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**MIDDLE EAST TECHNICAL UNIVERSITY**

**ELECTRICAL & ELECTRONICS ENGINEERING**

***EE464 – STATIC POWER CONVERSION II***

*HARDWARE PROJECT*

**SIMULATION AND MAGNETIC DESIGN REPORT**

**Mert Eren Kandilli – 2304855**

**Kubilay Kaya – 2304905**

**Emre Çakmakyurdu – 2231595**

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# INTRODUCTION

DC-DC converters are a crucial part of power electronics and they are used almost in every circuitry. In this project, we are going to design an isolated DC-DC converter. This report investigates the possible topologies that can be used and why the chosen topology is selected. After topology selection, magnetic design and controller design parts are deeply discussed. The calculations contain both controller components and magnetic components. Computer simulations are added to the report. Also, selected components are explained in detail.

# REQUIREMENTS

In this project, an isolated DC-DC converter will be designed with following characteristics shown in Table 1.

*Table 1.* Project Requirements

|  |  |
| --- | --- |
| **Minimum Input Voltage** | 24 V |
| **Maximum Input Voltage** | 48 V |
| **Output Voltage** | 15 V |
| **Output Power** | 45 W |
| **Output Voltage Peak-to-Peak Ripple** | 3 % |
| **Line Regulation** | 3 % |
| **Load Regulation** | 3 % |

In the following section, different possible topologies are discussed by investigating their advantages and disadvantages.

# TOPOLOGY SELECTION

In this section three different topologies are discussed. These are:

* Forward Converter
* Push-Pull Converter
* Flyback Converter

## 1) FORWARD CONVERTER

Forward converter is a DC-DC converter that is derived from buck converter. It can both increase or decrease the output voltage based on the duty cycle and transformer turn ratio. Input and output relation of forward converter is as follows.

The schematic of the forward converter can be found in Figure 1.

Diagram, schematic

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*Figure 1.* Schematic of practical forward converter

In the forward converter energy is directly transferred from primary side to secondary side. It is usually used in off-line supplies which provide 100-200W. Advantages and disadvantages of forward converter are discussed in the next section.

**ADVANTAGES**

* Power is directly transferred from input side to the output side which eliminates the need of energy storage which means an air gap. So, the core size becomes smaller.
* Core has no air gap so magnetizing inductance is increased and ripple is decreased.
* Due to the output inductor and freewheeling diode, output current is almost constant. So, output current ripple hence output voltage ripple is decreased significantly.

**DISADVANTAGES**

* Transformer needs to be reset before the next ON period. If the reset circuit is not implemented, the core could be saturated and power transfer could be problematic. So, additional snubber circuit or third winding should be added to reset the transformer. Adding a snubber circuit is cheap however, it decreases efficiency significantly. On the other hand, third winding is more efficient but harder to implement.
* MOSFET voltage requirement is higher.
* Gain changes a lot with DCM mode of operation.
* It can operate only in the 1st quadrant.

## 2) PUSH-PULL CONVERTER

Push-Pull converters are widely used where there is a need for galvanic isolation. It can both increase or decrease the output voltage based on the duty cycle and transformer turn ratio. Also, it uses a center tap transformer. Input and output relation of push pull converter is as follows.

The schematic of the push pull converter can be found in Figure 2.

Diagram, schematic

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*Figure 2.* Schematic of push pull converter

In the Push-Pull converter, there are two switches that work in an opposed manner. When one switch is on, the other switch is off. Also, there is a time period where both switches are off. The reason behind that phenomenon is to discharge the output inductor. In one period, all switches are opened once for ON period and both switches are off for OFF period. So, in the input/output relationship, there is a multiplication of 2. Advantages and disadvantages of push pull converter are discussed in the next section.

**ADVANTAGES**

* High efficiency
* Stable input/output current
* Requires no feedback since it has open loop configuration. So, it is easier to design.
* Transformer has good core utilization since current is drawn from both halves of the switching period.
* Core size is smaller than flyback and forward converter
* It can operate in the 1st and 3rd quadrant.

**DISADVANTAGES**

* It uses two switch
* Cost is increased.
* It is harder to implement

## 3) FLYBACK CONVERTER

Flyback converter is a DC-DC converter that is derived from buck-boost converter. It can both increase and decrease the output voltage based on the duty cycle and turns ratio. The input/output relation of the flyback converter is as follows.

