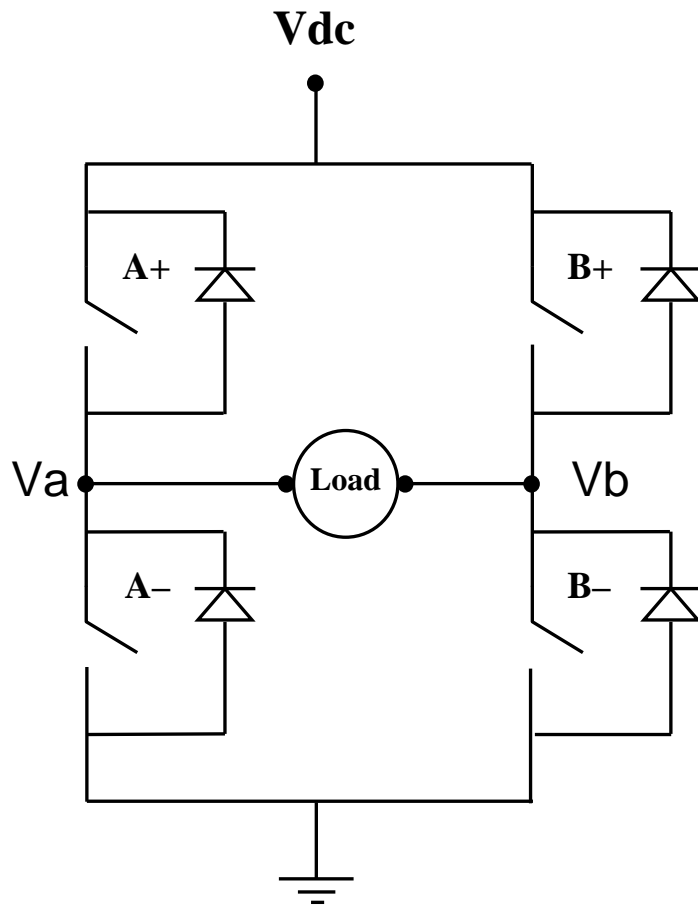## 1. Introduction

How do we make AC from DC? Answer – the H-Bridge Inverter.

H BRIDGE INVERTER
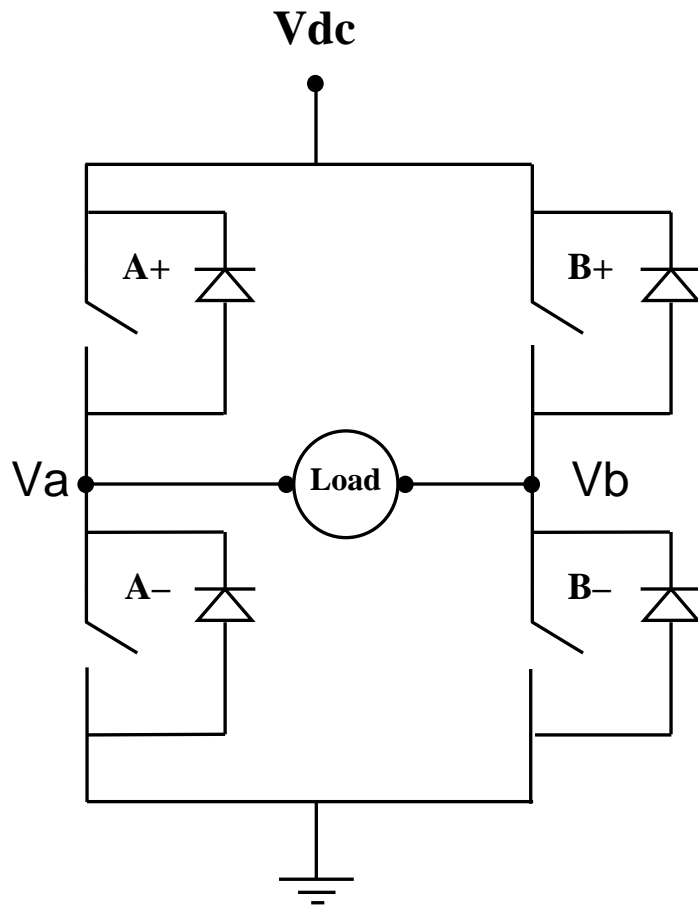

Switching rules
- Either A+ or A− is always closed, but never at the same time *
- Either B+ or B− is always closed, but never at the same time *

*same time closing would cause a short circuit from Vdc to ground

Corresponding values of Va and Vb
- A+ closed, Va = Vdc
- A− closed, Va = 0
- B+ closed, Vb = Vdc
- B− closed, Vb = 0

H BRIDGE INVERTER

Corresponding values of Vab
- A+ closed and B– closed, Vab = Vdc
- A+ closed and B+ closed, Vab = 0
- B+ closed and A– closed, Vab = –Vdc
- B– closed and A– closed, Vab = 0

- The free wheeling diodes permit current to flow even if all switches did open
- These diodes also permit lagging currents to flow in inductive loads

But is a square wave output good enough? Not for us! Sinusoidal load voltage is usually the most desirable. But how do we approximate a sinusoidal output with only three states (+Vdc, −Vdc, 0) ?
The answer: Unipolar PWM modulation
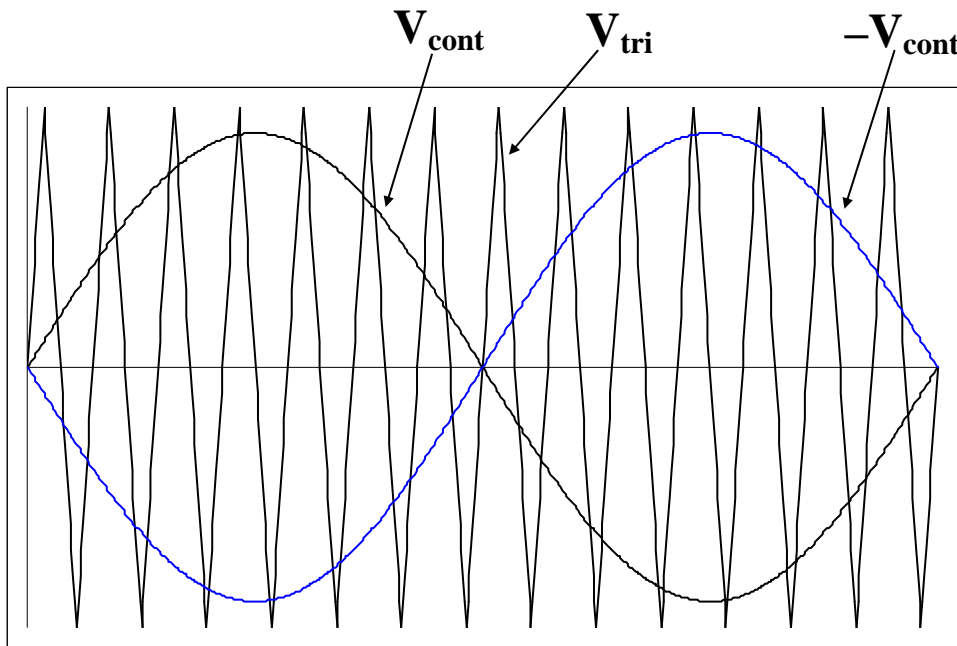
V$_{cont}$ **V**$_{tri}$ **−V**$_{cont}$

