Department of Electronics and Electrical Engineering

School of Engineering

Power Electronics

Experiment 1:

Basic Voltage and Current Waveform Measurements

and PWM Generation

Student Name :

Matriculation Number:

Acknowledgements

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AIMS AND OBJECTIVES

The objective of this laboratory is to

- Introduce you to a number of voltage and current waveforms commonly found in modern power electronic circuits, and to test your skill in measuring basic waveform parameters (frequency, V_{pk}, V_{rms} etc.) using the appropriate electronic test equipment.

- Use Pulse-Width-Modulation Control IC TL494 to construct a 30~50kHz PWM signal generator with adjustable duty cycle.

You must bring a laboratory notebook for recording your result and hand in the completed notebooks at the end of semester.

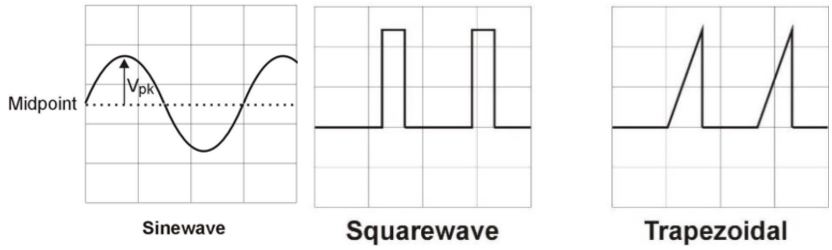
INTRODUCTION

Electrical/Electronic, Aerospace and Mechanical Engineering disciplines co-exist in many applications. In the modern workplace, engineers cannot consider their own specialisation in isolation; they must have at least some basic understanding of all disciplines to be able to function in this working environment. With this in mind it is essential in many applications that engineers of all branches have a basic appreciation of power electronics technology.

BACKGROUND-1: Periodic Waveforms and the definition of Peak, Mean and RMS

In power electronic circuits in their steady-state operation, the voltages and currents are either DC or have a periodic function with respect to time. In modern power electronics, the periodic function is not limited to 'traditional' sinusoidal functions (some examples being shown on Figure 1).

So when we talk about "current" or "voltage" we need to be precise about what measure we are using. A current can be measured by its peak, mean, RMS or instantaneous value. The peak value is the highest value (positive or negative). It determines peak mechanical forces on conductors (such as bonding wires or transformer windings). The mean value is important as the load current in a DC circuit, or in calculating the conduction loss in a diode, because in both these cases the power is proportional to the mean current (provided that the voltage is constant, which in DC circuits is usually the case). The RMS value is what determines the power loss in resistive circuit elements like resistors, MOSFETs, motor and transformer windings and cables. The same principles apply to voltage and current. In these notes, voltage is used as the main example.



a b c

Figure 1: Typical Power Electronic Voltage/Current Waveforms

Peak: The peak value for a sinusoidal signal is measured between the midpoint (typically at 0V, but not always) and the maximum voltage. (Refer Figure 1 a)

Mean or Average: A general periodic function $y(t)$, with period T, has an average or mean value Y_{av} given by:

$$Y_{av} = \frac{1}{T}\int_0^T y(t)dt \qquad \text{(Equation 1)}$$

In this context, "mean" and "average" are just two words with the same meaning. The true mean value of a pure AC signal is zero. If the AC signal also contains a constant DC offset then the mean value is equal to the DC offset. The mean value of sine and cosine functions is 0.

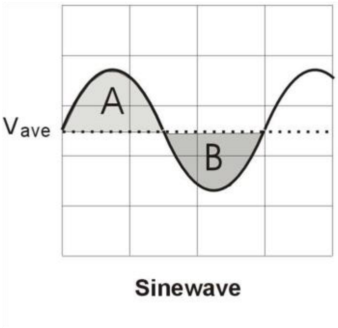


Figure 2: The average voltage corresponds to the level where the area about this line (A) is equal to the area below the line (B) over 1 period.

RMS: The Root Mean Square (RMS) or Effective value of a general periodic function *y(t)*, with period *T*, has an effective value Y_{rms} given by:

$$Y_{rms} = \sqrt{\frac{1}{T}\int_0^T y(t)^2\, dt} \qquad \text{(Equation 2)}$$

The RMS value of sine (e.g. $a\sin(\omega t)$) and cosine functions (e.g. $a\cos(\omega t)$) is $a/\sqrt{2}$.

