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Developing a Low-voltage Microgrid for Experiments in Renewable Energy Distribution

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Developing a Low-voltage Microgrid for Experiments in Renewable Energy Distribution

Background

Among the top engineering challenges today are those related to integrating renewable energy into the power grid efficiently and reliably; indeed, the economic development and deployment of solar energy are one of the NAE Grand Challenges [1]. Solar energy alone is undergoing a major worldwide deployment surge adding generating capacity at a remarkable rate, also increasing employment opportunities [2]. While many universities offer classes in power electronics and its role in renewable energy development, the enormous breadth of a modern electrical curriculum leaves little room to expose students to the issues of grid integration [3]. A typical first course in power electronics may well focus on the underlying power switching technologies, but the relevance to the associated technologies may be limited [4],[5]. Compounding this problem, the enabling technologies for renewable integration, embedded computing, and controls, are seldom taught within a context in which their applicability to energy production and distribution is brought to light. Furthermore, many university level electrical energy conversion courses are taught in a traditional lecture-lab dichotomy approach and may cover topics limited to transformers and rotary machines. While comprehension of these foundational topics is still essential, it is increasingly important to expose students to the broader range of concepts relevant to the power grid of the future.

This paper is a work-in-progress, describing our development of an open source, low voltage, and low-cost microgrid hardware platform that may be used for experiments in solar and wind generation and distribution. Our approach connects topics in power electronics, energy conversion, and controls in the form of an expandable and scalable low-voltage microgrid. The goal is to expose students to generation, grid, and distribution related topics early in a power curriculum, enhancing understanding of both renewable energy grid integration as well as conventional generation. We give students insight into the various components of a grid as well as the diverse engineering skills needed to ensure significant penetration of renewable energy into the overall power structure, emulating energy storage units as well as conventional generating plants to create a full power system. We will describe how this may be employed in coursework at several different levels in a typical undergraduate curriculum, ranging from an introductory/survey course to upper-level advanced topic courses.

Hardware Development Motivation

There are a number of hardware platforms available for power electronics teaching laboratories. A typical unit is both physically very large and expensive limiting its usefulness for a typical space-constrained university undergraduate laboratory [6]. Other devices available may be of a smaller form factor but require interconnection of many different components to create a single station for a laboratory, and each station may cost well over $10,000 [4]. This price level may well place these units out of consideration for smaller institutions, or those seeking to start power and grid-based curriculum from scratch.

One of our goals is a simple, compact setup that might be employed on a multi-use lab station in a typical undergraduate electronics laboratory or even in a studio environment such as shown in Figure 1 [7]. Our studio space facilitates combined lecture and laboratory learning environments in one area, and the students have access to a complete suite of laboratory test equipment for the desktop via the National Instruments *VirtualBench* [8]. Compared to the commercially available devices described above, our microgrid experimental setup allows a number of different inverters to all be connected on a single bench, with each inverter capable of being programmed to perform different roles. A typical connection is shown in Figure 2 below.

Figure 1 Studio learning Environment

Figure 2 Complete Microgrid Laboratory Setup

Implementation of a microgrid in our scenario involves interconnecting a plurality of low-voltage 3-phase inverters implemented with programmable controllers and operating at safe voltage levels. This approach allows us to employ a relatively simple board for the actual electronics while the control algorithms are exposed in the controller. Also, it eliminates the complex interconnection of the several boards required to implement a single inverter as described in [4]. Using a customizable controller enables us to easily set or modify limits on the performance of the inverter, controlling not only output power limits on the fly but also D.C. input voltage limits to ensure no harm can be done to the students or inverter board.

The schematic for the core of the inverter module is shown in Figure 3 below. It is based on widely used commercially available components commonly used for motor drives. Sensing for both phase voltage and currents is included as well as the necessary componentry to act in concert with a D.C. link. To improve simplicity in connections, all LC filters and a brake resistor are included on the board rather than as separate connections.

