OFFICIAL

PROCEEDINGS

OF THE ELEVENTH

INTERNATIONAL

PCI '86

CONFERENCE

JUNE 17-19, 1986
MUNICH, WEST GERMANY

PCI '86 - JUNE

TABLE OF CONTENTS

An Alternating Current Switch Mode Power Supply

Robert Rutter
Motorola
Semiconductor Research and
Development Laboratory
Phoenix, Arizona

ABSTRACT

Two novel alternating current switch mode power supply topologies have been devised which are capable of providing a continuously variable undistorted sine wave output. These designs allow for the electronic control of ac power to a degree previously confined to dc power control. This article describes the concept, demonstrates the results of a bench test unit and suggests some possible applications.

A useful starting point for the understanding of this circuit can be found in the direct current switching power supply. A simple Buck (step-down) inverter topology is shown in Figures 1A and 1B. Power transistor Q1 is driven with a variable duty cycle square wave, chopping the input current at a high frequency (20 khz or greater). Energy is stored during the "on time" of Q1 in the magnetic field created by the current flow through the inductor L1. Energy is recovered during the "off time" of Q1 from the magnetic field of L1 with the current flow completing its loop through the diode D1. In this circuit, an approximation of the output voltage is Vout = Vin x Duty Cycle of Q1.

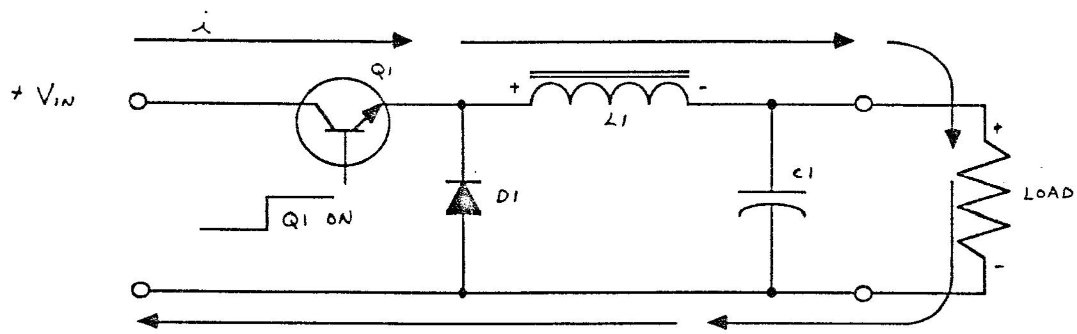


Figure 1A.

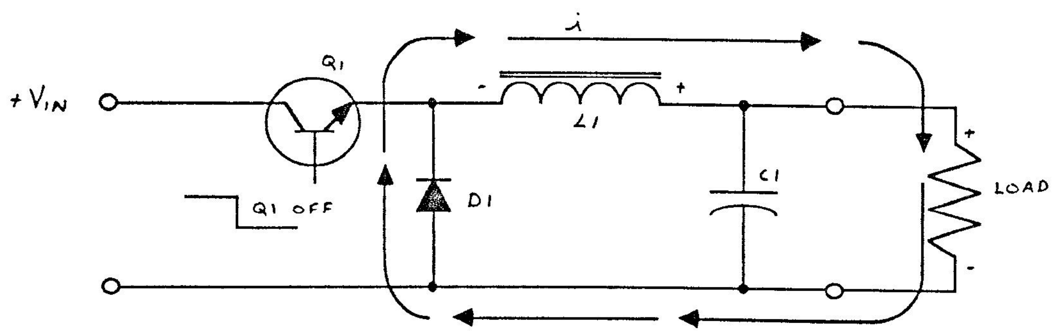


Figure 1B.

This circuit can be modified to function as an alternating current power supply by making both Q1 and D1 bidirectional. In the case of Q1 this can be easily accomplished by inserting Q1 inside a diode bridge. In the case of D1 both the problem and the solution are somewhat more complex. In the ac circuit D1 is required to both conduct the current through L1 bidirectionally and block the current allowed through Q1 bidirectionally. Two different solutions present themselves to this problem. Both methods will be described later in this article. For the moment let us assume that this has been accomplished. D1 is now replaced with a circuit that I call a "recovery circuit", as its function is to allow for the bidirectional recovery of the energy which has been stored in the inductor L1. Figures 2A through 2D show the operation of this circuit through a complete ac cycle.