The term "root mean square" tells us how to calculate the RMS value for any waveform: going backwards, we **S**quare the waveform (by replacing v with v^2); then we take the **M**ean value (over one period if the waveform is periodic); then we take the square **R**oot. The RMS value is important for one reason only: **heat**. Even then, it only applies to heat generated in resistive circuit elements. The instantaneous power dissipated in a resistance is $p = v\ i$, where $v = Ri$ is the voltage drop. Therefore $p = Ri^2$. If R is constant, the mean power is obviously proportional to the mean value of i^2. That is where the concept of RMS comes from. The mean power loss is therefore $P = Ri^2_{rms}$.

The following table outlines the values for DC and sinusoidal voltages:

Waveform	**Peak**	**Mean**	**RMS**
DC	V_{dc}	V_{dc}	V_{dc}
Sinusoid	V_{pk}	0	$V_{pk}/\sqrt{2}$

During the course of the laboratory you will determine these parameters for a number of other waveforms but a couple of points are worth noting at this stage:

1. For a DC signal peak, mean and rms are identical, and
2. The relationship $V_{rms} = V_{pk}/\sqrt{2}$ is ONLY valid for a sinusoidal waveform.

Experimental Equipment

Function Generator: The function generator is a device that is used to generate basic voltage signals such as sinusoidal and trapezoidal waveforms. Such signals can be used in a variety of applications to test given electrical and electronic equipment, examples being audio equipment, vibration testing and servo system evaluation. A brief outline of how to set up an output waveform is as follows (note that some functions are not used in some of the levels):

FUNCTION	DESCRIPTION
Select Waveform	Select the required waveform (sine, triangular or square)
Select frequency range	Select the desired frequency range
Set Desired Frequency	Adjust Frequency
Set Voltage Amplitude	Adjust Amplitude
Set DC Offset	Adjust offset and adjust
Set Duty Cycle	Adjust duty cycle

Notes:

1. Output Voltage is connected to the DMM and the Oscilloscope (not load)
2. TTL/CMOS output (if there is) – NOT USED
3. ATTN(衰减) -20dB button (if there is) – NOT USED

Digital Multimeter (DMM):

A digital multimeter is a very useful piece of test equipment and is used extensively in the industry. In its most basic form it is used to measure voltage, current and resistance (we will only use it for voltage measurement in this lab). For a periodic waveform we can select whether to measure the Mean (DC) or RMS (AC) of the waveform.

Points to Note about the DMM:

1. The DMM has a bandwidth limit (e.g. 1 kHz) which means that it is only accurate for voltage waveforms below this frequency.
2. The RMS (AC) reading is only true for a purely sinusoidal waveform. To measure rms values for other waveforms (square wave, trapezoidal) a true RMS digital multimeter is required. (Needless to say this is more expensive!)

Oscilloscopes:

The oscilloscope is by far the most commonly used instrument by electronic engineers and technicians. It is used to display instantaneous voltages as a function of time. A typical oscilloscope has 2 channels which can each display independent waveforms. Oscilloscopes come in two ‘flavours’: Analogue Oscilloscopes and Digital Sampling Oscilloscopes (DSO). The DSO is the more modern version, the main advantage being that waveforms can be stored on the display for subsequent analysis (even when the signal is no longer connected) and possible transfer to a PC. Another factor in oscilloscope performance is bandwidth. The bandwidth of the oscilloscope determines the maximum frequency which can be accurately displayed. The oscilloscope used in this laboratory has a bandwidth of 100MHz which is more than adequate for power electronic waveforms. Currents can also be displayed on oscilloscopes by using a current transducer (typically a Hall Effect device) which converts instantaneous current to an equivalent voltage which can then be output to the oscilloscope.

It is not assumed that you have previous experience in using an oscilloscope.

