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Power supply

EMC evaluation of a switched-mode power supply

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Summary

In this report has a power supply been designed with focus on its EMC behavior. The chosen design is a switched-mode regulator power supply. The switched-mode regulator power supply has a much higher efficiency and a lighter weight than the linear regulator, which are two of the reasons for the choice of design. In the evaluation of the design some considerations have been taken when choosing the components and the placement of them on the PCB. The components must have minimal influence on each other and when all of the components are operating together the power supply has to have minimal influence on other equipments. Other aspects to think of in an EMC perspective is how the input and output filters have to be design and if these really will be needed. No additional filters have been used in this design because the power supplies can give relatively stable output voltages of 5V, 7.8V and 12V respectively. In the test of the design some values have been measured to calculate the efficiency and stability for the different output voltages. The magnetic field have been measured to see how much influence this can have on other equipments. The measured value of the magnetic field is quite low.

Table of Contents

1 Introduction

Design and integrating of a power supply for a battery driven hovercraft, the power supply shall give the voltage levels of 5 V and 12 V and also the possibility to set a varying voltage level by switching components value.
The designed circuit will be evaluated from an EMC perspective and with regards to stability and efficiency.
The chosen design is a switched power supply built with a switched voltage regulator and extra connections for filters.

2 Theoretical background

An electrical device that takes power from an AC or DC source which is connected to other equipment has to have minimal influence on that source. The device or equipment must also have minimal influence on other equipment. There are limits for how much a device is allowed to give disturbances to its environment and the limits are defined by international standards.

2.1 Power Supplies

The power supply of a product is generally the primary source of conducted emissions. One exception to this is routing wires carrying data or clock signals near the output power wires. This will cause the digital signals to be coupled to the power cord and possibly causing the product to be out of compliance. The product's power supply generates noise that has to be addressed and each type of power supply has unique noise-generating properties. These generated noises are measured by the Line Impedance Stabilization Network (LISN). The reduction of conducted emissions can be addressed by use of a power supply filter. This method is a "brute force" method of reducing the conducted emissions. Any power supply filter can be used to reduce the conducted emissions only to a certain degree. But the most effective way to reduce the conducted emissions is to suppress them at their source. Despite the noise can be reduced at its source only to a certain degree it still can retain the functional performance of the supply.
Switched-mode power supplies (switchers) rely on fast rise/fall time pulses to operate and these pulses have a high-frequency spectral content. The pulses also reduce power losses in the supply. When reducing the noise in these types of noise sources, some compromises must be made between retaining the functional performance and reduction of the noise source.
It is important to consider the purpose of the product's power supply. Most of the electronic components of a product require DC voltages for proper operation. If a digital electronic component requires 5 V DC for proper operation, then the voltage must remain within certain tolerances about the nominal value of 5 V. Otherwise the logic function in the component will be impaired. An important function of a power supply is to maintain an output voltage close to the nominal value within certain bounds regardless of the changing load on the power supply. This is referred to as regulation.

2.2 Switched-Mode Power Supplies (SMPS)

Switching power supplies have efficiencies of order 60-90%, which is much higher than the linear supplies that have quite low efficiencies of order 20-40%. Comparing to linear supplies the switching power supplies are often much lighter in weight because the linear supplies require a transformer that will operate efficiently at 60 Hz. The reason for why the transformer tends to be heavy is that a large volume of core material is used to minimize losses due to eddy currents in the transformer. Switching power supplies need transformers to operate at the switching frequency of the supply, which is of order 20 – 100 kHz. This is another aspect of why switching power supplies have transformers that are lighter in weight than those in linear supplies. Because of the high efficiency and light weight of the switching power supplies, these have become more desirable than linear supplies.
There are many different switchers and one of them is the buck regulator which has a DC voltage supplied to a switching element. The switching element can be a MOSFET where a square-wave pulse train is supplied to the gate. The waveform of this pulse train has a pulse width τ and a period T, where the period is the inverse of the switching frequency, $f_s = 1/T$. The MOSFET is turned on and off by the pulse train and this gives a pulsed voltage of the same duty cycle at V_{in}. The average DC voltage for this waveform is given by

$$V_{av} = \frac{\tau}{T} V_{dc}$$

The duty cycle D is given by

$$D = \frac{\tau}{T}$$

At the output of the circuit an inductor L and a capacitor C is placed to form a low-pass filter to pass the desired DC voltage component of the waveform. A diode is placed in the circuit to provide a path to discharge the capacitor when the MOSFET turns off. A DC voltage is applied to the filter when the MOSFET is turned on and the diode is open. At this moment the inductor begins to store energy in its magnetic field and the capacitor begins to charge up. The voltage across the inductor reverses polarity according to Faraday’s law and the diode closes when the MOSFET is turned off. Now the circuit discharges through the diode.