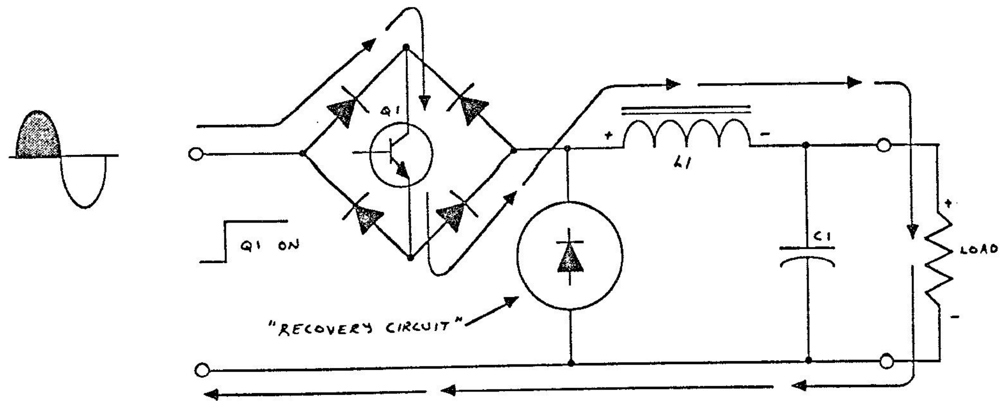


Figure 2A.

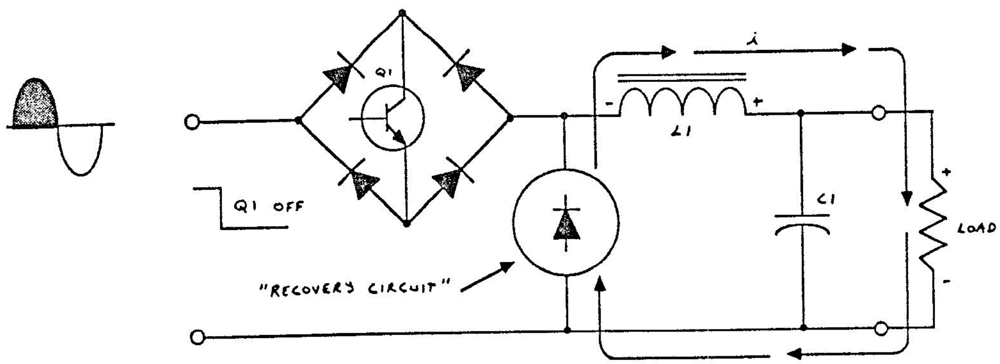


Figure 2B.

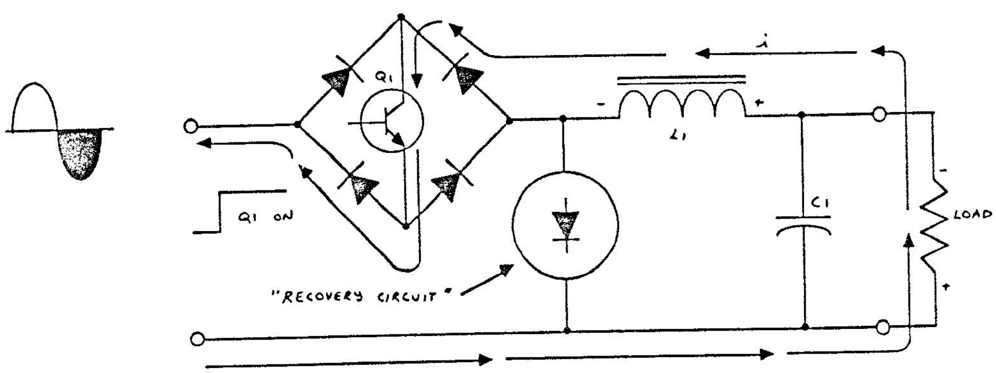


Figure 2C.