V$_{cont}$ **, −V**$_{cont}$ **, and V**$_{tri}$

Vcont > Vtri , close switch A+, open switch A− , so voltage Va = Vdc
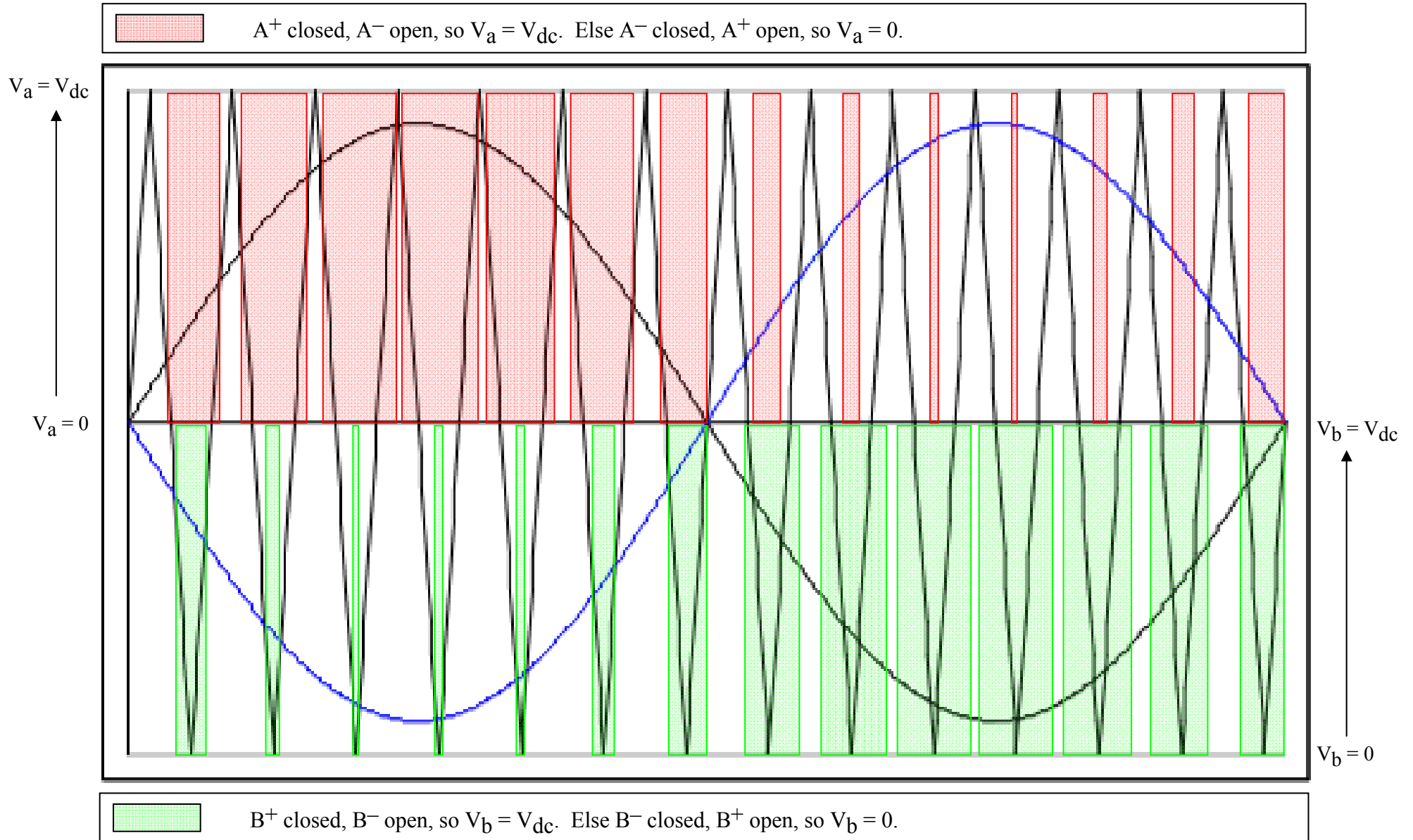
Vcont < Vtri , open switch A+, close switch A− , so voltage Va = 0

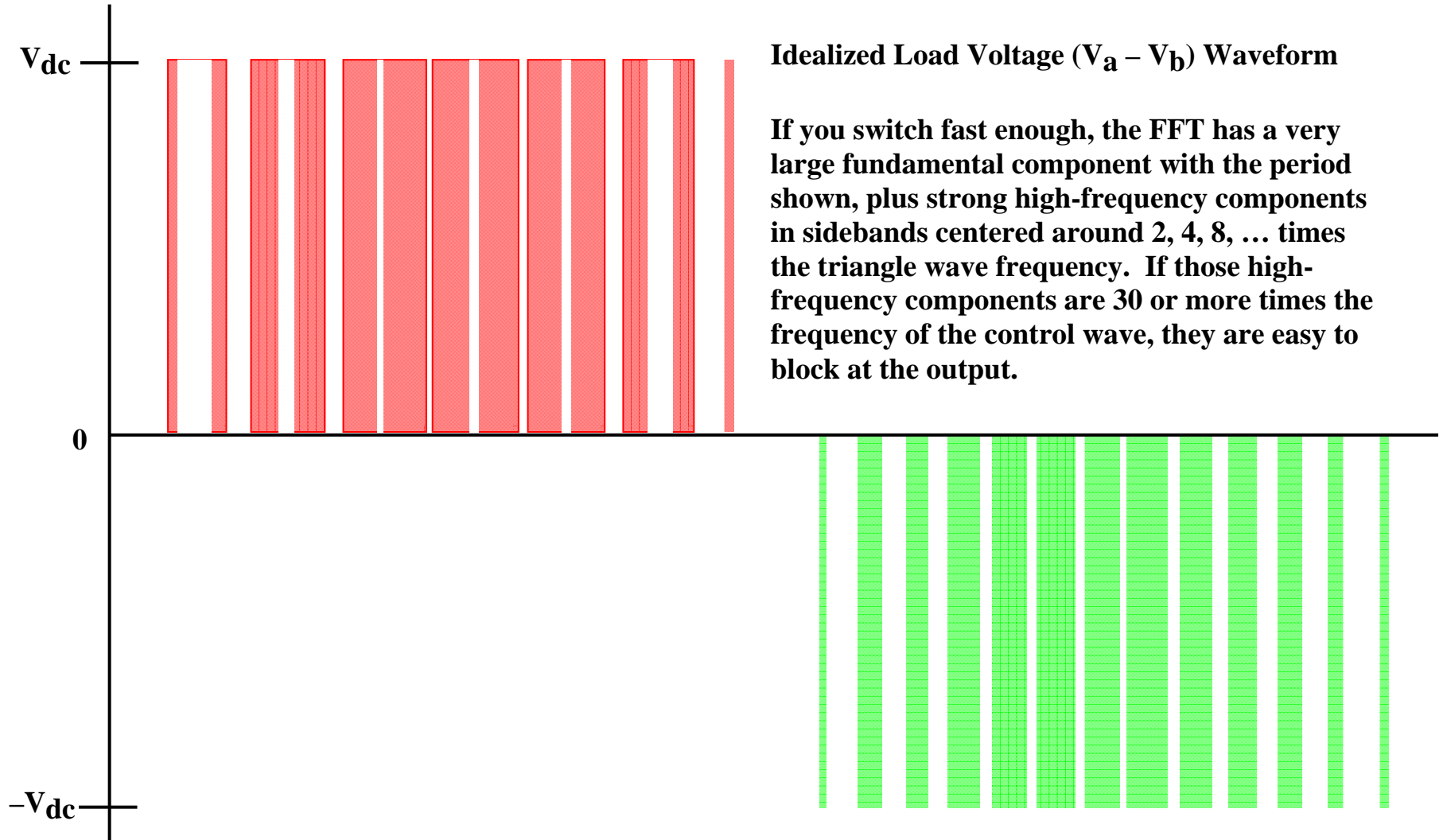−Vcont > Vtri , close switch B+, open switch B− , so voltage Vb = Vdc

−Vcont < Vtri , open switch B+, close switch B− , so voltage Vb = 0

A^+ closed, A^- open, so $V_a = V_{dc}$. Else A^- closed, A^+ open, so $V_a = 0$.

B^+ closed, B^- open, so $V_b = V_{dc}$. Else B^- closed, B^+ open, so $V_b = 0$.

Idealized Load Voltage ($V_a - V_b$) Waveform

If you switch fast enough, the FFT has a very large fundamental component with the period shown, plus strong high-frequency components in sidebands centered around 2, 4, 8, … times the triangle wave frequency. If those high-frequency components are 30 or more times the frequency of the control wave, they are easy to block at the output.

Unipolar PWM inverters (also known as Class D or switching amplifiers) efficiently amplify a small input signal V_{cont} . The output voltage to the load is either $+V_{dc}$, $-V_{dc}$, or zero, depending on whether V_{cont} and $-V_{cont}$ are greater or smaller than a reference triangle wave V_{tri}. The output load voltage contains a replica of V_{cont} , and also strong harmonics centered about even multiples of m_f, where m_f is the ratio of the reference triangle wave frequency with respect to the frequency of V_{cont}. , i.e, $m_f = \dfrac{f_{tri}}{f_{cont}}$.