The advantage of this switch-mode power supply over a linear regulator is that the MOSFET is either turned full on or full off, which means that the switch-mode power supply dissipates very little power as opposed to the linear regulator. The linear regulator has a transistor that always operates in the linear region and dissipating more power. The regulation is done by varying the duty cycle of the switching waveform that is applied to the gate of the MOSFET. A sample of the output voltage is fed to a pulse width modulator (PWM). The PWM gives an output with a form as a square wave and this is fed to the gate of the MOSFET. To obtain the desired DC output voltage in response to changes in load the duty cycle of the square wave is varied by the PWM. There are also other switchers who employ the same basic principle of chopping a DC waveform and varying the duty cycle to provide regulation.

2.3 Linear and switching regulators

The linear regulator is really nothing more than a variable resistor that varies its resistance according with the load resulting in a constant output voltage. The linear regulator is good at holding the voltage but if all excess power is dissipated in to heat. A basic schematic for a linear regulator is shown below in figure 1.

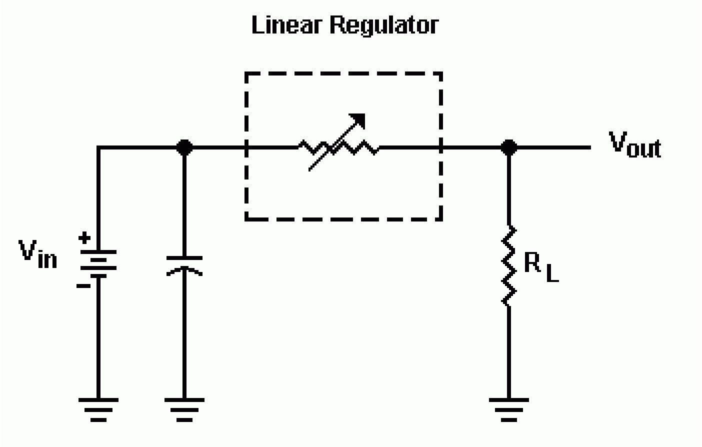


Figure 1: A basic schematic for a linear regulator

The only component that most linear regulators need is the input capacitor to remove 60 Hz ripple to regulator input.
Compared with the basic schematic for most switching regulators seen in Figure2 the main difference in components is that the switching regulator needs components at the output.

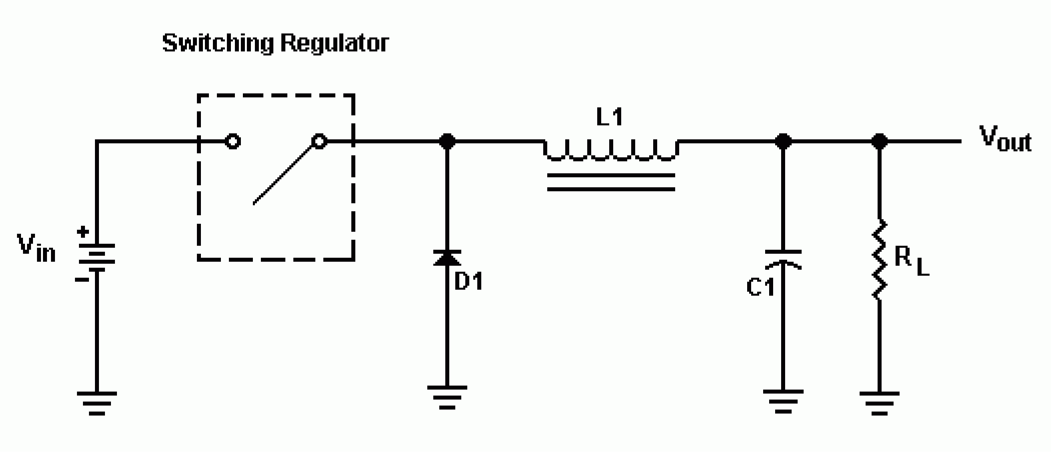


Figure 2: A basic schematic for a switched regulator

The most significant components (apart from the regulator) is the diode and inductor which are found in most switching regulators. The diode needs to be a schottky or another very fast switching diode and the inductor need to have a core that does not saturate under high currents.
The functionality of the diode and inductor is that when the switched regulator is closed the inductor begins to generate an electromagnetic field in its core, while the diode is reversed biased and is practically an open circuit while the regulator is closed.
When the switched regulator is then opened the electromagnetic field that was built up in the inductor is discharged and generates a current in the reversed polarity this results in that the diode is now conducting and will conduct until the inductors field is diminished. This can be compared with the charging and discharging of the output capacitor but the the inductor and diode connection gives even more efficiency and augments the filtering of the output capacitor.