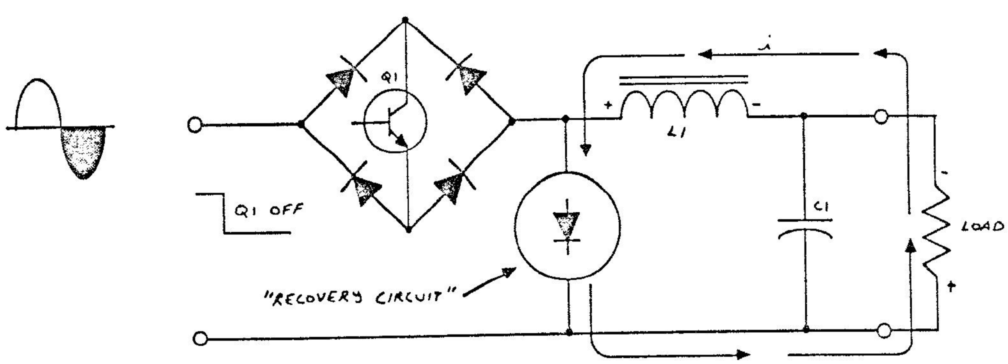


Figure 2D.

As discussed earlier two different approaches present themselves in the design of the recovery circuit. The first method is to have the direction of the recovery circuit controlled by the polarity of the input voltage. This method was inferred to in the operation cycle shown in Figures 2A through 2D. The second method is to have the operation of the recovery circuit to be controlled by the on or off state of Q1.

A simple two transistor recovery circuit is shown in Figure 3. During the positive half of the ac cycle Q2 will be switched off with Q3 switched on, providing for recovery of the inductor current through D1. During the negative half of the ac cycle Q3 will switch off with Q2 switched on, providing for the recovery of the inductor current through D2.

