ECEN-438/738 Power Electronics
Spring-2025

Lab 9: DC-AC PWM Inverter

Lab 9: DC-AC PWM Inverter Operation

The goal of this lab is to investigate the behavior of a DC-AC Pulse Width Modulated (PWM) Inverter, which is widely used in variable frequency AC drives for induction motors. First, we review the principle of operation and the main waveforms of a PWM Inverter, based on a MOSFET full-bridge converter topology. Next, we analyze the effect of L-C filter by means of simulations. Finally, we perform lab experiments to obseve the AC output voltage and perform ripple voltage measurements.

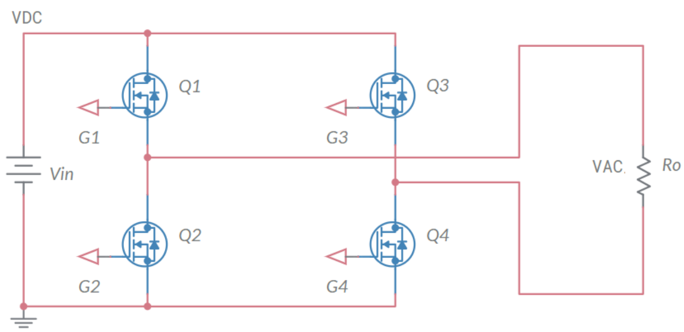


Figure 1-1. DC-AC Inverter

Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Given a DC-AC PWM Inverter, with specified modulation and switching PWM signals setup, you will calculate the amplitude of sinusoidal and ripple components of AC current and voltage, with specified units and accuracy, and determine the L-C output filter parameters needed to limit the amplitude of ripple components below given limits, under different switching frequency operating conditions.
2. Given a DC-AC PWM Inverter, you will simulate its operation under different PWM signals and L-C filter setup, to analyze the amplitude of sinusoidal and ripple components of AC current and voltage, and verify their consistency with theoretical predictions.
3. Given a real DC-AC PWM Inverter with configurable PWM signals and L-C output filter, you will observe the AC load voltage waveform, and measure the amplitude of sinusoidal and ripple components, with specified units and accuracy, under different L-C output filter and PWM signals setup.

1 Theory and Background

1-1 Introduction

In this section, we review the fundamental concepts relevant to the operation of a single-phase DC-AC PWM inverter based on a MOSFET full-bridge. First, we analyze the principle of operation and the resulting AC voltage waveform. Next, we discuss the filtering effect of load inductance. Finally, we analyze the effect of an L-C filter.

1-2 DC-AC Inverters Fundamentals

An ideal DC-AC inverter converts a DC voltage V_{DC} into an AC sinusoidal voltage $V_{AC}(t)$, as shown in Figure 1-2.

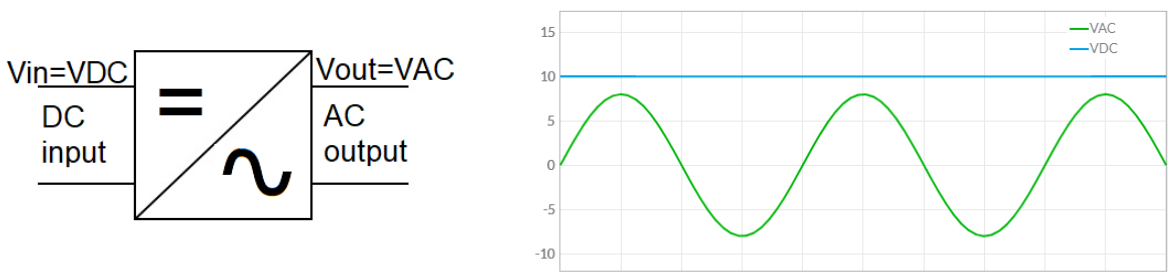


Figure 1-2. Inverter Input and Output waveforms.

The ideal output AC voltage of a DC-AC inverter is given by Equation 1-1:

Equation 1-1

$$V_{AC,ideal}(t) = kV_{DC}\cos(2\pi f_m t)$$

where f_m is the desired frequency and k is a constant. The DC-AC conversion can be performed by means of several circuit topologies and control techniques, providing an AC voltage characterized by different levels of accuracy with respect to the ideal sinusoid of Equation 1-1. The output of a real DC-AC inverter is given by Equation 1-2:

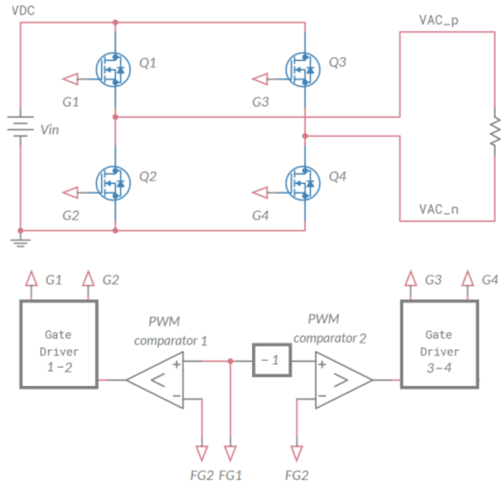
Equation 1-2

$$V_{AC,real}(t) = kV_{DC}\cos(2\pi f_m t) + \sum_{n=1}^{\infty} A_n \cos(2\pi n f_m t + \theta_n)$$

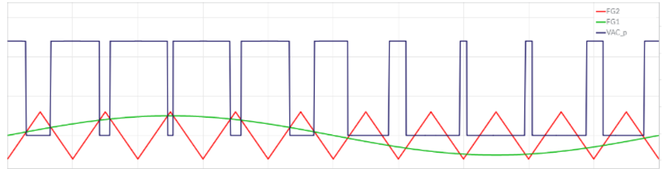
where the magnitude A_n of the harmonics is determined by the circuit topology and modulation technique. Harmonics are undesired high-frequency effects determined by DC-AC inverter operation. They must be kept with levels that are compatible with a correct and safe operation of load and source, and ensure that the electro-magnetic emission limits imposed by Electro Magnetic Compatibility (EMC) regulations are met.