The amplifier operates on the principle of comparing V_{cont} (and $-V_{cont}$) to a reference triangle wave V_{tri} . This principle is illustrated in Figure 1.
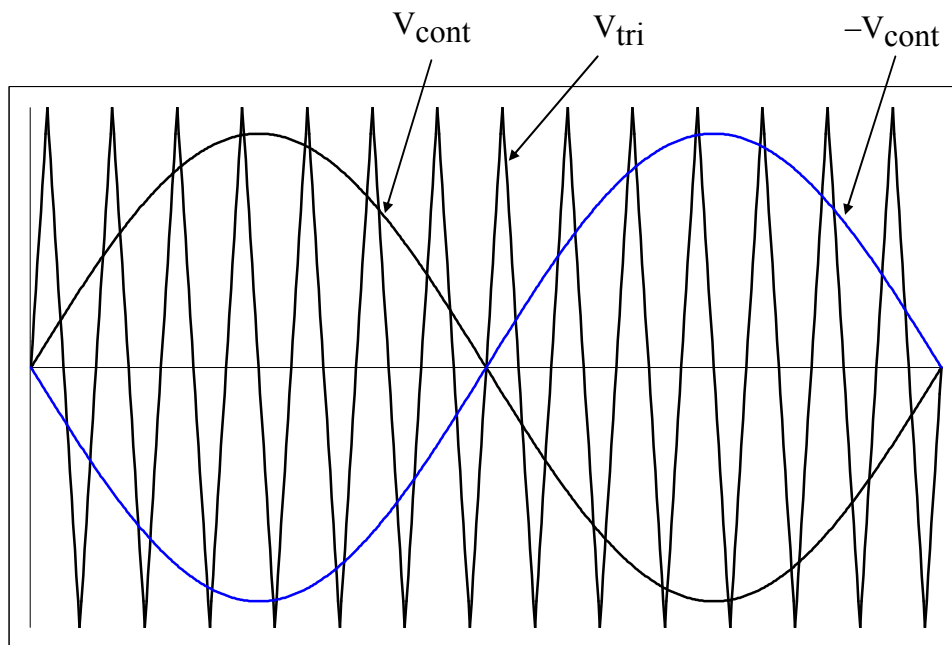

Figure 1. V_{cont} , $-V_{cont}$, and V_{tri}

The illustration given has $m_a = 0.9$, where m_a is the ratio of peak control voltage to peak triangle voltage. The logic used to operate the four switches in the H-Bridge configuration of Figure 2 is as follows:

$V_{cont} > V_{tri}$, close switch A^+, open switch A^- , so voltage $V_a = V_{dc}$

$V_{cont} < V_{tri}$, open switch A^+, close switch A^- , so voltage $V_a = 0$

$-V_{cont} > V_{tri}$, close switch B^+, open switch B^- , so voltage $V_b = V_{dc}$

$-V_{cont} < V_{tri}$, open switch B^+, close switch B^- , so voltage $V_b = 0$

30-40V_{dc}

A$^+$ B$^+$

Freewheeling diodes (optional in this circuit because the MOSFETS used have adequate internal reverse diodes)

a $\sim$ b

+V_{load} −

$+$

V_a A$^-$ B$^-$ V_b

$+$

High-frequency capacitor to provide ripple current from DC source
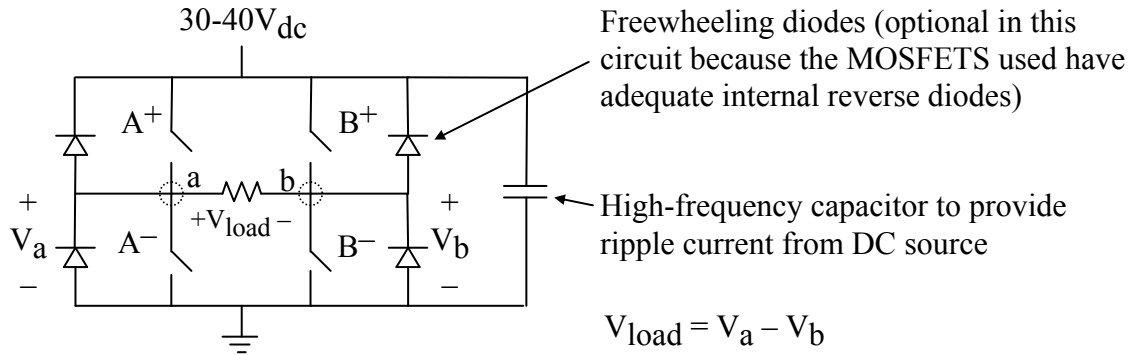
$-$ $-$

$V_{load} = V_a - V_b$

Figure 2. Four MOSFET switches configured as an H-Bridge
(note that the MOSFET source nodes are not all at the same potential, thus requiring isolated firing circuits for A$^+$ and B$^+$)

The resulting load voltage is shown in Figure 3. (Note – see the Appendix for a more complete graphical development of Figure 3). The harmonics in this waveform are high-frequency side bands $2kf_{tri} \pm f_{cont}$, $2kf_{tri} \pm 3f_{cont}$, $2kf_{tri} \pm 5f_{cont}$, and so forth, for k = 1, 2, 3, …), where f_{tri} is the frequency of the triangular wave, and f_{cont} is the frequency of V_{cont}. Waveforms for m_a = 0.5 and 1.5 are shown in Figures 4 and 5.

The magnitudes of the load voltage frequency components, taken from [1], are shown in Table 1. For small m_a, many of these values are large in relation to the fundamental. However, as long as m_f is large, the undesired high frequency components are relatively easy to filter at the load, so that the output load voltage resembles V_{cont} reasonably well.
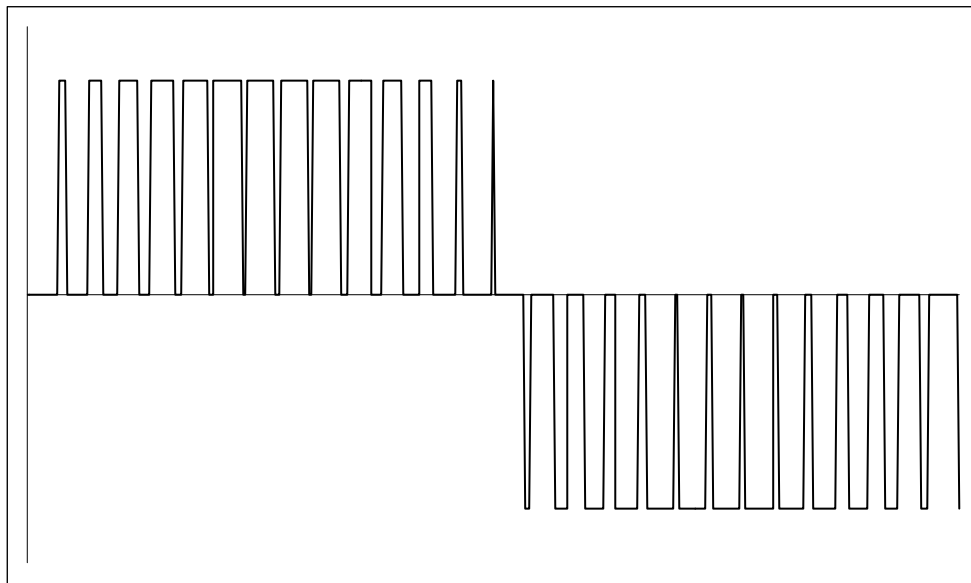

