INTRODUCTION

High power PWM amplifiers are now available in the 200V to 500V range with current ratings in the 10A to 20A range. Such PWM can be used to build transformerless AC/DC power supplies whose output DC voltage is linearly proportional to an input control signal. It operates just like linear amplifier's whose gain is set by resistor values. Such amplifier's efficiency is much higher, usually in the 90% range, because of PWM technique.

Why transformerless? In applications such as driving magnetic bearings, electric power in the order of kilowatts is required. A transformer at such power ratings is heavy and expensive. It is very desirable to do it without the transformer. In portable equipment that one has to carry from one place to another, the elimination of a heavy duty transformer makes it a lot lighter to carry around.
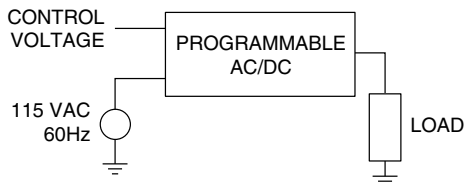

FIGURE 1A.   USE A PROGRAMMABLE AC/DC POWER SUPPLY AS A V/I SOURCE FOR ATE. SWITCHING NOISE IS USUALLY TOO HIGH TO BE ACCEPTABLE FOR SUCH APPLICATIONS.
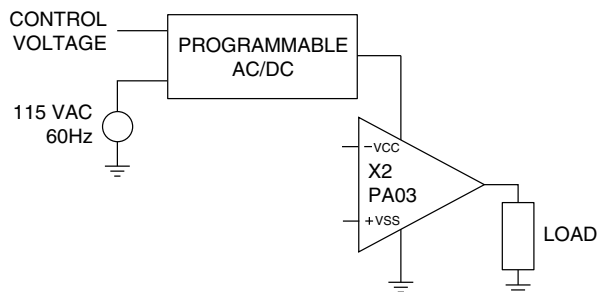

FIGURE 1B.   A LINEAR AMPLIFIER LIKE THE PA03 WITH POWER SUPPLY REJECTION IN THE 60 DB RANGE SUPPRESSES NOISE FROM THE PROGRAMMABLE AC/DC SUPPLY.

