12,12
			12	12,12
			15	12,12
			18	11,74
			21	11,35
			24	10,99
			27	10,58
			30	10,2
Actual lead-acid battery	Load= 50Ω		0	12,5
	Current drawn = 0.25A		3	12,5
	Time taken= 28 s		6	12,5
			9	12,5
			12	12,5
			15	12,5
			18	12,45
			21	12,3
			24	12
			27	11,4
			30	10,5

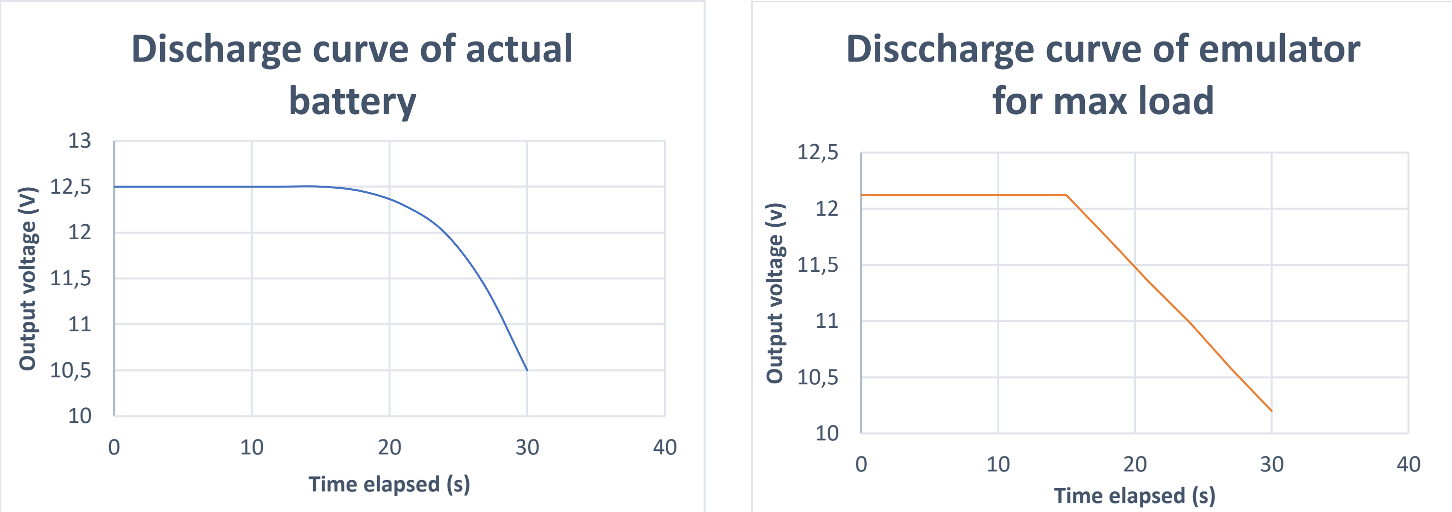


Figure 1: Discharge curves of battery and emulator for maximum load of 50Ω