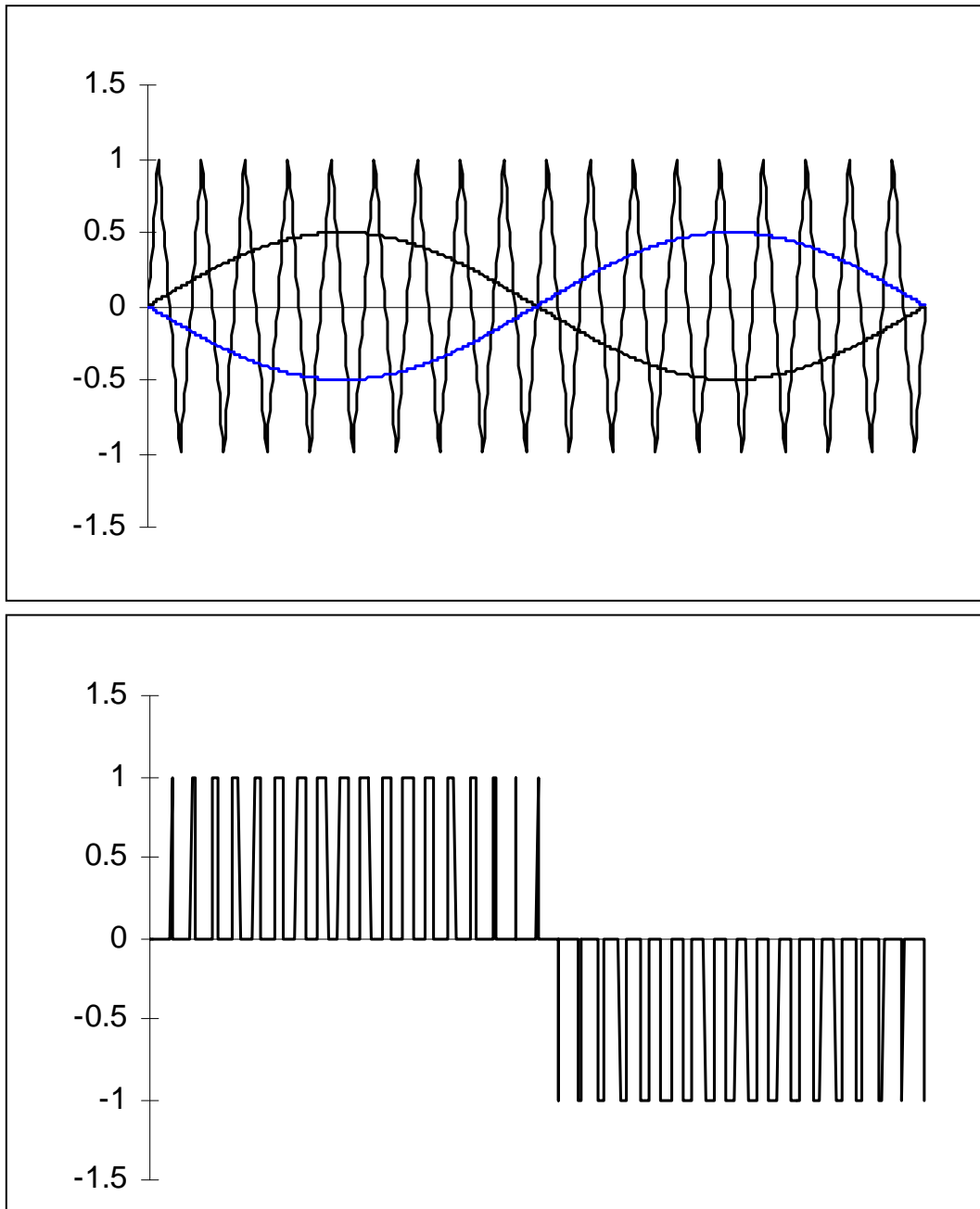Figure 3. Load voltage ($V_{load} = V_a - V_b$) with m_a = 0.9 (i.e., in the linear region)

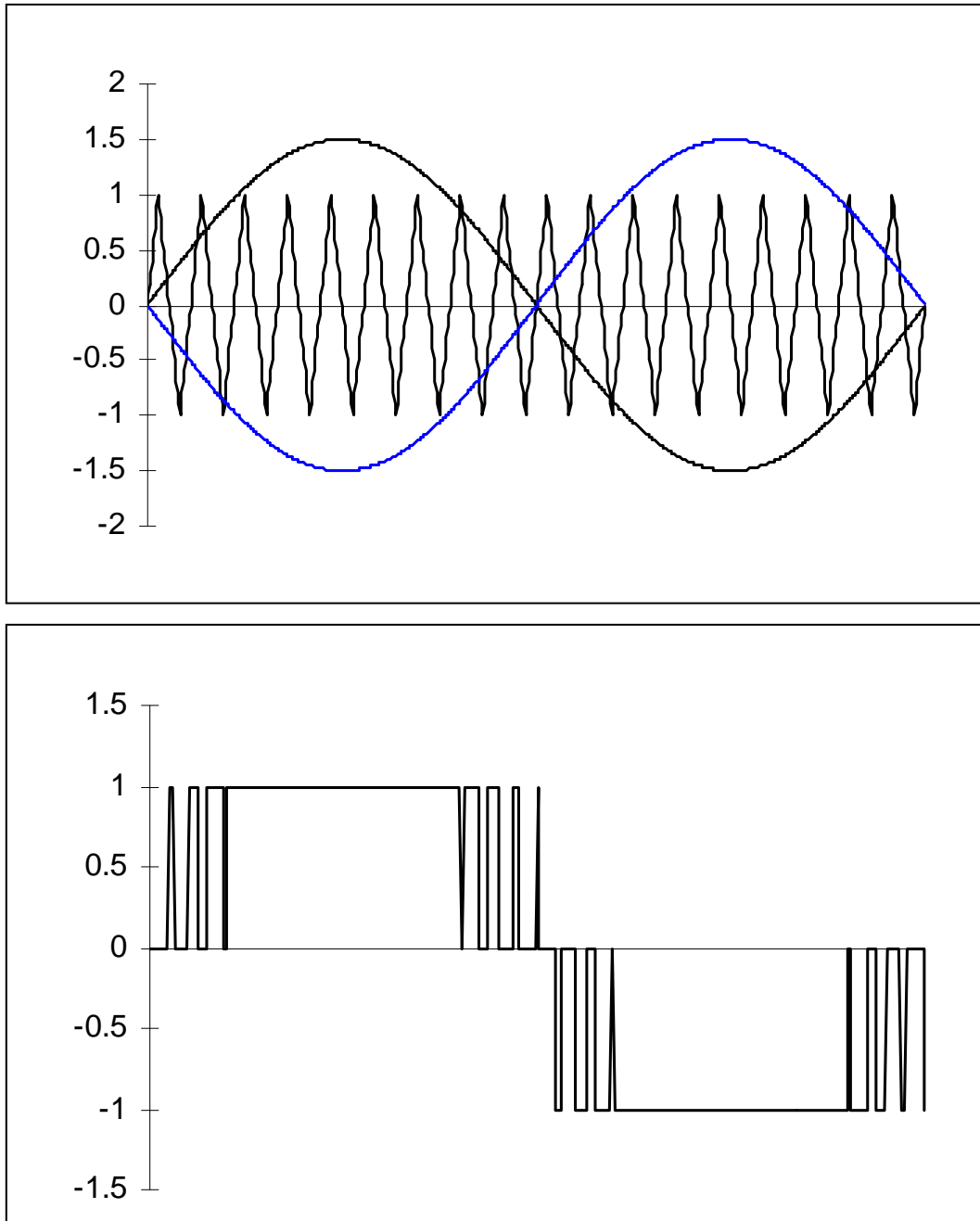Figure 4. Load voltage ($V_{load} = V_a - V_b$) with $m_a = 0.5$ (i.e., in the linear region)

Figure 5. Load voltage ($V_{load} = V_a - V_b$) with $m_a = 1.5$ (i.e., in the overmodulation region)

Table 1. RMS magnitudes of load voltage frequency components, with respect to $\dfrac{V_{dc}}{\sqrt{2}}$

(for $f_{tri} \gg f_{cont}$)

Frequency	$m_a = 0.2$	$m_a = 0.4$	$m_a = 0.6$	$m_a = 0.8$	$m_a = 1.0$	
f_{cont}	0.200	0.400	0.600	0.800	1.000	
$2f_{tri} \pm f_{cont}$	0.190	0.326	0.370	0.314	0.181	↑
$2f_{tri} \pm 3f_{cont}$		0.024	0.071	0.139	0.212	$2f_{tri}$ cluster
$2f_{tri} \pm 5f_{cont}$				0.013	0.033	↓
$4f_{tri} \pm f_{cont}$	0.163	0.157	0.008	0.105	0.068	↑
$4f_{tri} \pm 3f_{cont}$	0.012	0.070	0.132	0.115	0.009	$4f_{tri}$ cluster
$4f_{tri} \pm 5f_{cont}$			0.034	0.084	0.119	
$4f_{tri} \pm 7f_{cont}$				0.017	0.050	↓