The schematic of flyback converter can be found in Figure 3.

Diagram, schematic

Description automatically generated

*Figure 3.* Schematic of flyback converter

In the flyback converter, energy transfer is not direct. Energy is first stored in the air gap then it is transferred. Advantages and disadvantages of flyback converter is discussed in the next section.

**ADVANTAGES**

* Design is simple compared to other DC-DC topologies
* Switching element count is less.
* It can operate in a wide range of input voltages.
* Cost is less than other DC-DC topologies.

**DISADVANTAGES**

* Ripple at the output current is higher.
* Core is gapped so EMI problems can occur.
* Losses are increased.
* Requires additional snubber circuit to discharge the leakage inductance in the transformer.

We have decided to design a ***“FLYBACK CONVERTER”*** for this project. It is easier to implement and has a low cost so this is an advantage for us. However, increased losses are a little concern for the project but, by choosing the right components and designing better controller, efficiency can be increased and that problem can be compensated.

# MAGNETIC DESIGN

In order to design magnetic design, first the area product is calculated.

To have a realistic core model fill factor is chosen as 0.05. According to the research, frequency of 67kHz is the most used frequency for flyback converter, it might be said that 67kHz is the standard. After calculating the area product, available component list is checked and 0P43434EC is chosen. Then sample circuits are investigated in Texas Instruments web page. For flyback converter UC3842 is the most used current mode controller, therefore we decided to use that integrated chip

Diagram

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Figure 4: Sample Flyback Converter Circuit with UC3842

In this circuit the magnetizing inductance of primary side is calculated as 42uH and 47uH is decided to be used to have less current ripple. Then minimum number of turns is calculated to not to saturate the core.

Number of turns is chosen as 1.375 then;

These values are the minimum number of turns for primary and secondary.

In order to achieve 47uH, there should be some airgap in the core. To find the airgap, one should obtain the required air reluctance.

In order to have meaningful air gap AL is chosen as 400nH.

Considering an A4 paper, this airgap value corresponds about 2 A4 paper width. After airgap calculations, number of turns is calculated to achieve 47uH magnetizing inductance.

## CABLE SELECTION

In order to select an appropriate cable for transformer, RMS current on the primary and secondary side of the transformer are simulated.

Chart

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Figure 5: Current Waveform on Primary Side

Graphical user interface

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Figure 6: RMS Value of IL1

Chart, bar chart

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Figure 7: Current Waveform on Secondary Side

Graphical user interface

Description automatically generated

Figure 8: RMS Value of IL2

According to the results, current on primary side 3.4A and on secondary side is 4.32A.

Table 2: Cable Parameters

|  |  |  |  |
| --- | --- | --- | --- |
| AWG Number | Conductor Cross Section Area(mm2) | Ohms Per mm | Maximum Frequency for 100% Skin Depth |
| 26 | 0.162 | 0.0001061736 | 85kHz |

For primary side

For secondary side

According to the calculations, cables should be paralleled, 5 for primary and 7 for secondary. To do that, we twisted the cables to prevent proximity effect. After winding the transformer, we measured its inductance and leakage inductance.

Graphical user interface

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Figure 9: Inductance Measurement Figure 10: Leakage Inductance Measurement

In order to measure the leakage inductance, secondary side is shorted. Note that, since cables are isolated, to measure isolation on the cables are removed. However, because they are not removed completely the resistance is higher than expected. Leakage inductance is higher than the standards, it is because winding operation is completed without tools.

# CONTROLLER DESIGN

Diagram, schematic

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Figure 11: Overall Schematic of Flyback Converter with UC3842 Controller

In this project, we need to set our output voltage to 15V and it should be independent from the input voltage. Therefore, basic PWM generators do not meet our requirements.

After some research, we learned that there are a lot of chips to control different converter types. Since we are determined to build a flyback converter, we try to find the most suitable controller chip which can control the flyback converter

On the TI website, there are hundreds of controller chips. However, most of them do not exist in Turkey or are very expensive. After some searching in the Turkish market, we found the UC3842 chip. It is both cheap and useful for the buck-boost converters. In conclusion, we determined to use this chip in this hardware project.

**Note:** In the LTSpice, we cannot find the UC3842 chip. According to their datasheets, there should be no important differences between these two chips. So, we expect that the results should be similar.