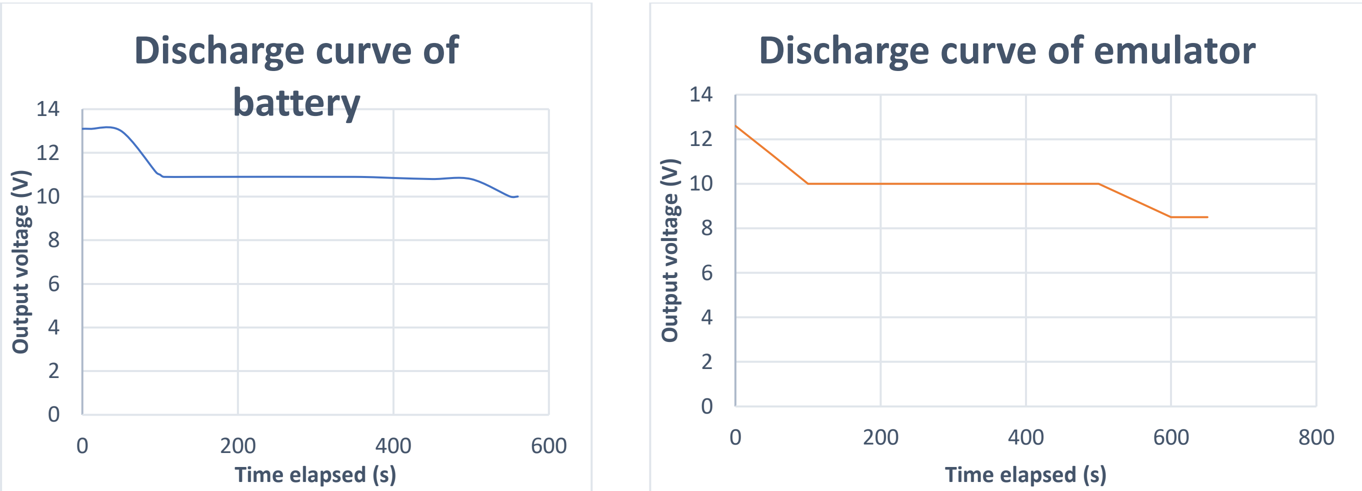


Figure 1: Discharge curves of battery and emulator for minimum load of 10 000

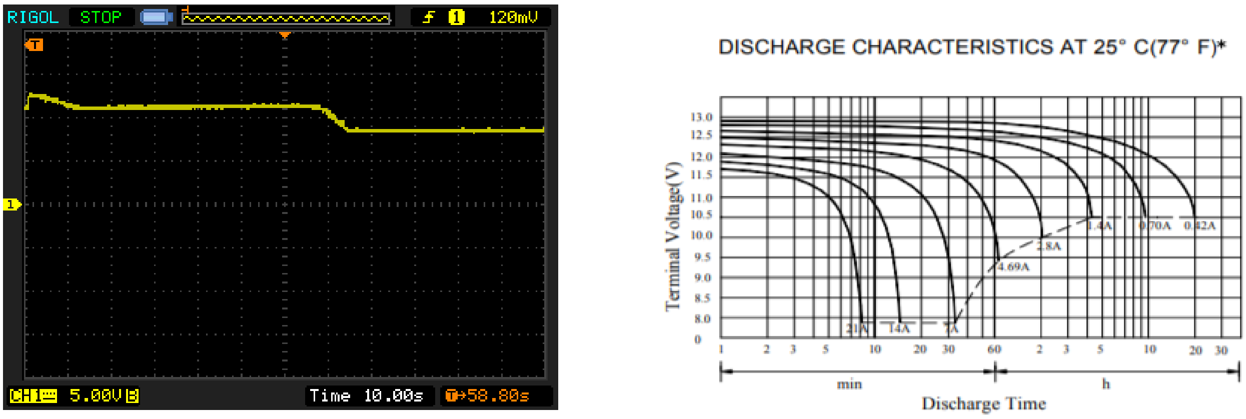


Figure 3: Oscilloscope measurement of emulator against actual 7 Ah discharge plots. Adopted from [*http://www.mantech.co.za/datasheets/products/PS7-12.pdf*](http://www.mantech.co.za/datasheets/products/PS7-12.pdf)

