EE362L, Power Electronics, Powering the Grid with Renewable Energy
Version Feb. 21, 2009

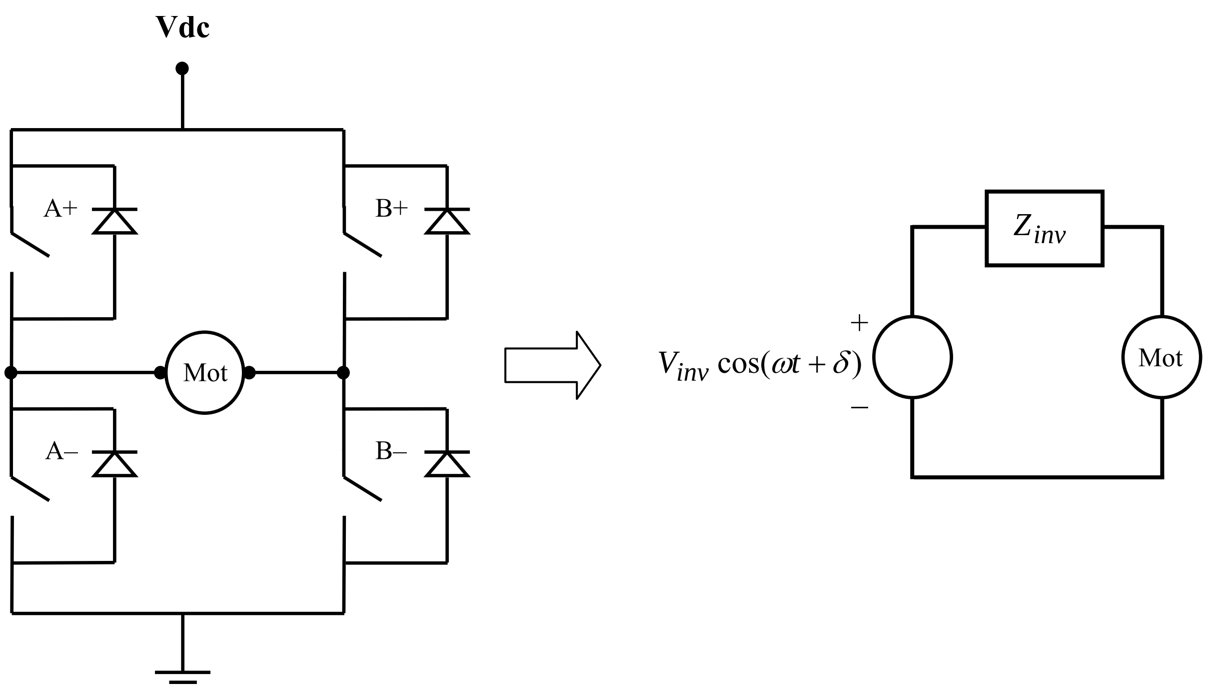
Introduction

You have successfully built a DC-AC inverter. You will now use your inverter to convert DC to AC and send power back into the AC grid. Your grid access point is a 120V wall outlet. **Make sure that your inverter is working properly before beginning this experiment.**

If you wish to use a solar panel pair (or two paralleled solar panel pairs) as your DC source, do so only when the net short circuit current is 3.5A or higher so that your results will be meaningful. Else, use a DBR as the DC source. And, when using solar, you must use the Solar Interface Circuit (described later in Figure 1) to eliminate 120Hz ripple current in the solar panels.

