

FINAL PROJECT REPORT  
EE3390 ELECTRONIC CIRCUITS DESIGN LAB

POWER INVERTER

Craig Danton  
Nimit Mehta

Submitted in partial fulfillment of the requirements for the  
Bachelor's of Science Degree

December 11<sup>th</sup>, 2008

Department of Electrical Engineering  
Columbia University

## TABLE OF CONTENTS

- I. EXECUTIVE SUMMARY
- II. BLOCK DIAGRAM, DESIGN TARGETS AND SPECIFICATIONS
- III. INDIVIDUAL BLOCK DESCRIPTIONS
- IV. BILL OF MATERIALS
- V. HEALTH, SAFETY, & ENVIRONMENTAL ISSUES
- VI. FINAL GANTT CHART
- VII. CRITICISM OF THIS COURSE

### APPENDICES

- VIII. WAVEFORM OUTPUTS
- IX. OSCILLATOR RESOURCES: TI-BUBBA OSCILLATOR

## I. EXECUTIVE SUMMARY

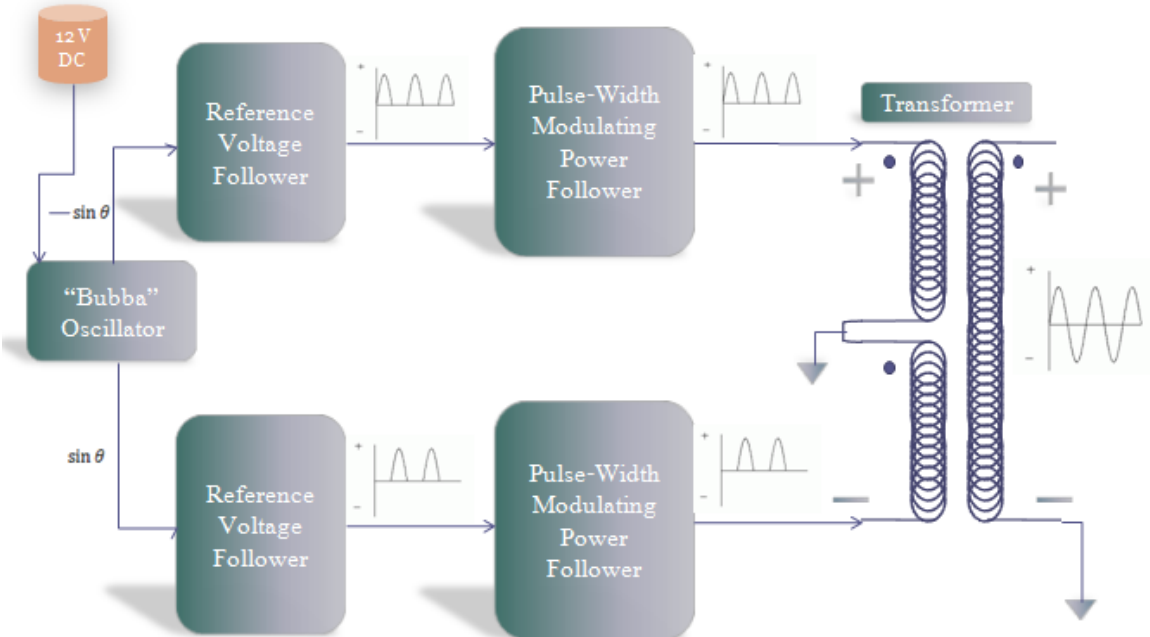
With the push in the past ten years to improve methods of energy generation, there has been an increasing need to optimize energy management. Our project was to create a DC to AC load-balanced inverter. The function would be to take in a DC voltage input, something like a battery or a solar cell, and output an AC voltage, resembling that which comes out of a wall outlet. The crux of the design would be that it would be “load balanced” meaning that no matter how large of a load (which could resemble anything from an array of lightbulbs to a laptop) the output voltage would not change.

The design starts with a DC voltage input that powers all circuits. From here, our circuit is broken into three sequential phases. In the first phase we use a loop of operational amplifiers to generate a perfect sine wave called the “Bubba Oscillator.” We also tweak the elements of this oscillator so that the sinusoidal wave travels at 60 Hz or approximately what is coming out of a wall outlet. We tap this circuit at two points to obtain two complementary sine waves. We are not using these voltages to power anything; they are used as what are called “reference voltages” or voltages that guide the operation of another part of the circuit. Because we cannot allow our circuit to use a negative rail (only have one power source), at this stage, our sine wave clips, and we have only the top half of both a sine wave and a  $-$ sine wave.

In the next phase after some manipulation of the circuit, the reference voltages are isolated and are converted from reference voltages to “drive voltages” or voltages that are able to power a load. This part of our project uses the technology of pulse width modulation (PWM) by dividing the voltage of a circuit into discrete pulses which vary in length depending on the magnitude of the pulse. Then another part of the circuit takes these pulses and restructures them back as a drive voltage sine wave. Using two PWM chips purchased online, we modified one of its application circuits to create drive voltages that directly model our reference voltages.

Finally, to combine both halves of the sine wave, we move into the synthesis of the circuit: combining the two wave forms. Using a transformer we subtract of the two circuits to produce a very close approximation to a sinusoid. The output of this circuit is aimed to model that which flows on the national grid, thereby able to be utilized by everyday appliances.

II. BLOCK DIAGRAM



### III. DIAGRAM EXPLANATION

#### A. OP-AMP SINE WAVE “BUBBA” OSCILLATOR BLOCK

The first step in building a precision sine wave inverter is to build a reference sine wave that can then be used in a power voltage follower to produce the desired output, however producing a circuit that oscillates accurately at 60 Hz can be challenging. Preferably, in addition we needed the circuit to produce a -sine wave, or negative rectify our sine wave to produce the input of our other voltage follower which would then be set up to be the negative half of the output sine wave.