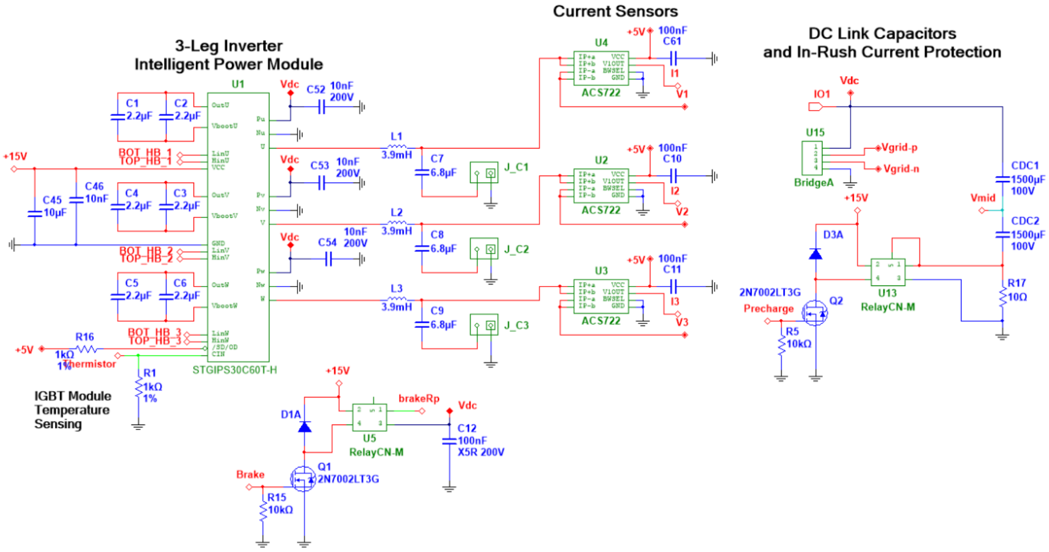


Figure 3 Inverter Schematic Design

The board design for the inverter is shown in Figure 4.

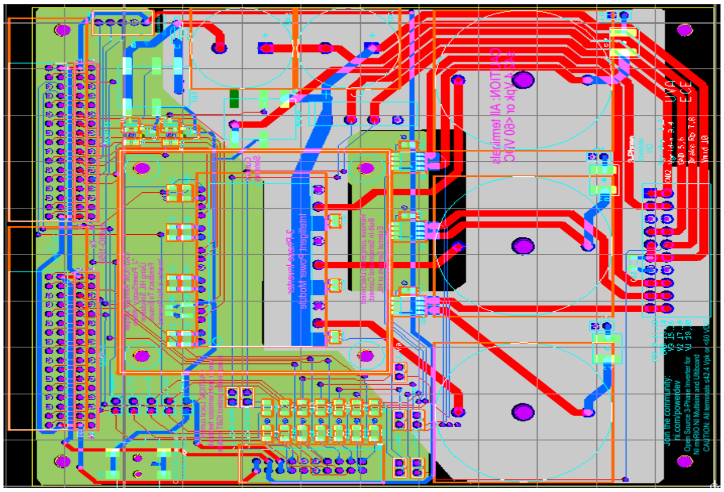


Figure 4 Inverter Board Design

The board is simple to build and requires no special tools or equipment to assemble. In keeping with our low-cost goals, the entire board may be assembled for less than $200 in parts, including the printed circuit. The entire design is open source and available through the authors.