3 Method

The power supply shall be able to give as stable power levels as possible and pass EMC standards.
The design should be able to at least give the different voltage levels:

- 5 V, with an error of maximum of ±0.5 V
- 12 V, with an error of maximum of ±0.8 V
- An varying voltage level with an error of maximum ±10 % compared to wanted output voltage. This voltage level was chosen to 7.8 V.

Since the power supply should be able to power electrical motors and fans there is also need for current around 1 to 3 A or more to get the needed power.
The design was chosen so that all the different voltage levels have its own separate PCB but the same layout is used.
Another concept in the design is that a modular thinking should be taken into account, this is so that there is a possibility to use one battery for several power supplies and add more power. The modular thinking was solved through the use of parallel input and output contacts so it is easy to connect the power supplies in parallel and receive the wanted power.

3.1 Components

The switched regulator chosen for this is the switched step-down (buck) voltage regulator LM2596, which has an operating frequency of 150 kHz. Benefits of this component are that it needs a minimum amount of external components and it has the same type of components for all the voltage levels needed, only with different component values.

For the input capacitor to the LM2596 a low ESR aluminum capacitor was chosen for bypass between input and ground. For this capacitor some properties are specified, like the RMS current rating most be at least ½ of the DC load current. This capacitor also needs to have a voltage rating of approximately 1.5 times the maximum input voltage.
The output capacitor is also a low ESR aluminum capacitor, were the ESR is extra important and needs to be around 100 kHz.

A fast Schottky diode specified with 5 A and 40 V was chosen to fulfill the requirements of 1.3 time’s greater current then maximum load and 1.25 times reverse voltage then maximum input voltage.

A toroid inductor was chosen for good EMI characteristics and with the use of the guide in the LM2596 data sheet to select the inductance values. Note here that for the different voltages levels, that has been specified, different inductance values are needed, so there is need of an inductor series that has all the specified inductance values and has the same footprint since the layout for the PCB’s shall be the same.

In the circuit there is also room for additional filters both before and after the LM2596 and surrounding components. Where the LC-filter before the output is there as an additional ripple filter, if there should be problem on a specific frequency and to ensure that no high-frequency currents leaves the PCB (high-frequency currents should not be any problem in this application due to the regulator and the corresponding components).

The first filter is mainly if the chosen input capacitor is not enough and needs some help an additional capacitor can be put here. The inductor in the filter is there to reduce cross coupling by forming an LC filter with the input capacitor; this is mainly if two or more of the power supply cards use the same input line. The filters can also be seen as a sort of T-filter design which is effective for most EMI applications.
With the LM2596 there was also a version with adjustable output voltage that only needed 3 extra components, so this was taken into the design as well since it could be useful if there should be a need for a more specified voltage level.
For the adjustable version the only extra components is a voltage division with two resistors and a capacitor in parallel with the first resistor. This capacitor and chosen with the formula

$$C_{FF}=\frac{1}{31*10^3*R}$$

Were the R is the resistor value that the capacitor is parallel with.
All components was chosen as through-hole which could be argued but it was chosen because of the needed toroid inductor is quite a large through-hole component and the LM256 regulator was chosen as through-hole as well so that there was a possibility to place a heat sink if necessary. With these components chosen and with other components such as contacts being through-hole as well the rest of the components were chosen as through-hole too, this would also simplify if changes in the prototype was needed. The schematic of the circuit is shown below in figure 3.