#### BUBBA OSCILLATOR & SUPPORT

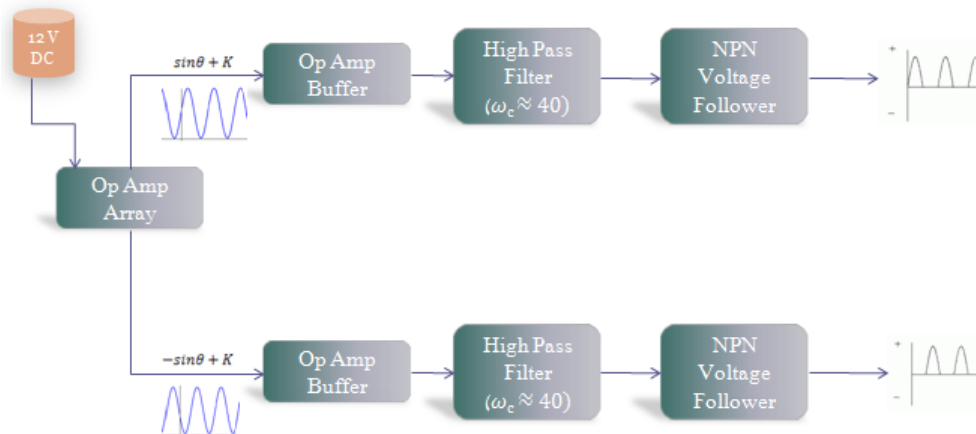


Fig. 1 Bubba Oscillator Block Diagram

#### Design Process

We initially began with the idea that making an oscillator that operated at a higher frequency (a multiple of 60Hz), to avoid having large capacitive circuit components. This signal would then be put through j/k flip flops to reduce the frequency by half every step until we got a 60Hz square wave. In theory this circuit could then be put into a low-pass filter to filter out the lower frequencies of the Fourier Series. This would in summation turn the square wave into a sine wave and finally it would be rectified to produce the necessary -sine wave components as well.

When we implemented this concept first, we were able to create the oscillator however, neither the digital counter logic, nor the sequential J/K flip flop arrangement was responding to input signal we gave it in any consistent manner. Finally we realized that making an inverting rectifier would also require a negative voltage rail, which is not present in the input of an inverter. We decided to approach the problem from a different perspective, and researched low frequency oscillator circuits that only use a positive rail and our solution was the so-called “bubba” oscillator

#### Final Design

A Bubba oscillator is an op-amp sine wave oscillator circuit, that relies on the principle of setting a circuit into an unstable oscillation using passive circuit components. In general to produce a lasting oscillation we need their to unity gain through the entire loop of op-amps. A gain of greater than one and the output will look more like a square wave and a gain of the less than one and the circuit will eventually stop oscillating. The second requirement is that we produce a 180 degree phase shift throughout the entire circuit and considering that we can achieve a maximum of 90 degrees per pole we will need at least two poles in the entire circuit. In theory then a sine wave oscillator can be made from one op-amp with two poles in its feedback however this makes the circuit extremely sensitive to changes in phase.

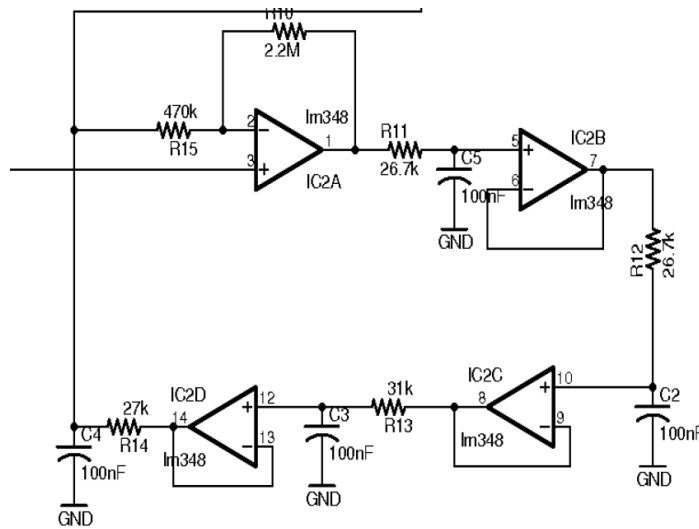


Fig. 2 Bubba Oscillator Op Amp Array

We are using a 4 op-amp circuit which means that at each stage we will be shifting the signal by 45 degrees this makes the circuit much less sensitive and hence more robust. In the circuit one can observe that all but one of the op-amps is unity gain, and we also have a one pole system between each op-amp causing the 45 degree phase shift. This design choice was also especially critical because if we took an output two sections or 90 degrees away from our sine wave output signal we would also have our -sine wave. This allowed us to avoid having to make another phase shifter or inverting rectifier which had been causing problem earlier.

Once we had our output sine-wave we had to deal with problem that is was DC-offset. To solve this problem we needed to put both the sine and -sine inputs through unity gain op-amp buffers (to isolate the reference signal) and a high-pass filter which would remove the DC offset. The -3Db cutoff of the circuit (by tuning with a potentiometer) is approximately at 40Hz

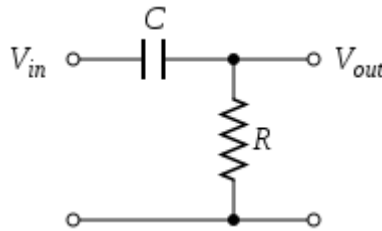


Fig. 3 First Order Low Pass Filter

Finally we wanted to ensure that if the power voltage follower circuit drew current it would not load our oscillator block so we included a common collector (voltage follower) circuit (see Fig 4).

