

## 4 Experiment 3: DC to DC Converters

### 4.1 Purpose and Goals

In this experiment the student will study DC-DC converters and their applications. It will introduce the use of PWM (“Pulse Width Modulation”) as a powerful technique for operating power electronics converters to manage the energy flow from an energy source to a load.

The objective of the DC to DC converter experiment is to:

- Learn the switching technique for DC-DC conversion and the types of DC-DC converters.
- Introduce the PWM technique.
- Examine current and voltage waveform for all components in a specific DC-DC converter.
- Calculate and understand the performance parameters of a DC-DC converter.
- Derive an expression for the ripple voltage and current.
- Understand the conversion factor between input and output voltages and currents.
- Determine the overall efficiency of the converter.

### 4.2 Apparatus required

K-ECS, oscilloscope, wattmeter, rheostat, transformer (120V: 12V/24V), multimeter.

Optional: variable DC power supply, resistors, Load inductor (only needed if using RL).

### 4.3 Pre-lab Assignment

In this Pre-lab, the student is required to perform a theoretical analysis of a DC-DC converter as shown in the right part of Figure 4.1. Use the following steps to set up the DC-DC Buck topology shown in Figure 4.1.

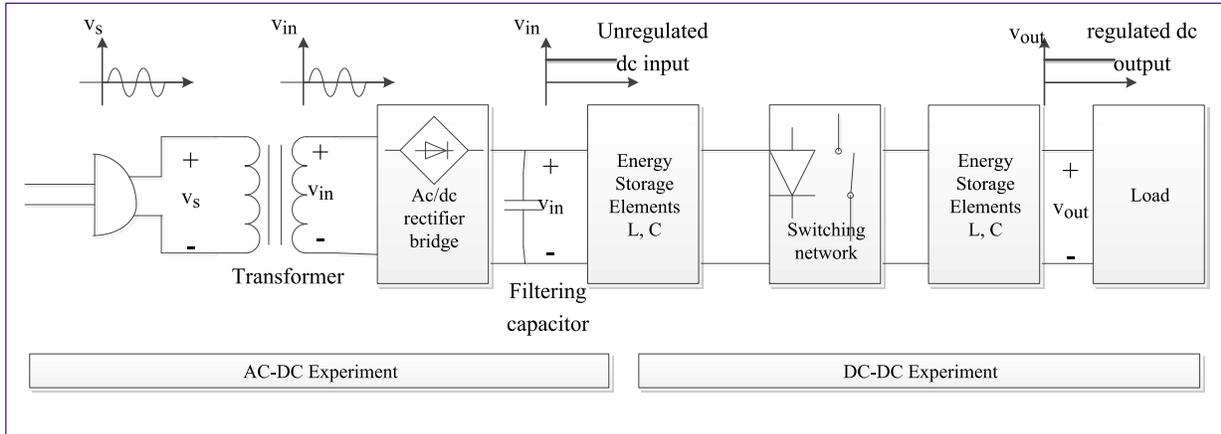


Figure 4.1: Power Converter Flow

(Ref. Figure 4 modified from Batarseh, Issa. Power Electronics Circuit)

1. The experiment will use a power MOSFET as a controlled switch
2. An uncontrolled switch like a diode, as shown in Lab 2 should be used as the flywheel diode. Use the second MOSFET in the K-ECS DC-DC Converter module to implement the flywheel diode
3. An inductor (390  $\mu\text{H}$ ) and a capacitor (200  $\mu\text{F}$ ) as energy storage elements for the buck converter.
4. Two types of load
  - a. A purely resistive load like in the previous experiment
  - b. A series resistor and inductor RL load (like a DC motor)

For the controlled switch in step 1, students are required to explain in one or two sentences how they will control the switch. Additionally, describe the mechanism and strategy used for this control. Students should use the datasheet of the power MOSFET (FDD3682) at the following link: (<http://www.fairchildsemi.com/ds/FD/FDD3682.pdf>).