As m_a decreases, the on-times pulses in Figure 3 get proportionally smaller, linearly decreasing the rms value of the fundamental component of the inverter output (see Figure 4). As m_a increases beyond 1.0, then overmodulation occurs, and the on-time pulses near the centers of the output waveform gradually merge (see Figure 5). As m_a becomes very large (i.e., 5 or 10), all of the on-time pulses merge, and the inverter output becomes a square wave with predominantly low-frequency harmonics (i.e., 3rd, 5th, 7th, etc.). The variation of the rms value of the no-load fundamental output with m_a is shown in Figure 6 (taken from [1]).
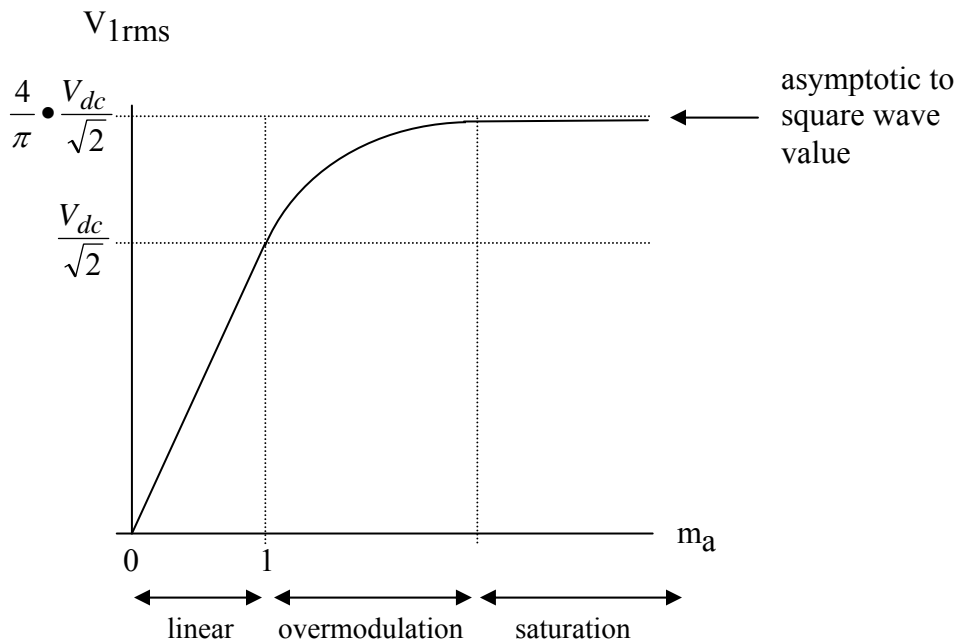

Figure 6. Variation of RMS value of no-load fundamental inverter
output voltage (V_{1rms}) with m_a

In our application, V_{cont} will be a 60Hz signal taken from a benchtop waveform generator. During the tune-up procedure, Vcont will have a peak value of 4.0V (which is displayed as VPP on the waveform generator). The triangle wave will be about 150kHz.

2. The Control Circuit and Firing Logic

The PWM inverter control circuit is shown in Figure 7. The purpose of this control circuit is to produce firing signals for the four H-Bridge MOSFETs. Firing signal VA controls MOSFETs A^+ and A^-. Firing signal VB controls MOSFETs B^+ and B^-. When VA is "high," A^+ is "on" and A^- is "off." When VA is "low," A^+ is "off" and A^- is "on." The "B-side" of the H-Bridge works the same way with VB. Thus,

- node voltages V_a and V_b in Figure 2 will be working-voltage replicas of firing signals VA and VB, respectively, and
- $V_{load} = V_a - V_b$ will be a working voltage replica of [VA – VB].

The purposes of the four ICs in this circuit are

- 2W, DC-DC converter chip to produce isolated ±12V from one plug-in 12V regulated "wall wart" DC power supply. The wall 0V output of the DC converter chip will not be connected to the wall wart ground.
- One dual Op Amp – one side sums two input voltages to produce a mono signal, and the other side can attenuate or boost the mono signal.
- Another dual Op Amp with only one side used. Has adjustable gain to produce –Vcont.
- Waveform generator – generates the triangle wave. Regulated ±12Vdc input keeps the waveform steady and helps to eliminate DC in the output.
- Comparator – performs the PWM comparison logic, and sinks enough current so that the MOSFET drivers switch on-and-off properly. Because comparisons are made between voltages that can be positive or negative, the comparator chip must powered by a ± supply voltage (in our case ±12V), and the comparator chip output is either +12V, or −12V.
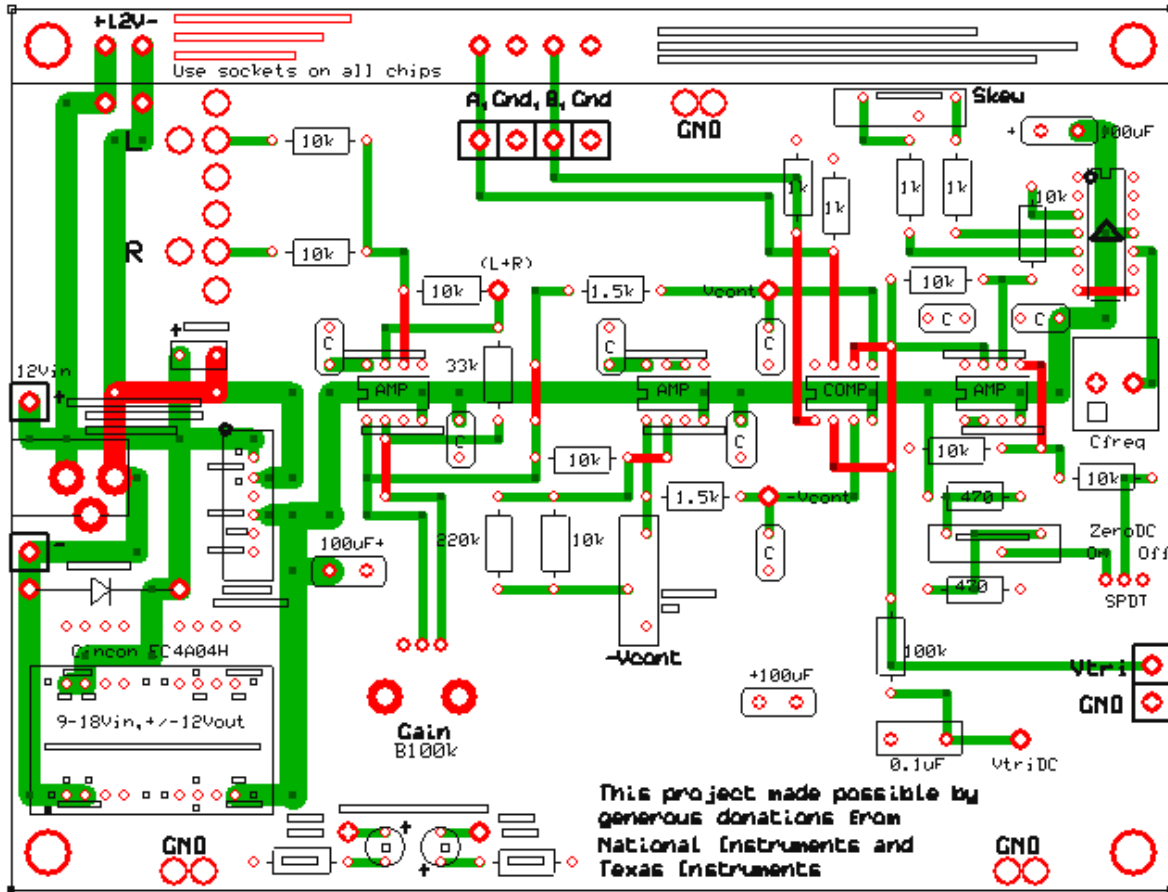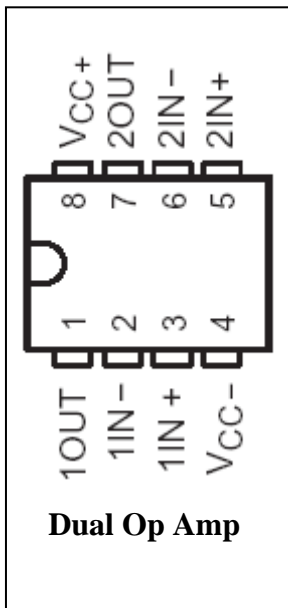
See the Appendix for IC pin configurations.

