Introduction to Power Electronics

Laboratory Experiment Manual

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Revision History

Date	Version	Description	Contributor
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1 Introduction

This manual includes three experiments that introduce the students to the principles and basic topologies used to develop power electronics applications. However, these very same topologies can be extended, by simply adding a few more components, to implement industrial grade projects widely used in power electronics commercial applications.

In order to make it easier for the novice student to fully understand the principles, we have designed these experiments to use basic circuit topologies and control algorithms. By omitting additional complexity, we allow the student to focus on the principles and metrics used in the industry to assess circuit performance. The labs are designed to allow students to understand the benefits and limitations of each topology, thereby allowing them to make conscious choices on when and how to use each topology.

For advanced students, the laboratory instructor may choose to propose the use of more advanced control algorithms such as harmonics minimization, power factor control or MPPT ("Maximum Power Point Tracking") to name a few. Therefore, the same training platform can be used by beginners as well as last year students or even graduate level ones. Throughout the manual, students will learn AC-DC, DC-DC and DC-AC energy conversion, some of the most important metrics related to the proper functioning of those circuits, and how to control the electronics to generate the required voltage and power level from different energy sources.

1.1 K-ECS Product Overview

In those experiments, students will be using K-ECS AM256 system "Shown in Figure 1.1", a product developed by Kylowave Inc. company. K-ECS is a small but powerful, feature-rich energy converter system for teaching renewable energy, control systems, mechatronics, power electronics and power systems teaching. Most systems currently used in these environments are very high power in addition to high cost. It's a low power and lower cost system, with additional features not available in existing systems. K-ECS creates a modern and stimulating learning environment to teach disciplines such as control systems, renewable energy and smart grid by providing ready-to-run hardware, software, and comprehensive experiment laboratory manuals including design files and examples.

The names of the connector pins are the same as those used in programming the embedded controller and are shown in the Figure 1.2. Pins are referenced in code by capitalizing box labels and prefixing them with "KECS_". The pins descriptions are given in APPENDIX 1.

K-ECS AM256 uses an Arduino controller under the Creative Commons Attribution Share-Alike 2.5 License. Details of the controller are available on the Arduino website, (http://arduino.cc/en/).