Verify the design with the instructor, then:

1. Use the techniques learned in class to analyze the design of a DC-DC converter and perform the following tasks for each type of load.
2. By moving around the inductor relative to the switches draw the schematic of three basic types of DC-DC converters that have been learned in class: Step-down converter; Step-up converter and Step-up-down converter.



3. Draw an approximate graph (using pen and paper) or an exact one (using Matlab) of the PWM signal that can control the 18 V DC from the AC-DC converter down to 5 V output of the DC-DC converter.
4. Use this PWM signal as a timing reference to explain and draw the voltages and currents output for each component in the buck converter design. For simplicity, start with the following assumptions, the power switching devices and the converter components are lossless such as  $P_{in} = P_{out}$ . The current that flows through the inductor is periodic. The buck converter can operate in continuous conduction mode CCM or discontinuous conduction mode DCM based on the condition that current flowing in the inductor L is continuous or discontinuous.
5. Find the equivalent circuits when the switch is on and the diode is off and vice versa.
6. For each case determine the voltage and current across the inductor and the diode.
7. Calculate the ripple current in the inductor L.
8. Calculate the transfer functions  $V_o/V_{in}$  and  $I_o/I_{in}$ .
9. Write a simple algorithm to control the 18 V DC output from the AC-DC converter down to 5 V DC using a 10 kHz PWM generated with the Arduino controller inside the K-ECS.
10. Calculate an approximate expression for the efficiency of the DC-DC converter.

You can use either Matlab or pen and paper to do the pre-lab assignment in both cases the student must clearly show the scientific methods that lead to the specific results. This means if the student uses pen and paper there is a need to explain and develop all mathematical models. If Matlab is used the student needs to present the programs and commands used in a way that anyone can understand the results without the student's help or personal explanation.

#### **4.4 Procedure**

Ensure that the DC-DC converter design is approved by the instructor to verify that the input and output of this design is the same as the ones used in the input and output of the K-ECS.

Thus the student can view, map and understand the input and output of the KECS DC-DC converter as illustrated in Figure 4.2 and explained as follows:



1. Assembling sequence: first build and test the **DC-DC Converter** of “Figure 4.2a” only, a wiring diagram is given by “Figure 4.2c”.

**Initially do not assemble** the AC-DC rectifier. It is a good practice to test the DC-DC converter first before connecting it to the AC-DC rectifier. Use a variable DC power supply  $V_i$  to drive the input of the DC-DC converter (pin 3: DCDC\_In in the DC-DC CONVERTER connector). **Note** that the current (mAmps) will be too low to appear on the power supply's current meter (Amps).

2. Write an Arduino sketch to drive a PWM signal on signal PWMDC\_H and test PWMDC\_L is driven to zero. See the File->Examples->KECS sketch: "PWMHalfBridgeGraph", but use *"myPWM.setBuck (highPin, frequency, duty);"* instead of *"myPWM.setHalfBridge (highPin, frequency, duty, gap);"*

Forcing PWMDC\_L to zero will disable the lower MOSFET creating the freewheel diode needed for the Buck converter to operate properly. Run the sketch with a few different duty cycles and ensure the voltage on DCDC\_Out is as expected. (See <http://arduino.cc/en/Tutorial/SecretsOfArduinoPWM> for more information).

3. Afterwards, remove the DC power supply  $V_i$  and connect the output of the AC-DC rectifier to the inputs of the **DC-DC Converter** (the junction point formed by **DCDC\_in** and **DCDC\_S1** as shown in “Figure 4.2d”).
4. Now, connect the negative terminal of the AC-DC rectifier (pin RectRef1Ph) to the junction point formed by **DCDC\_Ref** and DGND.
5. The buck output is available on the pin **DCDC\_Out** on connector **DC-DC Converter**.

#### NOTES:

i) If the controller pins PWMDC\_H and PWMDC\_L inside K-ECS are configured by the Arduino to be at high impedance, the buck converter can be controlled by an external controller. The control pins of this configuration are available on PWMDC\_H and PWMDC\_L on connector DIGITAL CONTROL (pins 22 and 21 respectively).

ii) On connector **DC-DC Converter**, pin **DCDC\_S4** can be used instead of **DCDC\_S3** to design a highly custom buck converter for very specialized needs. (These two pins are actually on the 3-Phase Rectifier connector - even if they are part of the DC-DC converter).