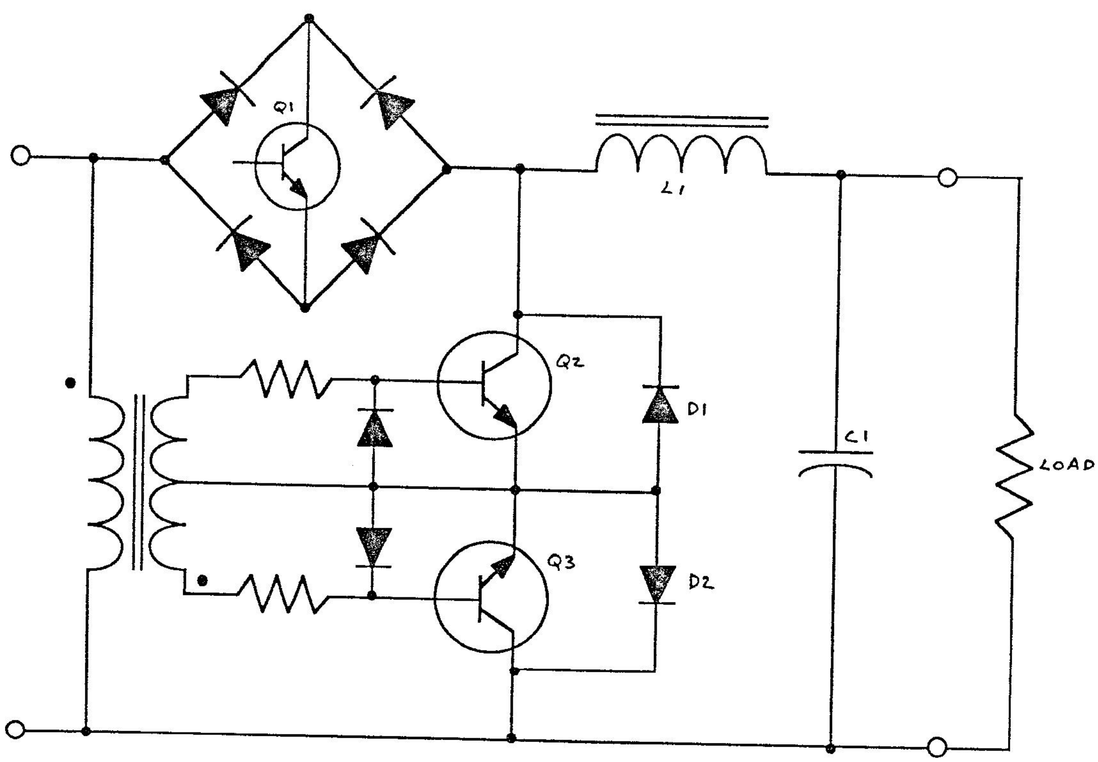


Figure 3.

The two transistor recovery circuit, while simple, is very inefficient. It consumes a fair amount of power to run and suffers from being unable to provide a good recovery path during the ac zero voltage crossover. Both transistors will be turned off just before and after this point. This limits this recovery circuit to loads of no more than 100 watts or so. A superior, if slightly more complicated method is to use power FETs in place of the transistors. Two operational amplifiers are used to detect ac polarity and drive the power FETs. This was utilized in the test stand #1 shown in Figures 4A and 4B.

While the polarity controlled recovery circuit has the advantage of being simple and reliable, it does have one major drawback. As the recovery circuit is tied to the polarity of the input voltage it cannot accommodate an inductive load. Experiments with this circuit have shown that the phase lag should not be allowed to exceed 2.5 degrees. This restriction makes this design adequate for lamps (both filament and gas discharge) but not applicable for motors or any other kind of inductive load.

The second approach to the recovery circuit is shown in Figure 5. In this design the recovery transistor Q2 is in a diode bridge. It is timed to switch off when Q1 is on and to switch on when Q1 is off. A fully bidirectional recovery path is thus created only when needed. This circuit can be used with any degree of inductive load. The only drawbacks of this design are in the critical timing relationship between Q1 and Q2.