Steady-State AC Equivalent Circuit of the H-bridge Inverter

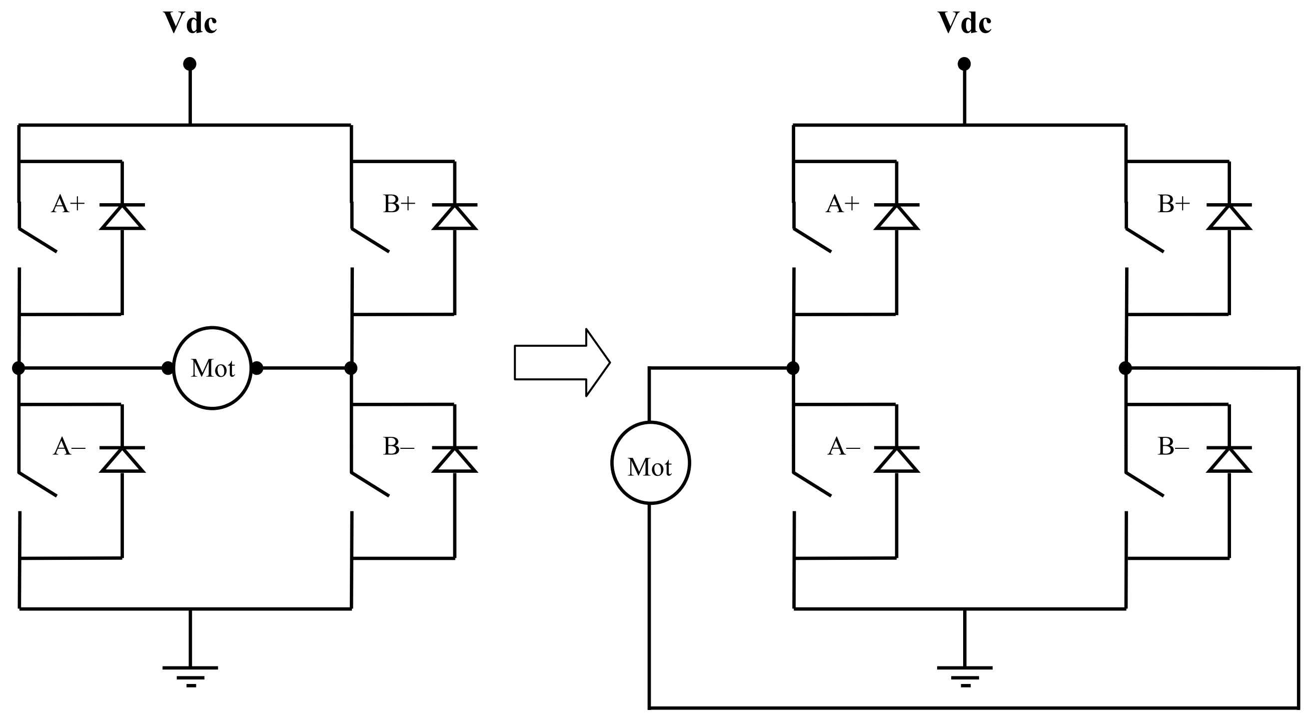
Consider the H-bridge inverter circuit illustrated below. We have observed in the H-bridge experiment that when 1. V_{cont} is steady-state AC, and 2. MOSFET firing is controlled using unipolar PWM, and 3. the inverter output is properly filtered, then the equivalent circuit "seen" by the load (e.g., motor) is



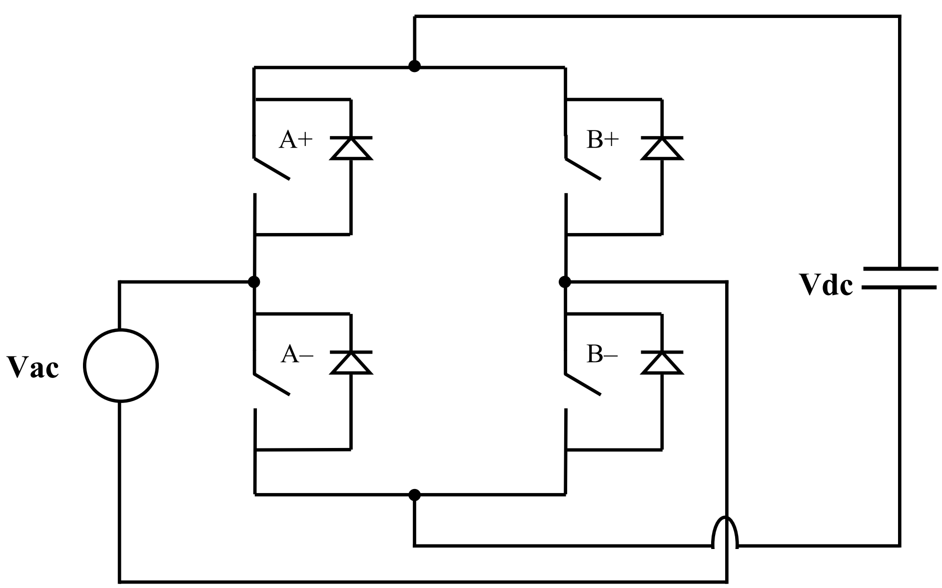
In the above figure, $V_{inv} = \frac{V_{dc}}{\sqrt{2}} \bullet m_a$ rms volts, and Z_{inv} is the impedance of the inverter at the AC operating frequency. Unless a very large inductor is intentionally added to the inverter output, Z_{inv} is mostly resistive in low voltage (i.e., less than 1kV) circuits.