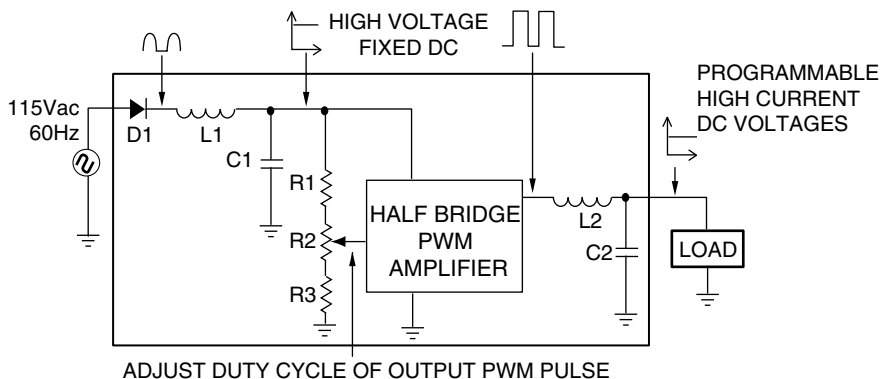ADJUST DUTY CYCLE OF OUTPUT PWM PULSE

FIGURE 2. TRANSFORMERLESS AC TO DC CONVERTER FUNCTIONAL DIAGRAM

Other applications that require the combined functions of AC/DC conversion plus amplification include DC motion control and powering high current linear amplifiers. In controlling brush type DC motors, one needs an AC/DC power supply plus an amplifier to control the voltage across the motor or the current through the motor. This AC/DC power supply does the job of both. You obtain the power from your 115 Vac wall socket and control the motion of your DC motor directly. Another application is in the testing of high current devices such as micro-processors, memory chips and logic circuits with pro-grammable V-I (voltage and current) sources that are built into most automatic test equipment. At first thought, you can use this transformer-less AC/DC power supply as a programmable V-I source, as shown in Figure 1a. In practicality, this power supply uses PWM switching technique and the switching noises are usually too high and not acceptable for such applications. To work around this problem, you can use this programmable AC/DC power supply to drive a linear amplifier like the Apex PA03 which in turn drives the real load, as shown in Figure 1b. A linear amplifier with power supply rejection in the 60 dB to 100 dB range will suppress the switching noises from this programmable AC/DC power supply. Key advantage of such an arrangement is to keep the internal power dissipation of the PA03 at its minimum. The PA03 is capable of delivering 30A of output current continuously. With a constant voltage at Vcc and the same load current, PA03's power dissipation increases as the load voltage drops. This programmable AC/DC allows PA03's Vcc to drop or to increase in proportion to the load voltage, and thus keeps the PA03's internal power dissipation at a constant level. Because this AC/DC uses PWM technique with efficiency in the 90% range, its internal power dissipation is minimal as compared to that of the PA03.

To design a complete transformer-less AC/DC power supply, we will first start out with a paper and pencil design, then use Spice simulation to verify the paper design and finally build a prototype to verify the Spice simulation.

FUNCTIONAL DIAGRAM

A block diagram to illustrate the functionality of a trans-former-less AC/DC power supply is shown in Figure 2. Power is taken from 115 Vac wall outlet and goes through a diode rectifier, D1, which converts the input sinewave into a half wave rectified output. L1 and C1 is a filter that attenuates the harmonics of the half wave sine wave and extracts its DC component out to supply the high voltage PWM amplifier. The output of the PWM amplifier is a pulse train whose duty cycle is controlled by its input voltage through a resistor divider made up of R1, R2 and R3. L2 and C2 is another filter that attenuates the harmonics of the PWM pulse train and extracts its DC components out as a programmable high voltage and high current DC source. Thus this AC/DC power supply's output DC voltage is linearly proportional to the PWM amplifier's input control voltage.
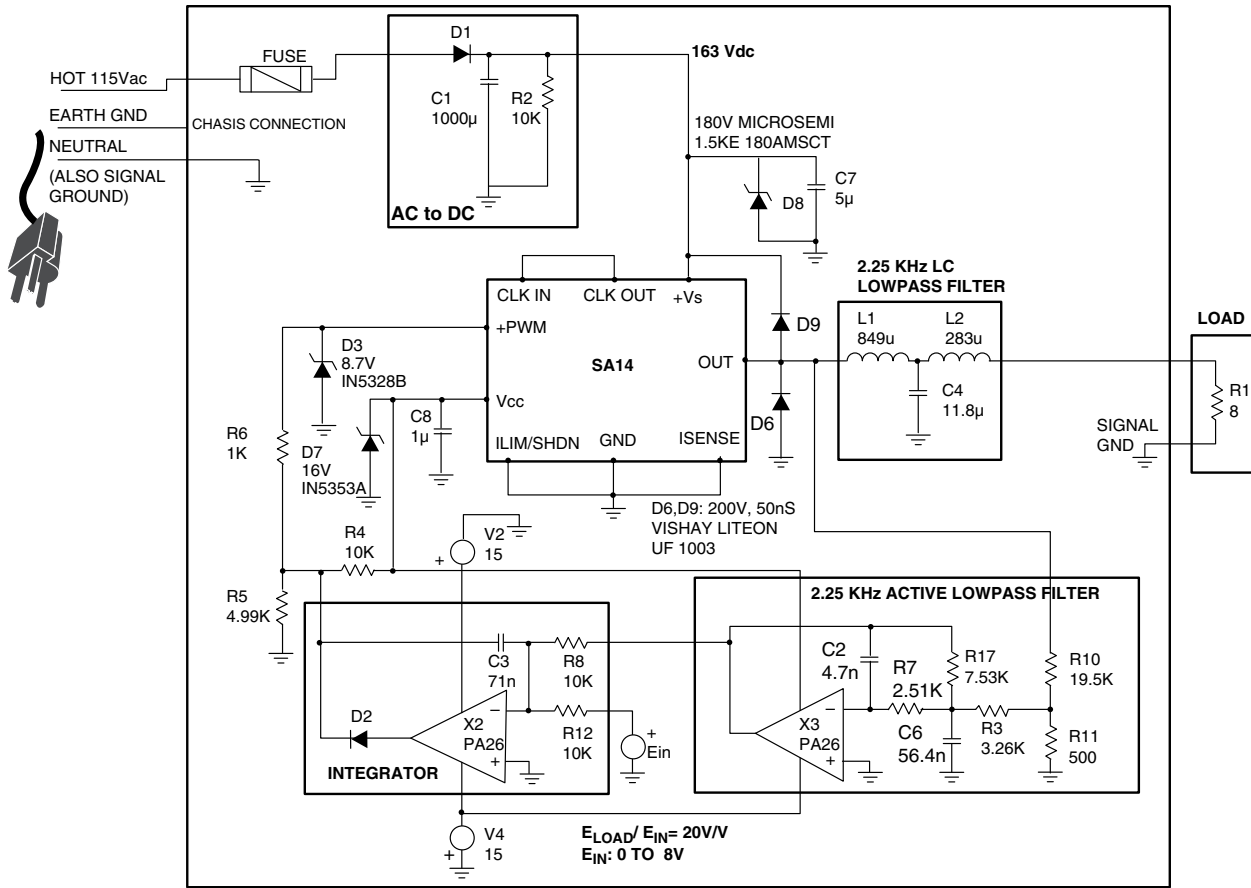
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FIGURE 3. DETAILED TRANSFORMERLESS AC TO DC CIRCUIT DIAGRAM.