## B. VOLTAGE FOLLOWERS

In concept these two blocks essentially are meant to receive a reference sine wave and be able to reproduce it using pulse-width modulation which will need to vary according to the size of the load.

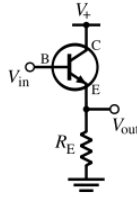


Fig. 4 NPN Voltage Follower Circuit

### Design Process

We needed produce a circuit that would be able to control a transistor using pulse-width modulated (PWM) signal. We began by doing research into PWM chips, and what their capabilities were. However we decided to take apart a 7W car inverter that claimed to be a pure sine wave inverter, to see if we could understand their methodology. We first reverse engineered the portions of the circuit that we thought we could apply but due to the fact that when we tested the inverter thoroughly the output under most loads only approximated a sine wave roughly which we did not think was acceptable (despite the fact that most normal loads will run well on non-pure sine waves). We did look into the chip that was used in this circuit, and it seemed suitable for the application we would use it for.

The chip was a KA7500C SMPS control chip made by Fairchild semiconductors. After looking into how to use this chip in a more effective way than the car inverter we decided to model our design on the constant 5V step down converter that we found as an application note for the chip shown below.

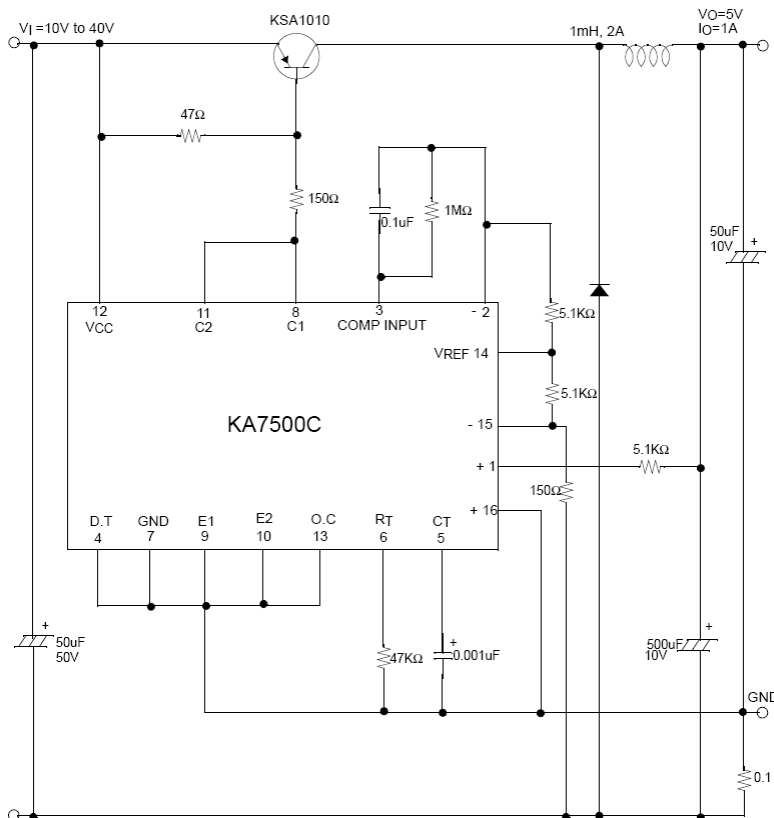


Fig. 5 PWM KA7500 Circuit Application

This circuit will take an input of between 10-40V and produce an output of 5V for up to ~5W of load. Using the block diagram below (of the chip's operation) as reference we needed to understand the functioning of the circuit to understand how to alter it to make it capable of following a sine wave input of

60Hz. First of all CT and RT (pin 5 and 6) together determine the internal oscillator frequency, we decided to set it to its maximum by keeping the components shown in the circuit which will help the circuit respond as fast as possible to variable load. Next notice the dead-time controller (pin 4) is pinned to ground this will keep the circuit to 50% duty cycle. This circuit uses pin 14 and internal voltage reference of 5V in order to keep its output, we noted this as one of the aspects we would need to change. Furthermore notice that this circuit is using only one of the input comparators and is tying the output transistors together which limits the functioning of the chip. Our next step was to make sure that this would track the input sine wave that we would pass it from our oscillator component.

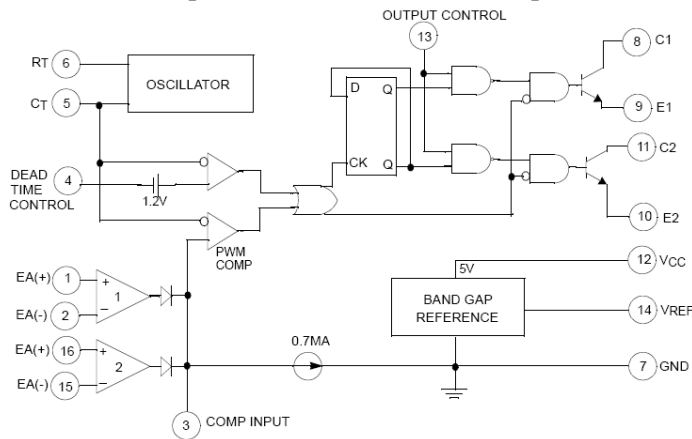


Fig. 6 KA7500 Internal Block Diagram

### Final Design

After testing the 5V step down converter from above we needed to convert it to a follower that would always push the circuit to follow the reference provided to it. Our first step was to remove the 5V reference and place a sine-wave instead, we could this by linking attaching a lead between the two 5.1k. We tested this and realized that the circuit was not responding properly as can be seen below. It appeared as if there was a charging and discharging capacitor that's time constant was too large to respond to the input. On Further examination of the original circuit we notice a larger 500uF capacitor that is part of the feed back loop, this is essentially trying to smooth anything heading into the feedback as much as possible, to ensure it will stay constant DC. By replacing this capacitor with a 10uF electrolytic capacitor we were able to drastically improve the response of the circuit. By replacing all but the input capacitors with 10uF electrolytic we were also able to improve the response noticeably, will still filter any noise on the sine wave.