These inverters can be programmed such that they may behave as a conventional energy source, i.e., a stable coal-fired power plant, as an intermittent renewable source, energy storage devices, or as several types of loads. Additionally, the inverters may be connected with interposing lumped-element model transmission lines and transformers simulating substations and local distribution networks, allowing expanding the range of experiments to include power grids of arbitrary complexity. Using a programmable controller allows for easy modifications to the depth of understanding of the underlying concepts involved. For example, we may hide the more advanced controls aspects of the underlying algorithms in an introductory course, or expose successive levels of complexity, allowing instructors to adapt the configurations as appropriate for their course sequences easily. Although any number of different programmable controllers might be employed, our current controller is a *myRIO* from National Instruments [9]. It is a very flexible unit and includes an on-board FPGA enabling sophisticated control algorithms in real-time. This gives us the ability to have students modify the various control elements to explore the resulting response from the inverter; customizing elements such as the ABC to DQ transform, the PID controller, as well as the PLL code all using LabVIEW to make informed decisions based on live data.

Course and Laboratory Exercises

We are currently offering a pilot version of a microgrids course at the University of Virginia. This course includes both a lecture and laboratory element and is available for students that are in their third or fourth year. There are no prerequisites other than the first two of our basic sequence: *Fundamentals 1 and 2* [7]. This course is intended as an introduction to microgrid concepts and basic power electronics and not to provide exhaustive coverage of the internal operations of the firmware controlling the inverter switch elements, i.e., a broad, high-level introduction. It is being offered as a 1.5 credit hour technical elective.

The source of inspiration for this course comes from the desire to have students interact with a fast-developing field of engineering on a physical level and gain insight into the requirements and tradeoffs necessary to implement a microgrid. It also is intended to offer insights into the strengths and weaknesses of renewable energy sources and provide background on how microgrids might be interfaced to the main power grid.

Our learning objectives may be summarized as:

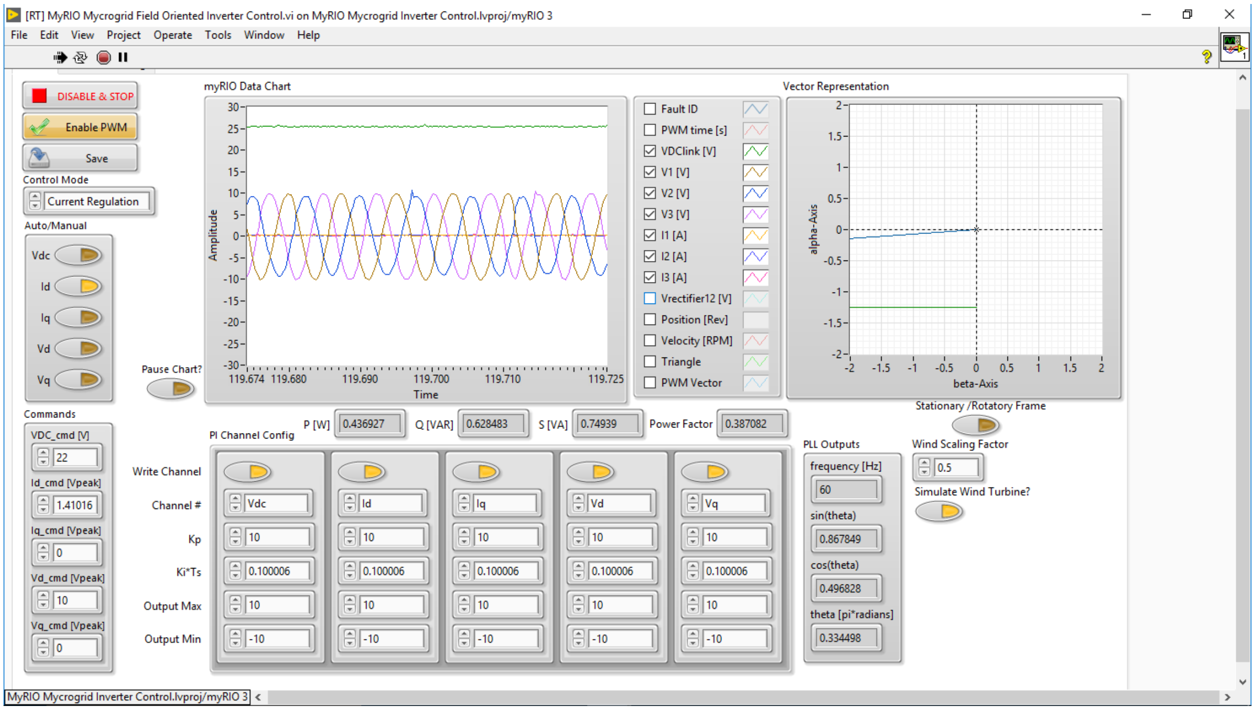
- Students will be able to explain and demonstrate how two or more sources can work together to generate a synchronized grid.
- Given a traditional grid, students will be able to explain the differences between the infinite bus and small grid models.
- Students will be able to visualize how power may flow from one source to another