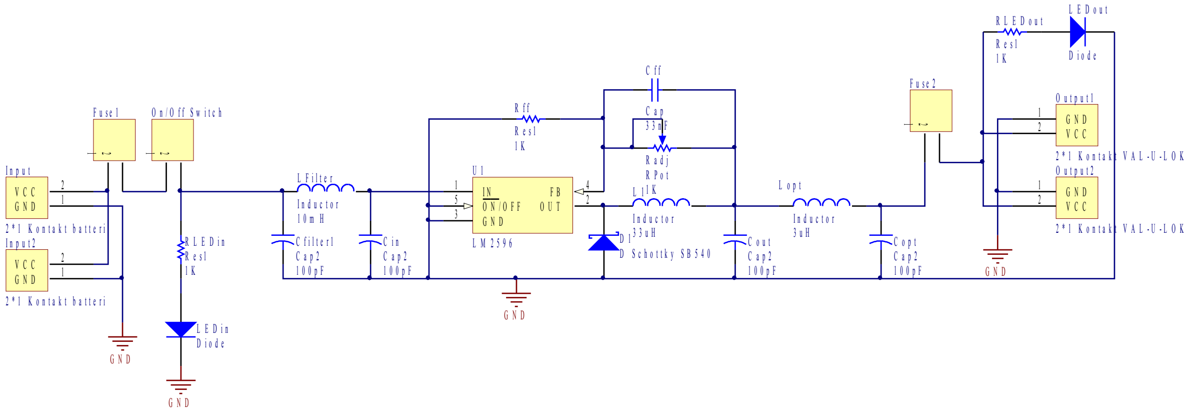


Figure 3: Schematic of the designed circuit

3.2 PCB layout

With all the component characteristics and specifications reviewed the next step is the PCB layout design. For the LM2596 some aspect was taken into consideration, all components needed for the regulator has been put as close together as possible to reduce line length. The feedback components have been place close to the regulator and away from the rest of the components as can be seen in figure 4.

In the PCB layout design EMC and EMI aspects was also taken into consideration.

A two layer PCB is used where both the top and bottom planes are grounded, this is to help reduce overall ground impedance and radiated noise.

With a solid ground plane the return for all components are insured and the ground layers also keeps noise loops small.

With the traces the design principle has been to try and avoid parallel traces and loop areas, due to the small number of components this has not been seen as a big issue. The avoidance of parallel traces is that they are often susceptible to cross-talk, where in this case the distance between two parallel traces have been kept at least 2 trace widths apart.