After placing a load on the output of our new voltage follower we realized that the response of the circuit was still dependent on the load, therefore we decided to use a similar idea as the oscillator circuit and use a voltage follower, however in this case we used a power transistor. This addition to the circuit also helped solve another problem that have been having with the output signal. As mentioned earlier the circuit had problems following a 60 Hz signal due to an RC roll-off, but even after tuning there was still a tail at the end of our sine pulse. The built in .7V bias of the transistor actually clipped off the bottom of the sine wave which removed the tail, without having to add a diode. Also as the transistor heats up it appears as if the sine wave begins to expand to match the original sine wave (prior to .7 voltage bias cutoff) but without the tail, meaning there will be less separation between the positive and negative sine wave pulses.

### C. TRANSFORMER

The last step of our circuit is to turn the half-wave sine and half-wave -sine into the scaled sine-wave output we desire. In order to do this we needed a circuit component that would act or actually be isolated



from the rest of the circuit and be able to impose a negative voltage across a load. This would then mean we could use the half-wave -sine as the negative half of the output sine-wave and use the other half-wave sine wave as the top half, but we needed a circuit that could add these signals together.

### *Design Process*

We initially considered an H-bridge to be the solution to the problem as these can often be used with pulse-width modulating systems. After further review however we have already gone through the trouble of making a sine wave (the stage after the PWM), and so an H-bridge would have been very challenging. Instead we decided to use a transformer that would not only serve to isolate the load from the circuit but also step up the voltage to the desired value. In order for this solution to work we would need an unusual transformer, with 4 leads on the primary coil (oppositely wound) and two leads on the output. This would then mean that we could apply the two signals separately to the primary coil and it would flip the -sine wave at the output and add the two waves together producing the desired output wave. It was for this reason that the old tails that existed in our circuit prior to have adding the power follower circuit, would have been harmful to the output as they would interfere with each other in the transformer. After trying the existing transformers in the lab we attempted to wrap our own transformer to prove the concept that this system should work with the correct transformer. During testing however it appeared that the magnetic conductor in the transformer did not suite being used for 60Hz and so no output was observed at this frequency.

Finally, we decided to return to our reverse engineered car inverter and take the transformer used there as our transformer. The underlying theory was that if the transformer can operate by doing exactly what we want to do, it should be able to handle our circuit. The problem was that the inverter operates at 60 Hz and  $120V_{\text{ptp}}$ . This meant that the transformer was not able to realize and actually perform the subtraction that we wanted to occur. With the terrible outputs we were getting from the transformer, we were at an impasse. Then by fortuity we fell upon our solution.

### *Final Design*

We finally connected the transformer to a small 4 input/ 2 output mouser transformer. The transformer output was approximately 75% of what we wanted to occur. The output of the circuit (see Appendix VIII) is something that would be able to power an output. The wave is not sinusoidal but is periodic with a frequency of  $\approx 60\text{Hz}$  and models a sine wave. Two things to note, when we tested a plug-in car inverter, the output was a very jagged sinusoidal wave. Thus, if a car inverter was able to be marketed and used as an inverter, then our wave would actually get the job done. Secondly, the transformer we used was an ad-hoc choice for a transformer. We were unable to custom-design a transformer for the circuit however the mouser transformer we used was simply a transformer that was available in the design lab. Next steps are twofold. First, we will first find a transformer that is correct for the specifications for our circuit and then second, we will tune the circuit going into the transformer, to make sure our output is a pure 60Hz sine wave.

IV. BILL OF MATERIALS

Part	Sourced From	Price/U	Qty Used	Qty Bought	Circuit Cost	Total Cost	Bill #
1. KA7500C	Fairchild Semicond	0.70	2	10	\$1.40	\$7.00	3
2. KSA1010YTU	Fairchild Semicond	0.76	2	10	\$1.52	\$7.60	4
3. LM741	EE-Student Proj. Lab	0.00	1	0	\$0.00	\$0.00	-
4. LM348	Digi Key	1.39	1	4	\$1.39	\$5.56	1
5. 1mH Inductor	Digi Key	2.20	2	4	\$4.40	\$8.80	2
6. 10 uF 35V Capacitor	EE-Student Proj. Lab	0.00	4	0	\$0.00	\$0.00	-
7. .025uf Capacitor	EE-Student Proj. Lab	0.00	8	0	\$0.00	\$0.00	-
8. 100uf 35V capacitor	EE-Student Proj. Lab	0.00	4	0	\$0.00	\$0.00	-
9. .001uf capacitor	Digi Key	0.11	2	10	\$0.22	\$1.08	1
10. 100nF capacitor	EE-Student Proj. Lab	0.00	4	0	\$0.00	\$0.00	-
11. 26.7K +/-1%	Digi Key	0.10	2	5	\$0.20	\$0.49	1
12. 27.0K +/-1%	Digi Key	0.17	1	10	\$0.17	\$1.71	1
13. 30.9K +/-1%	Digi Key	0.10	1	5	\$0.10	\$0.49	1
14. 470K +/-1%	Digi Key	0.64	1	5	\$0.64	\$3.18	1
15. 2.2M +/-1%	Digi Key	0.24	1	5	\$0.24	\$1.19	1
16. 47 ohm +/-5%	EE-Student Proj. Lab	0.00	2	0	\$0.00	\$0.00	-
17. 150 ohm +/-5%	EE-Student Proj. Lab	0.00	4	0	\$0.00	\$0.00	-
18. 5.1K ohm +/-5%	EE-Student Proj. Lab	0.00	6	0	\$0.00	\$0.00	-
19. 47K ohms +/-5%	EE-Student Proj. Lab	0.00	2	0	\$0.00	\$0.00	-
20. 1M ohm +/-5%	EE-Student Proj. Lab	0.00	2	0	\$0.00	\$0.00	-
21. Mouser Transformer	EE-Student Proj. Lab	0.00	1	0	\$0.00	\$0.00	-
22. 498722185ND JFET	Digi Key	0.77	0	2	\$0.00	\$1.54	1
23. KSA7500 CDTF	Fairchild Semicond	0.43	0	10	\$0.00	\$4.30	3
24. KSP44TA	Fairchild Semicond	0.17	0	10	\$0.00	\$1.70	3
					<b>Gross</b>	<b>\$10.27</b>	<b>\$44.64</b>