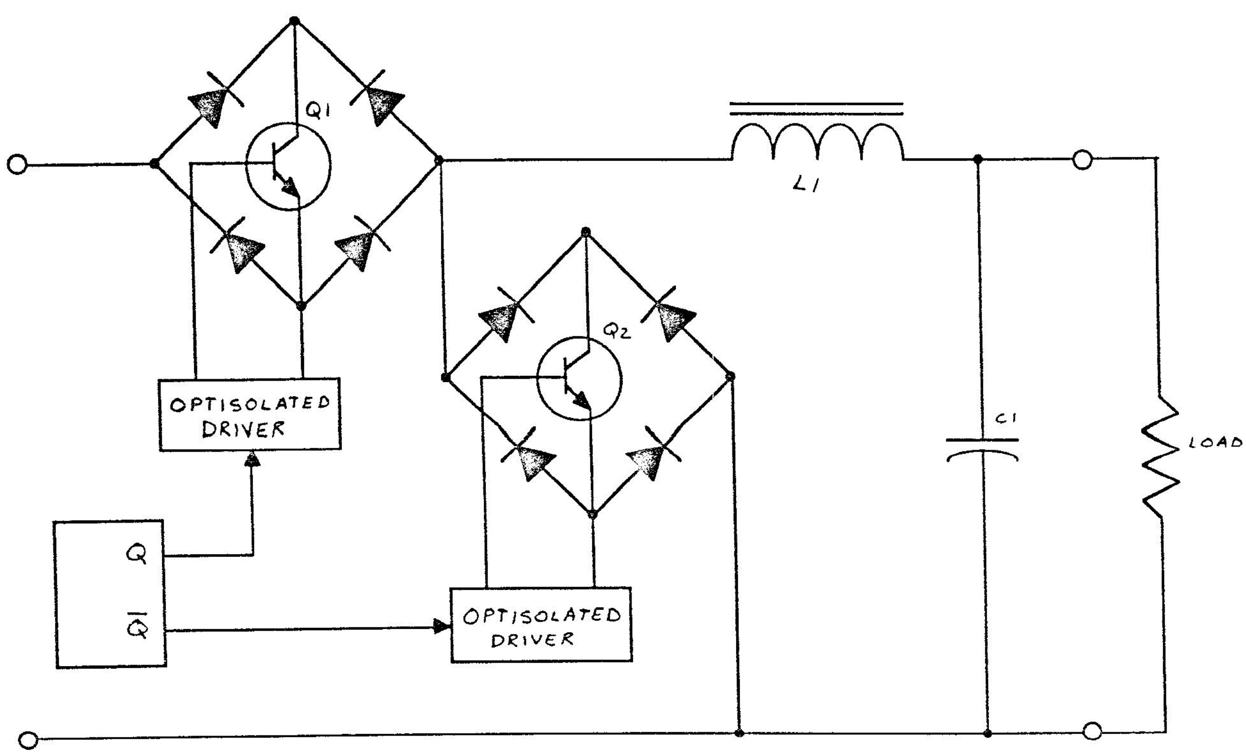


Figure 5.

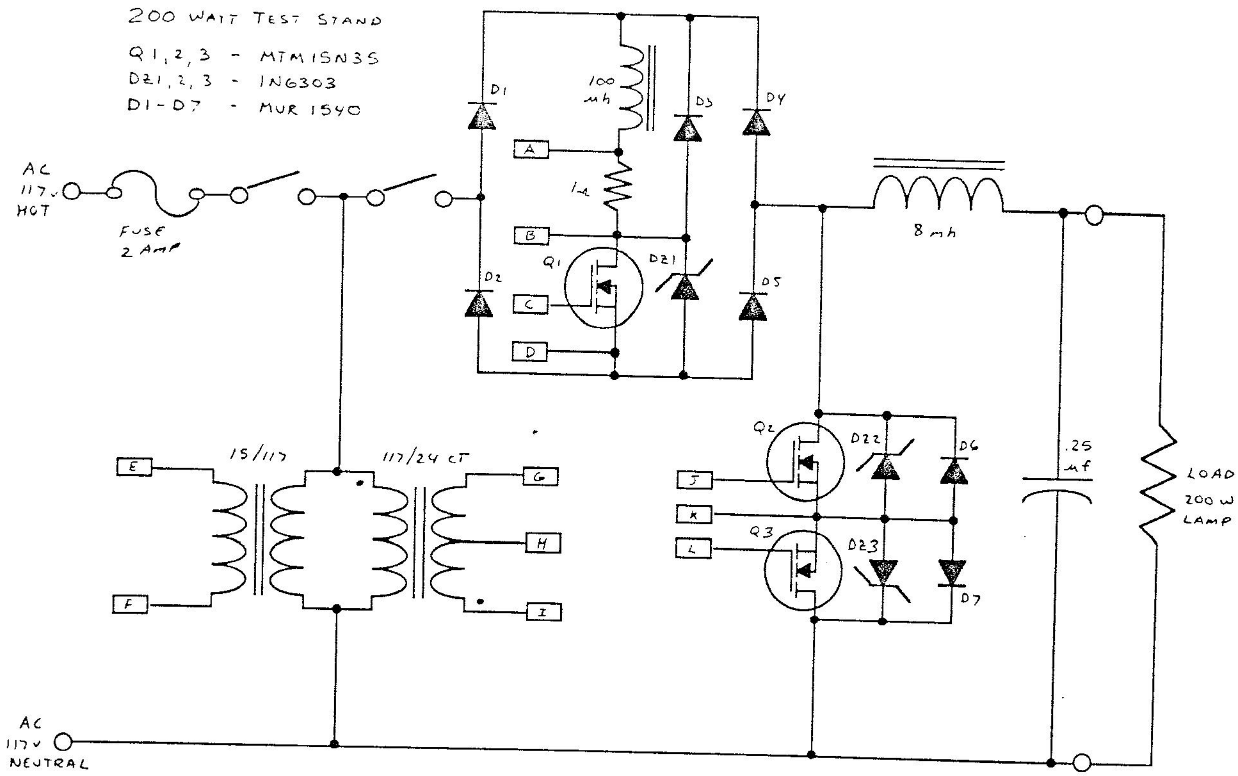


Figure 4A.