**WARNING:** This feature should be used with care and under the instructor supervision.

iii) **WARNING:** The DGND connection must be made on the DGND pin available on the DC-DC converter power connector (the green connector) as these pins are meant to be used in high current applications. **DO NOT** use the DGND pins on the black connectors as reference to power circuits as these pins have very limited current capacity.

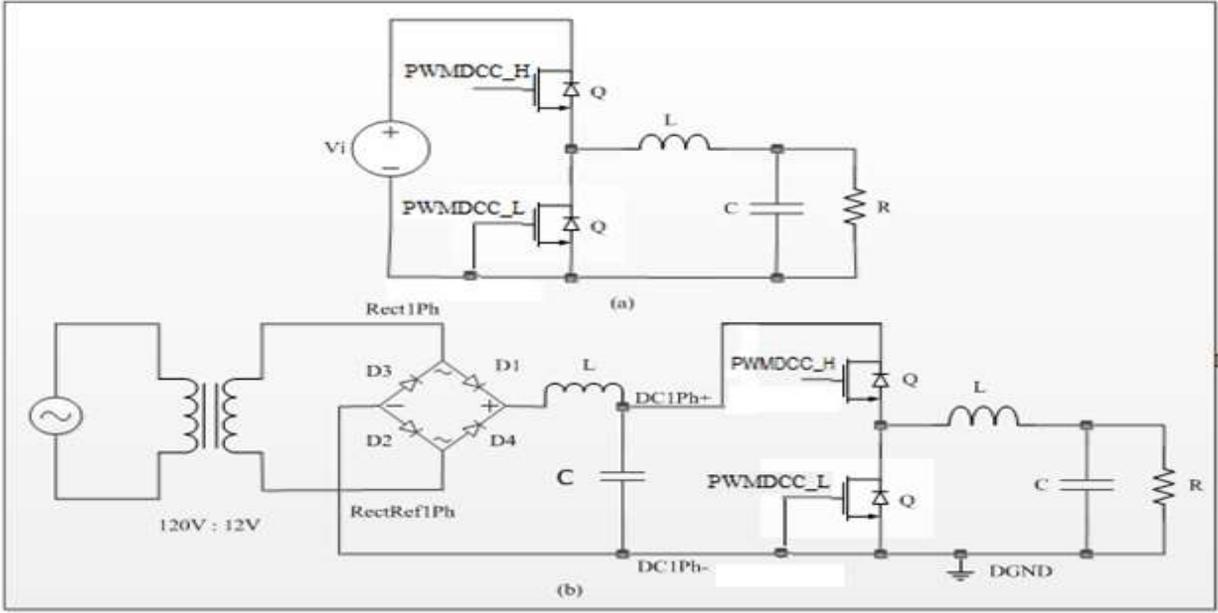


Figure 4.2: Circuit for DC-DC Experiment

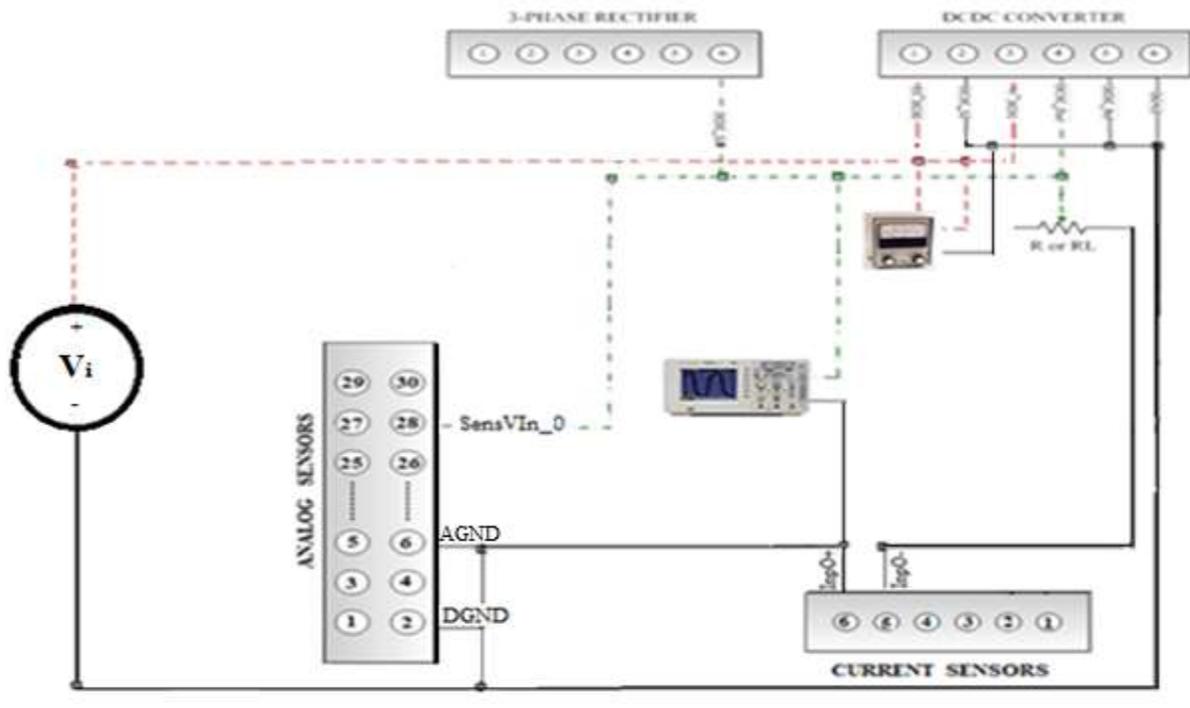


Figure 4.2c : Connection Diagram for DC-DC converter test using a DC power supply at the input