COMPLETE CIRCUIT DESIGN EXAMPLE

The functional diagram in Figure 2 has no feedback or voltage regulation. Thus, the output DC voltage will not be very stable and will change with external environment such as load change, temperature, +Vs ripple, ... etc. In a real world circuit, feedback control is necessary to compensate for such environmental changes. Figure 3 is a complete circuit made up of the following blocks:

AC-TO-DC.

D1 is a diode rectifier whose reverse voltage must be at least 326V (= 2 x 115V x 1.4142). C1 is a smoothing capacitor whose value affects the output ripple. The larger, the better but also more expensive and bulky. We will arbitrarily start out with C1 = 1000 uF because it is available with voltage rating of 200 V, in electrolytic type, and at reasonable price. Analytical calculation of output ripple versus C1 is very complex because of the PWM waveform. It is not practical if not impossible. We will later use Spice to see the output ripple reduction with increased C1. R2 is a bleeder resistor whose value determines how fast it will discharge the capacitor C1 after power is turned off. R2's wattage must be equal or greater than (163*163/R2). With R2 = 10K, it must be 2.66W or larger.

SA14.

Apex SA14 is the PWM amplifier of choice because of its 200 V, 20 A rating. The 115 Vac will provide a peak voltage of 163 V (= 115*1.4142) so the PWM amplifier must have a voltage rating of at least 163 V. In some foreign countries where the ac power source is 230 Vrms, choose the Apex SA16 or SA08 whose voltage rating is 500 V.

2.25 KHZ LC LOWPASS FILTER.

L1, L2 and C4 form a 3-pole lowpass filter with Butterwoth (maximum flatness) frequency response for the 8 ohm load. The corner frequency is set at 2.25 KHz, one decade below SA14's 22.5 KHz PWM frequency. As the load changes, the filter's corner frequency will not change but its peaking, or Q factor will change. To achieve even lower ripple and noise, use higher pole filters. The design of LC filters can be found in reference 1 and reference 3.