	Shipping	Sales Tax	Total
Bill 1: DigiKey	\$16.68	\$2.67	\$19.35
Bill 2: DigiKey	\$18.37	\$2.28	\$20.65
Bill 3: Fairchild	\$10.00	\$2.00	\$12.00
Bill 4: Fairchild	\$10.00	\$2.00	\$12.00
<b>Total</b>	<b>\$55.05</b>	<b>\$8.95</b>	<b>\$64.00</b>

<b>Gross Circuit Cost</b>	\$10.27
<b>Gross Parts Cost</b>	\$44.64
<b>Total Sales &amp; Ship</b>	\$64.00
<b>Total Circuit Cost</b>	74.27
<b>Total Cost</b>	108.64

## V. HEALTH, SAFETY, & ENVIRONMENTAL ISSUES

There are only a few problems and risks associated with our project. When working with power however, one has to constantly look for areas of overheating and electrical shock. Multiple transistors on the board, namely the voltage followers get very hot during times of operations (around 200° C) and the pulse width modulating chip, though still operating within its required bounds, heats up as well. The non linear objects in the circuit are cause for concern if heat is not accounted for.

The project meets all FCC standards and has not many issues with health. However, in terms of safety, heat sinks are most crucial for the circuit to not cause adverse problems.



## VII. COURSE CRITICISM

Overall though it was more difficult and more vague in guidance, we liked how the course carried itself out. We were given the chance to view many parts of the engineering design process and, unlike the first time around in Gateway, we were able to do it justice through using all of the electronic and design techniques we have learned throughout the past three years.

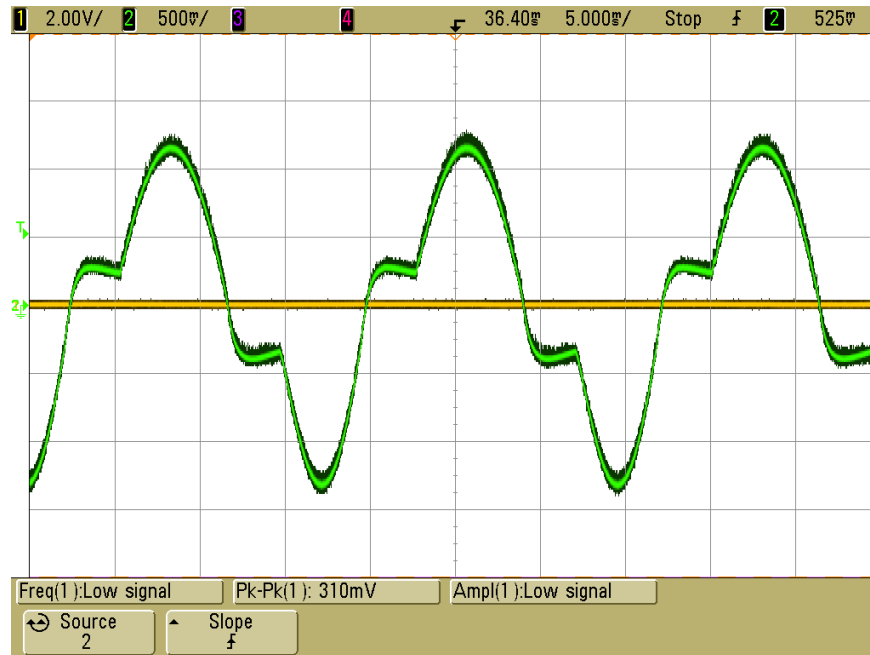
Only a few suggestions for the course:

1. The student projects lab is a very poor location to have design projects stationed. I don't know if there is any way to monitor cleanliness in labs but coupled with the cramped space there is hardly any place to work there. Secondly, the equipment is poor, wires and resources are scarce, and there is only one viable choice for an oscilloscope. It is hard to believe that as seniors, we are using much worse off equipment than sophomores and juniors use in their labs. There were many options for circuit parts in terms of capacitors, inductors, resistors etc. but the rest of the lab was lacking in almost everything.
2. Realistic goals are also so difficult to make early in a semester in terms of anticipating how quickly a project will finish. We are very close to finishing the work that we set out to do but our transformer is not working and therefore our project is in the twilight stages but still incomplete. The thing is that early on in the semester we had no real idea that we needed a transformer. There is a large time-inconsistency that comes into play when forecasting a timeline and though we tried our best to meet the standards set, we weren't able to. We think there must be a way to be graded to take this into account.

We both loved the helpfulness of all three of the support staff and really could not have finished the project without your guidance.