Re-examination of the H-Bridge Circuit

The H-bridge is not limited to inverter operation. For example, without changing circuit topology, move the motor to the left, outside the bridge, as shown on the next page.



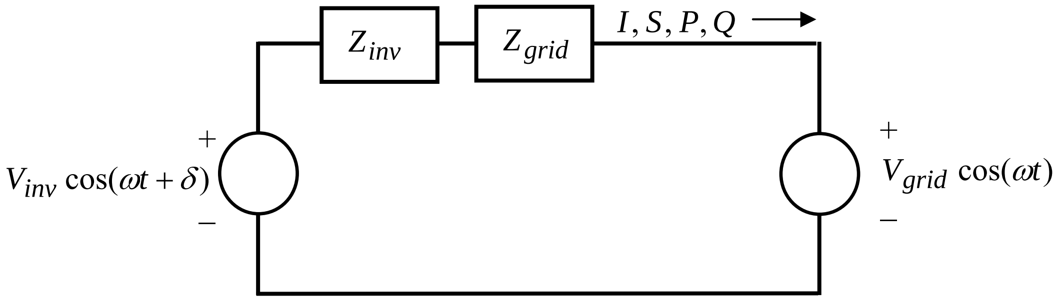
Now, move the DC terminals to the right, and replace Vdc with a capacitor. Then, replace the motor with an AC source.



You can see that if the MOSFETs are never switched "on," the above circuit behaves like a DBR circuit because of the parasitic antiparallel diodes! Thus, it is clear that the H-bridge circuit can also be a rectifier (like the DBR), where power moves from the AC side to the DC side. Thus, by controlling the firing of the MOSFETs, the H-bridge can be either a rectifier or an inverter.

Control of Power Flow into the Grid

Consider the AC equivalent, but replace the motor with the grid (i.e., a wall outlet, either "straight in" or scaled down using a variac). The grid has some impedance, but it is much smaller than the inverter impedance.



The phasor current that flows is

$$I = \frac{V_{inv}\angle\delta - V_{grid}\angle 0}{Z_{inv} + Z_{grid}} ,$$

and the complex power, active power, and reactive power flowing into the grid are

$$S = V_{grid} I^*, \; P = real(S), \; Q = imaginary(S).$$

Define

$$Z_{tot} = Z_{inv} + Z_{grid} \text{ , where } Z_{tot} = R_{tot} + jX_{tot} .$$

Then

$$S = V_{grid}\angle 0 \bullet \left(\frac{V_{inv}\angle\delta - V_{grid}\angle 0}{Z_{tot}} \right)^* = \frac{\left(V_{grid}V_{inv}\angle -\delta\right) - \left(V_{grid}^2\right)}{R_{tot} - jX_{tot}} .$$

Expanding yields

$$S = \frac{V_{grid}V_{inv}\left(\cos(-\delta) + j\sin(-\delta)\right) - V_{grid}^2}{R_{tot} - jX_{tot}} = \frac{V_{grid}V_{inv}\left(\cos\delta - j\sin\delta\right) - V_{grid}^2}{R_{tot} - jX_{tot}} . \quad (1)$$

The Resistive Impedance Case
(typical for circuits below 1kV)

Now, consider the usual low-voltage situation where $R_{tot} >> X_{tot}$. Then

$$S = \frac{V_{grid} V_{inv} (\cos\delta - j\sin\delta) - V_{grid}^2}{R_{tot}} = \frac{V_{grid} V_{inv} \cos\delta - V_{grid}^2 - jV_{grid} V_{inv} \sin\delta}{R_{tot}}$$

$$= \frac{V_{grid}}{R_{tot}} \left(V_{inv} \cos\delta - V_{grid}\right) - j\frac{V_{grid} V_{inv}}{R_{tot}} \sin\delta \ .$$

Thus, when X_{tot} is neglected,

Resistive impedance case: $P = \frac{V_{grid}}{R_{tot}} \left(V_{inv} \cos\delta - V_{grid}\right)$, (2)

Resistive impedance case: $Q = -j\frac{V_{grid} V_{inv}}{R_{tot}} \sin\delta$. (3)

Thus, when X_{tot} is neglected, then P is proportional to $\left(V_{inv} \cos\delta - V_{grid}\right)$. Clearly V_{inv} must be greater than V_{grid} for inverter action to occur. In our lab experiment, angle δ is zero because the inverter control signal is a replica of V_{grid} . Thus, in our experiment, $\left(V_{inv} - V_{grid}\right)$ controls P , and Q is zero.