2.25 KHZ ACTIVE LOWPASS FILTER

This filter block and the next integrator block form voltage feedback control for the AC/DC power supply. Active filter is used here because this is the small signal processing path, not the power transmission path. Active filter is smaller and cheaper. The design of active filters can be found in reference 2. The SA14 is an inverted PWM amplifier, that is, as SA14's input increases, the duty cycle of its output decreases. We choose the multiple feedback active filter configuration because of its polarity inversion to reverse SA14's polarity.

You can verify if your feedback loop has the correct polarity by using the following check:

Start out with SA14's +PWM input and arbitrarily assume that it is increasing. SA14's output will decease because it is an inverted PWM amplifier. Op amp X3's output will then increase because SA14's output drives the (-) input of X3. Op amp X2's output will decrease again because X3's output drives the (-) input of X2. Since X2's output drives SA14's +PWM input, the former decreases while the latter was arbitrarily assumed increasing. They go in

opposite directions and that is negative feedback. If they go in the same direction, it becomes positive feedback and your circuit won't work.

INTEGRATOR

This integrator completes the voltage feedback loop when the filtered output of SA14 is compared with an external voltage Ein. In this example, the transfer function is given by:

Eload/Ein = 20 V/V where Ein ranges from 0V to 8V.

PROTECTION COMPONENTS.

Each and every functional block described above is necessary for the functionality of the AC/DC power supply. The following protection components are highly recommended to protect the SA14 from accidental blow out. It is a cheap insurance.

D6 AND D9

Fast recovery diodes used to protect the SA14 from inductive kickbacks. Model UF1003 from Vishay Liteon is chosen because of its 50 nsec reverse recovery time and 200V reverse diode break down voltage. You need at least 163V and the diodes should be 200 nsec or faster.

D3 AND D7

These are zener diodes to prevent over-voltage at various inputs. D3 prevents the +PWM input from going above 8.7V and from going below -0.65V. D7 prevents the Vcc input from going above 16V and from going below 0.65V.

D8

This is a transzorb (transient absorber) to prevent over-voltage at the +Vs terminal, and it also absorbs energy from high voltage spikes. Model 1.5KE180AMSCT from Microsemi is chosen because of its 180 V rating, which must be above the 163 V needed to operate the SA14 and must be equal or below SA14's rated voltage of 200 V.

C7 AND C8

These are power supply bypass capacitors and must be located as close to the Vcc pin and +Vs pin as possible. In no case should these capacitors be more than 2 inches away from their respective pins. Use low ESR capacitors such as ceramic.

D2, R4, R5 AND R6

These components prevent the SA14 from going into tri-state condition upon powering on. R4 and R5 set SA14's +PWM input at the mid range of 5V which puts SA14's output at 50% duty cycle immediately upon powering on. D2 prevents op amp X2 from sinking current which should never happen under normal operation. R6 prevents D3 and the +PWM input from over-current.

FUSE

Remember to include a 20A slow blow fuse in series with V1, your 115 Vac input power source.