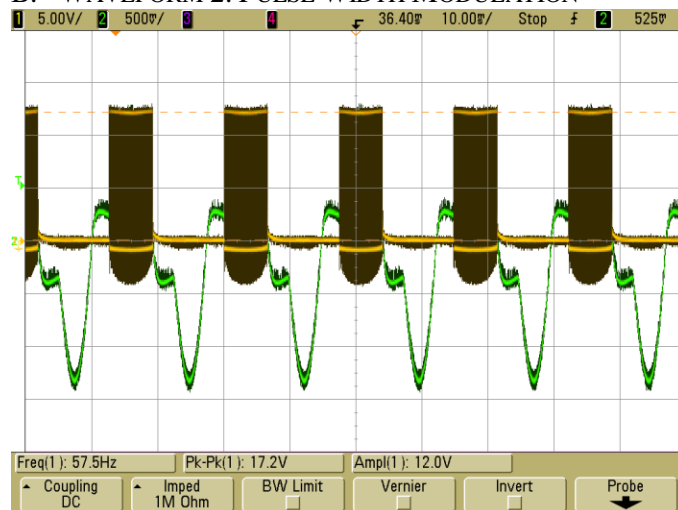
## VIII. WAVEFORMS

### A. WAVEFORM I: TRANSFORMER OUTPUT



This output shows the final output of our 12V DC circuit. The sinewave, fully summed together shows the approximation of a  $2.5V_{\text{ptp}}$  sine wave. Important issues to note. First, the wave is non-problematic and non-attenuating for loads of 10k~50k ohms. With further tuning of the circuit these ranges could be made larger. Secondly, the “impurities” of the sine wave seem to be due to capacitive elements of the input waveforms. This could either come from the current that the step up voltage winding is drawing (issues from the circuit itself) or from the windings and properties of the transformer. We will be able to fix this by purchasing/making a transformer with more time and more tailored to the needs of our circuit.

### B. WAVEFORM 2: PULSE WIDTH MODULATION



This waveform shows the pulses made for the pulse width modulation of the circuit. The amount of samples taken is so large that when the circuit is positive, there are many pulses and from a view of zoomed output, the pulses look like one black rectangle, though this is not actually the case.

## IX. TI- SINE WAVE OSCILLATOR ARTICLE: "BUBBA OSCILLATOR"



# Sine-Wave Oscillator

*Ron Mancini and Richard Palmer*
*HPL (Dallas)*

## ABSTRACT

This note describes the operational amplifier (op-amp) sine-wave oscillator, together with the criteria for oscillation to occur using RC components. It delineates the roles of phase shift and gain in the circuit and then discusses considerations of the op amp. A brief analysis of a Wien-Bridge oscillator circuit is provided. Several examples of sine-wave oscillators are given, although it is recognized that there exist many additional types of oscillator to which the principles of this application note also apply.

## Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
<b>2</b>	<b>Sine-Wave Oscillator Defined</b>	<b>3</b>
<b>3</b>	<b>Requirements for Oscillation</b>	<b>3</b>
<b>4</b>	<b>Phase Shift in the Oscillator</b>	<b>5</b>
<b>5</b>	<b>Gain in the Oscillator</b>	<b>6</b>
<b>6</b>	<b>Effect of the Active Element (Op Amp) on the Oscillator</b>	<b>7</b>
<b>7</b>	<b>Analysis of Oscillator Operation (Circuit)</b>	<b>8</b>
<b>8</b>	<b>Sine-Wave Oscillator Circuits</b>	<b>10</b>
	8.1 Wein-Bridge Oscillator	10
	8.2 Phase-Shift Oscillator, Single Amplifier	14
	8.3 Phase-Shift Oscillator, Buffered	16
	8.4 Bubba Oscillator	17
	8.5 Quadrature Oscillator	18
<b>9</b>	<b>Conclusion</b>	<b>19</b>
<b>10</b>	<b>References</b>	<b>20</b>

## List of Figures

1	Canonical Form of a System With Positive or Negative Feedback	4
2	Phase Plot of RC Sections	5
3	Op-Amp Frequency Response	7
4	Distortion vs Oscillation Frequency for Various Op-Amp Bandwidths	8
5	Block Diagram of an Oscillator	9
6	Amplifier With Positive and Negative Feedback	9
7	Wein-Bridge Circuit Schematic	10

Trademarks are the property of their respective owners.

8	Final Wein-Bridge Oscillator Circuit	11
9	Wein-Bridge Output Waveforms: Effects of RF on Distortion	12
10	Wein-Bridge Oscillator With Nonlinear Feedback	12
11	Output of the Circuit in Figure 10	13
12	Wein-Bridge Oscillator With AGC	14
13	Output of the Circuit in Figure 12	14
14	Phase-Shift Oscillator (Single Op Amp)	15
15	Output of the Circuit in Figure 14	15
16	Phase-Shift Oscillator, Buffered	16
17	Output of the Circuit Figure 16	16
18	Bubba Oscillator	17
19	Output of the Circuit in Figure 18	18
20	Quadrature Oscillator	19
21	Output of the Circuit in Figure 20	19

## 1 Introduction

Oscillators are circuits that produce specific, periodic waveforms such as square, triangular, sawtooth, and sinusoidal. They generally use some form of active device, lamp, or crystal, surrounded by passive devices such as resistors, capacitors, and inductors, to generate the output.

There are two main classes of oscillator: relaxation and sinusoidal. Relaxation oscillators generate the triangular, sawtooth and other nonsinusoidal waveforms and are not discussed in this note. Sinusoidal oscillators consist of amplifiers with external components used to generate oscillation, or crystals that internally generate the oscillation. The focus here is on sine wave oscillators, created using operational amplifiers op amps.