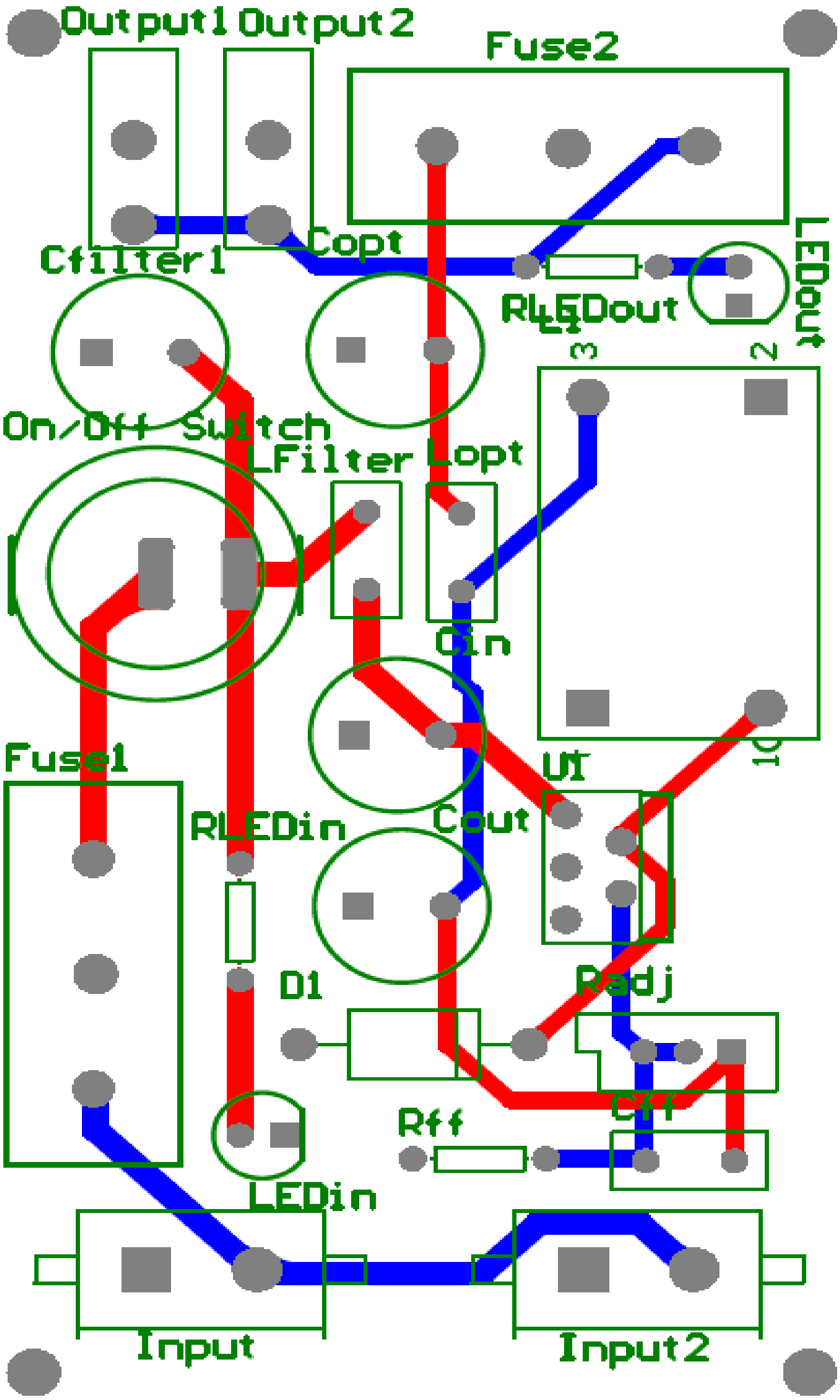


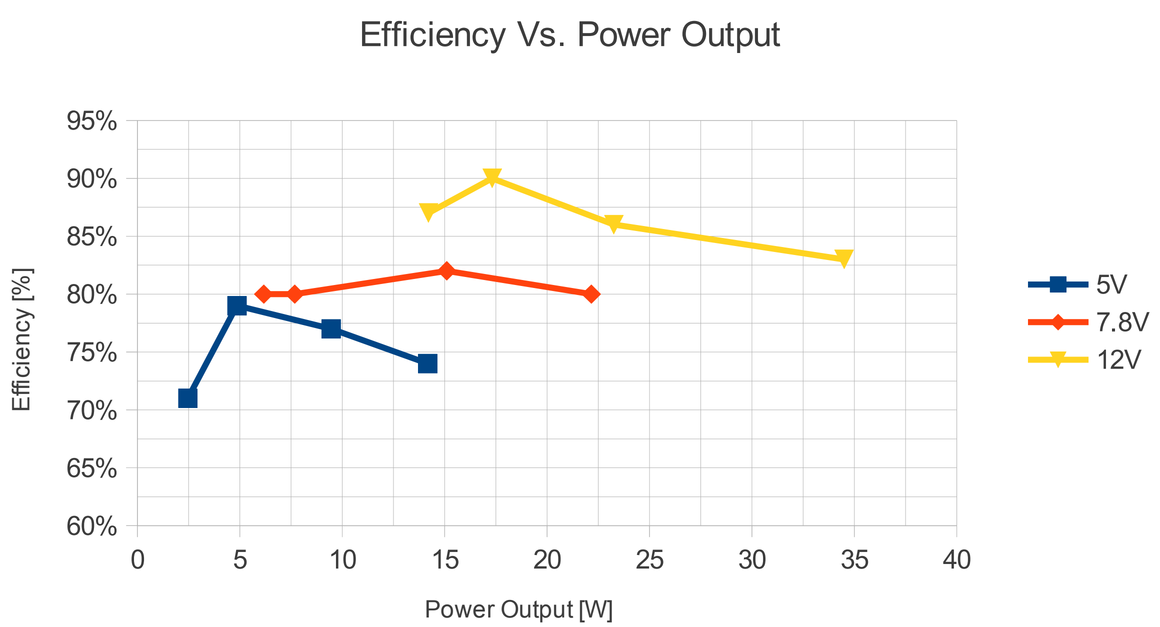
Figure 4: PCB layout of the circuit

3.3 Measurement

To evaluate the performance of the power supply were three different measurements performed. Firstly the efficiency was measured by comparing the input power with the output power, secondly was the stability of the DC-voltage for different power outputs evaluated. This was done by measuring the output voltage when the load was changed. Finally was the radiated magnetic field measured by using a magnetic field logger.