1-3 DC-AC PWM Inverter.

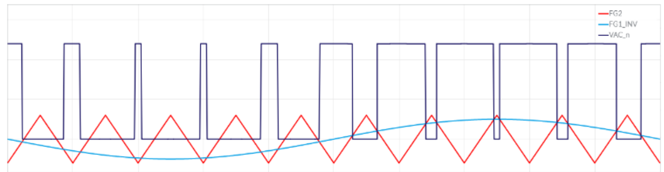
Figure 1-2 shows a DC-AC Pulse Width Modulated (PWM) inverter.



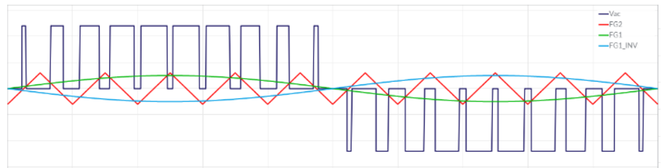
(a) DC-AC PWM Inverter With Ohmic Load



(b) Half-Bridge Q1-Q2 Voltage $V_{AC\_p}(t)$



(c) Half-Bridge Q3-Q42 Voltage $V_{AC\_n}(t)$



(d) Load AC Voltage $V_{AC}(t) = V_{AC\_p}(t) - V_{AC\_n}(t)$

Figure 1-2. MOSFET Full-Bridge Inverter.

The MOSFET full bridge is comprised of two half-bridges. The half-bridge Q1-Q2 operates in PWM mode (see **Lab5**), driven by PWM comparator 1. As shown in Figure 1-2(b), the signal $FG1(t)=V_{ref}\cos(2\pi f_m t)$, of period $T_m = 1/f_m$, is the *modulation reference* for the output voltage $V_{AC}(t)$. The triangular waveform $FG2(t)$, of period $T_s = 1/f_s$, is the *modulation carrier*. Normally the *switching frequency* f_s is much greater than the *modulation frequency* f_m. For AC frequency f = 50Hz, the PWM switching frequency f_s can be 5kHz. The resulting output voltage $V_{AC\_p}(t)$ of the half-bridge Q1-Q2 is the modulated square pulses train shown in Figure 1.2(b). The half-bridge Q3-Q4 also operates in PWM mode, driven by PWM comparator 2, with an inverter reference signal *FG1_INV(t) = - FG1(1)* (see Figure 1-2(c)). The resulting output voltage $V_{AC\_n}(t)$ of the half-bridge Q3-Q4 is the modulated square pulses train shown in Figure 1.2(b). The resulting voltage $V_{AC}(t) = V_{AC\_p}(t) - V_{AC\_n}(t)$ applied to load resistor R_o is the sequence of square pulses of amplitude V_{DC} shown in Figure 1-2(d). The width of pulses is modulated by the reference sinusoidal signal $FG1(t)$. If the PWM triangular carrier has a peak-peak amplitude V_{rpp}, the average $V_{AC,av}(t)$ of the AC voltage $V_{AC}(t)$ over each half switching period $T_s/2$ is given by Equation 1-3:

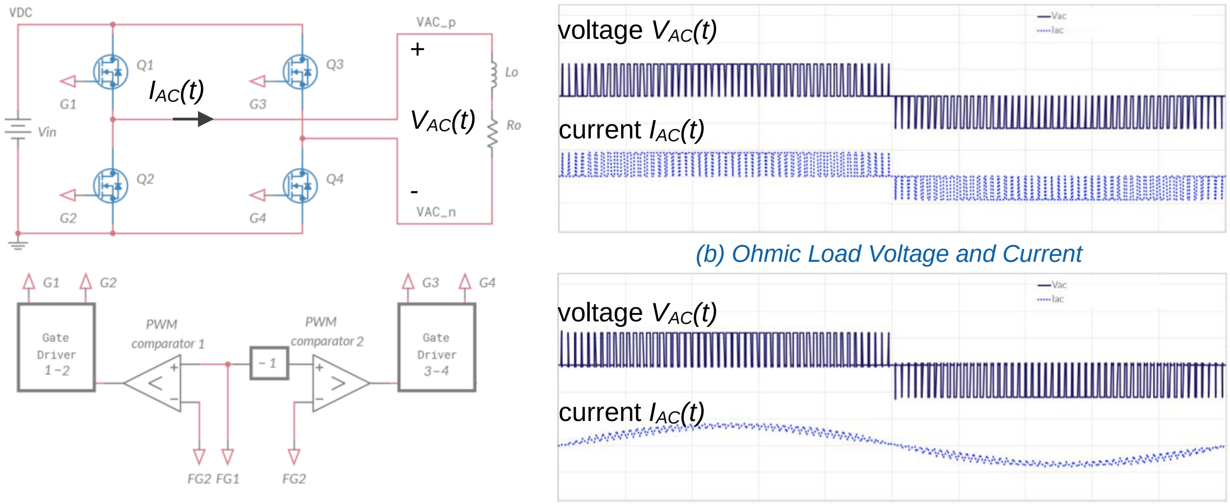
Equation 1-3

$$V_{AC,av}(t) = \frac{2}{T_s}\int_{t_0}^{t_0+T_{s/2}} V_{AC}(t)dt \cong D(t)V_{DC}; \qquad D(t) = \frac{2V_{ref}}{V_{rpp}}\sin(2\pi f_m t)$$

where *D(t)* is the *modulation duty-cycle* of the DC-AC PWM inverter output voltage.

1-4 Impact of Load Inductance.