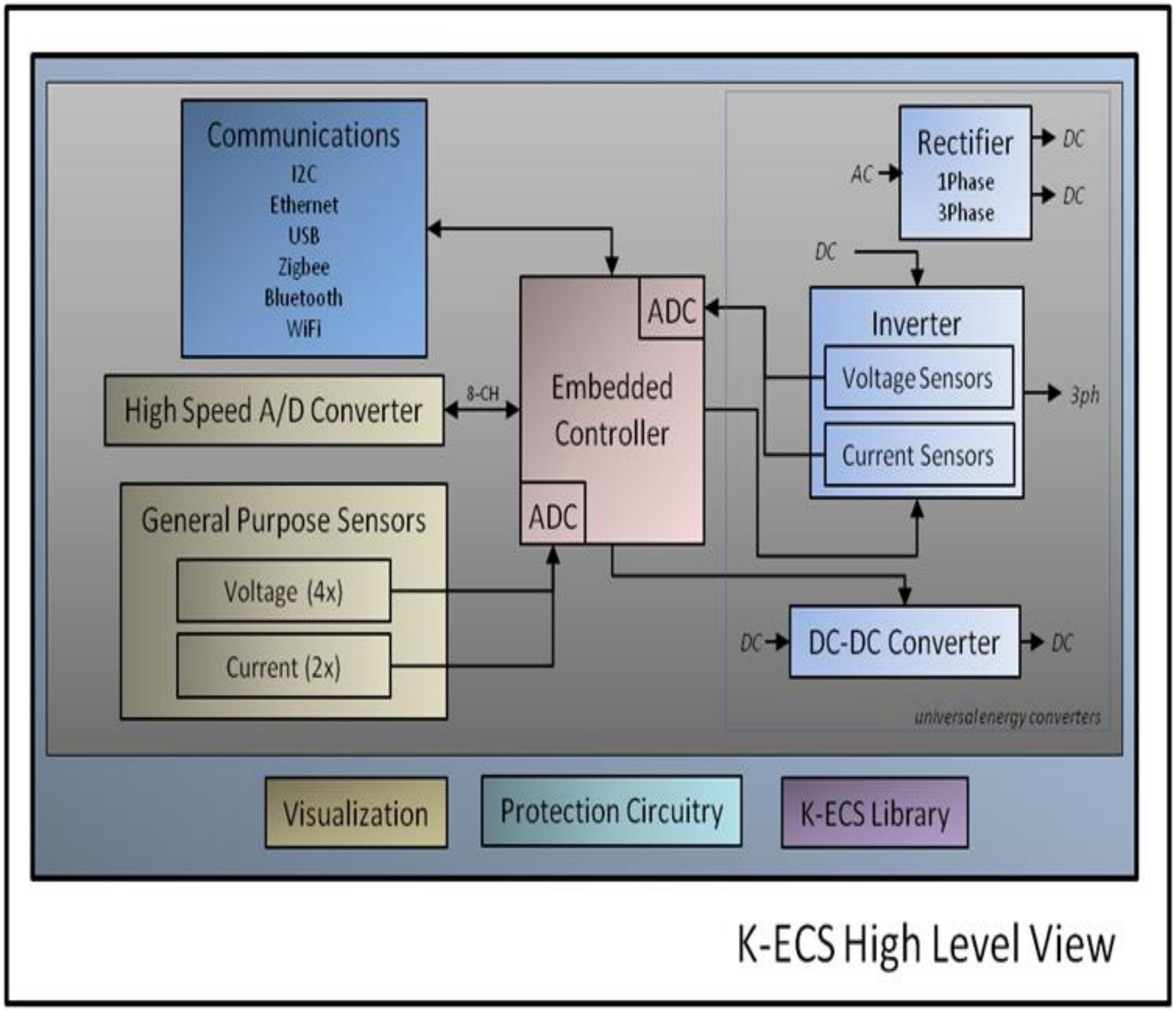


Figure 1.1 K-ECS high level architecture

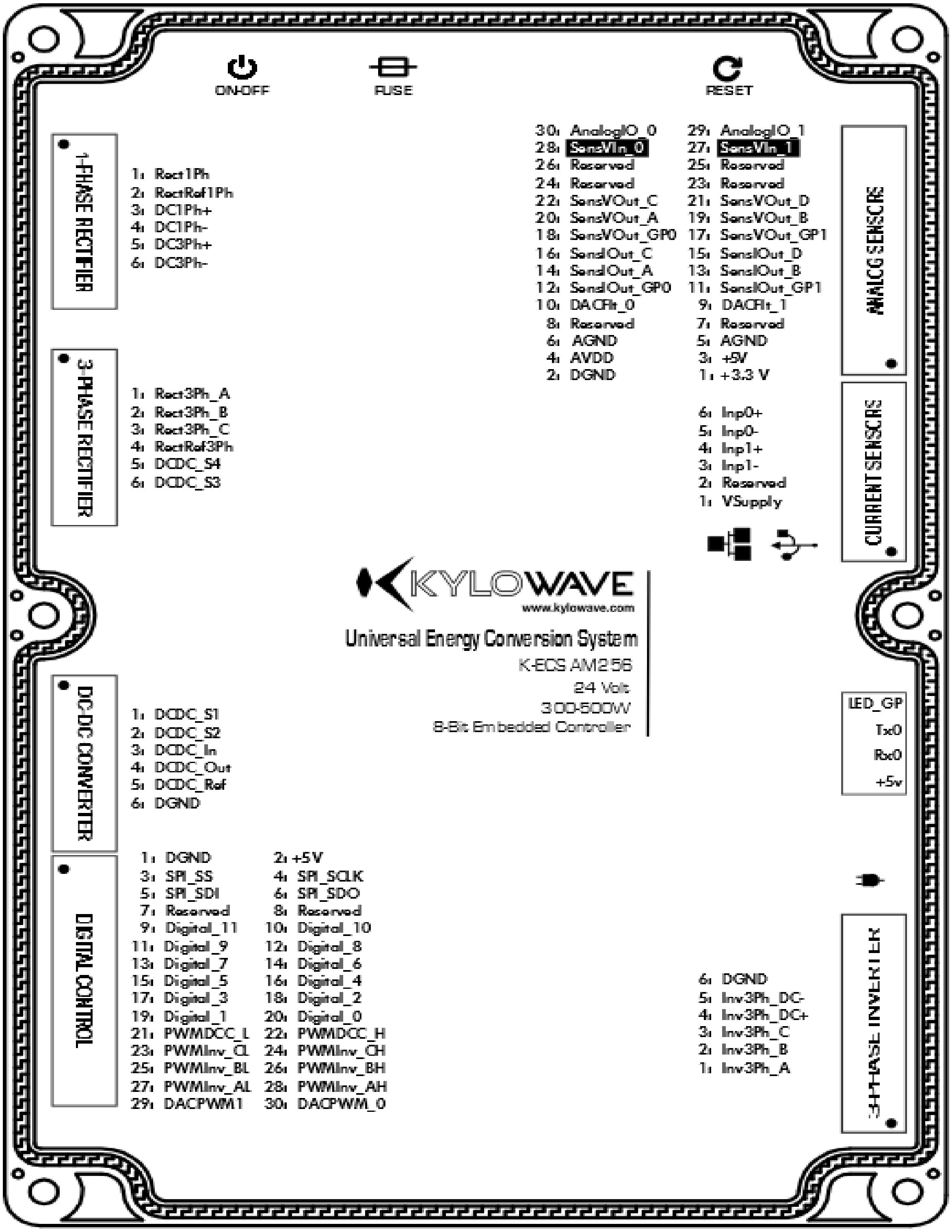


Figure 1.2 K-ECS Connector Pins

2 Experiment 1: Introduction to PWM in Arduino

2.1 Purpose and Goals

What is Arduino? From Arduino's official website (www.arduino.cc), *"Arduino is an open source prototyping platform based on flexible, easy-to-use hardware and software. It's intended for artists, designers, hobbyists, and anyone interested in creating interactive objects or environments".*

Why is it important to learn Arduino? Arduino can sense the environment around it through a variety of sensors and uses an ATMEL processor to control various peripherals or actuators in order to affect its surrounding. Despite its flexibility and various features, it is easy to use and counts with a huge open-source development community. Therefore, the user is free to focus in exploring and developing their ideas, instead of have to pay attention to the specifics of the hardware and software details. But most important of all, it is fun working with Arduino.

The objective of this experiment is to:

- Familiarize the student with the Kylowave K-ECS ("Energy Conversion System"), the Arduino and its free IDE ("Integrated Development Environment")
- Demonstrate techniques to read and generate analog and digital I/Os using the Arduino IDE
- Introduce the PWM ("Pulse Width Modulation") technique as a mean to generate analog signals to control external peripherals

2.2 Apparatus required

K-ECS, Oscilloscope, Multimeter, potentiometer, resistor, and a LED.

2.3 Pre-lab Assignment

In this Pre-lab the student is required to learn about Arduino. The student can find very useful information at the Arduino official webpage at www.arduino.cc. Specifically, the student should study the *Blink* and the *ReadAnalogVoltage* examples in the Arduino Tutorial Webpage (http://arduino.cc/en/Tutorial/HomePage). In addition, get familiarized with the Arduino programming language at its reference website (http://arduino.cc/en/Reference/HomePage).

2.4 Procedure

The experiment procedure is as follows:

1. Always have your wiring checked by the instructor before powering up.

2. Assemble the Analog sensor test circuit as shown in the diagram of Figure 2.1. All grounds (pins #2 and #6) are connected to a same point, as shown in the diagram.

3. Set up the potentiometer as shown in Figure 2.1, connect its central connection to K-ECS pin **AnalogIO_0**, and adjust the potentiometer such that the multimeter reads the following values: 0, 1, 2, 3, 4 and 5V. **Note: AnalogIO_0 is a 0-5V analog input pin.**

4. Write an Arduino sketch (this is what the Arduino community calls an Arduino program) to read the voltage value on the K-ECS analog input **AnalogIO_0** and print it to the serial monitor (See http://arduino.cc/en/Tutorial/ReadAnalogVoltage and FancyLEDTest example). Check that the printed value matches the value you would expect to see. Note that you need to include at least pins_kecs.h in code and Pins are referenced in code by capitalizing box labels and prefixing them with "KECS_".

5. Using the Arduino *map()* function, scale the digital value read at step 2 to the range [0, 100] such that the digital *value 0* corresponds to 0V and 100 corresponds to +5 V.

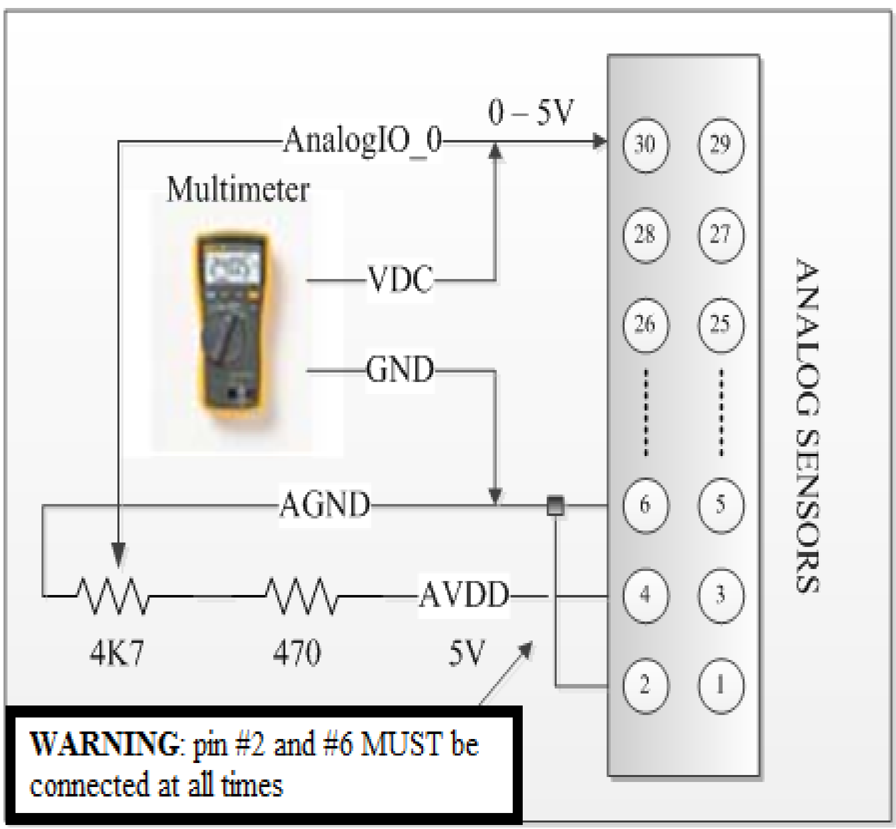


Figure 2.1: Analog sensor test circuit

6. Assemble the PWM test circuit as shown in the diagram of Figure 2.2.

7. Add code to the sketch created in step 3 to generate a 5 kHz PWM signal on K-ECS pin DACPWM_1. Use the PWM bit banging technique (http://arduino.cc/en/Tutorial/SecretsOfArduinoPWM). The PWM modulation index should be the digital value produced at step 4. Write your code to ensure that the PWM carrier frequency does not change with changes of the modulation index.