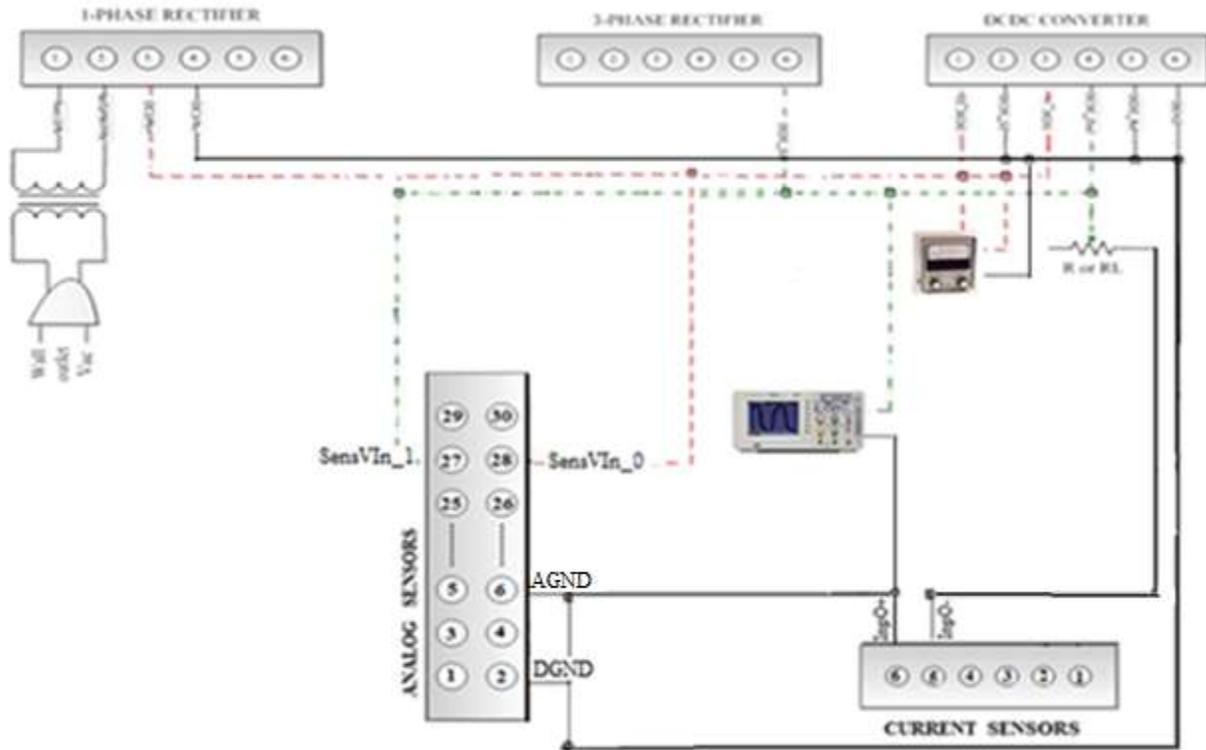


Figure 4.2d : Connection Diagram for DC-DC Experiment with AC-DC rectifier

The input **power supply** that provides power to all integrated circuits of the K-ECS is placed in the back as shown in the connector in “Figure 4.2e”. This power input up to this point is optional because the bridge rectifier is independent of the rest of the circuit. However if a student wants to use the Arduino controller inside the K-ECS to measure the performance parameters she will need to connect the **power supply** connector to the low voltage (24V/2A) DC power supply.

Also, ensure the current sensor is connected to the low voltage terminal of the load (Junction point formed by DC1Ph- and DGND).

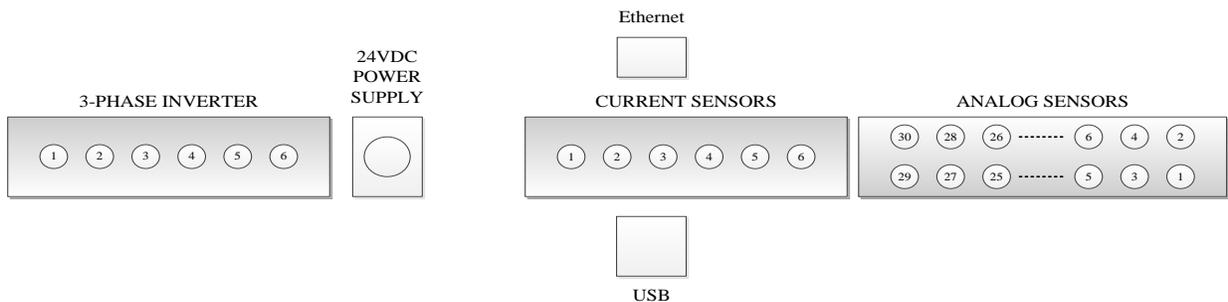


Figure 4.2e : KECS right hand sideconnectors



Use the laboratory equipment such as oscilloscope, current probe and multimeter to measure and prove the relationship between the theoretical studies in the pre-lab assignment and the practice in the lab experiment.