Figure 1-3(b) shows the current waveform of an AC ohmic load. Many AC loads, like induction motors, are ohmic-inductive. If the PWM switching frequency f_s is sufficiently high, the L-R low pass nature of the load determines the current waveform shown in Figure 1-3(c).



(a) DC-AC PWM Inverter With Ohmic-Inductive Load

(b) Ohmic Load Voltage and Current

(c) Ohmic-Inductive Load Voltage and Current

Figure 1-3. AC Currents of Ohmic and Ohmic-Inductive Loads Powered by a DC-AC PWM Inverter.

The current of the ohmic-inductive load exhibits a sinusoidal component at modulation frequency f_m of the reference signal and a triangular ripple component at PWM switching frequency f_s. The sinusoidal component is given by Equation 1-4:

Equation 1-4

$$I_{AC}(t) = \frac{V_{DC}}{Z_{f_m}} D(t); \qquad Z_{f_m} = \sqrt{R_o^2 + (2\pi f_m L_o)^2}$$

The peak-peak amplitude of the switching frequency ripple component is time varying, and is given by Equation 1-5 (see **Lab6**):

Equation 1-5

$$\Delta I_{AC,pp}(t) = \frac{V_{DC} - R_o I_{AC}(t)}{2L_o f_s} D(t) = \frac{V_{ref} V_{DC}}{L_o f_s V_{rpp}} \left(1 - \frac{2V_{ref} R_o}{Z_{f_m} V_{rpp}} \sin(2\pi f_m t)\right) \sin(2\pi f_m t)$$

From Equation 1-5, the amplitude of the peak-peak ripple component $\Delta I_{AC,pp}(t)$ is maximum at the instant t_{max} given by Equation 1-6:

Equation 1-6

$$\text{if } \frac{Z_{f_m} V_{rpp}}{4R_o V_{ref}} \le 1: \; t_{\max} = \frac{T_m}{2\pi} \arcsin\left(\frac{Z_{f_m} V_{rpp}}{4R_o V_{ref}}\right); \quad \text{if } \frac{Z_{f_m} V_{rpp}}{4R_o V_{ref}} > 1: \; t_{\max} = \frac{T_m}{4}$$

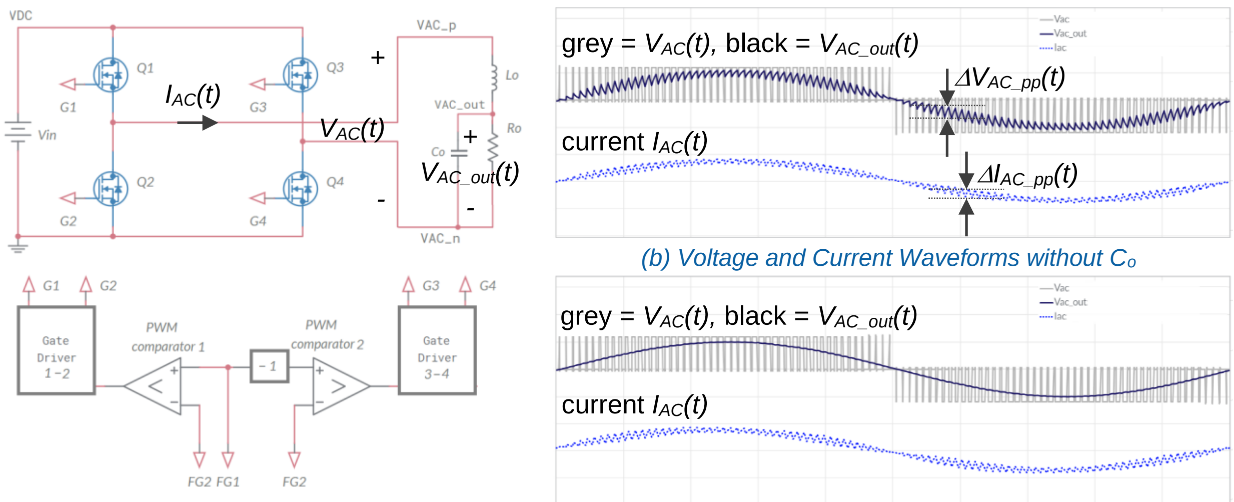
The maximum amplitude of peak-peak AC ripple component is given by Equation 1-7:

Equation 1-7

$$\text{if } \frac{Z_{f_m} V_{rpp}}{4R_o V_{ref}} \le 1: \; \Delta I_{AC,pp\max} = \frac{V_{DC} Z_{f_m}}{8R_o L_o f_s}; \quad \text{if } \frac{Z_{f_m} V_{rpp}}{4R_o V_{ref}} > 1: \; \Delta I_{AC,pp\max} = \frac{V_{ref} V_{DC}}{L_o f_s V_{rpp}} \left(1 - \frac{2V_{ref} R_o}{Z_{f_m} V_{rpp}}\right)$$

1-5 DC-AC PWM Inverter with L-C Filter.

If an ohmic load requires an AC voltage with low harmonic content, the modulated square wave voltage generated by the MOSFET full-bridge must be filtered by means of an L-C filter (insight the same concept in **Lab6**), resulting in the waveforms shown in Figure 1-4.



(b) Voltage and Current Waveforms without C_o

(a) DC-AC PWM Inverter With L-C Filter

(c) Voltage and Current Waveforms with C_o

Figure 1-4. AC Currents of an Ohmic Load Powered by a DC-AC PWM Inverter with L-C Filter.