8. For each voltage in step 2, read the PWM signal duty cycle using the oscilloscope. Then, build a table showing the measured voltage, duty cycle, the digital number read from pin and the digital number resulting from the map() function.

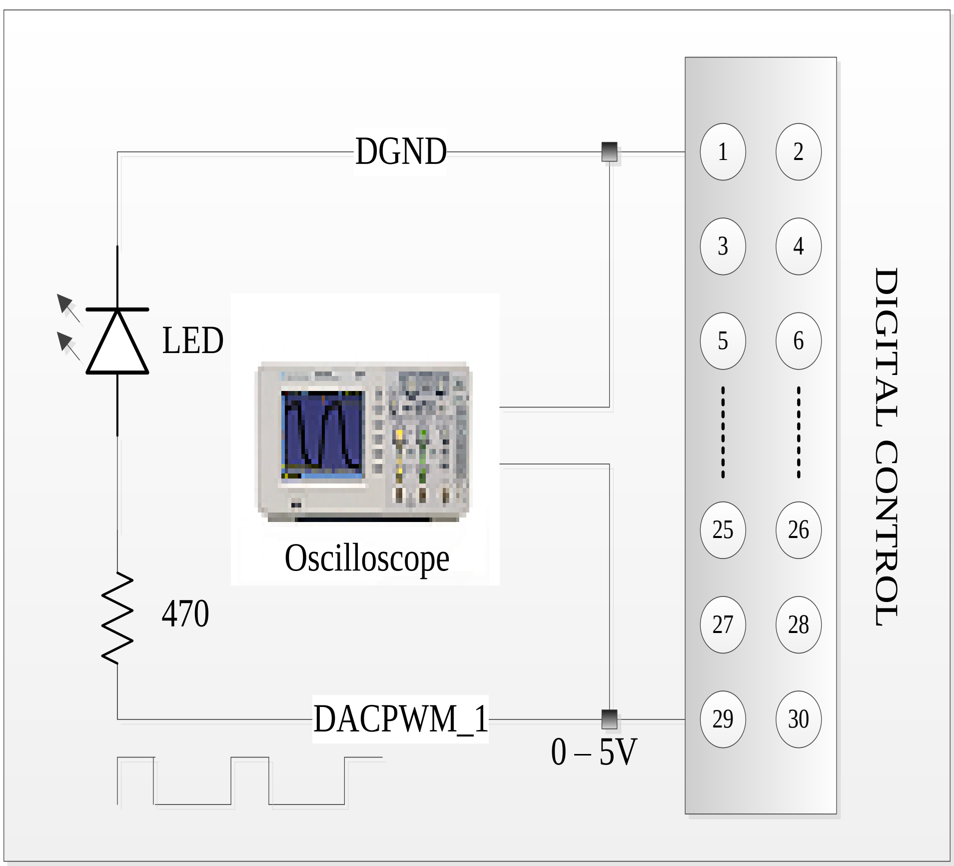


Figure 2.2: PWM test circuit

2.5 Study Questions

1. Consider the table built in section 2.4. Explain any differences between digital values measured from pin 30: **AnalogIO_0** and the expected values calculated from the DC values measure by the multimeter.

2. What is the number of bits and maximum values of the Arduino A/D converter? What value would have to be applied at pin **AnalogIO_0** in order to obtain the maximum value for the Arduino A/D converter?

3. What is the maximum PWM carrier frequency that the Arduino can achieve when using the bit banging technique? Hint: change the code written in "section 2.4 step 6" to experimentally determine the maximum value.

4. What happens to the LED of Figure 2.2 when the potentiometer is used to change the voltage value on pin 30: **AnalogIO_0**? Explain the observed behavior.

Note: The differences in any one of the following lead to discrepancies in readings between K-ECS and multimeter.

• Consistency of inputs (sensitivity).

• Calibration/Indication.

In order to achieve the greatest accuracy, you must take the necessary steps to eliminate potential measurement errors from a multimeter (See multimeter manual).

3 Experiment 2: Diode Rectifiers

3.1 Purpose and Goals

Diode rectifiers are one of the oldest power electronics circuits. Despite the fact that modern power switches allow for more advanced topologies, these circuits are still widely used because of their simplicity, robustness and low cost. In applications that do not require challenging performance (such as very low harmonics and unity power factor), these benefits may make the diode rectifiers the best choice.

The objective of the diode rectifiers experiment is to:

- Explain the power flow control in conjunction with transformers and diodes rectifiers.
- Define different types of semiconductor converter.
- Explain and analyse the characteristics of uncontrolled diode switching in power electronics.
- Explain and analyse the operation of a full-wave rectifier AC-DC converter.
- Explain and analyse the coupling transformer and full-wave bridge.
- Explain the purpose of a power filter.

3.2 Apparatus required

K-ECS, oscilloscope, wattmeter, resistors (3x56 Ohm), transformer (120V: to 12V/24V), multimeter, variable DC power supply.

Optional: rheostat

3.3 Pre-lab Assignment

In this Pre-lab the student is required to do a theoretical analysis of an AC-DC converter as shown in the left part of the Figure 3.1 below

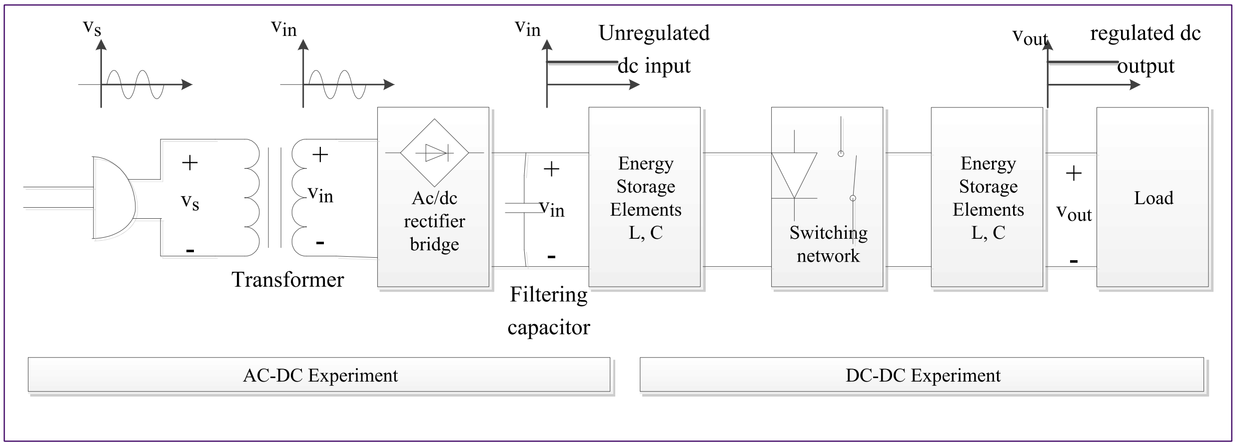


Figure 3.1: Power converter flow
(ref. Figure 2.1 modified from Batarseh, Issa. Power Electronics Circuit)

Use the datasheet of the GBJ1005 diode bridge rectifier IC (integrated circuit) to design a full-wave diode rectifier. This datasheet can be found at Micro Commercial Components Web site (http://61.222.192.61/mccsemi/up_pdf/GBJ10005-GBJ1010(GBJ).pdf) . Verify the design with the instructor in accordance to the following specifications:

- Input transformer (Primary: 120V AC and Secondary: 12V/24V AC)
- Diode bridge GBJ1001
- LC filter at the DC output of the bridge (L = 470 μH and C = 3300 μF)
- A rheostat as a load, the student will define its specifications in terms of resistor values and power for a maximum of 2 A load current.