The Inductive Impedance Case
(typical for circuits higher than several kV)

Now, consider the alternate case, i.e., $X_{tot} >> R_{tot}$, as might occur if a large series inductor is inserted in the power path. Re-evaluating (1) yields

$$S = \frac{V_{grid} V_{inv}}{X_{tot}} \sin\delta + j\frac{V_{grid}}{X_{tot}} \left(V_{inv} \cos\delta - V_{grid}\right).$$

Thus, when R_{tot} is neglected,

Inductive impedance case: $P = \frac{V_{grid} V_{inv}}{X_{tot}} \sin\delta$, (4)

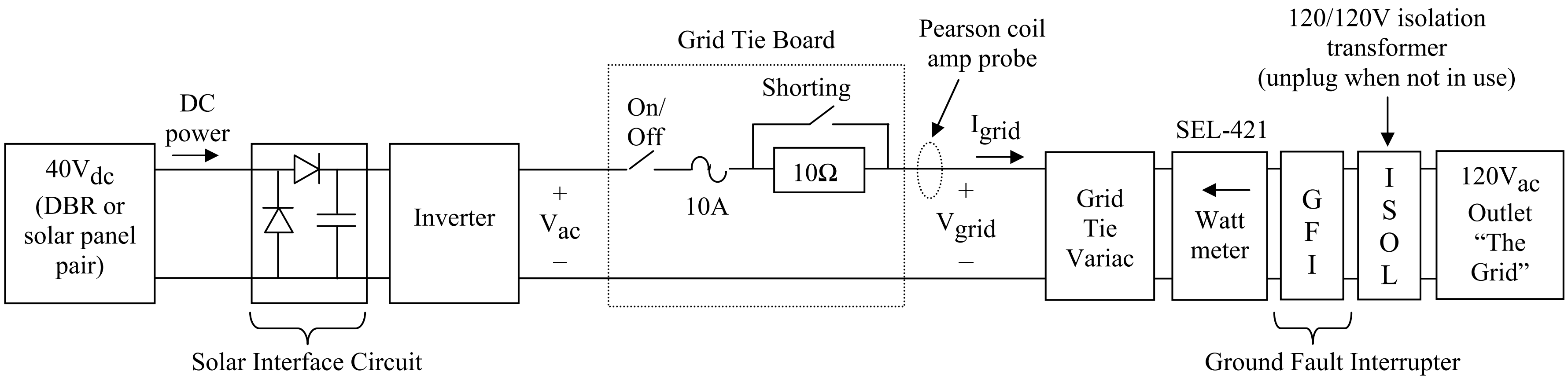
Inductive impedance case: $Q = \frac{V_{grid}}{X_{tot}} \left(V_{inv} \cos\delta - V_{grid}\right)$. (5)

For this case, P is usually controlled by angle δ , and Q is controlled by V_{inv} .