As discussed in Section 1-4, the current of an ohmic-inductive load has a sinusoidal component at frequency f_m of the reference signal and a triangular ripple component at switching frequency f_s. Adding an inductor L_o in series to an ohmic load R_o determines the same effect of an ohmic-inductive load. The inductance L_o needed to keep the peak-peak amplitude of AC ripple component below a given limit $\Delta I_{AC\_out,ppmax}$, is given by Equation 1-7:

Equation 1-7

$$L_o = \frac{V_{DC}}{4 f_s \Delta I_{AC\_out,pp\max}}$$

Without a parallel capacitor, the resulting maximum peak-peak amplitude of ripple voltage on load resistor R_o will be $\Delta V_{AC\_out,ppmax} = R_o \Delta I_{AC\_out,ppmax}$. The maximum peak-peak amplitude of load ripple voltage with a parallel capacitor of capacitance C_o is given by Equation 1-8:

Equation 1-8

$$\Delta V_{AC\_out,pp\max} = \frac{\Delta I_{AC\_out,pp\max}}{8 f_s C_o}$$

From Equation 1-8, the capacitance C_o needed to keep the maximum peak-peak amplitude of switching frequency load ripple voltage below a given limit $\Delta V_{AC\_out,ppmax}$ is given by Equation 1-9:

Equation 1-9

$$C_o = \frac{\Delta I_{AC\_out,pp\max}}{8 f_s \Delta V_{AC\_out,pp\max}}$$

Check Your Understanding

Note: The following questions are meant to help you self-assess your understanding so far. You can view the answer key for all "Check your Understanding" questions at the end of the lab.

1-1 What is the function of a DC-AC inverter?

A. to convert a DC source voltage into an AC load voltage
B. to invert the flow of energy between a DC source and a DC load
C. to invert the polarity of a DC source voltage

1-2 How can we achieve the conversion of a DC voltage into an AC voltage?

A. by means of a transformer
B. by means of a MOSFETs full-bridge
C. by means of a diodes full-bridge

1-3 What type of AC waveform we obtain with a DC-AC PWM inverter?

A. a sinusoid with a triangular ripple component
B. a sinusoid with a DC component
C. a train of square pulses

1-4 What type of AC load powered by DC-AC PWM inverter absorbs a quasi-sinusoidal current?

A. an ohmic-capacitive load
B. an ohmic-inductive load
C. an ohmic load

1-5 How do we obtain a sinusoidal AC voltage for an ohmic load from a DC-AC PWM inverter?

A. by mean of an L-C filter
B. by means of capacitors in parallel to the MOSFETs
C. by means of an inductor in series to the source

1-6 How do the values of the inductance and capacitance of the L-C filter of a DC-AC PWM inverter, needed to limit the amplitude of AC current and voltage ripple components, change as the PWM switching frequency increases?

A. they increase
B. they decrease
C. they do not depend on the PWM switching frequency

2 Exercise

The MOSFET full-bridge of the DC-AC Inverter Section of the TI Power Electronics Board for NI ELVIS III can be connected to a 50Ω load resistor R_o through an L-C filter, comprised of a 6.8mH series inductor L_o and a 10µF parallel capacitor C_o.

2-1 Assuming that the DC source provides a DC voltage V_{DC} = 10V, the PWM modulator triangular carrier has a 5kHz switching frequency f_s and a 6.0V peak-peak amplitude V_{rpp}, the AC reference voltage has a 50Hz modulation frequency f_m and 2.5V amplitude V_{ref}, use the rules and equations provided in the **Theory and Background** section to calculate:

- the amplitude of AC sinusoidal component $I_{AC}(t)$ of the series R_o-L_o at modulation frequency f_m, in Ampère with three decimal digits of accuracy:
  I_{AC} = ____________
- the maximum peak-peak amplitude of AC ripple component $\Delta I_{AC,pp}(t)$ of the series R_o-L_o at switching frequency f_s, in Ampère with three decimal digits of accuracy, and the ratio between the instant t_{max} where that maximum is reached and the modulation period T_m, with two decimal digits:
  $\Delta I_{AC,pp\max}$ = ____________ t_{max}/T_m = ____________
- the maximum peak-peak amplitude of AC ripple component $\Delta V_{AC\_out,pp}(t)$ of voltage on ohmic load resistor R_o at switching frequency f_s, in Volt with three decimal digits of accuracy:
  $\Delta V_{AC,pp\max}$ = ____________

2-2 Assuming R_o= 50Ω, for the values of switching frequency f_s listed in Table 2-1, use the equations provided in the **Theory and Background** section to calculate:

- the L-C filter inductance L_o needed to limit the maximum peak-peak amplitude of AC current ripple component $\Delta I_{AC,pp\max}$ to 50mA, in milli Henry with two decimal digits of accuracy;
- the L-C filter capacitance C_o needed to limit the maximum peak-peak amplitude of AC voltage ripple component $\Delta V_{AC\_out,pp\max}$ to 100mV, in micro Farad with two decimal digits of accuracy.

Table 1-1 Inductance and Capacitance of L-C filter as Function of PWM Switching Frequency f_s.

f_s [kHz]	1	5	10	50
L_o [mH]				
C_o [µF]				

3 Simulate

The goal of the simulations you will perform in this section is to analyze the operation of a DC-AC PWM Inverter. You will observe the AC voltage and current waveforms under different operating conditions, to verify the impact of PWM switching frequency and the consistency of the theoretical model.

3-1 Instructions

1. Open *Lab9 – DC-AC PWM Inverter Operation* from this file path: https://www.multisim.com/content/kTPAgYp6A2aPhxtxVMBdMd/lab-9-dc-ac-inverter-pwm-operation/
   The circuit schematic for the analysis of the DC-AC PWM inverter is shown in Figure 3-1. The MOSFETs are modeled by means of two *Single Pole Single Throw (SPST)* switches. The gate drivers include time delays *td1–td4* and gates A1–A4 to prevent cross conduction of the MOSFETs. The switches *JLo* and *JCo* allow the output L-C filter configuration. An input L-C filter is also included, which can be configured by means of switches *JLin* and *JCin*. Voltage-Controlled sources *AC_probe* and *AC_out_probe* allow AC differential voltage measurements.