Use the techniques learned in class to analyze the design of a diode rectifier and calculate the following performance parameters:

- Average and root-mean-square (RMS) value of the output voltage.
- Average and RMS value of the output current.
- Input and output power.
- Efficiency or rectification factor of the diode rectifier.

- The form factor and ripple factor values of the output voltage.

- The displacement angle or displacement factor.

- The harmonic factor.

Draw a sketch or a diagram that approximates the voltages and currents at the input of the bridge, each diode in the bridge and highlight their uncontrolled switch behaviour, output of the bridge and output of the filter across the load.

You can use either Matlab or pen and paper to do the pre-lab assignment in both cases the student has to clearly show the scientific steps that lead to the specific results. That 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.

3.4 Procedure

Ensure that the full-wave diode rectifier 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 K-ECS diode bridge rectifier as follows:

1. In this experiment a transformer is used to couple the AC input voltage from the power utility source to the rectifier inside the K-ECS as shown in Figure 2.2. Transformer coupling provides two advantages. First, it allows the source voltage to be stepped up or down as needed. Second, the AC source is electrically isolated from the rectifier, thus preventing a shock hazard in the secondary circuit.

2. The high power AC voltage was brought down to 12 volts. Now, the low AC voltage is supplied to the single phase diode bridge of K-ECS using the AC-DC rectifier pins **Rect1Ph** and **RectRef1Ph** on 1-Phase Rectifier connector. The DC rectified output voltage is available on pins **DC1Ph+** and **DC1Ph-** on the same connector.

3. Construct the circuit shown in Figure 3.2 by connecting the K-ECS interface as shown in Figure 3.3.

4. Use the oscilloscope and the multimeter to measure and prove the relationship between the performance parameters calculated in the pre-lab assignment theoretically and the practice in the lab experiment.

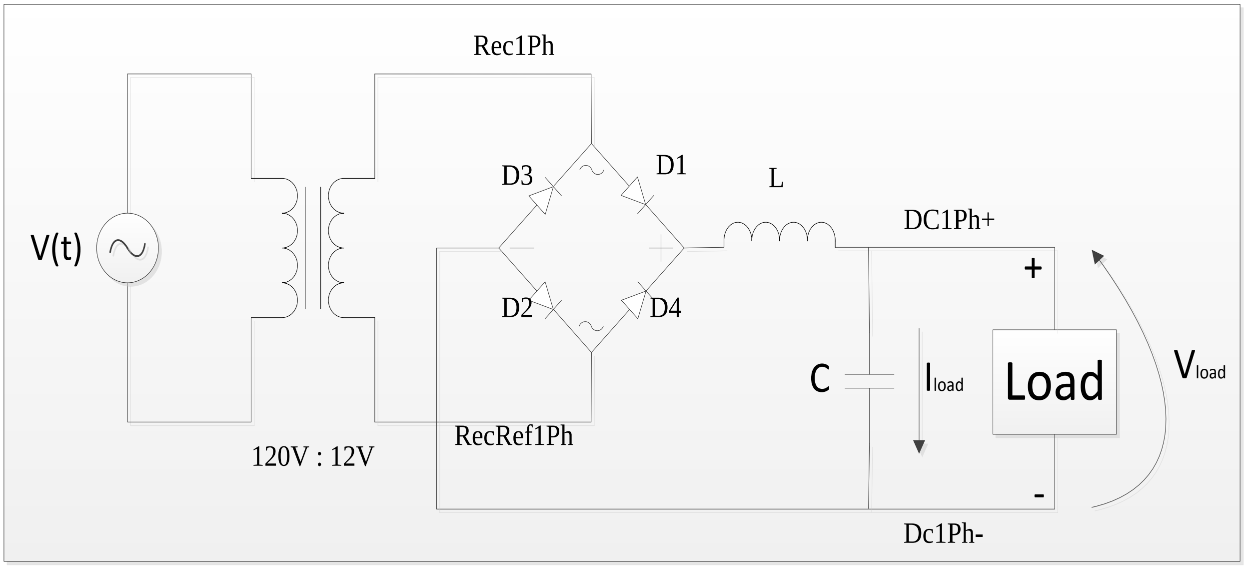


Figure 3.2: AC-DC diode rectifier test circuit

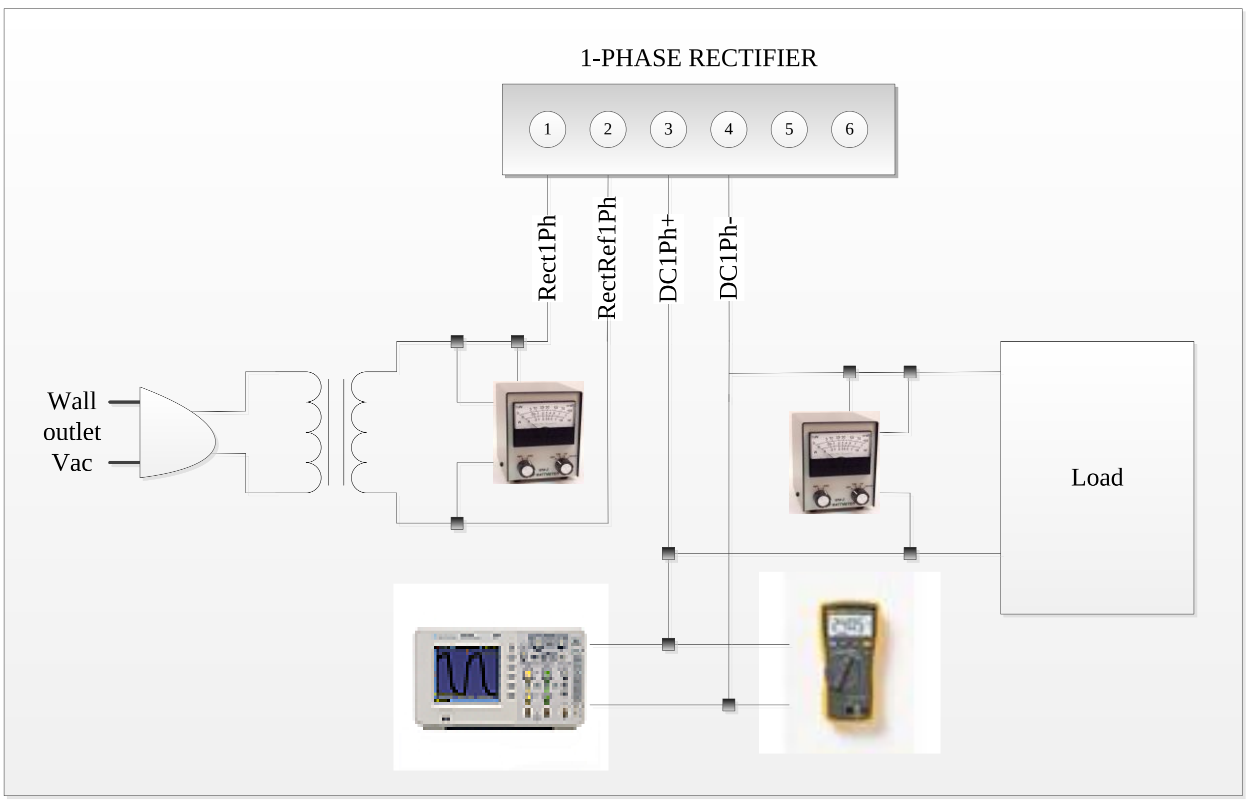


Figure 3.3: K-ECS Connections for AC-DC diode rectifier experiment

Note that the input power supply that provides power to all integrated chips of the K-ECS is placed as shown in the connector in Figure 3.4. This power input, up to this point, is optional because the bridge rectifier is independent of the rest of the circuit. However if students want to use the Arduino controller inside the K-ECS to measure the performance parameters they need to connect the **power supply c**onnector to the low voltage (24V/2A) DC power supply.