#### **4.5 Study Questions**

1. For the same loads used in the AC-DC diode rectifier experiment, tabulate the voltage values at the input and the output of the DC-DC converter (For a 50% of PWM modulation index for example). Are the results the same? Explain your answer?
2. Set the PWM modulation index to the following values: 60%, 50% and 40%. Tabulate ratios of  $V_{load(avg)} / V_{dcIn(avg)}$  for your data ( $V_{DCIN} = ((DC1Ph+) - (DC1Ph-))$ ). Are the results consistent with the duty cycle settings? (Take a resistance of  $112 \Omega$  for example).
3. For each load, estimate the average input power  $P_{in}$  and output power  $P_{out}$  at the input and the output of the DC-DC converter from the average readings of  $(V_{dcIn}, I_{dcIn})$  and  $(V_{load}, I_{load})$ . Compare these results to the wattmeter readings. Calculate efficiency  $P_{out}/P_{in}$ , from the wattmeter readings. Compare the DC-DC converter efficiency to the values calculated in the AC-DC rectifier experiment.

Knowing that the storage energy inductor value is  $390 \mu H$ , use this value to compute the load voltage ripple at 10 kHz PWM carrier frequency. How do your results compare with the measured data? If the inductor value were to double, how would this affect the behavior of the buck converter?