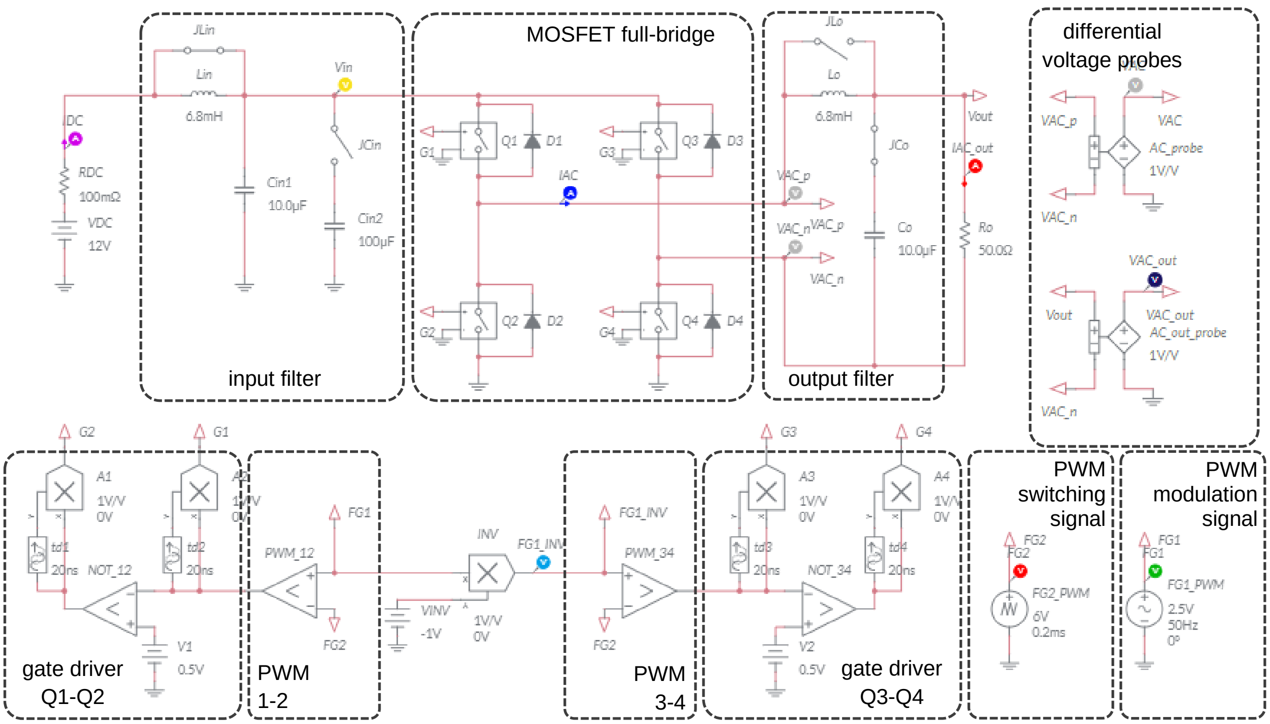


Figure 3-1. Multisim Live Circuit Schematic for the Analysis of the DC-AC PWM Inverter Operation.

3-1-1 Simulation 1 - PWM inverter operation with ohmic load.

1. Set the switches as indicated in Table 3-1-1.

Table 3-1-1 Switches Setup for Simulation 1

JLin	JCin	JLo	JCo
shorted	open	shorted	open

2. Set the circuit parameters as follows:
   - *FG1 (sinusoidal modulation signal)*: *VA* = 2.5V, *Freq* = 50Hz, Offset 0.0V;
   - *FG2 (triangular switching signal)*: *VA* = 6V, *Per* = 500µs, *TF* = 250µs, Offset -3V;
3. Double click on probes *FG1*, *VAC_out* and *IAC_out,* and check the *Show plot* option box. Uncheck the *Show plot* option box for all the other probes.
4. *Interactive* simulation and *Grapher* visualization options.
5. Run the simulation and wait until it stops.

3-1-1 Is the waveform of AC voltage of load resistor *VAC_out* a train of square pulses, whose width is proportional to the instant value of the modulation sinusoid *FG1*?

A. yes
B. no
Please provide your comments: ____

____

3-1-2 Are the waveforms of load resistor voltage and current *VAC_out* and *IAC_out* similar?

A. yes
B. no
Please provide your comments: ____

____

3-2-1 Simulation 2 - PWM inverter operation with ohmic load and series filter inductor.

1. Set the switches as indicated in Table 3-2-1.

Table 3-2-1 Switches Setup for Simulation 1

JLin	JCin	JLo	JCo
shorted	open	open	open

2. Set the circuit parameters as follows:
   - *FG1 (sinusoidal modulation signal)*: *VA* = 2.5V, *Freq* = 50Hz, Offset 0.0V;
   - *FG2 (triangular switching signal)*: *VA* = 6V, *Per* = 500µs, *TF* = 250µs, Offset -3V;
3. Double click on probes *FG1*, *VAC, VAC_out* and *IAC_out,* and check the *Show plot* option box. Uncheck the *Show plot* option box for all the other probes.
4. Select *Interactive* simulation and *Grapher* visualization options.
5. Run the simulation and wait until it stops.

3-2-1 Do the waveforms of AC voltage *VAC_out* and current *IAC_out* of load resistor show a sinusoidal component at modulation frequency f_m and a ripple component at switching frequency f_s?

A. yes

B. no

Please provide your comments: ____

____

3-2-2 Is the peak-peak amplitude of AC voltage *VAC_out* and current *IAC_out* ripple component variable during the modulation period T_m?

A. yes

B. no

Please provide your comments: ____

____

3-2-2 Detect the instant t_{max} where the peak-peak amplitude of AC voltage *VAC_out* and current *IAC_out* ripple component reach the maximum and calculate the ratio t_{max}/T_m. Is the result consistent with the value calculated by means of *Equation 1-6* provided in the **Theory and Background** Section?