Sine wave oscillators are used as references or test waveforms by many circuits. A pure sine wave has only a single or fundamental frequency—ideally no harmonics are present. Thus, a sine wave may be the input to a device or circuit, with the output harmonics measured to determine the amount of distortion. The waveforms in relaxation oscillators are generated from sine waves that are summed to provide a specified shape.

## 2 Sine-Wave Oscillator Defined

Op-amp oscillators are circuits that are unstable—not the type that are sometimes unintentionally designed or created in the lab—but ones that are intentionally designed to remain in an unstable or oscillatory state. Oscillators are useful for generating uniform signals that are used as a reference in such applications as audio, function generators, digital systems, and communication systems.

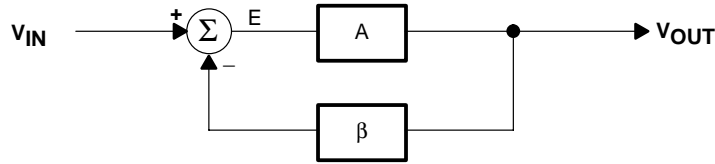
Two general classes of oscillators exist: sinusoidal and relaxation. Sinusoidal oscillators consist of amplifiers with RC or LC circuits that have adjustable oscillation frequencies, or crystals that have a fixed oscillation frequency. Relaxation oscillators generate triangular, sawtooth, square, pulse, or exponential waveforms, and they are not discussed here.

Op-amp sine-wave oscillators operate without an externally-applied input signal. Instead, some combination of positive and negative feedback is used to drive the op amp into an unstable state, causing the output to cycle back and forth between the supply rails at a continuous rate. The frequency and amplitude of oscillation are set by the arrangement of passive and active components around a central op amp.

Op-amp oscillators are restricted to the lower end of the frequency spectrum because op amps do not have the required bandwidth to achieve low phase shift at high frequencies. Voltage-feedback op amps are limited to a low kHz range because their dominant, open-loop pole may be as low as 10 Hz. The new current-feedback op amps have a much wider bandwidth, but they are very hard to use in oscillator circuits because they are sensitive to feedback capacitance. Crystal oscillators are used in high-frequency applications up to the hundreds of MHz range.

## 3 Requirements for Oscillation

The canonical, or simplest, form of a negative feedback system is used to demonstrate the requirements for oscillation to occur. Figure 1 shows the block diagram for this system in which  $V_{IN}$  is the input voltage,  $V_{OUT}$  is the output voltage from the amplifier gain block (A), and  $\beta$  is the signal, called the feedback factor, that is fed back to the summing junction. E represents the error term that is equal to the summation of the feedback factor and the input voltage.



**Figure 1. Canonical Form of a Feedback System With Positive or Negative Feedback**

The corresponding classic expression for a feedback system is derived as follows. Equation 1 is the defining equation for the output voltage; equation 2 is the corresponding error:

$$V_{\text{OUT}} = E \times A \quad (1)$$

$$E = V_{\text{IN}} + \beta V_{\text{OUT}} \quad (2)$$

Eliminating the error term, E, from these equations gives

$$\frac{V_{\text{OUT}}}{A} = V_{\text{IN}} - \beta V_{\text{OUT}} \quad (3)$$

and collecting the terms in  $V_{\text{OUT}}$  yields

$$V_{\text{IN}} = V_{\text{OUT}} \left( \frac{1}{A} + \beta \right) \quad (4)$$

Rearrangement of the terms produces equation 5, the classical form of feedback expression:

$$\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{A}{1 + A\beta} \quad (5)$$

Oscillators do not require an externally-applied input signal; instead, they use some fraction of the output signal created by the feedback network as the input signal.

Oscillation results when the feedback system is not able to find a stable steady-state because its transfer function can not be satisfied. The system goes unstable when the denominator in equation 5 becomes zero, i.e., when  $1 + A\beta = 0$ , or  $A\beta = -1$ . The key to designing an oscillator is ensuring that  $A\beta = -1$ . This is called the *Barkhausen criterion*. Satisfying this criterion requires that the magnitude of the loop gain is unity with a corresponding phase shift of  $180^\circ$  as indicated by the minus sign. An equivalent expression using the symbology of complex algebra is  $A\beta = 1 \angle -180^\circ$  for a negative feedback system. For a positive feedback system, the expression is  $A\beta = 1 \angle 0^\circ$  and the sign of the  $A\beta$  term is negative in equation 5.

As the phase shift approaches  $180^\circ$  and  $|A\beta| \rightarrow 1$ , the output voltage of the now-unstable system tends to infinity but, of course, is limited to finite values by an energy-limited power supply. When the output voltage approaches either power rail, the active devices in the amplifiers change gain. This causes the value of A to change and forces  $A\beta$  away from the singularity; thus the trajectory towards an infinite voltage slows and eventually halts. At this stage, one of three things can occur: (i) Nonlinearity in saturation or cutoff causes the system to become stable and lock up at the current power rail. (ii) The initial change causes the system to saturate (or cutoff) and stay that way for a long time before it becomes linear and heads for the opposite power rail. (iii) The system stays linear and reverses direction, heading for the opposite power rail. The second alternative produces highly distorted oscillations (usually quasi-square waves), the resulting oscillators being called relaxation oscillators. The third produces a sine-wave oscillator.