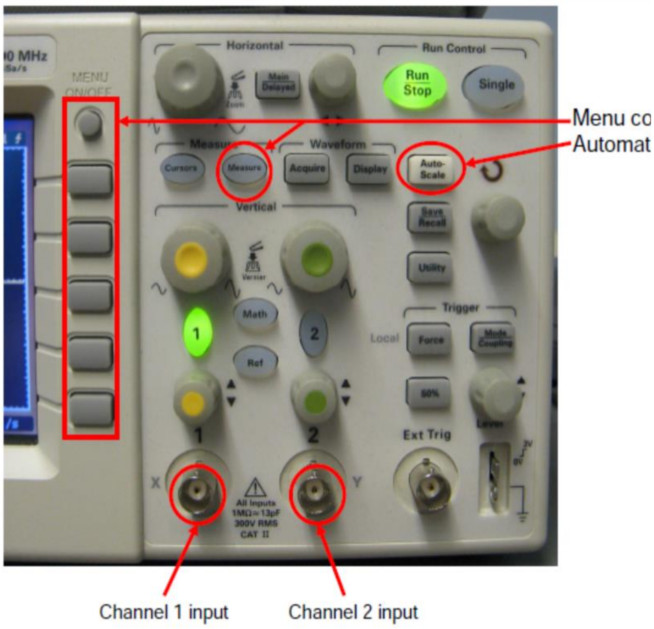


Figure 3: Digital Storage Oscilloscope Controls

Waveform position: It is essential that the full vertical extent of the waveform is on the oscilloscope display and that the zero volt position is known. Press the appropriate channel button (‘1’ or ‘2’) then, using the menu, set the coupling to ‘GND’ and adjust the trace position to the desired level. Set the coupling back to ‘DC’ when you have completed this to resume normal operation.

For each test waveform, you should strive to produce a waveform similar to that shown in Appendix A. The height of the waveform should be maximised using the vertical control knob and between one and two periods should be displayed using the horizontal control knob. This is an important point as it ensures the maximum possible resolution in each of the parameter measurements. Adjust the TRIGGER LEVEL knob to achieve a stable waveform if required.

It is also necessary to ensure you know the probe (input) attenuation factor. The oscilloscope permits the selection of 1X, 10X, 100X or 1000X probes. Using the menu controls, make sure you have selected the correct attenuation factor (1X) for the experiments.

Before starting the experiments you should take a few minutes to explore the different adjustments and measurement functions the oscilloscope offers and familiarise yourself with the operation of the controls. The following diagram shows the locations of the most frequently used controls.

Experimental Work

The setup for all experiments is shown in Figure 4 (note: Different Oscilloscope, DMM and Signal Generator may be used on lab benches):

<u>Experiment 1: Measurement of waveform period and calculation of frequency</u>

Aim

The aim is to accurately measure the period of a sinusoidal waveform using the oscilloscope timebase and from this determine the frequency of the waveform.

Experiment

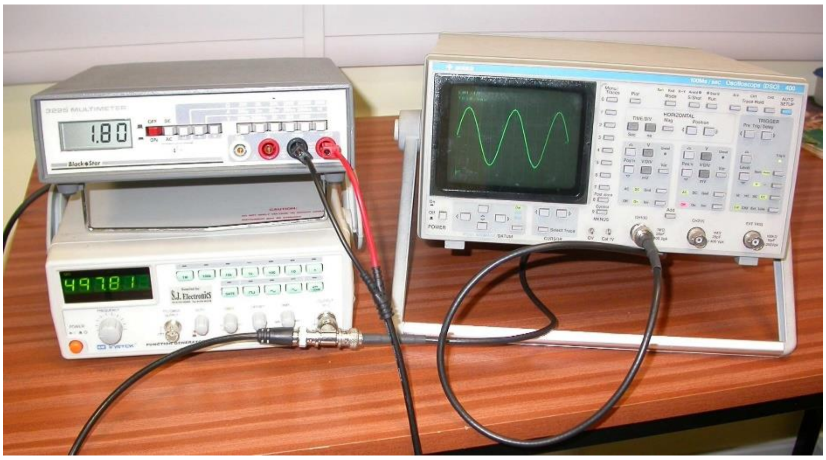


Figure 4: Experimental Setup

Frequency Generator Set Up:

Waveform	Frequency Range	Voltage Amplitude	DC Offset	Duty Cycle
Sinusoidal	1k	5V	Disable	Disable
User Control:	Frequency (knob)			

Using the CH1 volts/div control, the time base control and the triggering level control obtain a stable waveform similar to the one shown on **Appendix A**. Using the example shown as reference determine the period and the frequency of the frequency generator signal and confirm that the calculated frequency is similar to the value shown on the frequency generator display. Repeat this for a number of different frequencies (adjust frequency knob and/or frequency range on frequency generator) until you are comfortable with this measurement.