SPICE SIMULATION RESULTS

The Spice model of SA14 is given in Figure 4 and is discussed in great detail in Reference 1. The SA14 is a half bridge PWM amplifier so one side of the H-bridge, or two of the four output Mosfet's, is removed from the full bridge PWM amplifiers discussed in Reference 1. In Figure 3, CLK IN, CLK OUT and ILIM/SHDN are the bells and whistles of the SA14 and are not modeled in Spice. Protection components discussed in the above paragraph are also excluded from Spice simulation because they do not affect normal circuit functionality. PA26's Spice model , which is the same as that of PA21,
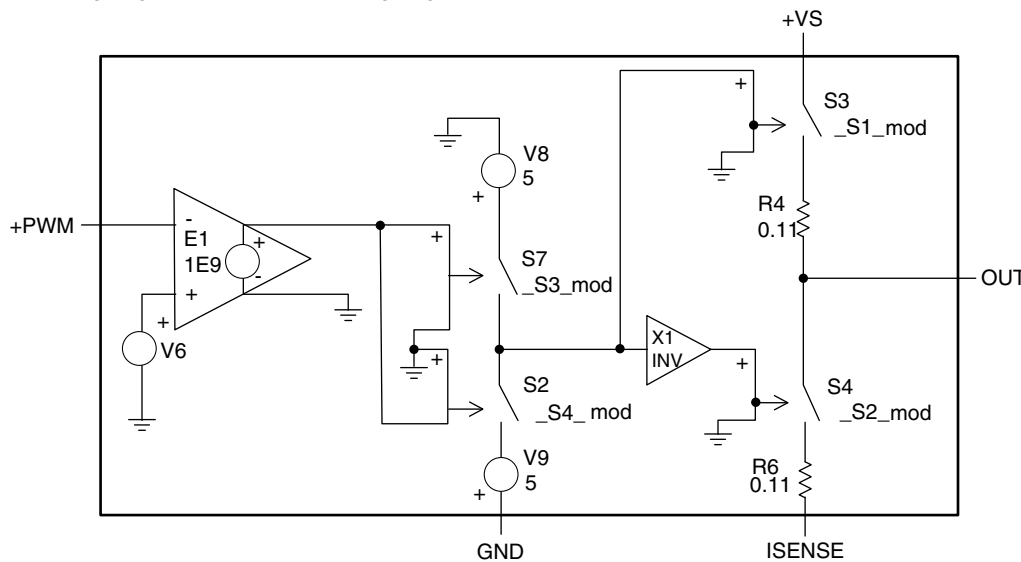

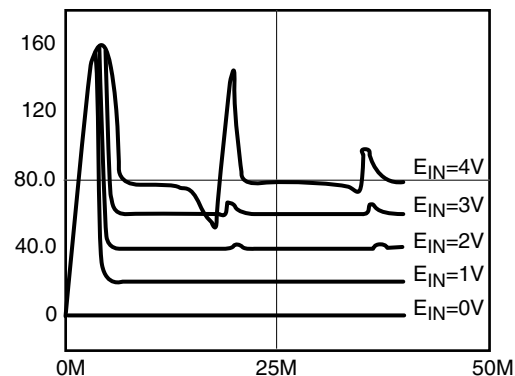**FIGURE 4.** SA14 HALF BRIDGE PWM AMPLIFIER SPICE MODEL.
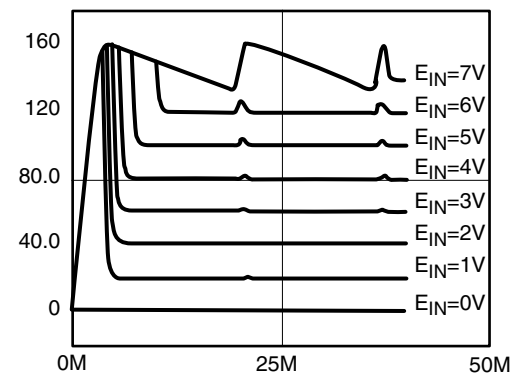

FIGURE 5A. SMOOTHING CAPACITOR C1 = 1000µF

FIGURE 5B. SMOOTHING CAPACITOR C1 = 10,000µF

FIGURE 5. TRANSIENT RESONSE OF LOAD CURRENT.

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can be downloaded from the Apex Website (www.apexmicro-tech.com). The rest of the circuit components are standard components available from most Spice libraries.

Figure 5a shows the transient response of the load current with different values of Ein. Note that the ripple increases as Ein, also the load voltage, increases. At 40V load voltage, the ripple is around 2 to 3 Vpp. If you need lower ripple, use a bigger smoothing capacitor. Figure 5b shows significantly lower ripples when the smoothing capacitor is increased to 10,000 uF.

MEASUREMENT RESULTS

In the actual prototype circuit, we tried to find components that are as close to the calculated values as practical. Sometimes calculated components are not available from our engineering stock and substitutes are used. Component deviations from the calculated values given in Figure 3 are listed below:

L1 = 820 uH
L2 = 200 uH
C3 = 82 nF
C4 = 10 uF
C6 = 57 nF.

