ENEL 585 Experiment 4

The Single-Phase Two-Level Inverter

Purpose:

To become familiar with the single-phase pulse width modulated (PWM) full-bridge inverter.

Introduction:

In this experiment, a dc supply is connected to the input of a converter which produces an ac output. To do this, active switches (ie, transistors) are necessary, as well as a simple control circuit to gate (ie, turn on) the switches. In this experiment, the inverter contains a full-bridge (ie, four) switch structure, and we will employ a simple gating control of the bridge, producing a "two-level" output (ie, positive $V_d$ or negative $V_d$). Two-level inversion can be employed in two ways, ie, producing a square wave output, or producing a pulse width modulated output (which when filtered produces a good approximation of a sinusoidal waveform). Various filter methods and various loads are considered in the lab.

Tutorial:

Shown in Fig. 1 is the schematic of a full-bridge single-phase inverter. Note that the switches are MOSFET n-channel transistors, though other types of transistors can be employed. Note also that each MOS transistor contains a "back-connected" diode as part of its internal construction. These back-connected diodes are necessary if an inductor is employed in the filter part of the converter.

To understand how the transistors of the inverter can be controlled, consider the case where transistors Q1 and Q4 are turned on for half a cycle, making $v_{ac} = V_d$, then transistors Q2 and Q3 are turned on (Q1 and Q4 now off), making $v_{ac} = -V_d$ for the second half cycle. The bridge voltage is simply a square wave. Note that the controller determines the frequency of the square wave; e.g. 50Hz (as used in Europe), 60Hz (as used in North America), or even 400Hz (as used for aircraft power supplies -why? you ask -less iron is needed in transformers and inductors at 400Hz and hence an aircraft power supply is lighter compared to a 60Hz

Figure 1: Single-phase inverter with possible LC filter
counterpart). As \( V_{ac} \) is either positive or negative, square wave inversion is considered "two-level" inversion (see Lander, Fig. 5-26 page 206 for an example of two-level verses three-level inversion). In some applications, this is all that is needed, and the bridge output is connected directly to the load. More often a "smoother" ac voltage is needed, so either an inductor or an inductor-capacitor filter is used (note a capacitor by itself cannot be used as excess currents would result). However, the possible LC filter would have to be quite large (both L and C values, and physical size), and worse yet, the output waveform would still not be sinusoidal, ie, just a square wave with smoothed corners. This is partly because there is a limit on how large the L and C filter components can be. If too large, the output ac voltage, \( v_o \), will become too attenuated, not to mention the cost of employing large L and/or C filter components.

To reduce the size and cost of the LC filter, and to obtain a more sinusoidal output voltage, the transistors in the bridge can be turned on and off more frequently. Still considering the case of two-level inversion (ie, at any time one pair of diagonal transistor is on), if the controller can vary the time for which each pair of transistors is on, then it is possible to control the average output voltage (note: in steady-state \( V_{ac,\text{avg}}=V_{o,\text{avg}} \).

If we slowly change the on time of say transistor Q1 (Q4 is on at the same time), and the LC low-pass filter is used to filter out the high frequency ac component of \( v_{ac} \), then it is possible to obtain a low frequency sinusoidal voltage for \( v_o \). In theory, as the transistor switching frequency goes to infinity, the \( v_o \) waveform becomes perfectly sinusoidal. This type of operation of a converter, where the on time of the transistors is changing slowly, to control the desired average output voltage, is sometimes called quasi-static operation (that is, over two or three transistor switching periods, we can take the transistor duty-ratio to be almost constant). The average output voltage over one switching period is sometimes called a "local average". Finally, note that there are two frequencies of interest; the transistor switching frequency (usually constant at a value of several kHz say), and the output sinusoidal "power frequency" (e.g. 60Hz in North America, 50Hz in Europe).

**Pre-Lab (one per lab group collected at the start of the lab):**

1. Consider a single-phase full-bridge inverter as in Fig. 1 above, where no L or C filter components are used. Let \( V_d \) be 6 V, and the load be a pure resistance of 10\( \Omega \). Let the output voltage waveform be a square wave of 50Hz. Calculate the rms output voltage and current, as well as the rms value of the output fundamental voltage. Calculate the input power and average input current to the converter. Also find the THD (total harmonic distortion) of the output voltage waveform. Sketch the output voltage waveform.

2. Consider a single-phase full-bridge inverter as in Fig. 1 above, where a single inductance filter of 25mH is used. Let \( V_d \) be 6 V, and the load be a pure resistance of 10\( \Omega \). If the bridge voltage, ie, \( v_{ac} \), is a square wave of 50Hz, estimate the rms output voltage and current, as well as the input power and average input current to the converter. Sketch the bridge and load voltage waveforms. Hints: Some of your answers may be the same as in problem 1. Also, the L/R time constant is an important parameter for sketching the load voltage waveform.

3. Consider a single-phase full-bridge inverter as in Fig. 1 above, where an LC filter is employed to filter out the switching frequency component of the bridge voltage waveform, with an inductor of 10mH. Let \( V_d \) be 6 V, and the load be a pure resistance of 10\( \Omega \).

   If the bridge voltage is sinusoidal pulse width modulated, with a modulation index of 0.75 (this means that the load voltage is roughly sinusoidal with a peak value of about 0.75\( V_d \)), and the power frequency is 50Hz, calculate the rms output voltage and current, as well as the input power to the converter (you may assume a switching frequency approaching infinite). Sketch the load voltage waveform.