## PIN DEFINITIONS

### COMP

Comp pin is the “Error amplifier compensation pin”. As can be seen below, Comp pin is connected to output of voltage comparator op-amp inside the our chip. We can connect this pin to a parallelly connected capacitor and resistor in order to decrease the noise at the output. Also, It is possible to connect this pin directly to the ground in order to obtain a zero duty cycle. In conclusion, it can be said that this pin is a “shut down” pin to stop our flyback converter.

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Figure 12: Compensation Connection

### GROUND

As can be understood, ground pin is connected to the ground of the source. Notice that, the ground of this pin isolated from the seconder side. The only connection between the UC3842 and the seconder site is provided by an optocoupler and this connection is not physical.

### ISENSE

In order to check if MOSFET is ON or OFF, UC3842 uses Isense pin. The Isense pin checks the current and convert it to the voltage. This voltage goes to the PWM comparator which is inside the chip. Finally, PWM comparator uses this signal in order to terminate the MOSFET’s conduction.

According to the datasheet, the R12 value should be about 5kOhm. However, when we set this value, the output voltage for the 24V and 48V cases are different. When we put smaller resistor instead of 5kOhm, the difference is observed very small. Therefore, during the implementation, we will try different resistors in order to see real difference and determine what we will do.

Diagram, schematic

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Figure 13: ISENSE Connection

### OUTPUT

This pin is connected to MOSFET’s gate. In EE463 hardware project, we need to drive MOSFET’s gate with an optocoupler. In this case, we don’t need to do that because the necessary circuits are at the inside of our chip. The connection of this side can be seen below. We put an 10Ohm resistor here. This resistor determines the MOSFET’s turn-on turn-off time. Therefore, we will probably put there a very small resistor.

### RT/CT

By using this pin, we can set the frequency. According to connection, the frequency can be fixed a constant. We will probably use 67kHz frequency in our circuit. We are doing our calculations according to this value. The details will be explained in the following sections

### VCC

Vcc is the power input connection pin for our chip. In our circuit, instead of directly connecting this pin to the voltage source, we need to put a resistor between them because our maximum source voltage is much larger than the maximum Vcc value. In conclusion, by increasing the source impedance, we try to decrease the input voltage of chip. Also, we put a zener diode in order to prevent any over-voltage problem due to the source voltage.

Diagram, schematic

Description automatically generated

Figure 14: Vcc Pin Connections

### VFB

Vfb pin is the inverting input of the error amplifier. This pin is connected to the output of optocoupler. As can be seen below, the R11 and R10 values have a critical role of the feedback voltage. In the project, by changing R11 value, we try to reach exactly 15V output voltage.

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Figure 15: Feedback Pin Connection Diagram

Diagram

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Figure 16: Isolated Feedback

### VREF

This pin is the voltage reference pin for the error amplifier.

## TUNING PARAMETERS

### HOW TO SET OSCILLATION FREQUENCY

For the UC3842 flyback controller chip, the frequency is equal to half of the oscillating frequency due to the internal flip flops. In our design, we calculated the necessary turn ratio for our transformer in order to prevent going over this limit.

We decided to choose a 67kHz frequency in order to decrease any losses on core and cables. Even if, operating at higher frequency decreases the core size, losses are more important parameters considering our topology. Therefore, we set our oscillating frequency of controller as

According to the formula below, we choose Rrt = 12.7kΩ and Cct = 1nF.

### HOW TO SET OUTPUT VOLTAGE

Output voltage can be set by changing some resistors which are on the feedback loop. As can be seen below, we seperate two circuit physically by using an optocoupler. This optocoupler senses the output voltage and create a current using a BJT. Afterward, it sends a signal to the primary side by using LEDs. As you can see R5 determines the sensibility of this signal. Also, R11 determines how much of this signal should be transmitted to the feedback pin. In conclusion, we can control the amplitude of output voltage by changing this resistors. We will probably put a potentiometer instead of R11 resistor while setting the output voltage during the implementation.

Diagram

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Figure 17: R­11 Resistance

### THIRD WINDING

Third winding is used to supply minimum operating voltage to the Vcc terminal in order to provide stability. Therefore, we determine its turn ratio equals the seconder of our transformer. 15V is above our minimum Vcc value and it is enough to sustain our controller application

### SNUBBER CIRCUIT

According to our calculations, our leakage current of the transformer is about 1.7uH. Due to this leakage inductance, we need to choose a bigger MOSFET because when the switch is opened, the voltage over mosfet increases dramatically. At that point, we need to choose one of these alternatives: choose a larger mosfet or put a snubber circuit between the terminals of the transformer. We have chosen the second one.