Actual oscilloscope waveforms are shown in Figure 6a. The three load waveforms, from bottom to top, are respectively with inputs at 1 Vdc, 2 Vdc and 3 Vdc. There are two groups of ripple in each waveform. The ripple marked (A) is caused by the 60 Hz, 115 Vac power source, and can be lowered by increasing the capacitance for C1. Figure 6b shows the improved 60 Hz ripple by paralleling another 10,000 uF with C1 of 1000 uF. The improvement is especially noticeable with Ein = 3 Vdc. The high frequency ripple marked (B) in Figure 6a is caused by insufficient attenuation of the 22.5 KHz PWM pulse train by the three pole LC filter made up of L1, L2 and C4 in Figure 3. You can lower ripple (B) by increasing the number of poles for the LC filter. Figure 6c is the same as Figure 6a except R1 becomes open circuit. Note that high frequency ripples are noticeably higher because the LC filter no longer has a balanced load and its frequency response is no longer maximally flat. But, the 60 Hz ripple disappears because it is proportional to the load current.

This AC/DC power supply was designed with a gain of 20V/V. With Ein = 1 Vdc, Eout should be 20 Vdc and this is what Figure 6a shows in its bottom waveform. In the top waveform where Ein = 3 Vdc, Eout should be 60 Vdc while Figure 6a shows about 58 Vdc. The error is caused by the winding resistances of the inductors L1 and L2; and the error is higher at high output voltage and high current levels. You can eliminate this error by moving the voltage feedback point from the output of SA14 to the load, positive terminal of R1 (Figure 3). You will get better load voltage accuracy but at the expense of very restricted load variation. For example, if R1 becomes an open circuit, the LC filter will resonate near the corner frequency of 2.25 KHz. With voltage feedback taken at the positive terminal of R1, the whole feedback circuit will become unstable. On the other hand, if voltage feedback is taken from SA14's output, the load R1 and its associated LC filter do not affect loop stability.

HALF BRIDGE OR FULL BRIDGE

If you replace the half bridge rectifier in the AC to DC block of Figure 3 by a full bridge rectifier as shown in Figure 7, you will get significantly lower 60 Hz ripple with the same smoothing capacitor C1. Figure 8 shows the equivalent transient response as that of Figure 5a except with a full bridge rectifier.
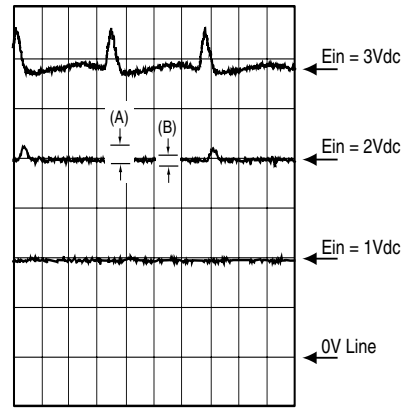

FIGURE 6A. MEASURED LOAD WAVEFORM.
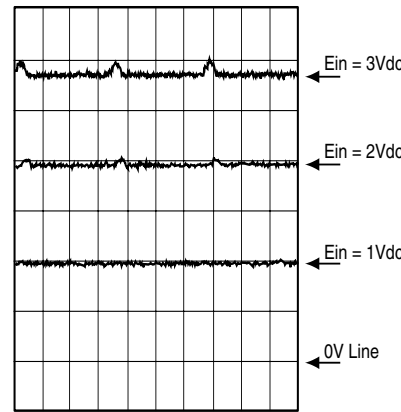X SCALE: 5MS PER DIVISION; Y SCALE 10V PER DIVISION.