A. yes

B. no

Please provide your comments: ____

____

3-3-1 Simulation 3 - PWM inverter operation with ohmic load and L-C Filter.

1. Set the switches as indicated in Table 3-3-1.

Table 3-3-1 Switches Setup for Simulation 1

JLin	JCin	JLo	JCo
shorted	open	open	shorted

2. Set the circuit parameters as follows:
   - *FG1 (sinusoidal modulation signal)*: *VA* = 2.5V, *Freq* = 50Hz, Offset 0.0V;
   - *FG2 (triangular switching signal)*: *VA* = 3V, *Per* = 500µs, *TF* = 250µs, Offset -3V;
3. Double click on probes *FG1*, *VAC, IAC, VAC_out* and *IAC_out,* and check the *Show plot* option box. Uncheck the *Show plot* option box for all the other probes.
4. Select *Interactive* simulation and *Grapher* visualization options.
5. Run the simulation and wait until it stops.

3-3-1 Is the peak-peak amplitude of ripple components of load voltage and current at switching frequency f_S lower than in Simulation 2?

A. yes

B. no

Please provide your comments: ____

____

3-3-2 Is the peak-peak amplitude of AC ripple component at switching frequency f_S bigger in current *IAC* or in current *IAC_out*?

A. bigger in current *IAC*

B. bigger in current *IAC_out*

C. other: ____

____

Please provide your comments: ____

____

Troubleshooting tips:

If the simulation does not converge and you get some error message, reload *Lab9 – DC-AC PWM Inverter Operation* from this file path https://www.multisim.com/content/kTPAgYp6A2aPhxtxVMBdMd/lab-9-dc-ac-inverter-pwm-operation/ and restart the simulation following the instructions.

4 Implement

The experiments you perform in this section allow you to observe the voltage and current waveforms of a real DC-AC PWM inverter operation, under different operating conditions. The **DC-AC Section** of the TI Power Electronics Board for NI ELVIS III shown in Figure 4-1 will be used to perform the experiments. The full-bridge uses four TI's CSD16322Q5C MOSFETs, two TI's TLV7011DPWR comparators and two TI's UCC27712DR MOSFET drivers. The full-bridge AC output can be connected to a 50Ω resistance R_o, by means of the Jumper J21. The jumpers J24 and J27 allow to connect a 6.8mH inductor in series and a 10µF in parallel to the load resistor R_o, respectively. The modulation sinusoidal signal *FG1* and the triangular switching signal *FG2* are available at test points TP71 and TP70, respectively. The datasheets of TI's components are available at these links:

- CSD16322Q5C MOSFET: (http://www.ti.com/lit/ds/symlink/csd16322q5c.pdf)
- TLV7011DPWR COMPARATOR: (http://www.ti.com/lit/ds/symlink/tlv7011.pdf)
- UCC27712DR GATE DRIVER: (http://www.ti.com/lit/ds/symlink/ucc27712.pdf).

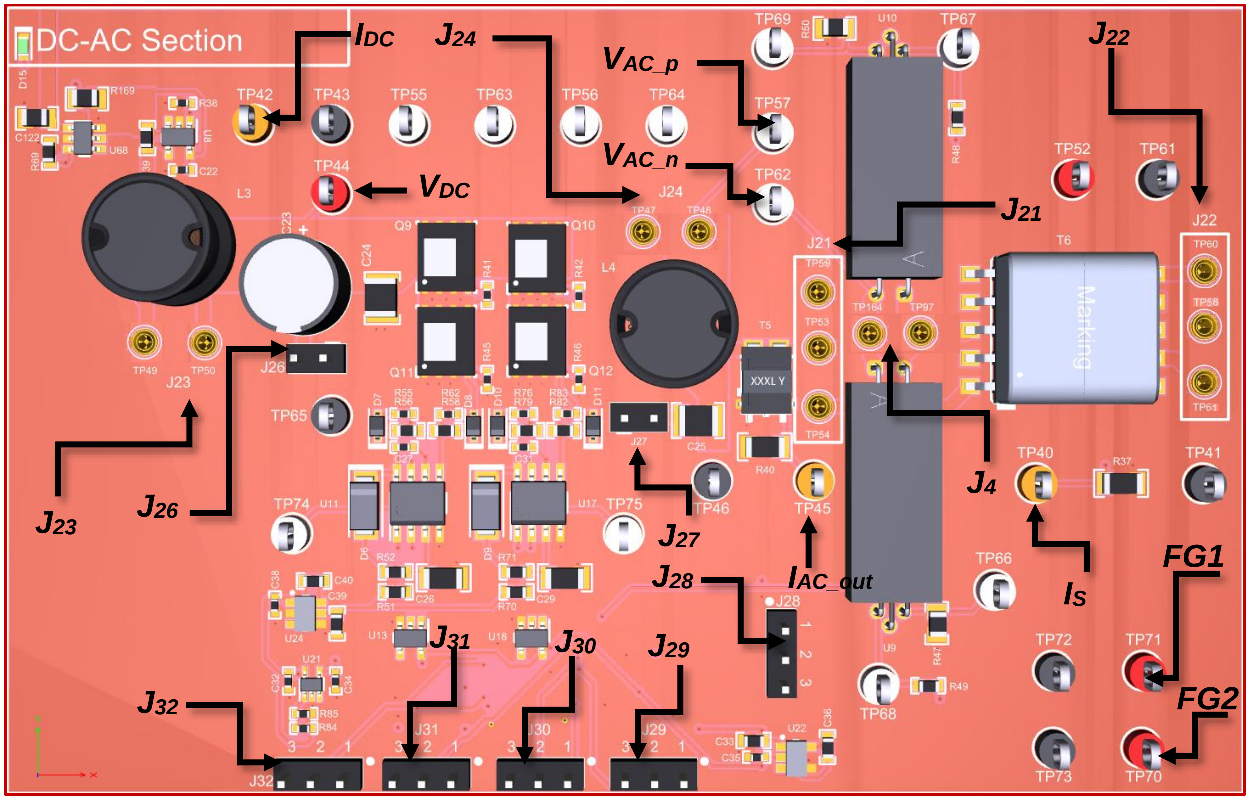


Figure 4-1. TI Power Electronics Board for NI ELVIS III – DC-AC Section Used for the Analysis of MOSFET DC-AC PWM Inverter Operation.