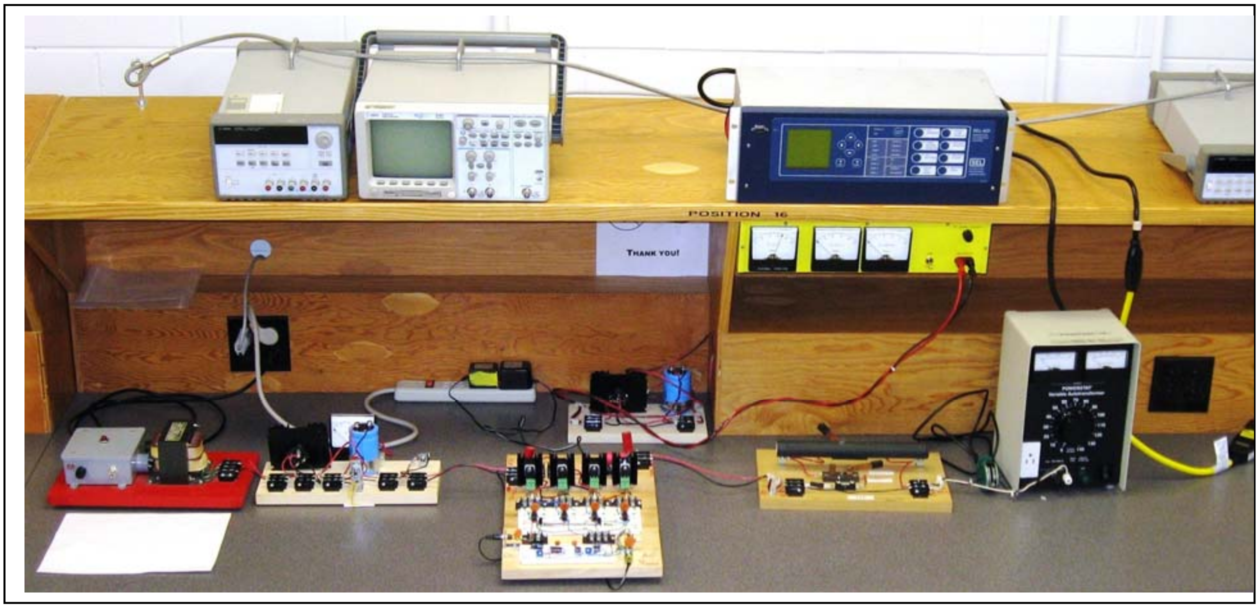
The Experiment

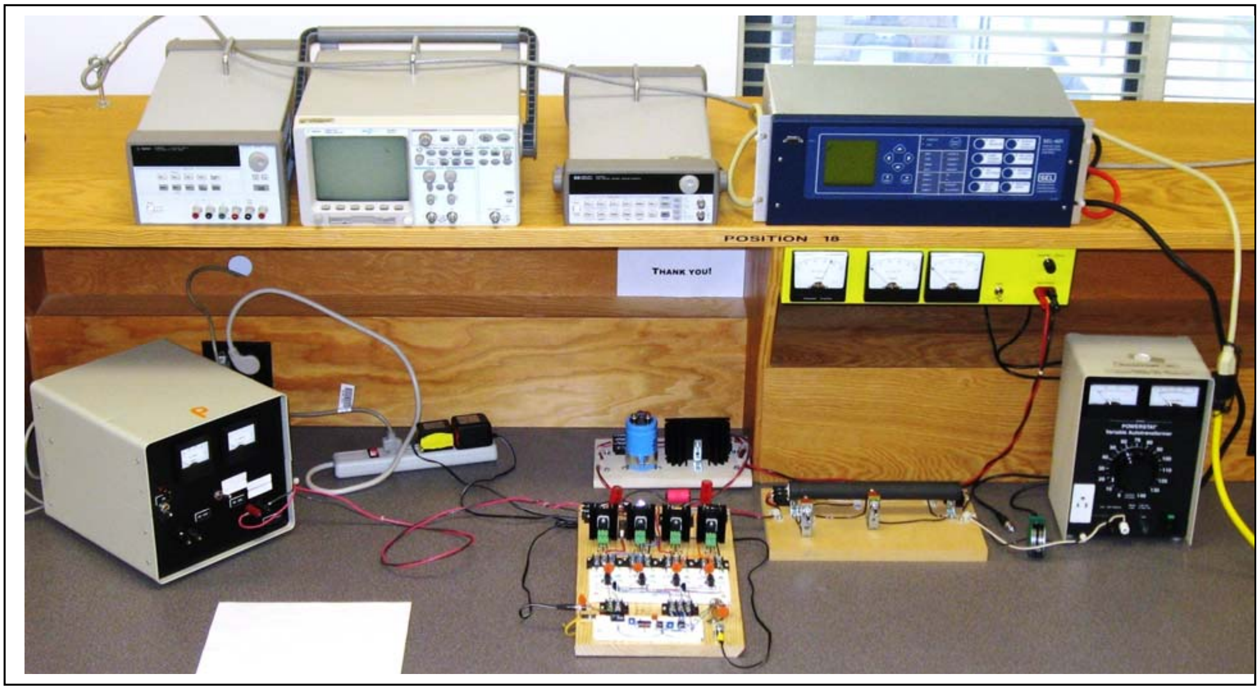
Make sure that your inverter is working properly before beginning this experiment. There are only two power-to-grid stations, so please use the signup sheet (with one-hour time slots) and be considerate of others who are waiting.

To send power back to the grid, it is essential that V_{cont} be a scaled-down version of the AC grid voltage so that there is no phase shift or frequency error introduced. In a commercial building, such as ENS, wall outlets are distributed among the three phases (i.e., a-b-c) to balance the load. The three phases have 120° phase spacing. **To avoid a 120° error in phase shift, it is important that you plug your AC wall wart into the same lab bench to which you will send power**. That way, you can be assured that your control voltage and output voltage are on the same a-b-c phase.