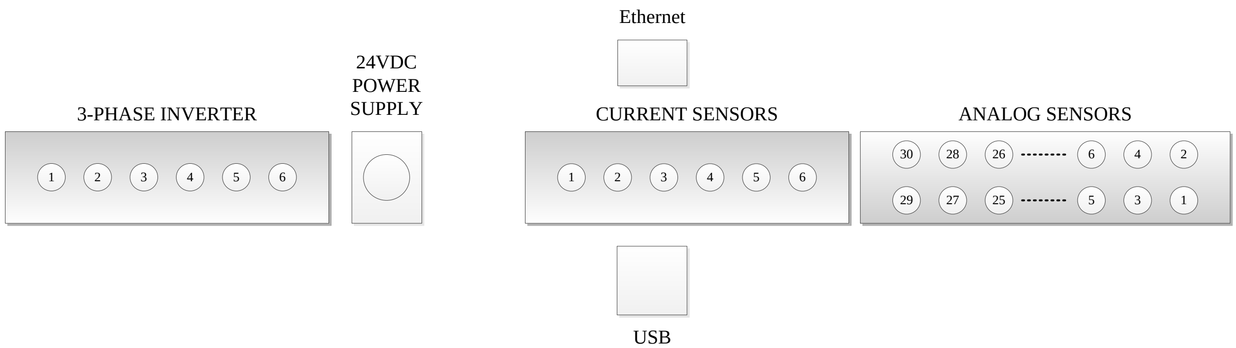


Figure 3.4: K-ECS right hand side connectors

3.5 Study Questions

1. Sketch the waveforms for the output voltage of a single phase half-bridge rectifier assuming R, R-L and R-C loads (See examples PWMHalfBridgeGraph and SinePwmHalfBridge).

2. Sketch the waveforms for the output voltage of a single phase full-bridge rectifier assuming R, R-L and R-C loads.

3. Explain how the diode forward voltage affects the waveforms in the full-bridge rectifier.

4. Create a table showing the average output voltage measured by the multimeter and the load resistor RL. Plot the table values in a graphics such that both axes are linear. What is the shape of the graphics? Compare the result with the behaviour expected from an ideal voltage source and explain why the AC-DC output voltage source does not behave as an ideal voltage source.

5. For the same load resistor values of step 4, create a table showing the ripple around the average output voltage measured by the multimeter and the load resistor RL. Plot the table values in a graphics such that both axes are linear. What is the shape of the graphics? For each resistor value, use the oscilloscope to visualize the output voltage waveform.

6. Also for the same load values, use a wattmeter to measure the electrical power at the input and the output of the AC-DC rectifier, and calculate its efficiency. Does the efficiency changes significantly for each load value. Why?

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.

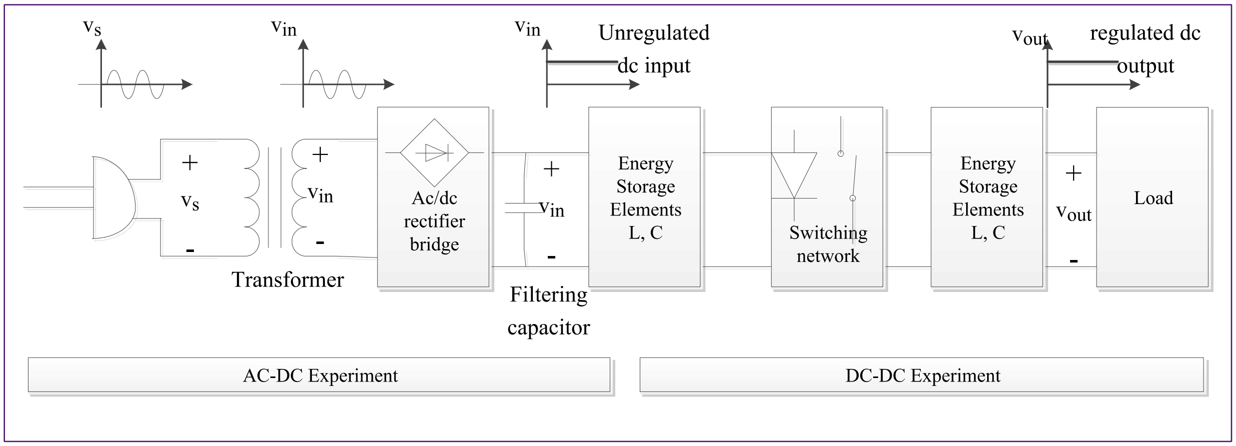


Figure 4.1 : Power Converter Flow

(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 μH) and a capacitor (200 μF) 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 Pin = Pout. 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 Vo/Vin and Io/Iin.

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 Vi to drive the input of the DC-DC converter (pin DCDC_In in the DCDC COVERTER 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 PWMDCC_H and ensure PWMDCC_L is driven to zero (http://arduino.cc/en/Tutorial/SecretsOfArduinoPWM). Forcing PWMDCC_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.

3. Afterwards, remove the DC power supply Vi 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)**.

4. Now, connect the negative terminal of the AC-DC rectifier (pin RectRef1Ph) to the junction point formed by **DCDC_Ref** and DGND.

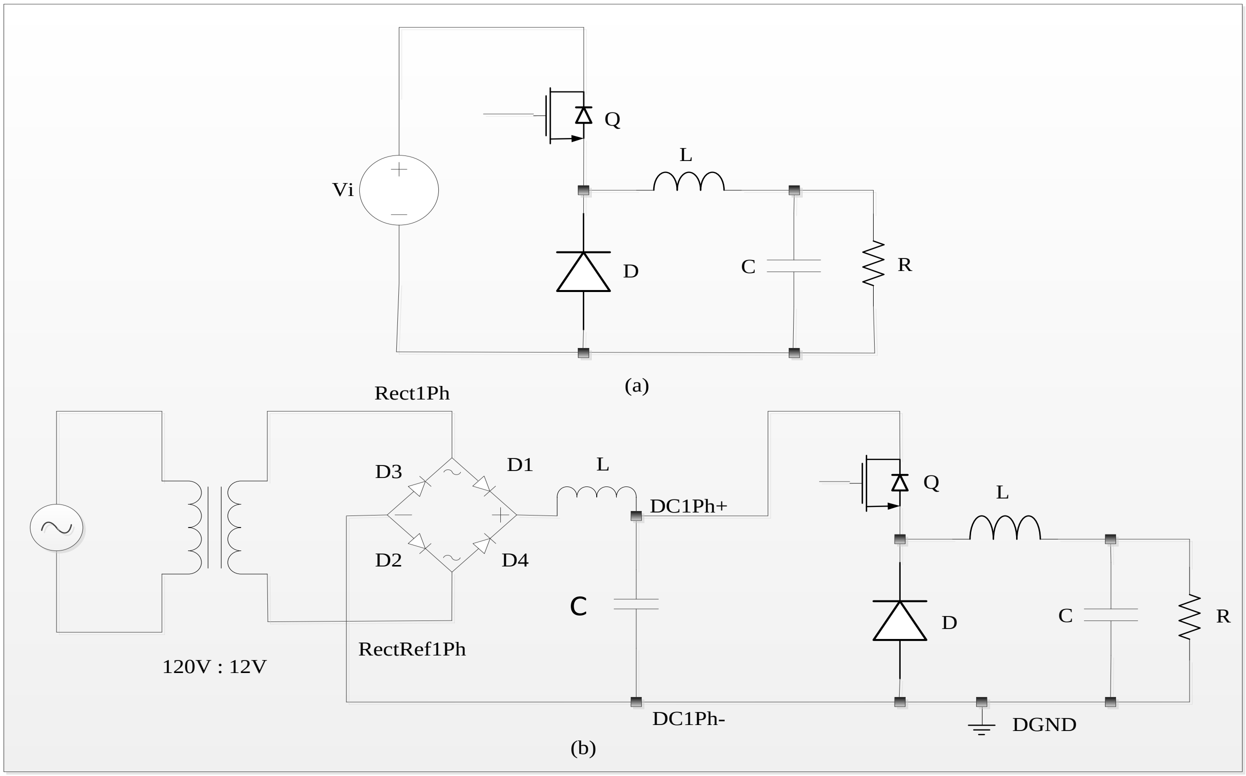
5. The buck output is available on the pin **DCDC_Out** on connector **DC-DC Converter**.