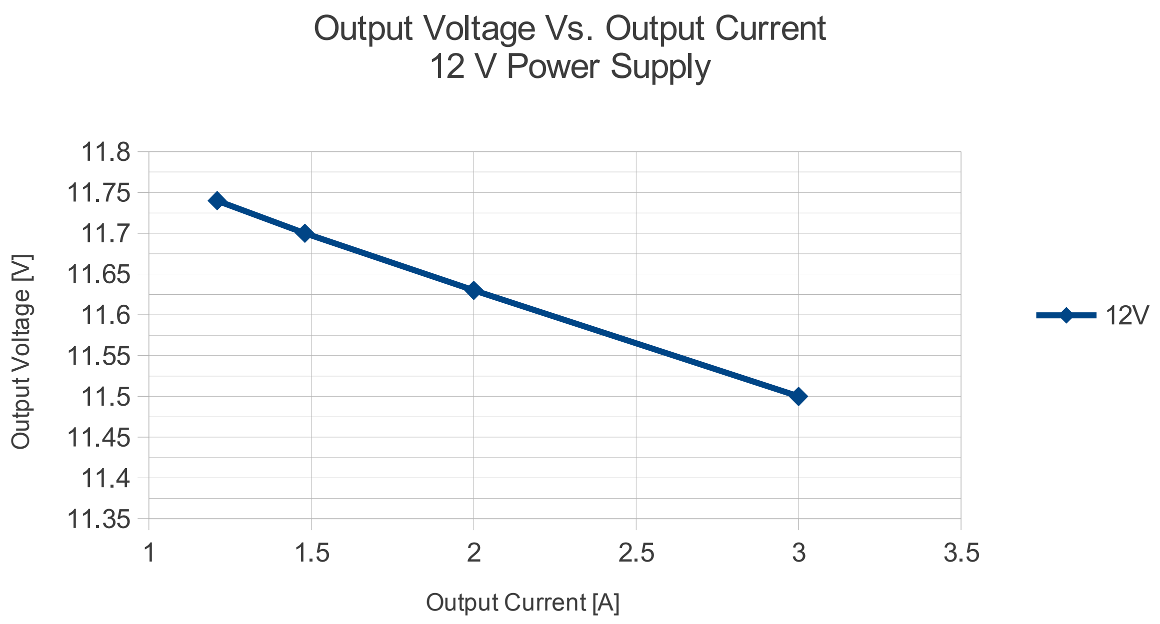
4 Results

In graph 1 below is the results of the efficiency for the power supply for the three different levels of voltage.

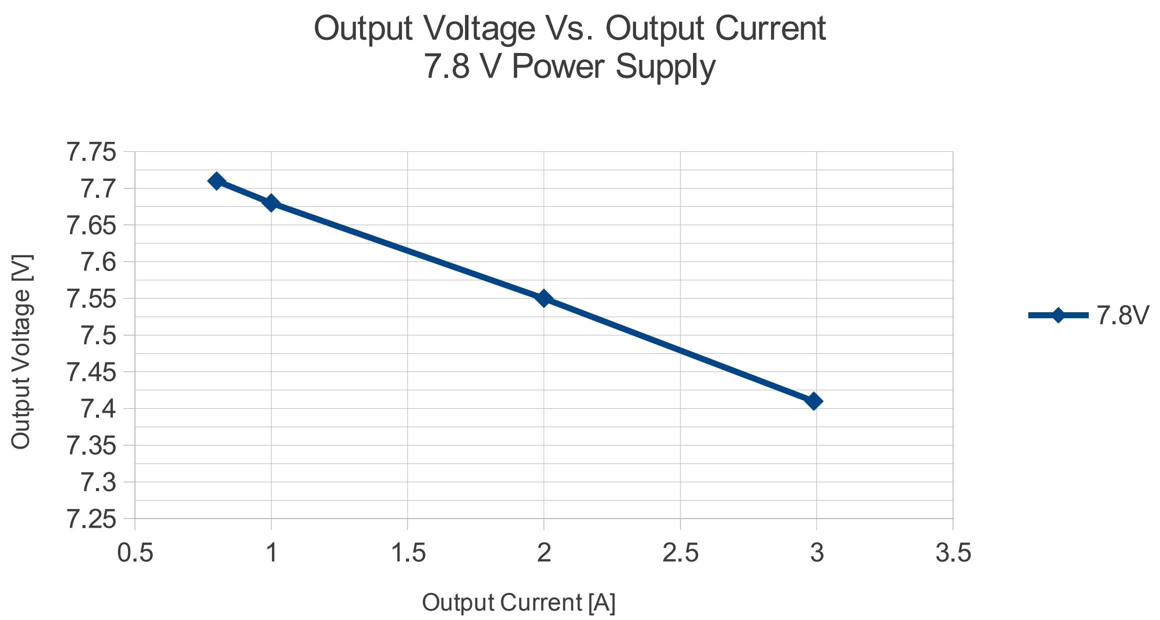


Graph 1: Efficiency for three different power supplys at different output currents