Make a copy of the output for your lab book, and record your measured data.

Challenge

With the frequency generator value hidden determine the period and frequency of the waveform using the oscilloscope. Compare resultant calculated frequency with frequency generator display. The calculated value should be within +/-2% of display value. Check your answers by using the oscilloscope's frequency and period measurement functions.

<u>Experiment 2: Measurement of the peak/RMS value of a sinusoidal waveform</u>

Aim

The aim is to accurately measure the peak value of a sinusoidal waveform using the oscilloscope and from this calculate the corresponding RMS value.

Experiment

Frequency Generator Set Up:

Waveform	Frequency Range	Voltage Amplitude	DC Offset	Duty Cycle
Sinusoidal	500 Hz	5V	Disabled	Disabled
User Control:	Voltage Amplitude (knob)			

Using the oscilloscope's channel 1 volts/div control, the timebase control and the triggering level control obtain a stable waveform similar to the one shown on Appendix A. Measure the peak voltage of the waveform and from this determine the RMS value using the sinusoidal relationship Vpk = √2.Vrms. Connect a DMM to the frequency generator output and select the AC option to measure the RMS value. Compare with the calculated value. Repeat this for a number of different amplitudes (adjust Amplitude knob on frequency generator) until you are comfortable with this measurement.

Make a copy of the output for your lab book, and record your measured data.

Challenge

Measure the peak voltage for an unknown sinusoidal waveform using the oscilloscope and calculate the corresponding RMS voltage. The answer should be within +/-5% of the measured value on a DMM. Check your answers by using the oscilloscope's RMS measurement function.

<u>Experiment 3: Measure of RMS value of Sinusoidal waveform with DC Offset</u>

Aim

In a number of applications the applied voltage consists of a sinusoidal voltage with a DC voltage offset. This type of waveform can be broken down into two components; a purely AC component and purely DC component (see Figure 5) and using the principal of superposition the total RMS value can be determined using the following equation:

$$V_{TOTAL\,rms} = \sqrt{({V_{ACrms}}^2 + {V_{DCrms}}^2)} \qquad \text{(Equation 3)}$$

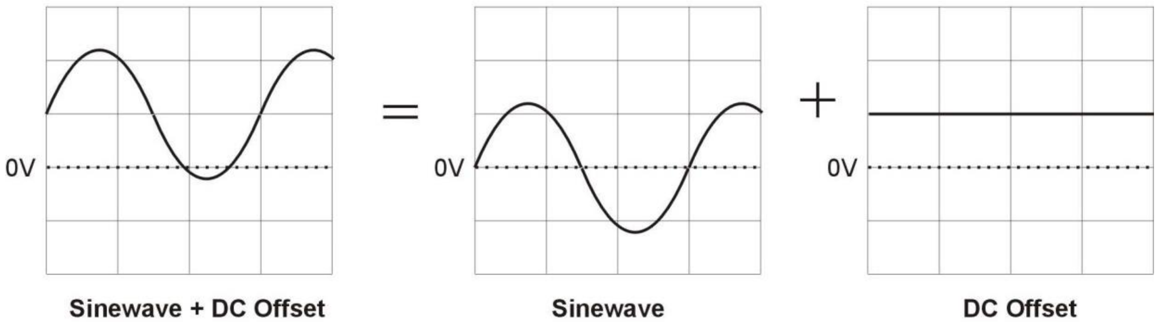
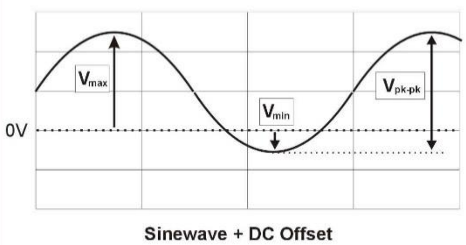


Figure 5: Splitting a AC+DC waveform into AC and DC parts



$$V_{pk\text{-}pk} = V_{max} - V_{min}$$

$$V_{ac\ pk} = \frac{V_{pk\text{-}pk}}{2} \qquad V_{dc} = V_{min} + V_{ac\ pk}$$

$$V_{ac\ rms} = \frac{V_{ac\ pk}}{\sqrt{2}}$$

Figure 6: Calculation of V_{dc} and V_{ac} rms values

NOTE: if V_{min} is negative then the negative value should be used in the above calculations: e.g. if V_{max} = 3V and V_{min} = -1V then V_{pk-pk} = 4V etc.