NOTES:

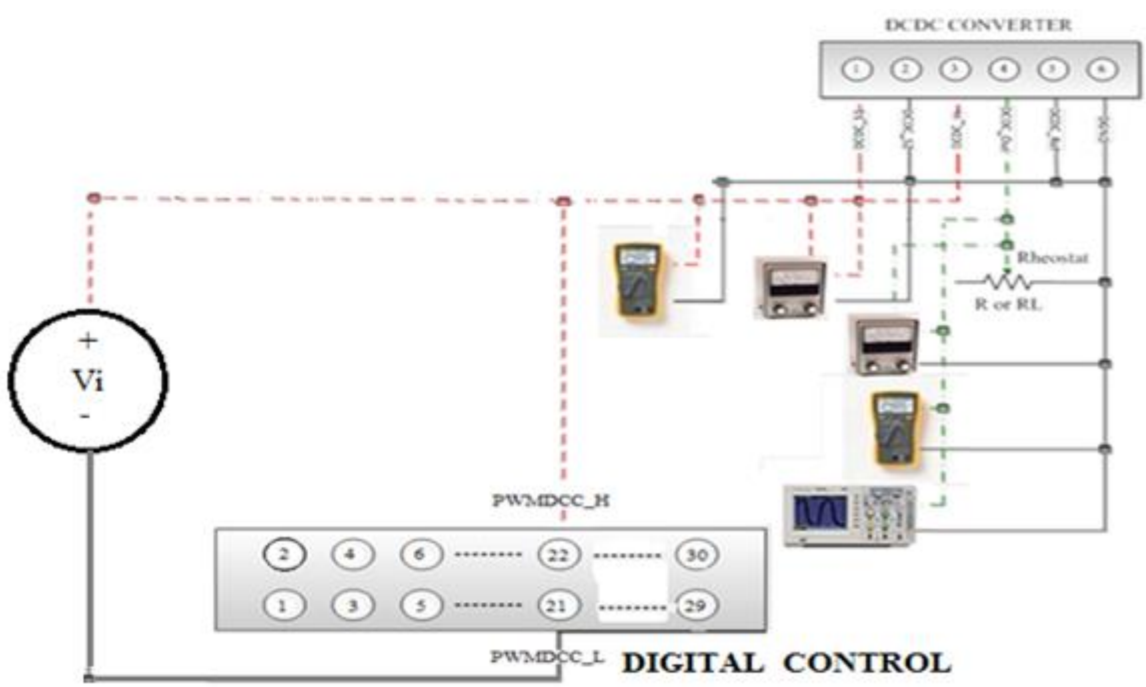
i) If the controller pins PWMDCC_H and PWMDCC_L inside K-ECS are configured by the Arduino to be at high impedance, the buck converter can be controlled by an external controller. The control pins of this configuration are available on PWMDCC_H and PWMDCC_L on connector DIGITAL CONTROL (pins 22 and 21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

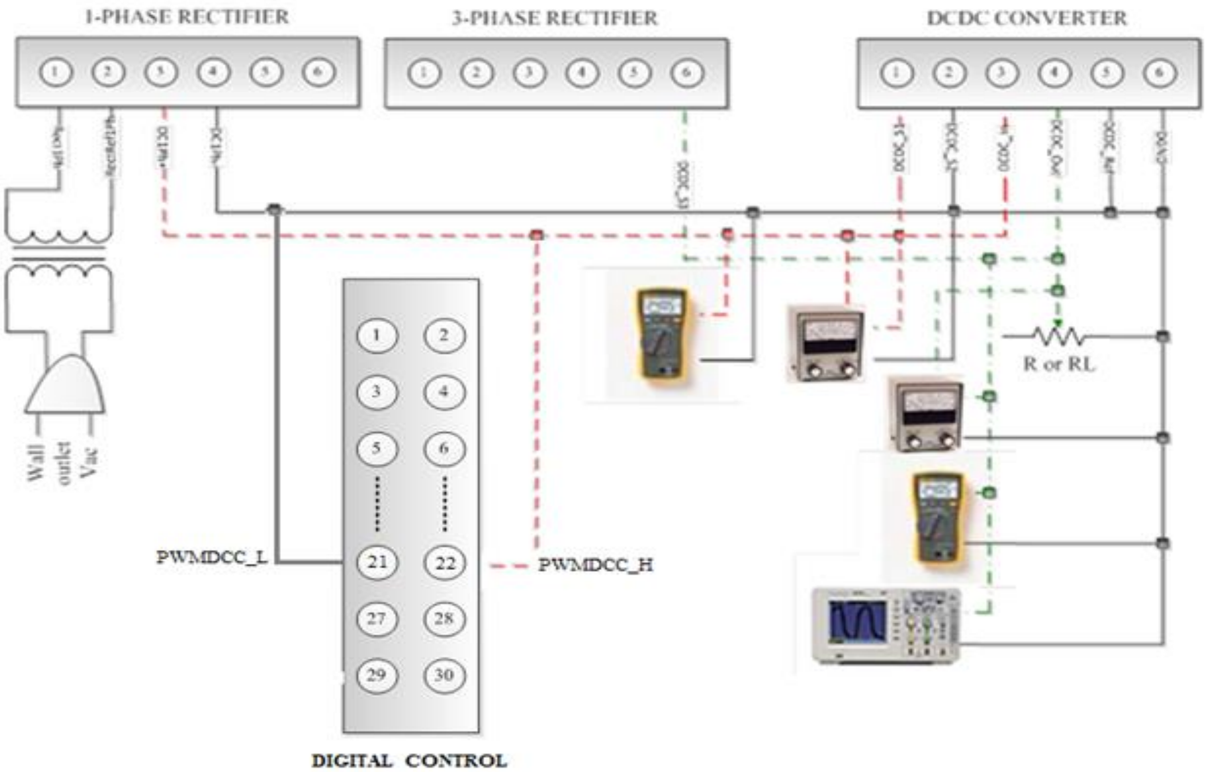


Figure 4.2d : Connection Diagram for DC-DC Experiment

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.