Figure 7. PWM Control Circuit

Dual Op Amp

**NTE864 Precision Waveform
Generator. Spec on Cfreq is**
- **680pF yields 200kHz,**
- **500µF yields 0.001Hz**

Pin #	Symbol	Type	Description
1	SA1	I	Wave Form Adjust Input 1.
2	SWO	O	Sine Wave Output.
3	TWO	O	Triangle Wave Output.
4	DCA1	I	Duty Cycle Adjustment Input.
5	DCA2	I	Duty Cycle Adjustment Input.
6	V_{CC}		Positive Power Supply.
7	FMBI	I	Frequency Modulation Input.
8	FMSI	I	Frequency Sweep Input.
9	SQO	O	Square Wave Output.
10	TC	I	Timing Capacitor Input.
11	V_{EE}		Negative Power Supply.
12	SA2	I	Wave Form Adjust Input 2.
13	NC		No Connect.
14	NC		No Connect.

+12V　　VA　　Vtri　　Vcont

Vcc　　OUTPUT 2　　IN2(−)　　IN2(+)

OUTPUT 1　　IN1(−)　　IN1(+)　　GND

VB　　Vtri　　−Vcont　　−12V
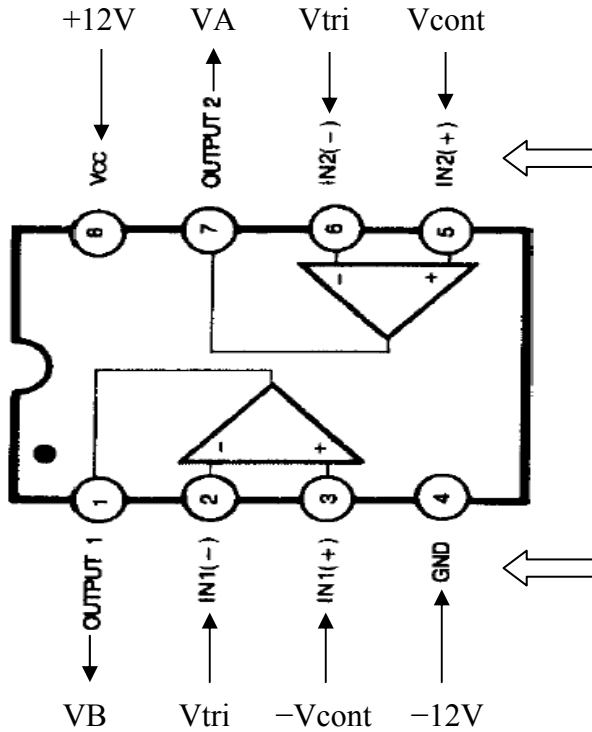
Dual Comparator

If Vcont > Vtri, Then
　VA = 12V, so
　VA = 24V (w.r.t. –12V)
Else
　VA = –12V, so
　VA = 0V (w.r.t. –12V)
Endif

If –Vcont > Vtri, Then
　VB = 12V, so
　VB = 24V (w.r.t. –12V)
Else
　VB = –12V, so
　VB = 0V (w.r.t. –12V)
Endif

220kΩ resistors between Inputs+ and Outputs provide hysteresis to prevent rapid switching due to noise
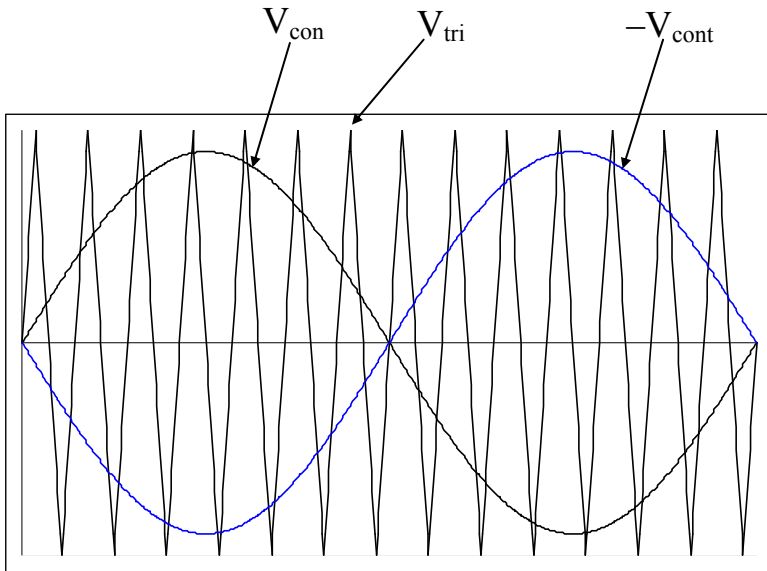
V_{con}　　V_{tri}　　$-V_{cont}$

Vcont > Vtri , close switch A+, open switch A− , so voltage Va = Vdc

Vcont < Vtri , open switch A+, close switch A− , so voltage Va = 0

–Vcont > Vtri , close switch B+, open switch B− , so voltage Vb = Vdc

–Vcont < Vtri , open switch B+, close switch B− , so voltage Vb = 0

- VA and VB outputs, relative to –12V, are produced to switch the H-bridge MOSFET driver chips. These two voltages are related to the logic on page 1 and to the circuit in Figure 7.

3. Calibration and Checkout
For tests 3b through 3e, I suggest that you use one of the AC wall warts (marked with yellow paint) for Vcont. Its output is isolated, so there will be no grounding issues between it and the scope.

Note – From now on, anytime that you use your circuit, you should always
- Make sure that your triangle wave skewness is OK
- Tune out any DC in the triangle wave
- Make sure –Vcont is a negative replica of Vcont

The results shown here were taken with one of the older scopes. However, you will be able to obtain approximately the same screen shots with the newer benchtop scopes.

3a. View and Adjust the Triangle Wave
For my tests, I used a 1.5nF capacitor for C_F. You can use either 1.0nF or 1.5nF. The frequency of my triangle wave generator varied with C_F as follows:

Cap Marking	Freq
10**2** = 10**00** pF = 1 nF	200 kHz
15**2** = 15**00** pF = 1.5 nF	137 kHz
22**2** = 22**00** pF = 2.2 nF	98 kHz
47**2** = 47**00** pF = 4.7 nF	44 kHz
10**3** = 10**000** pF = 10 nF = 0.01 µF	19 kHz
10**4** = 10**0000** pF = 100 nF = 0.1 µF	1.7 kHz
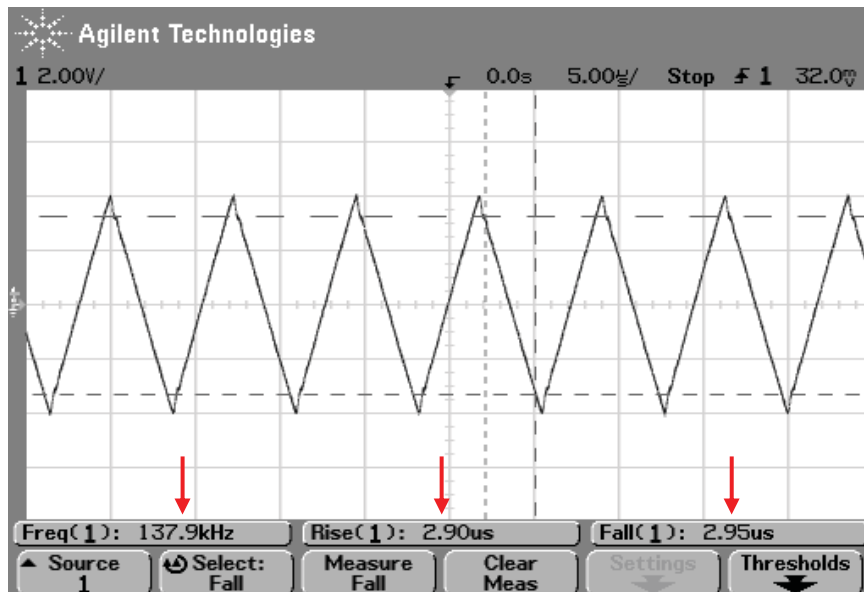
- Adjust the skewness multiturn pot so that rise and fall times match in the first two digits.
- Use a multimeter to read the DC voltage at point VtriDC on your PCB. Switch on the ZeroDC switch, and adjust the 100Ω multiturn pot to reduce VtriDC to about ±1mV.