- Students will be able to understand the role of the D.C. link.

In a typical laboratory session, each student team is given a pre-assembled bi-directional 3-phase inverter connected to our controller. This board is the basis for the course and is used to create a microgrid and demonstrate the advanced power electronics and controls concepts in real-life conditions.

Creating the microgrid is as simple as connecting the three phases on two or more inverter modules and running the software. This enables the students to develop an understanding of the end-goal rather quickly, applying a real scenario and real experiment to all of the math and theory to come in follow-on courses also currently in development.

Our approach offers considerable flexibility in configuring experiments. For example, in Figure 5, students can visualize the operation of a microgrid consisting of 2 synchronized inverters. Exploiting the capabilities of the controller, we can employ one to simulate a wind turbine by playing back actual waveforms recorded at a functioning wind farm. Students can see the waveforms both as a time domain waveform as well as a D-Q representation.



Control Mode: Current Regulation

☐ Fault ID
☐ PWM time [s]
☑ VDClink [V]
☑ V1 [V]
☑ V2 [V]
☑ V3 [V]
☑ I1 [A]
☑ I2 [A]
☑ I3 [A]
☐ Vrectifier12 [V]
☐ Position [Rev]
☐ Velocity [RPM]
☐ Triangle
☐ PWM Vector

Commands
VDC_cmd [V]: 22
Id_cmd [Vpeak]: 1.41016
Iq_cmd [Vpeak]: 0
Vd_cmd [Vpeak]: 10
Vq_cmd [Vpeak]: 0

P [W]: 0.436927
Q [VAR]: 0.628483
S [VA]: 0.74939
Power Factor: 0.387082

PI Channel Config

Channel #	Vdc	Id	Iq	Vd	Vq
Kp	10	10	10	10	10
Ki*Ts	0.100006	0.100006	0.100006	0.100006	0.100006
Output Max	10	10	10	10	10
Output Min	-10	-10	-10	-10	-10

PLL Outputs
frequency [Hz]: 60
sin(theta): 0.867849
cos(theta): 0.496828
theta [pi*radians]: 0.334498