[**Note:** the parameters provided in the following instructions for instruments setup may require some adjustment due to thermal effects and tolerances of TI Power Electronics Board components]

4-1 Instructions

1. Open *Power Supply*, *Function Generator*, *Oscilloscope* and *Pattern Generator* using Measurements Live. For help on launching instruments, refer to this help document: http://www.ni.com/documentation/en/ni-elvis-iii/latest/getting-started/launching-soft-front-panels/
2. Open the *User Manual* of TI Power Electronics Board for NI ELVIS III from this file path: http://www.ni.com/en-us/support/model.ti-power-electronics-board-for-ni-elvis-iii.html
3. Read the *User Manual* sections *Description*, *Warnings* and *Recommendations* regarding *Discrete Buck Section*.
4. Open the *TI Top Board RT Configuration Utility* of TI Power Electronics Board for NI ELVIS III (See Required Tools and Technology section for download instructions), and select *Lab9 – DC-AC PWM Inverter Operation*.
5. Connect and configure the instruments as indicated in Tables 4-1 and 4-2. [**Note:** the AC load voltage can be observed on the *Oscilloscope* Math channel, which provides the difference between CH-1 (V_{AC_p}) and CH-2 (V_{AC_n})]

Table 4-1 Instruments Connections

Power Supply	connect to red and black banana connectors
Oscilloscope	connect CH-1 to TP57 (V_{AC_p}), connect CH-2 to TP62 (V_{AC_n}) connect CH-3 to TP70 (*FG2*), connect CH-4 to TP71 (*FG1*)
Function Generator	connect CH-1 to FGEN1 BNC connector (→TP71 = *FG1*) connect CH-2 to FGEN2 BNC connector (→TP70 = *FG2*)
Pattern Generator	connect TRIG to DIO 0 (red) and GND (black) using a BNC-to-Alligator Cable

Table 4-2 Instruments Configuration and setup

<table>
<tr><td>Power Supply</td><td colspan="20">Channel "+": Static, 10.00V, Channel "-": Inactive</td></tr>
<tr><td rowspan="2">Oscilloscope</td><td colspan="5">Trigger:
Analog Edge,
CH-4, set to 50%</td><td colspan="5">Horizontal:
2ms/div</td><td colspan="5">Acquisition:
average</td><td colspan="5">Measurements:
hide</td></tr>
<tr><td colspan="4">Channel 1: ON
• DC coupling
• 5V/div
• offset 15V</td><td colspan="4">Channel 2: ON
• DC coupling
• 5V/div
• offset 0V</td><td colspan="4">Channel 3: ON
• DC coupling
• 1V/div
• offset 0V</td><td colspan="4">Channel 4: ON
• DC coupling
• 1V/div
• offset 0V</td><td colspan="4">Math: ON
• CH1-CH2
• 5V/div
• offset -15V</td></tr>
<tr><td>Function Generator</td><td colspan="20">follow instructions provided below</td></tr>
<tr><td>Pattern Generator</td><td colspan="20">follow instructions provided below</td></tr>
</table>

6. Configure the jumpers of the board as indicated in Table 4-3.

Table 4-3 Jumpers Setup

J21	J22	J23	J24	J26	J27
short TP53-TP59	open	shorted	shorted	shorted	open
J4	J28	J29	J30	J31	J32
shorted	short 2-3	short 2-3	short 2-3	short 1-2	short 2-3

7. Perform the Experiments 1 to 5 in the sequence they are presented.

4-2 Experiment 1 - PWM inverter operation with ohmic load, 50Hz modulation frequency and 2kHz switching frequency.

1. On *Channel 1* of the *Function Generator*:
   a. select *Custom* and use the file selector to select the TDMS waveform *Lab9_FG1_sinusoidal_50Hz_450mVpp_25kSps*;
   b. set *Trigger source* to *TRIG*, set *Gain* to 1, set *Update rate* to 25kS/s, set *Generation mode* to *Loop*.
2. On *Channel 2* of the *Function Generator*:
   a. select *Custom* and use the file selector to select the TDMS waveform *Lab9_FG2_triangular_2kHz_1Vpp_25kSps*;
   b. set *Trigger source* to *TRIG*, set *Gain* to 1, set *Update rate* to 1MS/s, set *Generation mode* to *Loop*.
3. On *Logic Analyzer and Pattern Generator*:
   a. click on *"+"* in the *Pattern Generator* section;
   b. click on *Signal* to add a new signal to the *Pattern Generator*;
   c. check the box next to *Logic 0* to add the line and click on the whitespace in the instrument;
   d. set *Status* to *On*, set *Mode* to *Clock*, set *Frequency* to 1Hz, set *Duty cycle* to 50%.
4. Run *Oscilloscope, Pattern Generator*, *Function Generator* and *Power Supply*.
5. Stop *Power Supply, Function Generator, Pattern Generator* and *Oscilloscope*.
6. You should see on the *Oscilloscope* the 50Hz sinusoidal modulation waveform on CH4 and the 2kHz triangular switching waveform on CH3.

4-2-1 Please describe the waveforms you observe on *Oscilloscope* CH-1 and CH-2:

____

____

4-2-2 Please describe the waveforms you observe on *Oscilloscope* Math channel:

____

____

4-2-3 Is the waveform of the load voltage observed on Math channel corresponding to your expectation, based on **Theory and Background** learning and simulations?