Important – if using a solar panel pair as your DC source, insert the **Solar Interface Circuit**. The circuit is made from recycled DBR components. The large electrolytic capacitor supplies the 120Hz ripple current needed by the inverter, thus permitting the panel current to be practically ripple-free. The diodes prevent back-feeding and polarity errors.





Two Power-to-Grid Stations. One has a transformer/DBR combination with separate 10Adc ammeter. The other has the DBR in cabinet unit with built-in voltmeter and ammeter.

A. Getting Started

1. Before connecting your inverter, do the following:
   - Turn off the $40V_{dc}$ power supply (or solar panel pair).
   - Unplug the (isolation transformer/ground fault interrupter pair) that powers the SEL-421 relay (the SEL-421 is used as a wattmeter in this experiment)
   - Turn off the Grid Tie Variac, and rotate its knob to the zero position.
   - If using solar, connect the Solar Interface Circuit between the solar panels and your inverter input.
   - Open the 10Ω shorting switch on the Grid Tie Board.
   - Open the on/off switch on the Grid Tie Board.
   - Make sure that the oscilloscope attached to the inverter output has a "ground buster" power plug adapter for isolation.

B. Warm Up (with Grid Tie Open)

2. Make sure that your inverter output filter is properly connected.
3. Connect the DC and AC wall warts to your inverter.
4. Lower m_a to zero.
5. One by one, observe the four V_{GS} waveforms on an oscilloscope to make sure they are firing properly.
6. Attach a scope probe and its ground clip to view inverter output V_{ac}. Apply $40V_{dc}$ to your inverter input. Use a scope time scale of 5ms/div, and set the acquire function to average the waveform for 1 cycle to denoise the display. Then, raise V_{cont} until m_a is about 1.0 (i.e., raise m_a until V_{ac} "flat tops," and then lower m_a slightly until flat-topping disappears).
7. **Check the DC idling current. If above 0.1A, then shut down and figure out why**.

C. Synchronize with the Grid

8. **Make sure that both switches on the Grid Tie Board are open, and that the Grid Tie Variac is switched off, and that the Grid Tie Variac knob is in the zero position.**
9. Plug in the (isolation transformer/ground fault interrupter pair) that powers the SEL-421 relay. The SEL-421 has a few-second turn on delay, and then shows the "Rotating Display." The SEL-421 scale factors are set so that

   - The kV shown on the screen is actually volts
   - The A shown on the screen is actually mA
   - The MW shown on the screen is actually W

10. Once on, then cycle through the voltage and current screens to the power screen as follows:

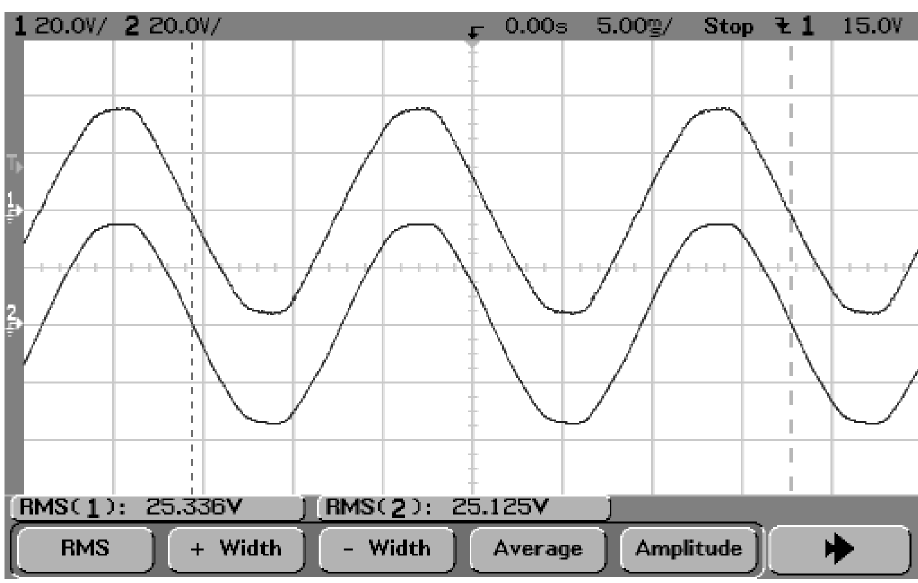
    A. Press ENT to reach the "Main Menu," then
    B. Press ENT to reach the "Meter Menu," then
    C. Press the down arrow to reach the "Fundamental Meter" selection, then

D. Press ENT to reach the "Meter Sub Menu," then
E. Press ENT to reach the "Fundamental Line Meter" to observe volts and amps, then
F. Press the down arrow three times to view P.