FIGURE 6B. ADDING A 10,000µF IN PARALLEL WITH C1 LOWERS OUTPUT RIPPLE, ESPECIALLY AT HIGH CURRENT LEVELS.
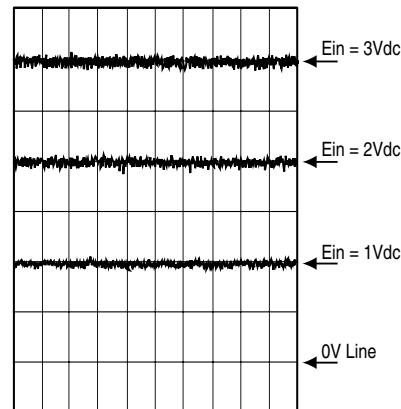

FIGURE 6C. WORKS WITH A WIDE RANGE OF LOADS. WITH R1 OPEN, HIGH FREQUENCY RIPPLE IS HIGHER BECAUSE OUTPUT LC FILTER IS UN-TERMINATED.

The main disadvantage with the full bridge rectifier is the circuits signal ground being at 57.5 Vrms (=115 Vac/2) above the power cord's neutral line which is connected in your building's circuit breaker box to the protective earth ground. When using an oscilloscope to probe test points, you cannot connect the scope probe's ground clip, which is internally connected to the power cord's neutral wire, to this circuit's signal ground. You will get false readings because

they are referenced to the wrong ground reference. Instead, use both channels of your oscilloscope and select "channel A minus channel B". Connect channel B to this circuit's signal ground and use channel A to do the probing. Connect the probes ground clip to power cord's neutral line.

SAFETY WARNING

The voltage in this AC/DC power supply can kill! It should only be worked on by a skilled person who is aware of the hazard involved. Insulated clip test leads should be used for hands off measurements while troubleshooting. After the power cord has been disconnected, it is advisable to wait at least 2 minutes to let high voltage capacitors discharge over their bleeders. Do not work alone unless another person capable of rendering first aid and resuscitation is present.

Because this power supply uses no transformer, it also has no isolation between the 115 Vac power line and its internal circuitry. It is mandatory to use a 3-prong wall plug and cannot be used in applications where government or company regulation does require transformer isolation from power line. The hot (115 Vac) wire and the neutral wire must be wired correctly in both the wall plug and the wall receptacle. Use a receptacle circuit tester to check for faults such as reverse polarity, open ground, open hot, open neutral, hot/ground reversed, hot on neutral. If this power supply is housed in a metallic chassis, connect the chassis to the wall plug's protective earth ground.

Most other AC/DC power supplies use transformers and have 3 output terminals as +V, –V and Ground; you can connect either +V to Ground or –V to Ground. The Ground terminal is internally connected to its chassis and to the power cord's protective earth ground. Not on this transformerless

power supply with no isolation. You cannot connect either one of the two output terminals to earth ground except, in the half bridge circuit, you can connect –V (marked as Signal Gnd in Figure 3) to the earth ground.

REFERENCES:

1. Y. J Wong, Spice Model Makes It Easy To Design With PWM Amplifiers, EDN, August 17, 1998
2. Y. J. Wong and W.E. Ott, Function Circuits, Design and Applications, McGraw-Hill Book Company, New York, 1976
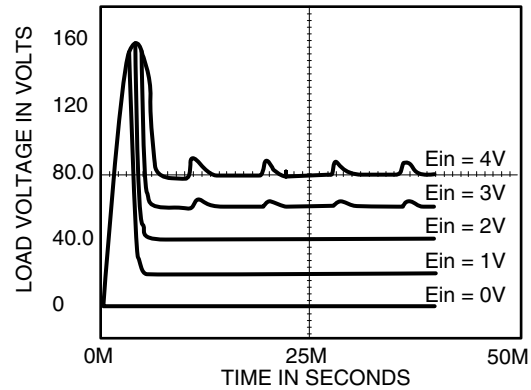3. Application Note 32, PWM Low Pass Filtering, Apex Microtechnology Corporation, Tucson, Arizona, 1998