4. For problem (3) above, let the switching frequency be 10kHz. What is a reasonable value for the filter
capacitance? Explain. Given this capacitance, calculate the approximate load voltage ripple, ie, the peak-to-peak value (Hint: in the stop band of the LC filter, there is an asymptotic attenuation slope of 40dB per decade). Sketch the load voltage waveform. What is the THD of the load voltage waveform?

Procedure:

1. Playing Around: When you come into the Lab, the inverter should be configured with a 10mH filter inductor, an $11\mu F$ filter capacitor, and a 39Ω load resistance. A volt meter should be connected to the dc lab supply. Check that the dc power supply voltage knob is set to about 5V (the current knob should be a about 1A, acting as a current limit). For 10 or 15 minutes just play with the inverter module and program. Try not to exceed a dc input of about 10V. Play with the carrier and modulating frequencies. Observe the triangle wave carrier and modulating waveforms and determine the relationship of these with the ac bridge output voltage. If the modulation index is high (above 100%), what do you notice about the bridge output voltage. What is the effect of modulation offset. Note anything else of interest. Write this all down for your observations. Have fun.

2. R Load: Set the dc supply to about 3.0V. Set the modulating frequency to 50Hz. Set the carrier frequency to 1kHz. Set the modulation index to 90%. Turn off the dc supply. Remove the filter capacitor, and short out the inductor connections. Now the bridge output is connected directly across the 39Ω load. Turn on the dc supply. Record the average and rms input current. Check power balance (ie, calculate $P_{in}$ and $P_{out}$). Examine the current waveforms. What do you notice about the transistor off voltage (the waveform shown is for transistor Q1)? If you have not done so yet, save relevant waveforms (e.g. load voltage, transistor voltage, load current, transistor current, perhaps supply current).

3. L filter R Load: Turn off the dc supply. Add a filter inductor of 10mH to the converter circuit. Turn on the dc supply. Make your observations. In particular, what do you notice about transistor current? Explain. Double the input voltage to 6.0V. What happens to the average input current? Explain the effect of input voltage on input power. How does the average input current compare to the rms value? Make any other observations. Save relevant waveforms (e.g. ac bridge and load voltage -note the Vaux terminals, left -, right +, may be connected across the output terminals to plot load voltage.

4. LC filter R Load: Turn off the dc supply. Add a filter capacitor of $50\mu F$ to the converter circuit. Turn on the dc supply. What is the effect of adding a filter capacitor on the power input? Explain. An LC filter is a 2nd order filter. What do expect for the phase relationship of the load voltage ripple waveform to the bridge voltage waveform? What do you actually observe. Explain. Make any other observations (e.g. peak-to-peak output voltage ripple). Save relevant waveforms (e.g. bridge and load voltage).

5. Smaller LC filter R Load: Keeping the bridge voltage, load voltage, and bridge current displayed on the computer, turn off the dc supply. Decrease the filter capacitance to $10\mu F$. Turn on the dc supply. Click-on the update button while watching the bridge current waveform. What did you see? Explain. Save relevant waveforms.

6. LC filter Non-linear Load: Turn off the dc supply.' Replace the 39Ω load with a non-linear load, namely, a diode in series with a 5.1Ω resistor. What would you expect to see for the load voltage and bridge current waveforms? What do expect the input power (or equivalently, the average input current) to be? Turn on the dc supply, and see what you get. Can you explain what is happening? It may help if you increase the carrier frequency, e.g. to 5kHz. It may help if you reverse the load connections. Make any other observations. Save relevant waveforms. Once you have a reasonable hypothesis, go on to the next step.
7. Larger LC filter Non-linear Load: Turn off the dc supply. Replace the filter capacitor with one of value 50µF. See what happens. Is your hypothesis supported? Save relevant waveforms.

8. LC filter No Load: Turn off the dc supply. Remove the load from the converter. Examine the waveforms, and note the average input current. What can you conclude? Save relevant waveforms.

9. LC filter and transformer coupled load: Make sure the dc supply is still at 6V. The current limit on the dc supply should already be set to 1A. Turn off the dc supply. Set the modulation index to 25%. Set the modulation offset to about 15% to obtain no offset in the voltage applied to the transformer. Replace the load with a transformer coupled load, with a load resistance of 200Ω. The transformer is stepping up the voltage. Connect the Vaux terminals to the transformer input. Turn on the dc supply. It will be necessary to adjust the modulation offset (ie, there is an offset in the offset) to obtain a balanced waveform across the transformer input. Once this is done, observe the transformer input voltage and the filter inductor current, while increasing the modulation offset by 20% (e.g. from 15% to 35%). Turn off the dc supply. Then move the Vaux connections to the transformer output. Turn on the dc supply. What do you observe? Continue to increase the modulation offset (up to a max of about 75%, beyond which over modulation occurs), while observing filter inductor current and the transformer output voltage. What do you observe (hint: also look at how much current is entering the converter)?

Analysis:

Consider some of the following questions.

1. What is the effect of over modulation?

2. If a filter inductor is employed in the converter, why is the rms input current so much larger than the average input current?

3. What is the purpose of the back connected diodes (if we had used BJTs in place of the MOSFET devices, these diodes would have to have been externally added)?

4. Given an LC filter in the converter, is the observed magnitude and phase of the ripple (ie, ac) component of load voltage reasonable?

5. What is the effect of varying the L or C filter values?

6. What is the effect of a non-linear load on the operation of a pulse width modulated inverter with an LC filter?

7. What is the effect of a dc offset on a transformer coupled load?

Conclusions:

Summarize what you have learned about inverter operation from this experiment. generalizations can you make regarding filtering and loading?