Pressing ENT several times will take you back to the "Rotating Display"

11. With the Grid Tie Variac control knob all the way to zero, turn on the Grid Tie Variac.
12. Record power reading **P1.** Since the Grid Tie Variac output switch is off, P1 is the power required to energize the Grid Tie Variac from the 120V wall outlet. Expect P1 to be a few watts.
13. Attach a second scope probe (without ground clip) to V_{grid}. Set the acquire function on the scope to average the waveforms for 1 cycle to denoise the display. Slowly increase the Grid Tie Variac knob until V_{grid} is visually equal to V_{ac}. **When making this determination, make sure that you use the same scale on the oscilloscope for both V_{ac} and V_{grid}.** Also, it helps to move the waveforms vertically until they are superimposed. **Important – double-check the values of V_{ac} and V_{grid} with a multimeter to make sure their rms values are approximately equal.**

14. **If V_{ac} and V_{grid} are not in phase, stop and figure out why**. If they are 180° out of phase, the simple solution is to plug the AC wall wart in upside down. Any phase shifts besides 0° or 180° indicate that V_{cont} and V_{grid} are connected to different a-b-c phases, **which must be remedied before proceeding!** When OK, save a screen snapshot of V_{ac} and V_{grid}.



Save screen snapshot #1

V_{ac} and V_{grid} with grid tie open

D. Connect to the Grid

15. Once V_{ac} and V_{grid} are in phase and approximately equal, then close the Grid Tie Board on/off switch. **The DC amps to the inverter should not change more than a few tenths of an ampere.** If it does, there is a voltage imbalance somewhere.
16. If no signs of problems, then close the Grid Tie Board 10Ω shorting switch.

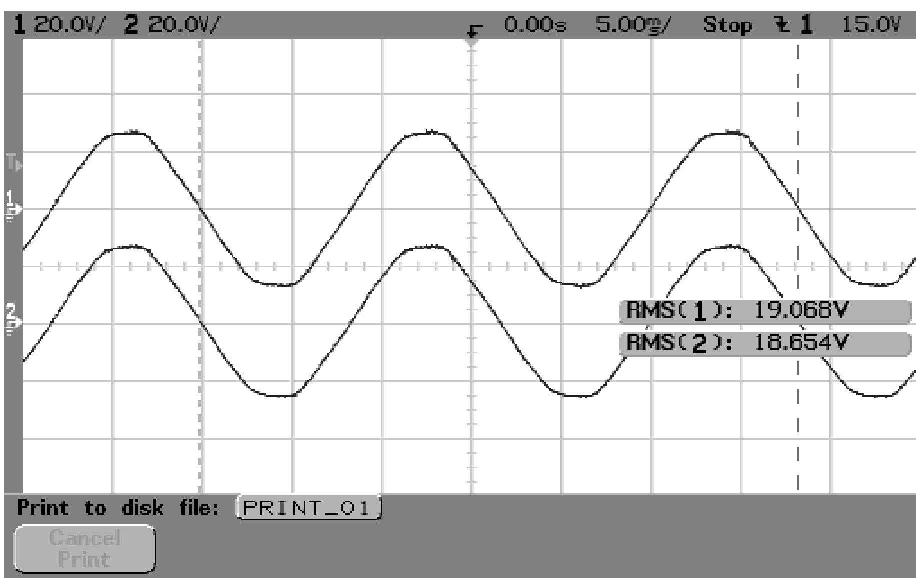
E. Send Power to the Grid

17. Leaving m_a = 1.0, **slowly decrease** the dial on the Grid Tie Variac until

- If using a DBR, the DC current is about 5A,
- If using solar, the wattmeter reading is most negative (occurs at about 32V panel voltage).

Record the DC voltage and current, V_{ac}, the AC current (from the Grid Tie Variac ammeter), the dial setting of the Grid Tie Variac, and the wattmeter power reading P2. Note that **P2** is a negative number, which means that power is flowing into the grid. If using the DBR, expect P2 to be in the -100 to -130W range. Accounting for Grid Tie Variac energization losses, the actual power flowing **out** of the inverter is **(P1 − P2)**.