The aim is to measure the peak AC and DC values using the oscilloscope and from these calculate the total V_{rms} for this type of waveform. The suggested technique for calculating V_{dc} and V_{ac-rms} is outlined on Figure 6.

Experiment

Frequency Generator Set Up:

Waveform	Frequency Range	Frequency (Approximately)	DC Offset	Duty Cycle
Sinusoidal	1k	1 kHz	Enabled	Disabled
User Control 1: User Control 2:	Voltage Amplitude (knob) DC Offset (knob)			

Connect the frequency generator output to the oscilloscope channel 1 and for a given sinusoidal + DC offset waveform (user control) determine the sinusoidal V_{pk} and the DC voltage. Calculate the AC and DC RMS voltages and use Equation 3 to calculate the total RMS voltage. Using the DMM determine the mean DC component of the waveform (note mean = RMS for DC) and the RMS of the sinusoidal waveform using AC measurement and from this calculate the total RMS voltage using equation 3. Compare with the oscilloscope value. Repeat this for a number of different combinations of AC and DC offset (adjust Amplitude knob and DC Offset knob on frequency generator) until you are comfortable with this measurement.

Make a copy of the output for your lab book, and record your measured data.

Challenge

Measure the peak voltage and the DC offset for an unknown sinusoidal + DC offset waveform using an oscilloscope and calculate the corresponding total RMS voltage. The answer should be within +/-5% of the value calculated from the DMM measurements. Check your answers by using the oscilloscope's measurement functions and switching between AC and DC coupling on the input channel.

Experiment 4: Measurement of Square wave Duty Cycle

Aim A large number of power electronic applications include a constant DC voltage supply from which a variable mean voltage is produced using Pulse Width Modulation (PWM) control of a power electronic switch (eg. MOSFET, IGBT). With reference to Figure 7 the control switch is turned on and off at a high frequency (typically > 1kHz) such that the load (e.g. DC motor, heater element) 'sees' the average voltage during the PWM period (due to longer time constants).

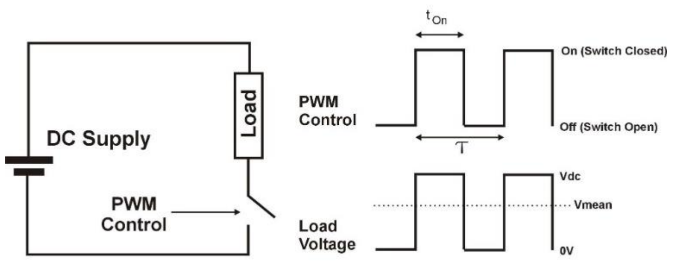


Figure 7: PWM Voltage Control in DC Systems

The Duty Cycle is defined as the ratio of the ON Time (t_{on}) divided by the Total PWM Period (τ) and has a value in the range 0 – 1. The aim of this experiment is to measure the duty cycle for a pulsed waveform.

$$Duty\ Cycle\ (D) = t_{on}/\ \tau$$

Often duty cycle is implemented in % by multiplying x 100.

Experiment

Frequency Generator Set Up:

Waveform	Frequency Range	Frequency (Approximately)	DC Offset	Duty Cycle
Squarewave	1k	2 KHz	Enabled	Enabled
User Control 1: User Control 2: User Control 3:	Voltage Amplitude (knob) Setup at Start of Experiment Only DC Offset (knob) Setup at Start of Experiment Only Duty Cycle (knob)			

The initial setup is to produce a 2V waveform with DC offset such that the lower voltage level is 0V (see Figure 8). This is achieved by setting the Voltage Amplitude and the DC Offset knobs and checking the waveform on the oscilloscope.

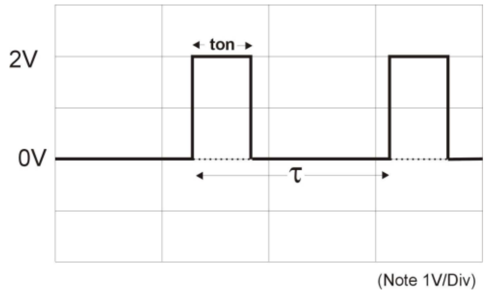


Figure 8: DC PWM Signal

Set the Duty Cycle knob to any value and using the oscilloscope determine the corresponding Duty Cycle value. Repeat for a number of duty cycle values until you are comfortable with this measurement.