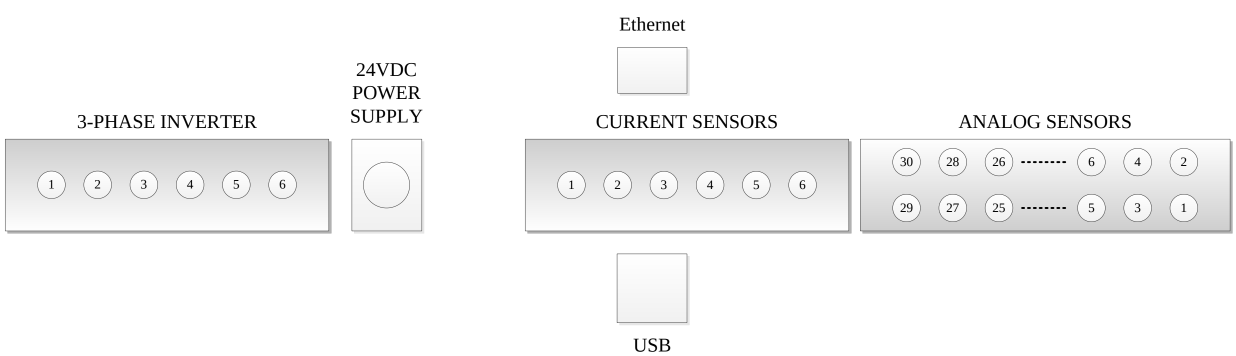


Figure 4.2e : KECS right hand sideconnectors

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. 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 Vload(avg) / VdcIn(avg) for your data (VDCIN = ((DC1Ph+)-(DC1Ph-)). Are the results consistent with the duty cycle settings?

3. For each load, estimate the average input power Pin and output power Pout at the input and the output of the DC-DC converter from the average readings of (VdcIn, IdcIn) and (Vload, Iload). Compare these results to the wattmeter readings. Calculate efficiency Pout/Pin, 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 μH, 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?

5 APPENDIX 1: PIN Descriptions

5.1 *Single-phase and three-phase rectifiers*

K-ECS External Connector	PIN	K-ECS Signal	Detailed Description
		1-PHASE RECTIFIER connector	
1-Phase Rectifier	1	Rect1Ph	Single-phase rectifier input AC phase voltage
1-Phase Rectifier	2	RectRef1Ph	Single-phase rectifier input AC reference voltage
1-Phase Rectifier	3	DC1Ph+	Single-phase rectifier positive output DC voltage
1-Phase Rectifier	4	DC1Ph-	Single-phase rectifier negative DC output voltage
1-Phase Rectifier	5	DC3Ph+	Three-phase rectifier positive output DC voltage
1-Phase Rectifier	6	DC3Ph-	Three-phase rectifier input output DC voltage
		3-PHASE RECTIFIER connector	
3-Phase Rectifier	1	Rect3Ph_A	Three-phase rectifier phase A input AC voltage
3-Phase Rectifier	2	Rect3Ph_B	Three-phase rectifier phase B input AC voltage
3-Phase Rectifier	3	Rect3Ph_C	Three-phase rectifier phase C input AC voltage
3-Phase Rectifier	4	RectRef3Ph	Three-phase rectifier input AC reference voltage
3-Phase Rectifier	5	DCDC_S4	DC-DC converter **5: DCDC_S4** signal (1)
3-Phase Rectifier	6	DCDC_S3	DC-DC converter **6: DCDC_S3** signal (1)

5.2 *DCDC Converter*

K-ECS External Connector	PIN	K-ECS Signal	Detailed Description
		3-PHASE RECTIFIER connector	
3-Phase Rectifier	5	DCDC_S4	DC-DC converter **5: DCDC_S4** signal (1)
3-Phase Rectifier	6	DCDC_S3	DC-DC converter **6: DCDC_S3** signal (1)
		DCDC CONVERTER connector	
DC-DC Converter	1	DCDC_S1	DC-DC converter **2: DCDC_S1** signal (1)
DC-DC Converter	2	DCDC_S2	DC-DC converter **2: DCDC_S2** signal (1)
DC-DC Converter	3	DCDC_In	DC-DC converter input voltage
DC-DC Converter	4	DCDC_Out	DC-DC converter negative output DC voltage
DC-DC Converter	5	DCDC_Ref	DC-DC converter reference voltage
DC-DC Converter	6	DGND	Power ground and Digital Ground

5.3 *Digital control interface*

K-ECS External Connector	PIN	K-ECS Signal	Detailed Description
Digital Control	1	DGND	Digital Ground
Digital Control	2	+5V	+5V Power Supply
Digital Control	3	SPI_SS	General Purpose Digital Signals + 3: SPI_SS (Slave Select) – used by Ethernet card
Digital Control	4	SPI_SCLK	General Purpose Digital Signals + **4: SPI_SCLK** (Serial Clock) – used by Ethernet card
Digital Control	5	SPI_SDI	General Purpose Digital Signals + **5: SPI_SDI** (Master Out Slave In) – used by Ethernet card
Digital Control	6	SPI_SDO	General Purpose Digital Signals + **6: SPI_SDO** (Master In Slave Out) – used by Ethernet card
Digital Control	7	Reserved	not connected
Digital Control	8	Reserved	not connected
Digital Control	9	Digital_11	General purpose I/O digital signal
Digital Control	10	Digital_10	General purpose I/O digital signal
Digital Control	11	Digital_9	General purpose I/O digital signal
Digital Control	12	Digital_8	General purpose I/O digital signal
Digital Control	13	Digital_7	General purpose I/O digital signal
Digital Control	14	Digital_6	General purpose I/O digital signal
Digital Control	15	Digital_5	General purpose I/O digital signal
Digital Control	16	Digital_4	General purpose I/O digital signal
Digital Control	17	Digital_3	General purpose I/O digital signal
Digital Control	18	Digital_2	General purpose I/O digital signal
Digital Control	19	Digital_1	General purpose I/O digital signal
Digital Control	20	Digital_0	General purpose I/O digital signal
Digital Control	21	PWMDCC_L	DC-DC converter PWM input low
Digital Control	22	PWMDCC_H	DC-DC converter PWM input high
Digital Control	23	PWMInv_CL	Three-phase inverter phase C PWM input low
Digital Control	24	PWMInv_CH	Three-phase inverter phase C PWM input high
Digital Control	25	PWMInv_BL	Three-phase inverter phase B PWM input low
Digital Control	26	PWMInv_BH	Three-phase inverter phase B PWM input high
Digital Control	27	PWMInv_AL	Three-phase inverter phase A PWM input low
Digital Control	28	PWMInv_AH	Three-phase inverter phase A PWM input high
Digital Control	29	DACPWM1	PWM input to a second order Sallen-Key low pass filter with output at **10: DACFlt_0** of analog connector
Digital Control	30	DACPWM_0	PWM input to a second order Sallen-Key low pass filter with output at **9: DACFlt_1** of analog connector

5.4 *Three-phase inverter*

K-ECS External Connector	PIN	K-ECS Signal	Detailed Description
3-PHASE INVERTER connector			
3-Phase Inverter	6	DGND	Digital Ground
3-Phase Inverter	5	Inv3Ph_DC-	DC power supply negative voltage terminal
3-Phase Inverter	4	Inv3Ph_DC+	DC power supply positive voltage terminal
3-Phase Inverter	3	Inv3Ph_C	Phase C AC signal
3-Phase Inverter	2	Inv3Ph_B	Phase B AC signal
3-Phase Inverter	1	Inv3Ph_A	Phase A AC signal