3b. View Vcont and establish –Vcont

Some of the yellow-painted AC wall warts are equipped with an audio jack to plug directly into your Left or Right input channel.
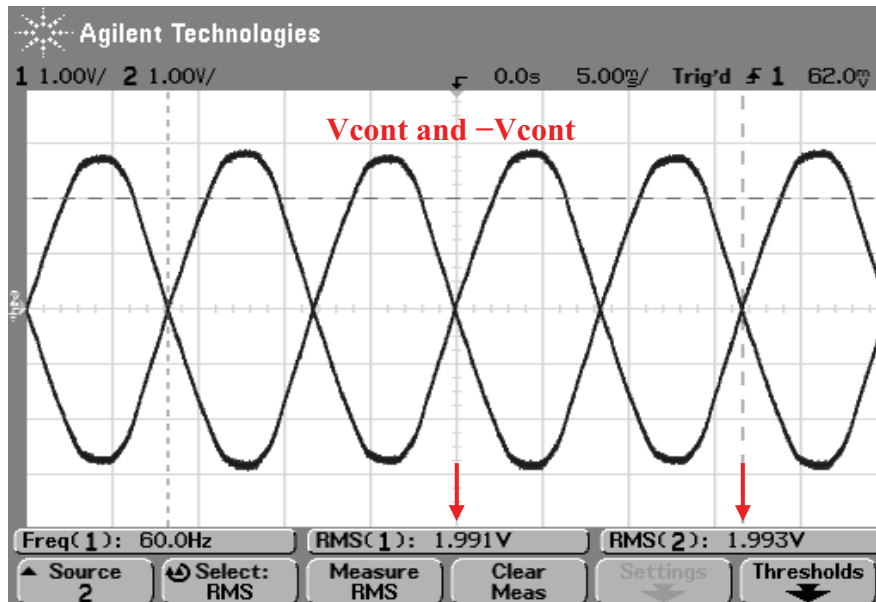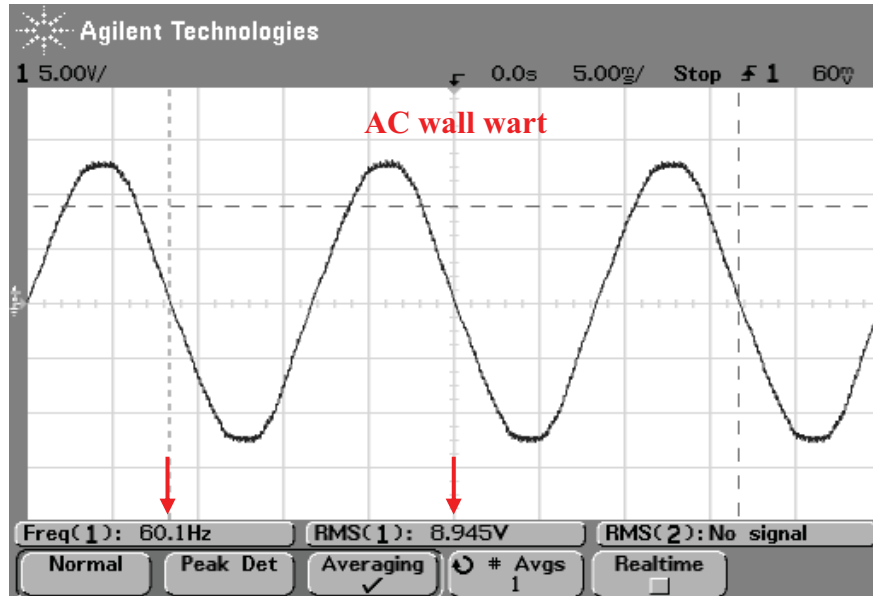
- Adjust B100k gain potentiometer so that Vcont is about 2.0 Vrms.
- Adjust the –Vcont multiturn pot so that –Vcont is the negative replica of Vcont.

3c. View Output VAB in the Linear Region

With Vcont ≈ 2 Vrms, ratio m_a will be less than one and thus in the linear region. Remove your channel 2 scope probe, and move channel 1 over to view output VAB. When the switching noise is filtered from the screen, VAB should be a close approximation to Vcont (but with a reduced magnitude).

Linear region. VAB without scope filter
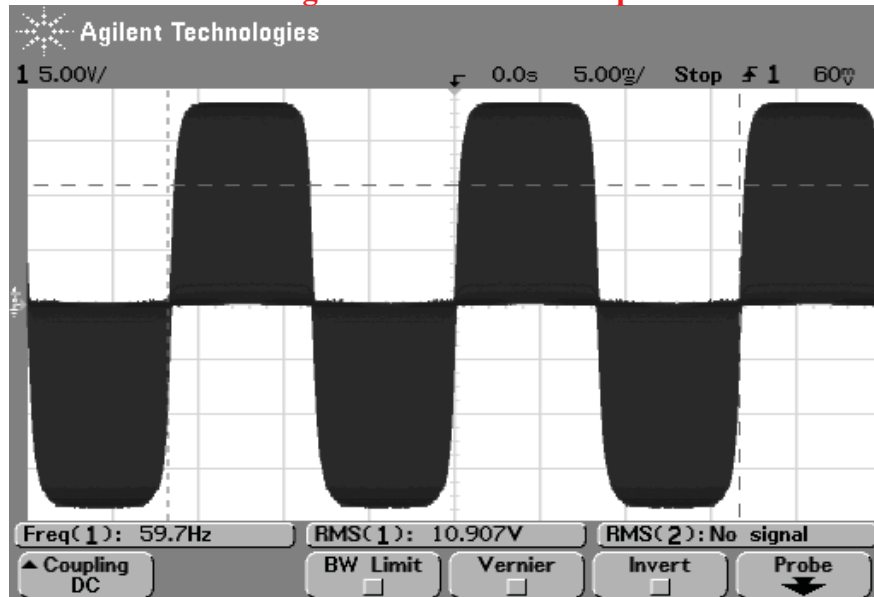

Linear region. VAB with scope filter
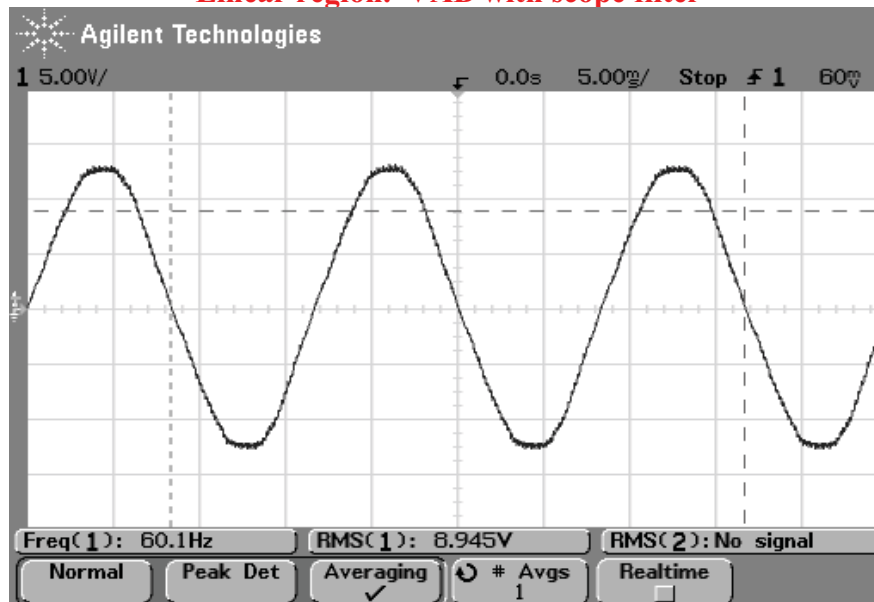
3d. View Output VAB in the Overmodulation Region

If Vcont has symmetry, output VAB should always have symmetry, too, even in overmodulation or full saturation. The flat spots should be symmetric in the positive and negative portions of VAB. Any DC offset in the triangle wave or in Vcont will produce asymmetry in VAB.