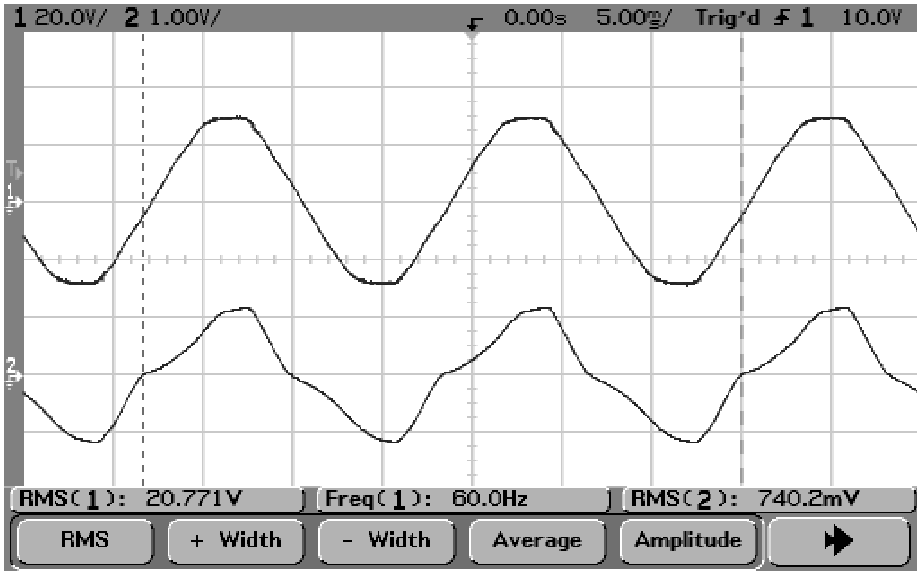
18. Save a screen snapshot of V_{ac} and V_{grid} .



Save screen snapshot #2

V_{ac} and V_{grid} with grid connection closed and $I_{dc} \approx$ 5A

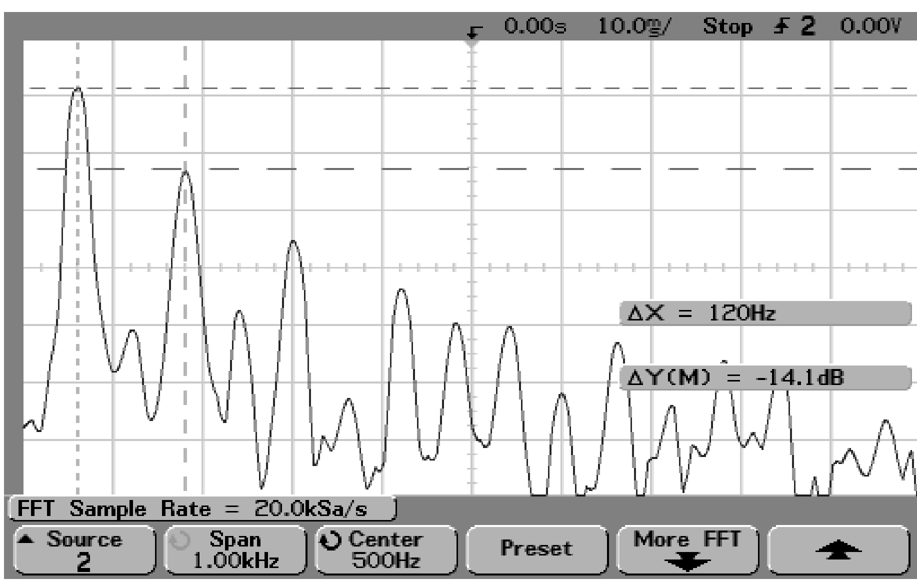
19. Remove scope probe 2 and replace it with the Pearson coil BNC connector to view I_{grid}. The Pearson coil reads 0.1V per amp. View V_{grid} and I_{grid}.



Save screen snapshot #3

V_{grid} and I_{grid}
(viewed on the low-voltage side of the Grid Tie Variac)

20. Display the FFT of I_{grid} and save a snapshot. Compute the relative magnitudes of the 3rd and 5th harmonic components (with respect to the fundamental). Use the 3rd and 5th values to estimate the total harmonic distortion (THD) of the current.



Save screen snapshot #4

FFT of I_{grid}
(10dB/division on the y-axis)

F. Shut Down

21. **Disconnect from the grid by opening the Grid Tie Board's on/off switch and 10Ω shorting switch.**

22. Return the equipment to the situation described in Step 1.

Items in ENS212

- Schweitzer SEL-421 relay (used as wattmeter in this experiment)
- In-line ground fault interrupter (Hubbell GFP2CA, Newark #88H7016)
- Thru-hole current monitor with BNC connector (Pearson #411, 0.1 Volts per Ampere)
- DBR in cabinet with built-in voltmeter and ammeter (or use a transformer/DBR combination with 10Adc ammeter).