Appendix C

Below is the circuit diagram of the final emulator design

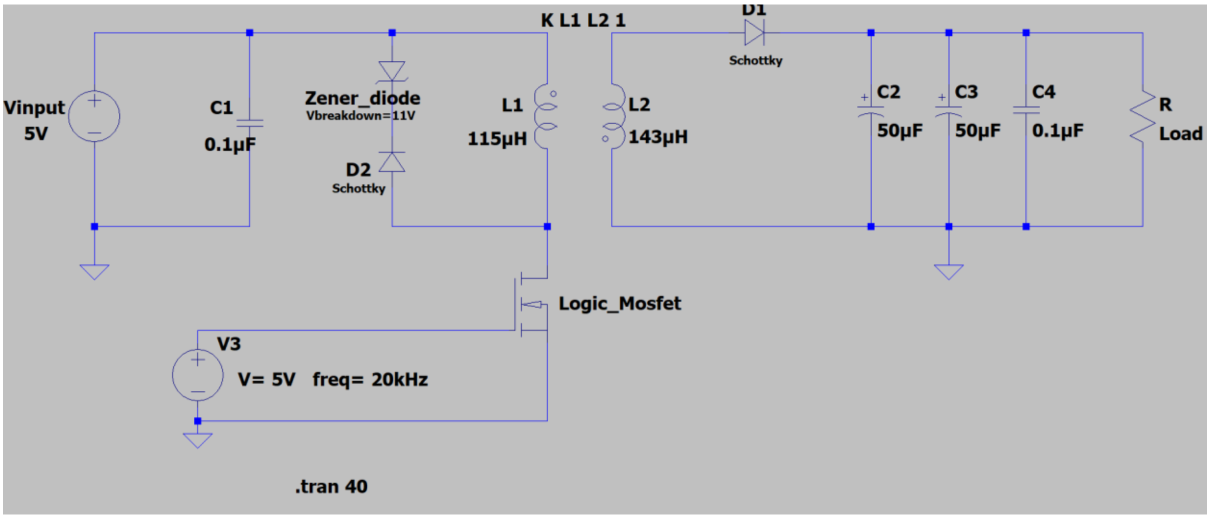


Figure 4: Circuit diagram

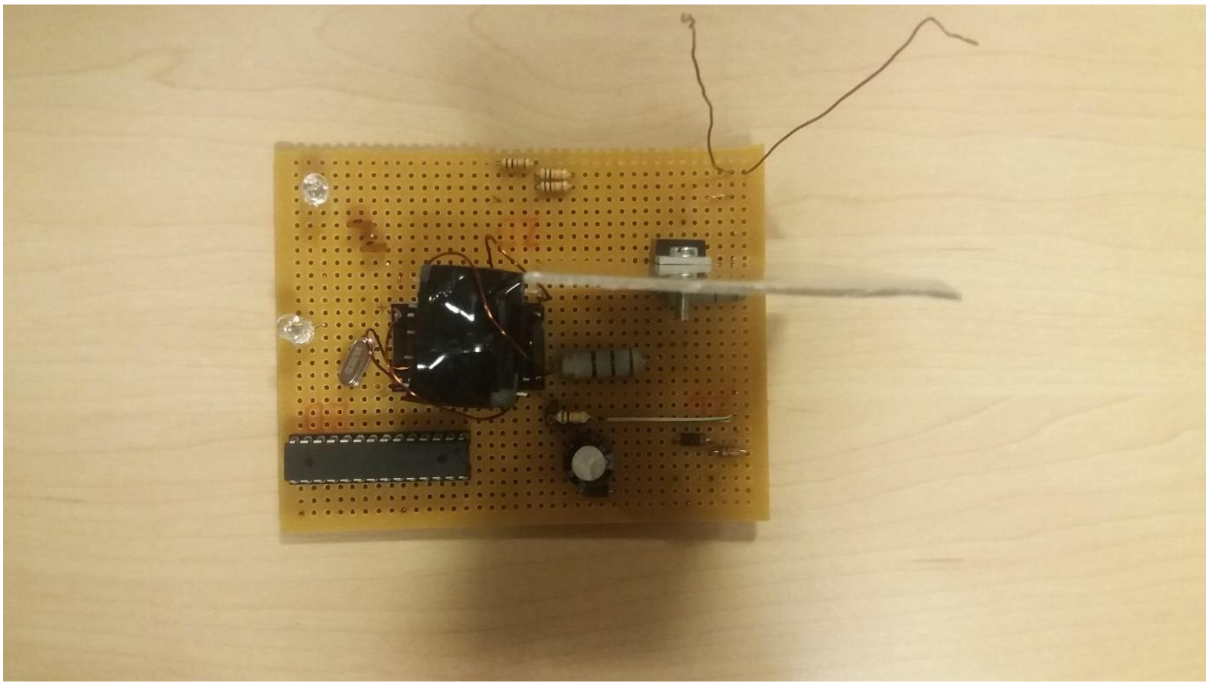


Figure 5: Picture showing system topology