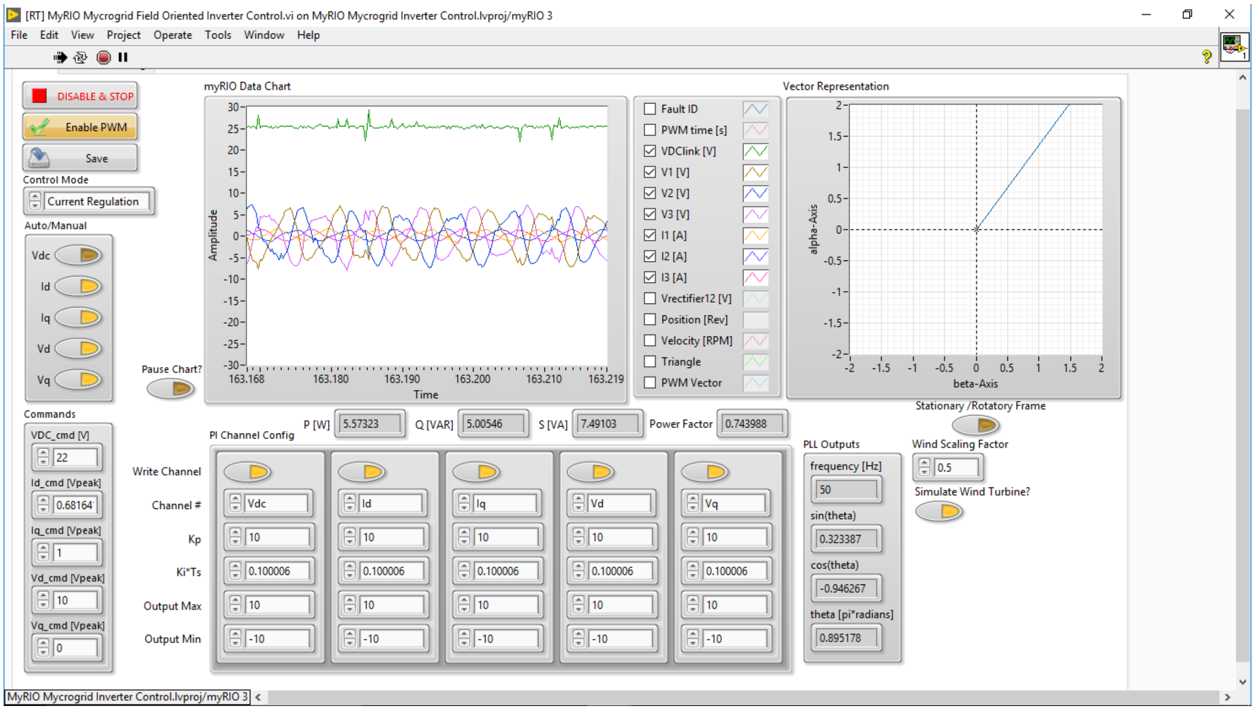
Wind Scaling Factor: 0.5

Figure 5 Two synchronized inverters with one playing back wind turbine waveform

As seen above, students have control over enabling or disabling the PI control of both real and reactive current and voltage, controlling the setpoint for these outputs, as well as the P and I constants from the controller for each output variable.

At this level of study, students may directly engage with the effects of how variable output from a wind turbine may affect the stability of the grid and understand the basic implications of power flow. In a more advanced course, this same experimental hardware may be employed, but the focus would turn to the FPGA algorithms operating the inverter. Indeed, achieving progressive levels of understanding has been shown to be an effective learning strategy for deep learning of complex topics [10].

In another scenario, we may expose students that are at an introductory level to the effects of unbalanced loads on a 3-phase system. In Figure 6 students may see the effects of unbalanced loads and reactive power.



☐ Fault ID
☐ PWM time [s]
☑ VDClink [V]
☑ V1 [V]
☑ V2 [V]
☑ V3 [V]
☑ I1 [A]
☑ I2 [A]
☑ I3 [A]
☐ Vrectifier12 [V]
☐ Position [Rev]
☐ Velocity [RPM]
☐ Triangle
☐ PWM Vector

Control Mode: Current Regulation

Commands
VDC_cmd [V]: 22
Id_cmd [Vpeak]: 0.68164
Iq_cmd [Vpeak]: 1
Vd_cmd [Vpeak]: 10
Vq_cmd [Vpeak]: 0

P [W]: 5.57323
Q [VAR]: 5.00546
S [VA]: 7.49103
Power Factor: 0.743988

PI Channel Config

Channel #	Vdc	Id	Iq	Vd	Vq
Kp	10	10	10	10	10
Ki*Ts	0.100006	0.100006	0.100006	0.100006	0.100006
Output Max	10	10	10	10	10
Output Min	-10	-10	-10	-10	-10

PLL Outputs
frequency [Hz]: 50
sin(theta): 0.323387
cos(theta): -0.946267
theta [pi*radians]: 0.895178

Wind Scaling Factor: 0.5

Figure 6 Unbalanced output waveform as reactive current is increased to 1A

At a more advanced course, the students may study techniques for controlling this situation and explore advanced control algorithms and methods of programmatically choosing controller constants based on load conditions. The actual implementation of the algorithms will be of interest to both electrical and computer engineers.