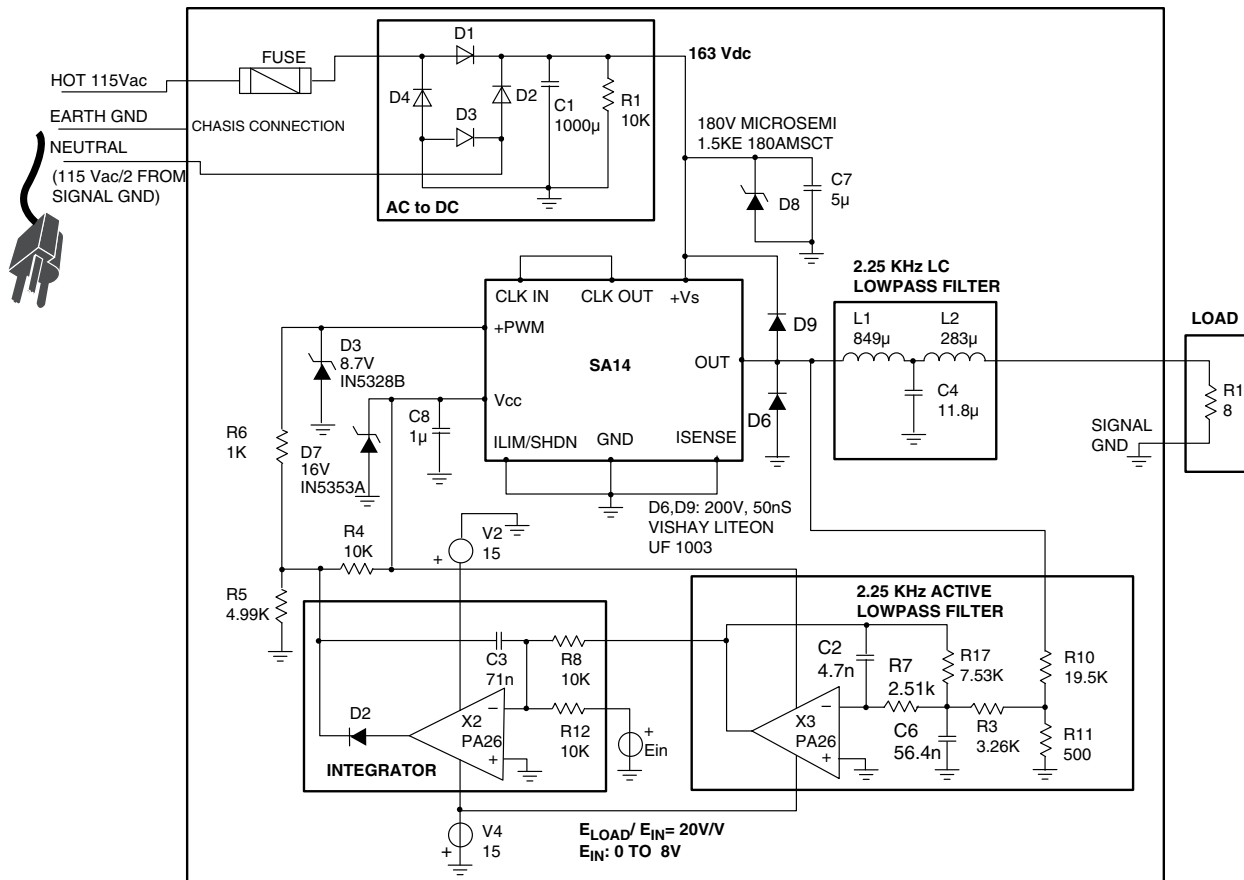**FIGURE 8.** TRANSIENT RESPONSE OF LOAD CURRENT WITH WAVE RECTIFIER. C1 = 1000μF

FIGURE 7. FULL BRIDGE RECTIFIER LOWERS OUTPUT RIPPLE BUT SIGNAL GROUND IS AT 57.5Vrms FROM POWER CORD NEUTRAL WIRE.