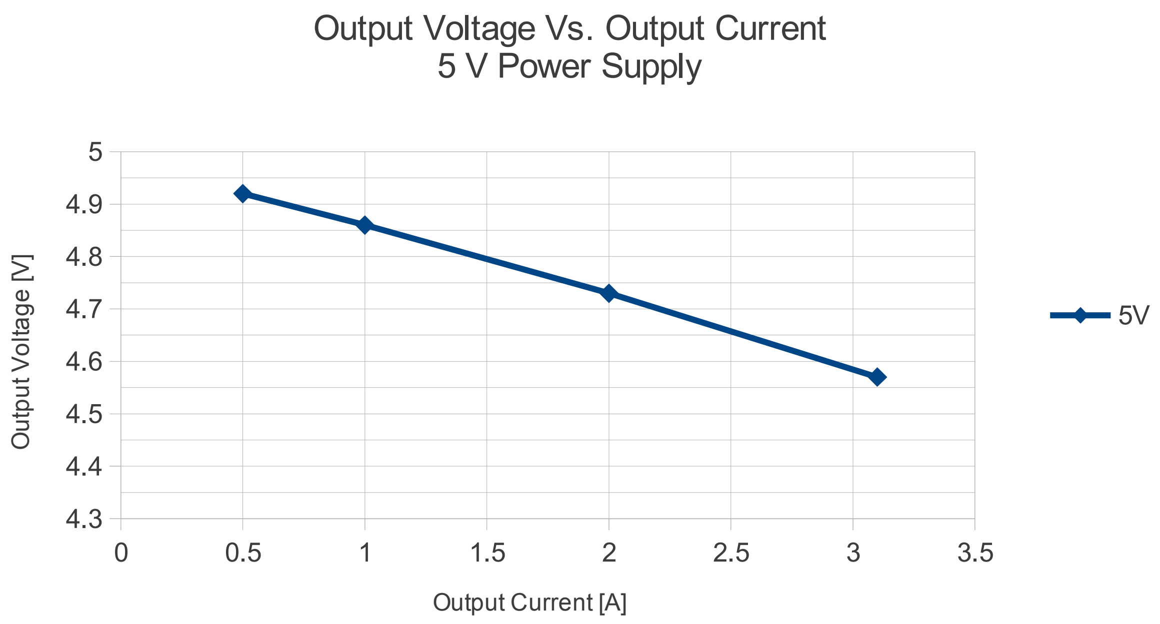
The stability of the three different levels of voltage can be seen in graph 2, 3and 4.



Graph 2: Output voltage drop for 12 V power supply



Graph 3: Output voltage drop for 7.8 V power supply



Graph 4: Output voltage drop for 5 V power supply

The measurements of the magnetic field shows that there is a background field of 0.02µT when the power supply is turned off. When it is turned on the field increases up to around 0.06µT. If the power supply is switched between on and off is the field increased until around 0.2µT.

5 Discussion

The measurements of the magnetic field seems to give a low value. The maximum value was 0.2 µT to compare with 100 µT that was measured from an ordinary AC to DC power supply in the laboratory. The reason that the magnetic field reached its maximum when the power supply was switched on and of is that the induced field wants to counteract the change in current.

The output voltage does not drop outside of the specified value for any of the three different levels of voltage even if the output current reached the maximum of 3 A. The result shows that the voltage drops with higher output current which is expected. The efficiency of the power supply is between 70 and 90 % depending on the output voltage level. The highest efficiency is for the highest voltage level. This is expected since the power supply does not need to decrease the voltage level as much as for the lower voltage levels. The measured efficiency matches the given value in the regulator data sheet.

The choice of the switched regulator compared to a power supply built up with just MOSFET could be argued. It had also been good if there was a choice to be able to a have higher current, instead of being limited to 3 A.

It would also have been interesting to compare our solution with a MOSFET solution in terms of efficiency and stability.

In the design there is room for additional filters, but in the design there already is a input capacitor that works well enough for the regulator. The reason for the input filter was due to the need to parallel connect several power supplies from the same batteries but the input filter has not been used since the batteries does not give any problematic characteristics.
There was also no problematic frequencies detected after the output capacitor and no unwanted ripple, so it was determined that the filtering effect from the diode, inductor and output capacitor was enough for the specified voltages. Thus the additional ripple filter is not used either and since they are not used in the finished product no values for the additional filter components have been determined.