A. yes

B. no

Please provide your comments: ____

____

____

4-4 Experiment 2 - PWM inverter operation with ohmic load and series inductor.

1. Set the jumper J24 to be OPEN.
2. Run *Oscilloscope, Pattern Generator*, *Function Generator* and *Power Supply*.
3. Stop *Power Supply, Function Generator, Pattern Generator* and *Oscilloscope*.

4-4-1 Does the waveform of the load voltage you observe on Math channel comply with your expectation, based on **Theory and Background** learning and simulations?

A. yes

B. no

Please provide your comments: ____

____

____

4-4-2 Is there a sinusoidal component at modulation frequency in the load voltage waveform?

A. yes

B. no

Please provide your comments: ____

____

4-4-3 Is there a triangular component at switching frequency in the load voltage waveform?

A. yes

B. no

Please provide your comments: ____

____

4-4-4 Does the peak-peak amplitude of the triangular component at switching frequency show a maximum over the modulation period? where? what is its value?

A. yes:

it is located at t_{max}/T_m = _______ , and its value is $\Delta V_{AC\_out,pp\max@fs}$ [mV] = _______

B. no

Please provide your comments: ____

____

[**Note:** the *Oscilloscope* sampling rate is 25kS/s when time base is set to 2ms/div: the resulting measurement of the peak-peak amplitude of the triangular component at switching frequency $\Delta V_{AC\_out,pp\max@fs}$ can be not accurate. To improve the measurement accuracy, you can reduce the *Oscilloscope* time base to 200µs/div]

4-5 Experiment 3 - PWM inverter operation with ohmic load, series inductor and parallel capacitor.

1. Set the jumper J27 to be SHORTED.
2. Run *Oscilloscope, Pattern Generator*, *Function Generator* and *Power Supply*.
3. Stop *Power Supply, Function Generator, Pattern Generator* and *Oscilloscope*.
4. Using the *Oscilloscope* cursors on the Math channel, measure the peak-peak amplitude of the load voltage waveform at the modulation frequency f_m, in Volts with one decimal digit: $V_{AC\_out,pp@fm}$ = _______;

4-4-1 Does the waveform of the load voltage you observe on Math channel complies with your expectation, based on **Theory and Background** learning and simulations?

A. yes

B. no

Please provide your comments: ____

____

4-4-2 Is the sinusoidal component at modulation frequency in the load voltage waveform the same you have observed in Experiment 3?

A. yes

B. no

Please provide your comments: ____

____

4-4-3 Does the peak-peak amplitude of the triangular component at switching frequency show a maximum over the modulation period? where? what is its value?

A. yes:

it is located at t_{max}/T_m = _______ , and its value is $\Delta V_{AC\_out,pp\mathrm{max}@fs}$ [mV] = _______

B. no

Please provide your comments: ____

____

[**Note:** the *Oscilloscope* sampling rate is 25kS/s when time base is set to 2ms/div: the resulting measurement of the peak-peak amplitude of the triangular component at switching frequency $\Delta V_{AC\_out,pp\mathrm{max}@fs}$ can be not accurate. To improve the measurement accuracy, you can reduce the *Oscilloscope* base to 200µs/div]

Troubleshooting tips:

- If the DC-AC PWM inverter does not work, or the waveforms look much different with respect to simulations, verify the correct setup and connections of jumpers and instruments, following the directions provided in Tables 4-1, 4-2 and 4-3, and restart the experiments.

5 Analyze

5-1 Compare the Oscilloscope waveforms to the simulated waveforms, and discuss their similarities and differences based on ***Theory and Background*** equations:

____

____

____

6 Conclusion

6-1 Summary

Write a summary of what you observed and learned about the operation of a DC-AC PWM Inverter, and discuss the impact of switching frequency, inductance and capacitance on the resulting load voltage waveform.

6-2 Expansion Activities

Investigate the DC source current determined by the operation of a DC-AC PWM Inverter, by means of Multisim Live simulations.

6-2-1. Open *Lab9 – DC-AC PWM Inverter Operation* from this file path:
https://www.multisim.com/content/kTPAgYp6A2aPhxtxVMBdMd/lab-9-dc-ac-inverter-pwm-operation/
The switches JCin and JLin allow connecting the additional 100µF parallel capacitor and 6.8mH series inductor to the DC source. These two component help filtering the switching frequency ripple current component of the AC current I_{AC}.

6-2-2. Set the switches as indicated in Table 6-2-1.

Table 6-2-1 Switches Setup

JLin	JCin	JLo	JCo
shorted	open	open	open

a. Set the circuit parameters as follows:
- *FG1 (sinusoidal modulation signal)*: *VA* = 2.5V, *Freq* = 50Hz, Offset 0.0V;
- *FG2 (triangular switching signal)*: *VA* = 6V, *Per* = 200µs, *TF* = 100µs, Offset -3V;

b. Double click on probes *IDC, FG1*, *VAC* and *IAC,* and check the *Show plot* option box. Uncheck the *Show plot* option box for all the other probes.

c. Select *Interactive* simulation and *Grapher* visualization options.
d. Run the simulation and wait until it stops.
e. Export the grapher image as .png format file, or the grapher data as .csv format file.
f. Set the jumper JCin to be CLOSED and repeat steps f-g.
g. Set the jumpers JCin to be OPEN and JLin to be OPEN, and repeat steps f-g.
h. Compare the switching ripple components of the DC source current I_{DC} waveforms you have obtained with the three different simulations.

6-4 Resources for learning more

- These book provides the fundamentals of DC-AC Inverters:
  - P.Krein, *Elements of Power Electronics*, Oxford Press
  - N.Mohan, T.M.Undeland, W.P.Robbins, *Power Electronics: Converters, Applications and Design*, John Wiley & Sons