### 8.4 Bubba Oscillator

The bubba oscillator in Figure 18 is another phase-shift oscillator, but it takes advantage of the quad op-amp package to yield some unique advantages. Four RC sections require 45° phase shift per section, so this oscillator has an excellent  $d\phi/dt$  resulting in minimal frequency drift. The RC sections each contribute 45° phase shift, so taking outputs from alternate sections yields low-impedance quadrature outputs. When an output is taken from each op amp, the circuit delivers four 45° phase-shifted sine waves. The loop equation is given in equation 15. When  $\omega = 1/RCs$ , equation 15 reduces to equations 16 and 17.

$$A\beta = A\left(\frac{1}{RCs + 1}\right)^4 \tag{15}$$

$$|\beta| = \left| \left(\frac{1}{j + 4}\right)^4 \right| = \frac{1}{\sqrt{2}^4} = \frac{1}{4} \tag{16}$$

$$\phi = \tan^{-1}(1) = 45^\circ \tag{17}$$

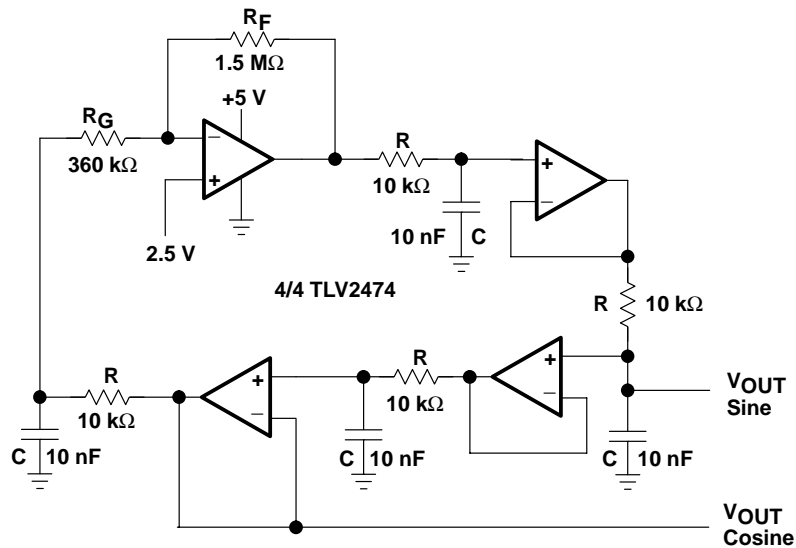
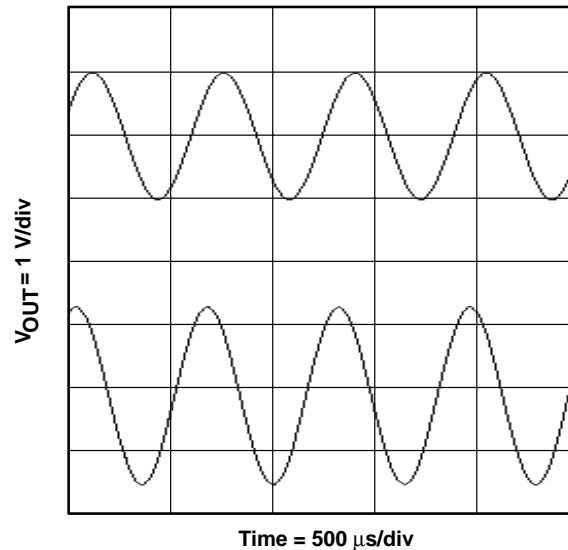


Figure 18. Bubba Oscillator



**Figure 19. Output of the Circuit in Figure 18**

The gain,  $A$ , must equal 4 for oscillation to occur. The test circuit oscillated at 1.76 kHz rather than the ideal frequency of 1.72 kHz when the gain was 4.17 rather than the ideal gain of 4. The output waveform is shown in Figure 19. Distortion was 1.1% for  $V_{OUTSINE}$  and 0.1% for  $V_{OUTCOSINE}$ . With low gain,  $A$ , and using low bias-current op amps, the gain-setting resistor,  $R_G$ , did not load the last RC section, thus ensuring oscillator frequency accuracy. Very low distortion sine waves can be obtained from the junction of  $R$  and  $R_G$ . When low-distortion sine waves are required at all outputs, the gain should be distributed among all the op amps. The noninverting input of the gain op amp is biased at 0.5 V to set the quiescent output voltage at 2.5 V for single-supply operation, and it should be ground for split-supply op amps. Gain distribution requires biasing of the other op amps, but it has no effect on the oscillator frequency.

## 8.5 Quadrature Oscillator

The quadrature oscillator shown in Figure 20 is another type of phase-shift oscillator, but the three RC sections are configured so each section contributes  $90^\circ$  of phase shift. This provides both sine and cosine waveform outputs (the outputs are *quadrature*, or  $90^\circ$  apart), which is a distinct advantage over other phase-shift oscillators. The idea of the quadrature oscillator is to use the fact that the double integral of a sine wave is a negative sine wave of the same frequency and phase, in other words, the original sine wave  $180^\circ$  phase shifted. The phase of the second integrator is then inverted and applied as positive feedback to induce oscillation [6].

The loop gain is calculated from equation 18. When  $R_1C_1 = R_2C_2 = R_3C_3$ , equation 18 reduces to equation 19. When  $\omega = 1/RC$ , equation 18 reduces to  $1\angle-180$ , so oscillation occurs at  $\omega = 2\pi f = 1/RC$ . The test circuit oscillated at 1.65 kHz rather than the calculated 1.59 kHz, as shown in Figure 21. This discrepancy is attributed to component variations. Both outputs have relatively high distortion that can be reduced with a gain-stabilizing circuit. The sine output had 0.846% distortion and the cosine output had 0.46% distortion. Adjusting the gain can increase the amplitudes. The penalty is reduced bandwidth.

$$A\beta = A \left( \frac{1}{R_1C_1s} \right) \left( \frac{R_3C_3s + 1}{R_3C_3s(R_2C_2s + 1)} \right) \quad (18)$$