**Overmodulation Region, unfiltered**
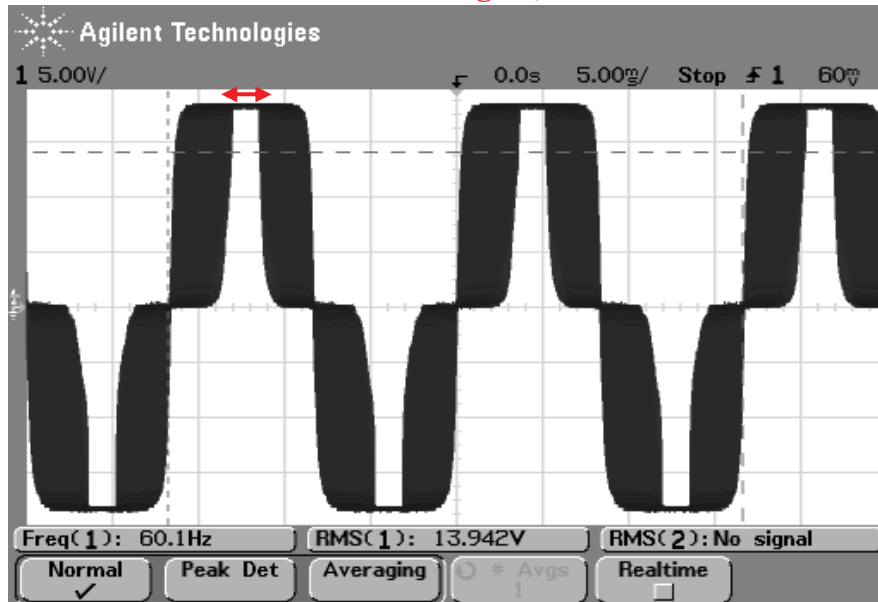
Overmodulation Region, filtered
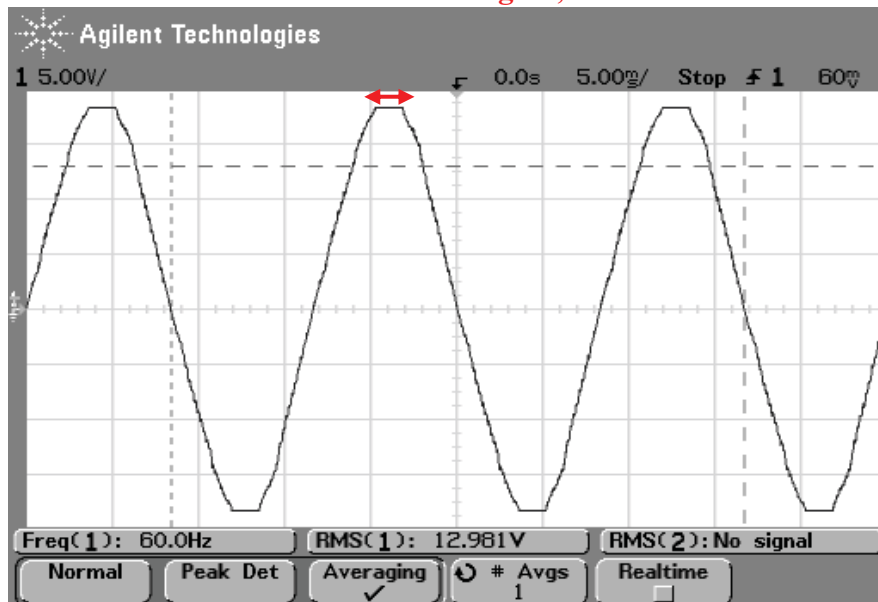
3e. FFT of VAB

The FFT of VAB shown here has span = 500 kHz, and center frequency 250 kHz. Theoretically the clusters of high-frequency switching noise should be centered around $2 \cdot F_{tri}$ (≈ 270 kHz) and $4 \cdot F_{tri}$ ≈ 540 kHz (which is off scale here).

The vertical scale is 20dB per division. It appears that the non-ideal 135 kHz cluster is about 40dB down from the ideal 270 kHz cluster. 40dB down is a factor of 100.
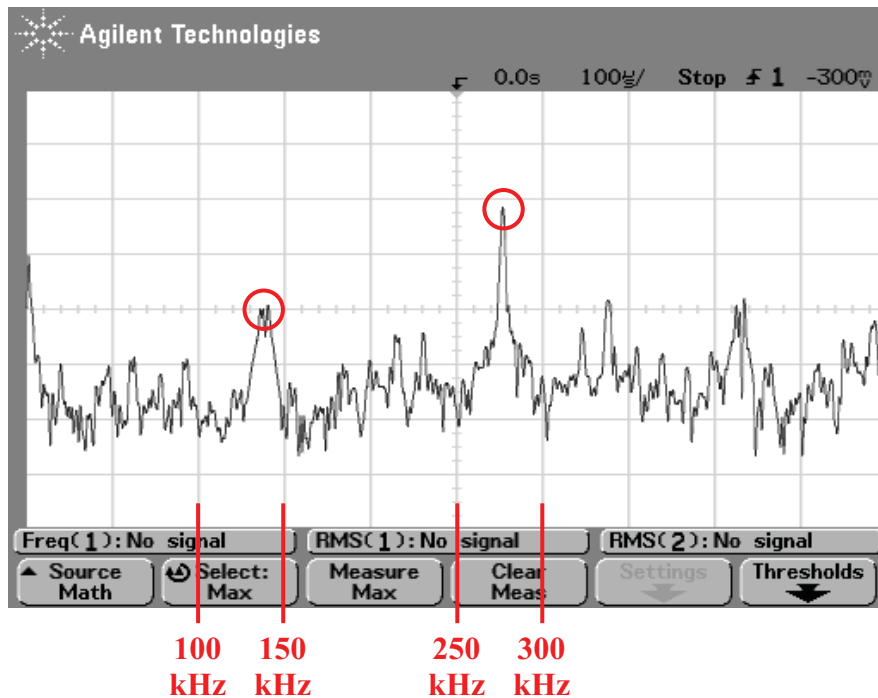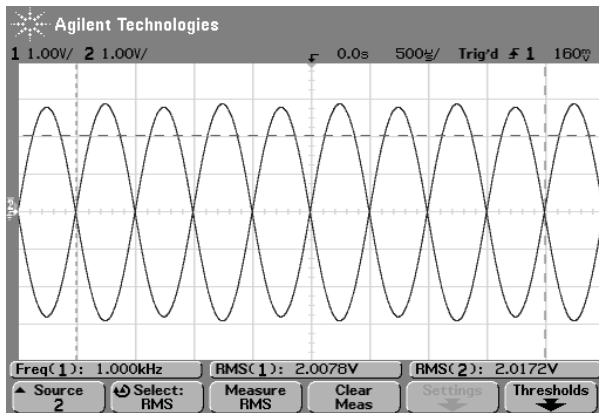
3f. Vcont, -Vcont, and VAB for 1 kHz and 10 kHz

Now, test out your circuit with higher frequencies. Take your Vcont signal from a benchtop waveform generator. It is essential that the scope be powered through a ground buster so that VAB can be viewed. Adjust gain B100k and the multiturn pot so that Vcont and –Vcont are 2.0 Vrms.

I temporarily placed a 0.01µF capacitor across VAB to help filter out the switching noise. That explains the drop in VAB magnitude. Remove the 0.01µF **before operating the H-bridge, else the PWM switching signal will not reach the H-bridge.**
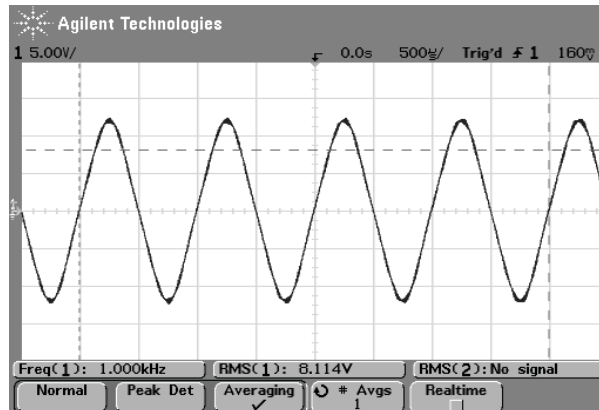
<div align="center">

Vcont and –Vcont for 1 kHz   **Vcont and –Vcont for 10 kHz**

</div>

<div align="center">
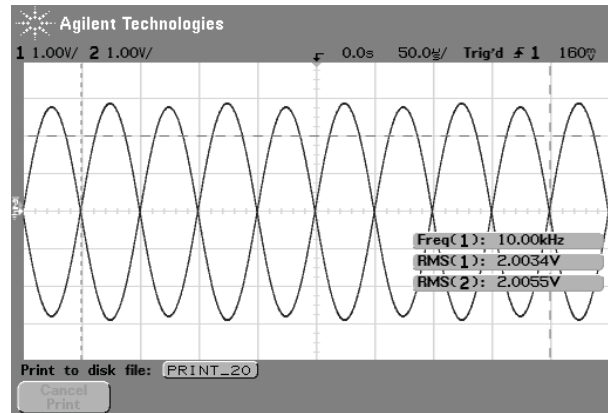
Filtered VAB for 1 kHz   **Filtered VAB for 10 kHz**

</div>