6 Conclusion

The chosen design of the power supply reaches all the requirements concerning stability, efficiency and EMC, set for this project. No problematic frequencies or ripple detected either so no additional filtering has been needed.

7 Abbreviations

EMC – Electromagnetic compatibility
EMI – Electromagnetic interference
PCB – Printed circuit board
ESR – Equivalent Series Resistance
RMS – Root mean square
SMD – Surface mount device
AC – Alternating Current
DC – Direct Current
LISN – Line Impedance Stabilization Network
SMPS – Switched-Mode Power Supply
MOSFET – Metal-Oxide Semiconductor Field Effect Transistor
PWM – Pulse Width Modulator (Pulse Width Modulation)

8 Reference list

http://www.ti.com/lit/ds/symlink/lm2596.pdf datasheet LM2596
http://power-topics.blogspot.se/2007/11/guide-to-emc-standards-for-power.html (2012-11-25)
Clayton R. Paul. (2006). *Introduction to Electromagnetic Compatibility*. Second edition. Wiley-Interscience

9 Appendix

BOM 12 V

Designator	Component type	Component Name	Value	Description

Input	Contact	Socket header 2P		
Fuse	Open fuse holders Fuse holder			Use 5-6.3A fuse
ON/Off Switch	Switch	Rocker switch black 1P		
RLEDin	Resistor		1 kohm	
LEDin	LED			
LFilter	Inductor			
Cfilter	Capacitor	Electrolyte Capacitor		
Cin	Capacitor	Electrolyte Capacitor	680 uF / 35 V	
U1	Step-down switching regulator	LM2596 – 12V		
D1	Schottky Diode	SB540	5A, 40V	
L1	Toroid Inductor	33680C	68 uH	
Cout	Capacitor	Electrolyte Capacitor	180 uF / 35 V	
Radj	Potentiometer		1-20 kohm	Only for adjustable version
Cff	Capacitor	Ceramic Capacitor	See equation	Only for adjustable version
Rff	Resistor		1 kohm	Only for adjustable version
Lopt	Inductor			
Copt	Capacitor	Electrolyte Capacitor		
RLEDout	Resistor		1 kohm	

LEDout	LED			
Output	Male connector 90° 2x1P			

For 5 V this components needs to be changed

Cin	Capacitor		680 uF / 35 V	
U1	Step-down switching regulator	LM2596 – 5 V		
L1	Toroid Inductor	33470C	47 uH	
Cout	Capacitor		330 uF / 35 V	

For 3.3 V this components needs to be changed

Cin	Capacitor		680 uF / 35 V	
U1	Step-down switching regulator	LM2596 – 3.3 V		
L1	Toroid Inductor	33330C	33 uH	
Cout	Capacitor		560 uF / 35 V	

For 7.8 V this components needs to be changed

Cin	Capacitor		680 uF / 35 V	
U1	Step-down switching regulator	LM2596 – adj		
L1	Toroid Inductor	33470C	47 uH	
Cout	Capacitor		220 uF / 35 V	

9.1 Contribution

Olle- Test and report
Rikard - Design, schematic, PCB-layout, mounting and soldering.
Jesper - Test and report

9.2 Measurements

5V						
I_{in} [A]	V_{in} [V]	P_{in} [W]	I_{out} [A]	V_{out} [V]	P_{out} [W]	Efficency
0.18	19.27	3.47	0.50	4.92	2.46	0.71
0.32	19.27	6.17	1.00	4.86	4.86	0.79
0.64	19.27	12.33	2.00	4.73	9.46	0.77
1.00	19.27	19.27	3.10	4.57	14.17	0.74
7.8V						
I_{in} [A]	V_{in} [V]	P_{in} [W]	I_{out} [A]	V_{out} [V]	P_{out} [W]	Efficency
0.40	19.27	7.71	0.80	7.71	6.17	0.80
0.50	19.27	9.64	1.00	7.68	7.68	0.80
0.96	19.27	18.50	2.00	7.55	15.10	0.82
1.44	19.27	27.75	2.99	7.41	22.16	0.80
12V						
I_{in} [A]	V_{in} [V]	P_{in} [W]	I_{out} [A]	V_{out} [V]	P_{out} [W]	Efficency
0.85	19.27	16.38	1.21	11.74	14.21	0.87
1.00	19.27	19.27	1.48	11.70	17.32	0.90
1.41	19.27	27.17	2.00	11.63	23.26	0.86
2.15	19.27	41.43	3.00	11.50	34.50	0.83

Table 1: Measurements done on the power supply