5.5 *Current sensors*

K-ECS External Connector	PIN	K-ECS Signal	Detailed Description
CURRENT SENSORS connector			
Current Sensors	6	Inp0+	General purpose current sensor #0 input current
Current Sensors	5	Inp0-	General purpose current sensor #0 output current
Current Sensors	4	Inp1+	General purpose current sensor #1 input current
Current Sensors	3	Inp1-	General purpose current sensor #1 output current
Current Sensors	2	Reserved	not connected
Current Sensors	1	VSupply	Main DC power supply from power connector

5.6 *Analog sensors*

K-ECS External Connector	PIN	K-ECS Signal	Detailed Description
Analog Sensors	30	AnalogIO_0	General Purpose analog input to Arduino (0 to 5V)
Analog Sensors	29	AnalogIO_1	General Purpose analog input to Arduino (0 to 5V)
Analog Sensors	**28**	**SensVIn_0**	**General purpose analog input to the voltage sensor (0 to 48V)**

Analog Sensors	**27**	**SensVIn_1**	**General purpose analog input to the voltage sensor (0 to 48V)**
Analog Sensors	26	Reserved	not connected
Analog Sensors	25	Reserved	not connected
Analog Sensors	24	Reserved	not connected
Analog Sensors	23	Reserved	not connected
Analog Sensors	22	SensVOut_C	Analog output from three-phase inverter phase C voltage sensor **(22: SensVOut_C = 3: Inv3Ph_C / 10)**
Analog Sensors	21	SensVOut_D	Analog output from three-phase inverter phase D voltage sensor **(21: SensVOut_D = 4: Inv3Ph_DC+/ 10)**
Analog Sensors	20	SensVOut_A	Analog output from three-phase inverter phase A voltage sensor **(20: SensVOut_A = 1: Inv3Ph_A / 10)**
Analog Sensors	19	SensVOut_B	Analog output from three-phase inverter phase B voltage sensor **(19: SensVOut_B= 2: Inv3Ph_B / 10)**
Analog Sensors	18	SensVOut_GP0	Analog output from the general purpose voltage sensor **(18: SensVOut_GP0 = 28: SensVIn_0 / 10)**
Analog Sensors	17	SensVOut_GP1	Analog output from the general purpose voltage sensor **(SenseV1 = 27: SensVIn_1 / 10)**
Analog Sensors	16	SensIOut_C	Analog output from three-phase inverter phase C current sensor (**16: SensIOut_C** = 1.65V + 0.175 * **IPhaseC**)
Analog Sensors	15	SensIOut_D	Analog output from three-phase inverter phase D current sensor (**15: SensIOut_D** = 1.65V + 0.175 * **Isupply**)
Analog Sensors	14	SensIOut_A	Analog output from three-phase inverter phase A current sensor (**14: SensIOut_A** = 1.65V + 0.175 * **IPhaseA**)
Analog Sensors	13	SensIOut_B	Analog output from three-phase inverter phase B current sensor (**13: SensIOut_B** = 1.65V + 0.175 * **IPhaseB**)
Analog Sensors	12	SensIOut_GP0	Analog output from the general purpose current sensor (**12: SensIOut_GP0** = 1.65V + 0.175 * 6: **Inp0+**)
Analog Sensors	11	SensIOut_GP1	Analog output from the general purpose **current s**ensor (**11: SensIOut_GP1** = 1.65V + 0.175 *4: **Inp1+**)
Analog Sensors	10	DACFlt_0	Analog output of the second order Sallen-Key filter **30: DACPWM_0**
Analog Sensors	9	DACFlt_1	Analog output of the second order Sallen-Key filter **29: DACPWM1**
Analog Sensors	8	Reserved	Spacing
Analog Sensors	7	Reserved	spacing
Analog Sensors	6	AGND	Analog ground
Analog Sensors	5	AGND	Analog ground
Analog Sensors	4	AVDD	Analog VDD (can be set up to +5V or +3.3V)
Analog Sensors	3	+5V	+5V DC Power Supply
Analog Sensors	2	DGND	Digital Ground
Analog Sensors	1	+3.3 V	+3.3V DC power supply

6 APPENDIX 2: Electric Safety Guidelines

• Read this guide before turning on K-ECS or connecting any component or device to its connectors (ex. Energy sources, loads, acquisition equipment, external controllers, etc.).

• Have your circuit checked by the TA before you switch it ON.

• It is highly recommended that you observe caution in working with equipment to avoid any risk to yourself and to your partner or cause damage to the lab or lab equipment.

• Keep the wires short and make an effort to color code your connections.

• Do not run wires over moving or rotating equipment, or on the floor, or string them across walkways from bench-to-bench.

• If you are working with a lab kit that has internal power supplies, turn the main power switch OFF before you begin work on the circuits. Wait a few seconds for power supply capacitors to discharge. These steps will also help prevent damage to circuits.

• If you are working with a circuit that will be connected to an external power supply, turn the power switch of the external supply OFF before you begin work on the circuit.

• Check circuit power supply voltages for proper value and for type (DC, AC, frequency) before energizing the circuit.

• When breaking an inductive circuit open the switch with your left hand and turn your face away to avoid danger from any arc which may occur across the switch terminals.

• All conducting surfaces intended to be at ground potential should be connected together.

• Keep the INTENSITY on oscilloscopes as LOW as possible when in use and all the way down when not in use to avoid burning out the screen.

• Always OBSERVE POLARITY when connecting components into a circuit, especially with electrolytic capacitors. When soldering a multi-pin component, avoid excessive heating to one area of the component; DO NOT go from pin to pin in a straight line.

• When measuring UNCERTAIN qualities, start with the range switch on the HIGHEST setting.

• No ungrounded electrical or electronic apparatus is to be used in the laboratory unless it is double insulated or battery operated.

• Voltages above 50 V rms ac and 50 V dc are always dangerous. Extra precautions should be considered as voltage levels are increased.

• Know the correct handling procedures for batteries, cells, capacitors, inductors and other high energy-storage devices.

• Always get instruction on how to use the tools and instruments. Use only the tool designed to do the job in hand.

• The ever-present hazard in an electronics Lab is the electric shock. In order to minimize the electric shock hazard, always power down the electrical equipment, disconnect the power cord, and wait for a few seconds before touching exposed wires. Do not assume that because your circuit is powered with 5 V, it is not dangerous.

• Never put conductive metal objects into energized equipment.

• Avoid contact with energized electrical circuits.

• Only use DRY hands and tools and stand on a DRY surface when using electrical equipment, plugging in an electric cord, etc.

• No open drinks and/or food should be allowed near the Lab benches. Spilled drinks can cause short circuits and damage equipment.

• Use care when operating K-ECS and always wear eye protection if the experiment includes moving objects such as motors and gears.

• Improper wiring, configuration or software programming can damage the K-ECS embedded controller, motherboard or communication interfaces. We recommend using a current-limited power supply during development. If current (Ampere) or power (Watt) rating at any K-ECS interface exceeds the interface specification, remove power immediately.

7 APPENDIX 3: Additional readings

Batarseh, Issa, *Power Electronic Circuits*, 2004.

Kazimierczuck, Marian K., *Pulse-Width Modulated DC-DC Power Converters*, 2008.

Rashid, Muhammad H., *Power Electronics: Circuits, Devices and Applications*, 3^{rd} ed., 2004.

Rashid, Muhammad H., Editor-in-Chief. *Power Electronics Handbook*, 2^{nd} ed., 2007.

Shaffer, Randall, *Fundamentals of Power Electronics with Matlab*, 2007.

Shepperd, William and Li Zhang, *Power Converter Circuits*, 2004.

Luiz Lopes, Fundamentals Of Electrical Power Engineering, Laboratory manual, Concordia University, 2011.

8 APPENDIX 4: Contact Kylowave

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