Make a copy of the output for your lab book, and record your measured data.

Challenge

Determine the Duty Cycle for an unknown waveform. Your measurement procedure will be checked by the laboratory supervisor.

Experiment 5: Relationship between Mean Voltage and Duty Cycle

Aim

As outlined in the previous level in DC systems the mean output voltage is controlled by the Duty Cycle (D) of the switch. For a square wave as shown on Figure 8 (V_{pk} = 2V in this case) this can be expressed mathematically as:

$$V_{mean} = \frac{1}{\tau}\int_0^{\tau} v(t)\partial t$$

$$V_{mean} = \frac{1}{\tau}\left(\int_0^{t_{on}} V_{pk}.\partial t + \int_{t_{on}}^{\tau} 0.\partial t\right)$$

$$V_{mean} = \frac{1}{\tau}\left[V_{pk}.t\right]_0^{t_{on}}$$

$$V_{mean} = \frac{t_{on}}{\tau}.V_{pk}$$

$$V_{mean} = D.V_{pk}$$

The aim of this level is to experimentally verify this relationship.

Experiment

Frequency Generator Set Up:

Waveform	Frequency Range	Frequency (Approximately)	DC Offset	Duty Cycle
Square wave	1k	2 kHz	Enabled	Enabled
User Control 1: User Control 2: User Control 3:	Voltage Amplitude (knob) Setup at Start of Experiment Only DC Offset (knob) Setup at Start of Experiment Only Duty Cycle (knob)			

The initial setup is similar to the previous level; produce a 2V waveform with DC offset such that the lower voltage level is 0V. Note the measurement is very sensitive to the two voltage levels of the waveform so try to set these as accurately as possible, also make sure you know where the 0V level is on the Oscilloscope.

Connect the frequency generator output to the oscilloscope and the DMM. Select DC reading on the DMM to measure mean voltage. For duty cycle values (use as much range in Duty as possible) measure the duty cycle on the oscilloscope and the corresponding mean output voltage measured by the DMM.

Make a copy of the output for your lab book, and record your measured data.

Challenge

Graph the Mean Output Voltage (y axis) against Duty Cycle (x axis) for the experimental results. On the same graph plot the theoretical relationship (V_{pk} should equal 2V) using the equation:

$$V_{mean} = D.V_{pk}$$

BACKGROUND-2: TL494 based PWM Generation

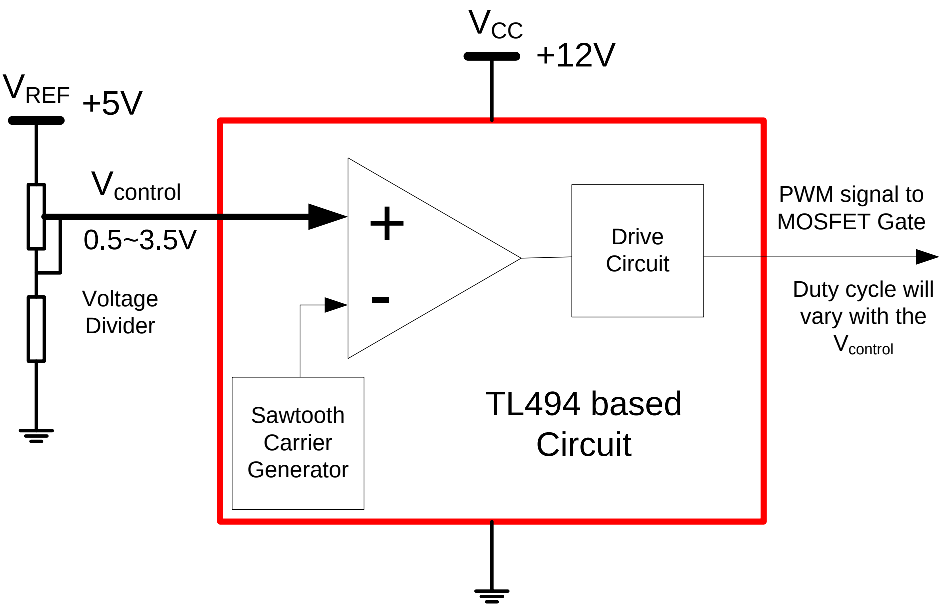


Figure 9: PWM Signal Generation Block Diagram

One of the fundamental control mechanisms for power semiconductors is to use high frequency on-off Control or Pulse Width Modulation (PWM) as shown in Figure 9. The TL494 is a fixed frequency, Pulse Width Modulation Control IC designed primarily for switch-mode power supply control. It incorporates all functions required in the construction of a pulse-width-modulation (PWM) control circuit on a single chip. Designed primarily for power-supply control, this device offers the flexibility to tailor the power supply control circuit to a specific application.

Experiment 6: TL494 based PWM Signal Generator

Aim

This experiment will take you through a step-by-step process of setting up the TL494 on breadboard as shown in Figure 10 and using it to generate output PWM control signals with adjustable duty-cycle. **The manufacturer's data sheet for the TL494 should be used with this lab sheet**.