Assessment of Learning Outcomes

As a means of interim evaluation of student learning for our introductory course, we are currently offering a series of quizzes based on class discussions and in-laboratory experiments. Some example quiz questions are shown below. These questions are intended to act as assessments of basic understanding of fundamental principles and not rely heavily on numerical calculations. Also, some of the questions refer to concepts that were presented theoretically in a lecture-only context and some refer to concepts that were explained in the lecture, but also included in the laboratory experiments with the inverter hardware.

Sample Question 1:

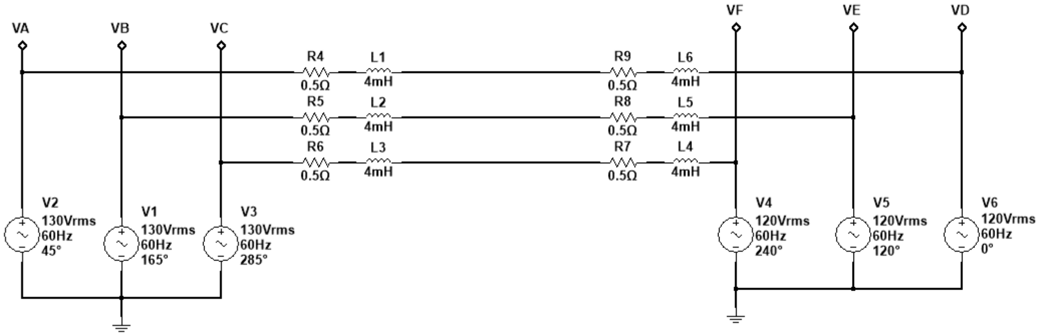


Figure 7

Consider the image of Figure 7 above. Which of the following is true?

A. *Since the magnitude of the line voltages from the left set of sources is greater than those on the right,* ***real*** *power will flow from left to right, regardless of the relative phases.*
B. *Given that the magnitude of the line voltages from the left set of sources is greater than those on the right,* ***real*** *power will flow from left to right, only if the phase on the left is greater than the phase on the right.*
C. *Since both sides of the above system are voltage sources, no real power can flow from 1 set of sources to the other.*
D. *None of the other choices is correct.*

In our current pilot version of the class, 66% of the class achieved the correct answer. The most commonly seen incorrect answer was for response “A”.

Sample Question 2:

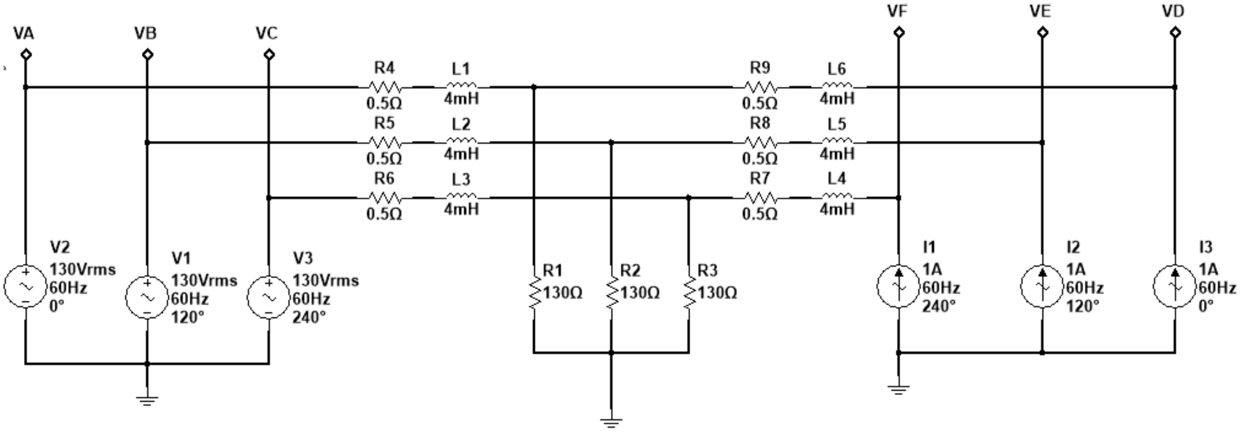


Figure 8

Consider the circuit of Figure 8 above. Which of the following are true?

A. *If each current source is configured to produce 1 amp RMS and at the phases shown, the net current through R4, R5, and R6 will be 0.*
B. *Current sources may not be connected to voltage sources.*
C. *The voltage on the line will be determined solely by the current sources.*
D. *None of the other choices is correct.*

On this question 100% of the class got the correct answer. Interestingly, while the information for the first quiz question was derived from content that was only presented in lecture, and through simulation, this question was derived directly from an in-class experiment with our inverter hardware, lending support to the efficacy of hands-on experimentation as a means of cementing understanding.

Sample Question 3:

Given the circuit of the previous problem, Figure 8, which of the following is true?

A. *If each current source produces more than 1 amp and at the phases shown, the surplus current will flow into the voltage sources.*
B. *Current sources may not be connected to voltage sources.*
C. *Real power may not flow into a voltage source.*
D. *None of the other choices is correct.*

On this question 70% of the class got the correct answer. Again, this concept, while illustrated in the laboratory experiment, was not emphasized – no energy storage devices were attached to the voltage source. This also attests to the value of increasing the hands-on component of learning in a class structure such as this one.

Sample Question 4:

Consider the circuit of the previous 2 problems, Figure 8. Assume that the frequency and phase of the current sources are set by a PLL. Which of the following is true?

A. *A PLL cannot set frequency.*
B. *The PLL locks the phase and frequency of the current source relative to the voltages present on the line.*
C. *The PLL will only function correctly if the voltage sources are turned off.*
D. *None of the other choices is correct.*

Students achieve a 100% correct response on this question. Again, this concept was illustrated in simulation, and also emphasized through in-laboratory experimentation.

The sample question below is intended to assess how well students understand the fundamental concepts of how the inverter works. This concept was illustrated using a mixture of lecture material and in-class simulations; no direct measurements were made at the switching nodes.

Sample Question 5:

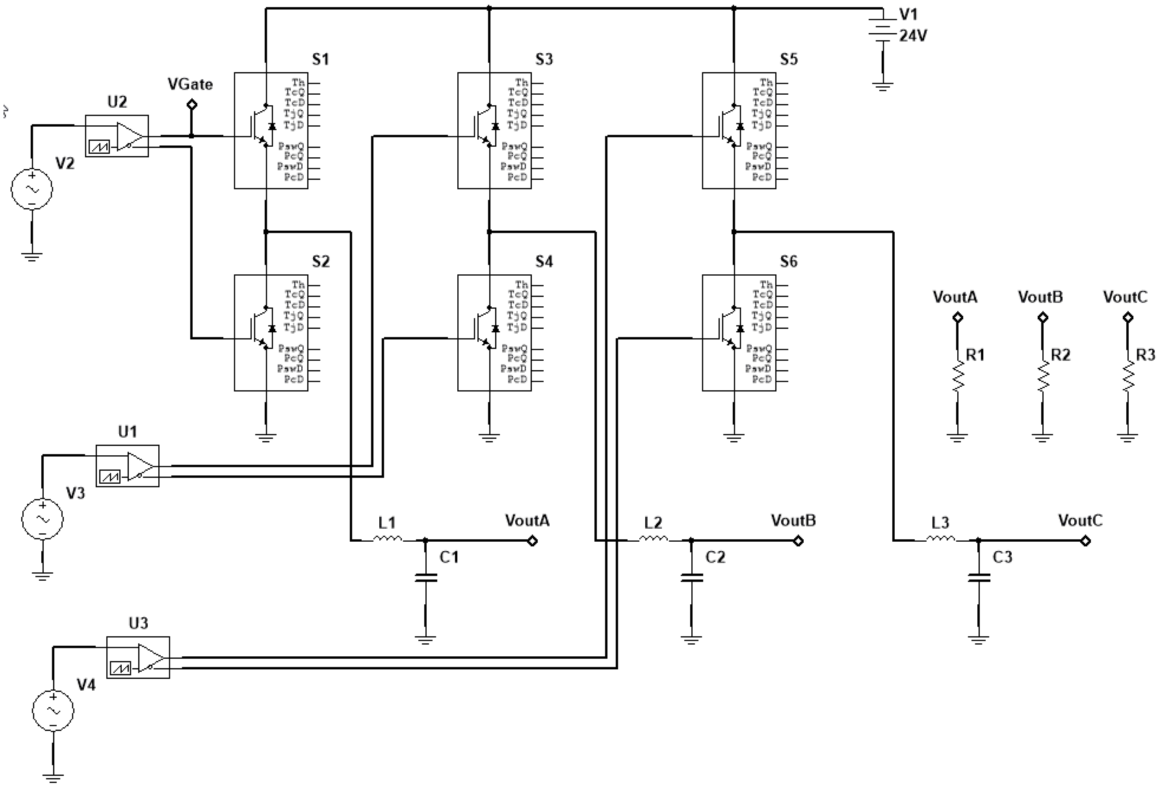


Figure 9

Consider the circuit above, Figure 9. Which of the following are true?

A. The Inductors serve no purpose under most conditions and may be eliminated to simplify the circuit.
B. Since the 6 transistors are operating purely as linear elements, in constant conduction, the circuit can achieve high efficiency.
C. Since the 6 transistors are operating as switched devices, the inductors and capacitors serve as filtering elements.
D. None of the other choices is correct.

On this question, 85% of students achieve the correct answer. At this point, we feel that further measurements made directly on the inverter board would be helpful.

At the conclusion of the current experimental course, we will further evaluate student learning as compared to our learning objectives listed above via several additional activities:

- Further concept quizzes of the style and format illustrated above.
- A design project, currently in process, in which students design a simple power flow measurement device, i.e., measure real and reactive power as well as the direction of power flow. Students will be graded on the thoroughness and effectiveness of their designs as well as a written report.

- A final presentation on a micro-grid related topic of the student's choice. Students are expected to produce a tutorial – not survey- on their chosen topics. Among the current topics being presented on are:
    - *The Feasibility of Electric Vehicle Charging in Microgrids*
    - *Microgrid Stability*

We expect to use these modes of evaluation as well as student responses to modify successive offerings of this course and to serve as input for the development of follow-on courses offered at a more advanced level.

Summary and Conclusions

The value of hands-on coursework has long been established, and power education is no exception [11],[12]. As the use of renewable energy resources becomes, more pervasive electrical engineering programs must adapt their energy-related offerings and move in a direction that includes a greater experiential component and integrate grid-related topics [13]. Our work-in-progress assessments indicate that the use of hardware experiments is an aid in solidifying understanding of topics in this area.

Our versatile inverter design is a simple and inexpensive alternative for teaching renewable energy topics and microgrid integration. It may be employed in various classroom and laboratory environments and serves well for both introductory as well as advanced topics in power, controls and grid integration. We see it as an important step in improving the educational experience for students interested in these topics and provides an opportunity to present it to students in an immersive and integrated curriculum.

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