Schematic

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Figure 18: Snubber Circuit

# SIMULATION RESULTS

## FOR 24V INPUT VOLTAGE

Chart, table, line chart

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Figure 19: Output Voltage Transient (24V Input)

eChart, line chart

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Figure 20: Output Voltage Steady-State (24V Input)

Chart

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Figure 21: MOSFET Voltage (24V Input)

Chart, bar chart, histogram

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Figure 22: MOSFET Voltage Waveform Transient (24V Input)

Note that, there are high peaks on MOSFET, improving the snubber cir cuit may help this problem.

Chart

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Figure 23: Gate Signal on MOSFET (24V Input)

## 48 VOLTS INPUT VOLTAGE

Line chart

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Figure 24: Output Voltage Transient (48V Input)

Chart, line chart

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Figure 25: Output Voltage Steady-State (48V Input)

Chart, histogram

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Figure 26: MOSFET Voltage Waveform Transient (48V Input)

Diagram

Description automatically generated with low confidence

Figure 27: Gate Signal on MOSFET (48V Input)

# EFFICIENCY CALCULATIONS

## 24 VOLTS INPUT VOLTAGE

According to simulation results, the resulted efficiency is smaller than our expectations. The reason is probably the snubber circuit. However, snubber is cheaper than the MOSFET’s, therefore, we will probably use this snubber in the implementation. In conclusion, we need to find another method to decrease loss.

The simulation results can be seen below.

For the 24V case, our efficiency is equal to

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Figure 28: Output Power (24V Input) Figure 29: Input Power (24V Input)

## 48 VOLTS INPUT VOLTAGE

For 48V input voltage case, calculation is shown below equation.

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Figure 30: Output Power (48V Input) Figure 31: Input Power (48V Input)

# EQUIPMENT SELECTION

## MOSFET SELECTION

To select the required MOSFET, voltage and current ratings at the transient state must be investigated.

Chart, box and whisker chart

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Figure 32. MOSFET Current Waveform Transient (48V Input)

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Figure 33. MOSFET Current Waveform Transient (24V Input)

The required ratings of the MOSFET can be seen in Table 3, which is obtained from Figures 22, 26, 32 and 33.

Table 3. Required Ratings of MOSFET

|  |  |  |
| --- | --- | --- |
| **Vin** | **Peak Voltage** | **Peak Current** |
| 24 V | ~280 V | ~27 A |
| 48 V | ~300 V | ~27 A |

Based on these specifications, IXFP38N30X3M N-Channel MOSFET is selected. This MOSFET can work up to 300V and 38 A.

## DIODE SELECTION

To select the required diode, voltage and current ratings must be investigated. The ratings are obtained from LTSpice.

A picture containing bar chart

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Figure 33. Diode Current Waveform Transient (24V Input)

Chart

Description automatically generated

Figure 34. Diode Current Waveform Transient (48V Input)

Graphical user interface, chart

Description automatically generated

Figure 35. Diode Voltage Waveform Steady State (24V Input)

Graphical user interface

Description automatically generated

Figure 36. Diode Voltage Waveform Steady State (48V Input)

The required ratings of the diode can be seen in Table 4, which is obtained from Figures 33, 34, 35 and 36.

Table 4. Required Ratings for the Diode

|  |  |  |
| --- | --- | --- |
| **Vin** | **Peak Voltage** | **Peak Current** |
| 24 V | ~-48 V | ~35 A |
| 48 V | ~-72 V | ~35 A |

Based on these specifications, ESAF92-03R diode is selected. This diode can work properly until 300 V and 60 A.

## CAPACITOR SELECTION

Based on the buck-boost converter output capacitor selection formula, output capacitor is found as 47uF. However, as it can be seen in Figure 37, output voltage has unwanted peaks so, we have decided to continue with 400uF capacitor to decrease the voltage ripple also to decrease the transient oscillations. The output capacitor formula can be found below.

Chart, line chart

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Figure 37. Output voltage when C = 47uF ( 48V input)

Graphical user interface, chart

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Figure 38. Output voltage when C = 400uF ( 48V input)

So, based on the voltage specifications of the output capacitor, 470uF 25 V capacitor is selected.