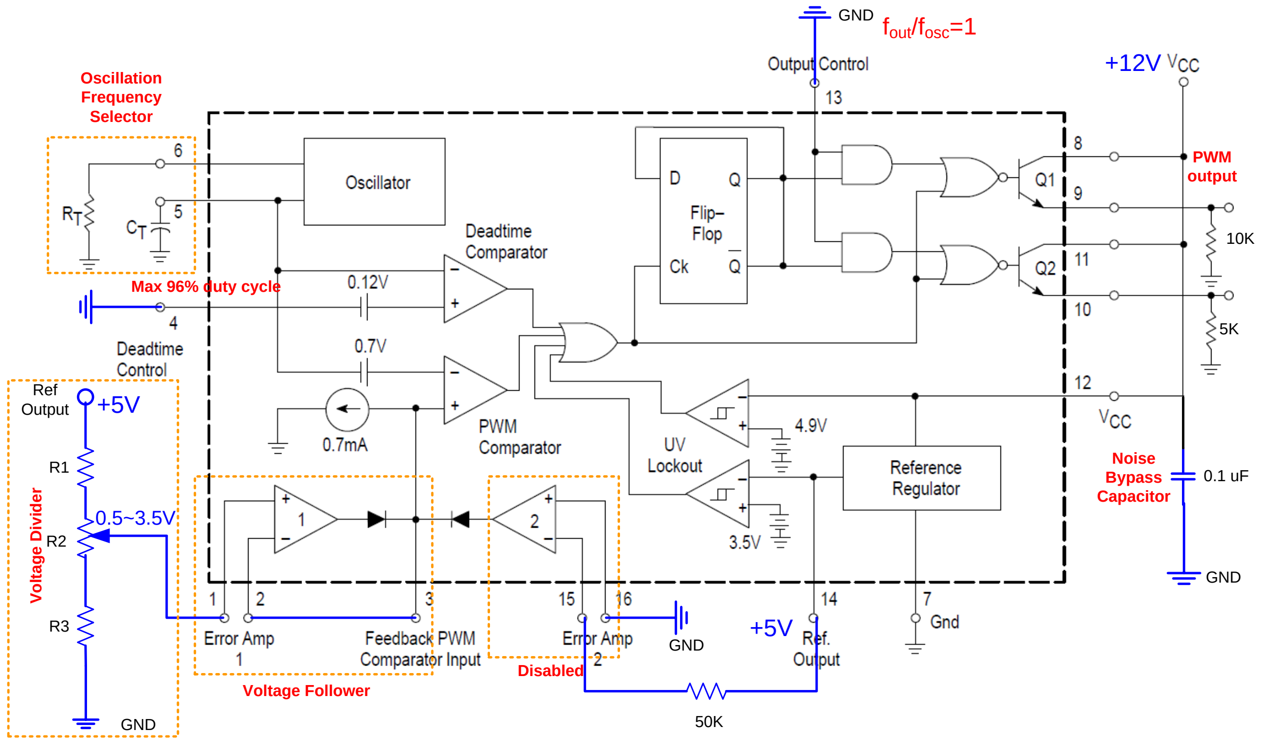


Figure 10: TL494-based PWM Signal Generation Circuit Connection

Experiment

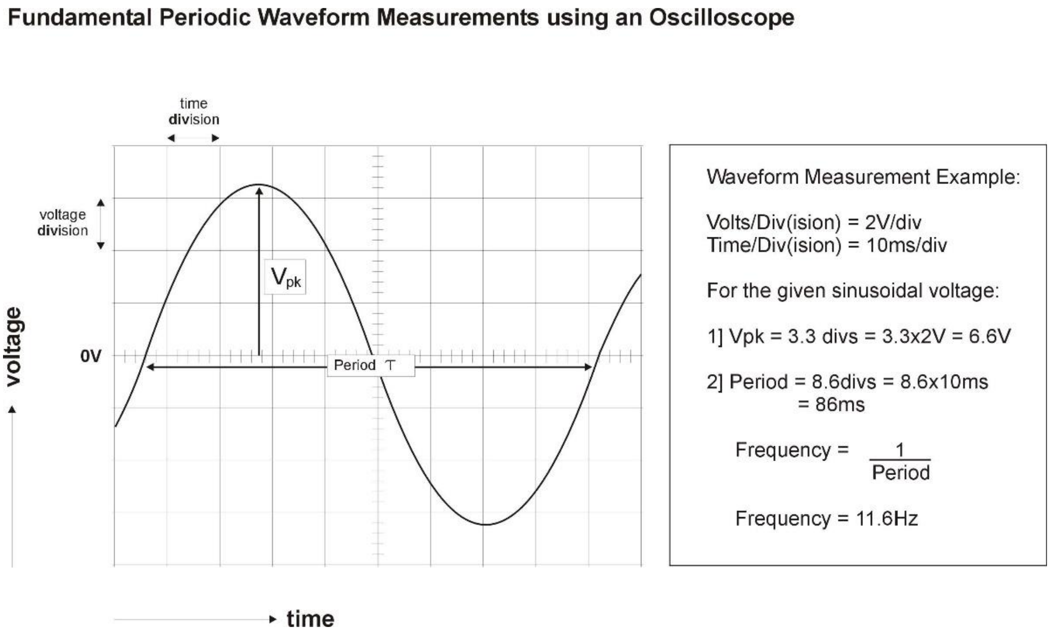
1. Connect a DC power supply (12V) to the TL494. During this experiment we will not change the deadtime control or use the Error Amplifier 2 , so pins 4 and 16 should all be tied down to ground, pin 15 is tied to Reference Output pin 14 via a 50k resistor.
2. Use Figure 3 in the data sheet to choose timing components to achieve an oscillator frequency of about 50 kHz. What values of RT and CT did you choose? On which pin does the sawtooth waveform appear? Measure the amplitude and frequency of the sawtooth.
3. Measure the Reference output voltage at pin 14. Use a voltage divider circuit to generate a variable voltage 0.5V~3.5V from the Reference output voltage. We will use this variable voltage as the control signal and it will be fed to pin 1. Pin 2 and 3 are connected to enable the Amplifier 1 to be a voltage follower.
   - What value resistors would you choose and why?
4. Single-ended Configuration
   Pin 13 is tied to the ground. Using the information of Figure 17 of the data sheet connect your TL494 in the single-ended configuration. Remember that the chip outputs Q1 and Q2 are open collector and you will need to tie the emitters to ground via a resistor.
   - What value resistor would you choose and why?

   Now vary your input control voltage at pin 1 from low to high, while observing the output from Q1 and Q2.
   - What is the minimum control voltage to produce any output?
   - What is the maximum control voltage when the output saturates?
   - What is the maximum duty cycle you can achieve?

Before you apply power to the circuit, ask a laboratory demonstrator to check your connections (especially pins Vcc and Gnd).

Make a copy of the output waveforms (sawtooth at pin 5, PWM outputs from Q1 and Q2) for your lab book, and adjust the control voltage value at pin 1 from 0.5 to 3.5V and record your measured data set (control voltage at pin 1, duty cycle of PWM outputs from Q1 and Q2).

Appendix A



Appendix B

Calculation of Percentage Error

The equation used to calculate Percentage Error between two measurements is given by:

$$\%Error = ((V_{theory} - V_{measured}) / V_{theory}) \times 100\%$$

Where if both values are measured values, then choose the most accurate as the theory value (DMM in this case).