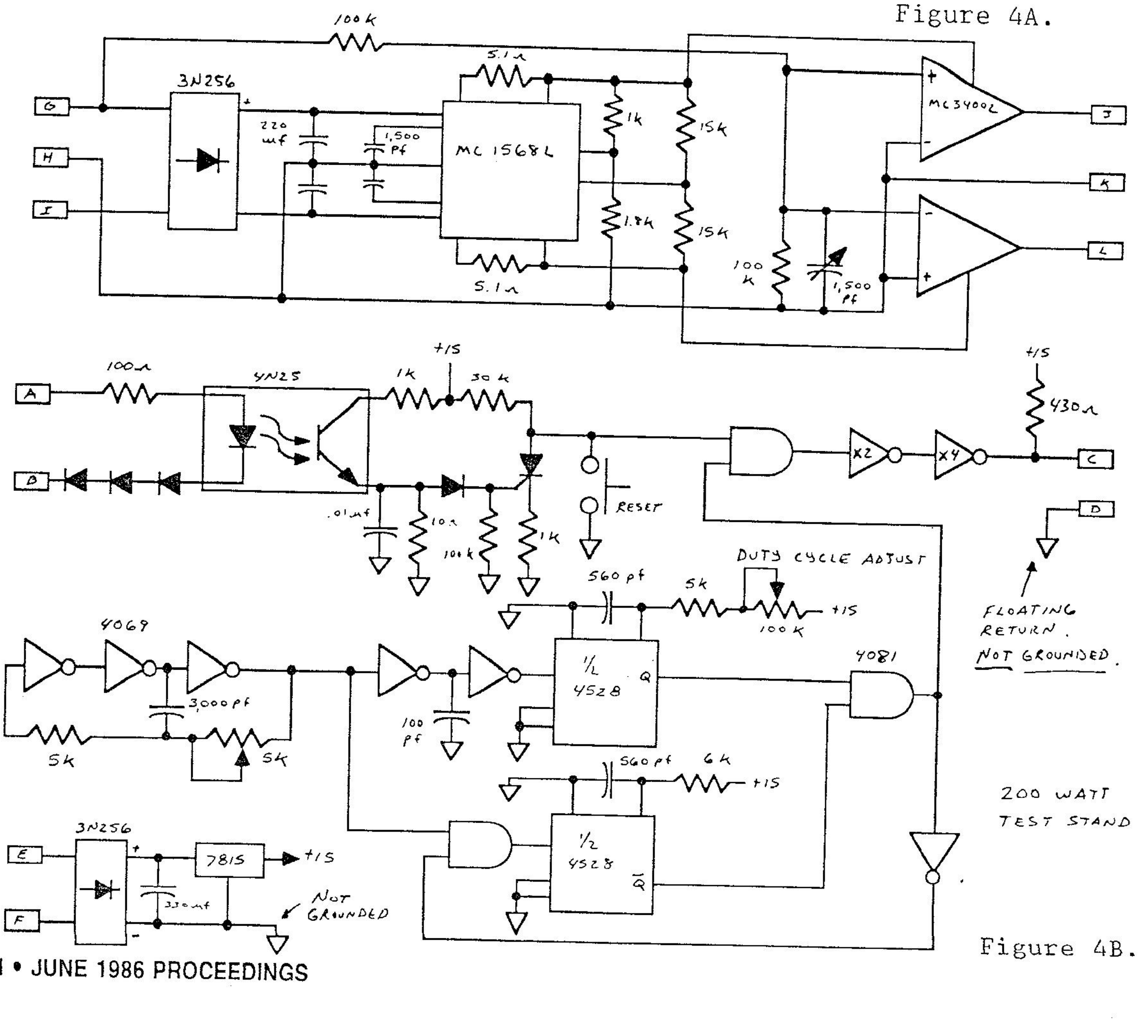
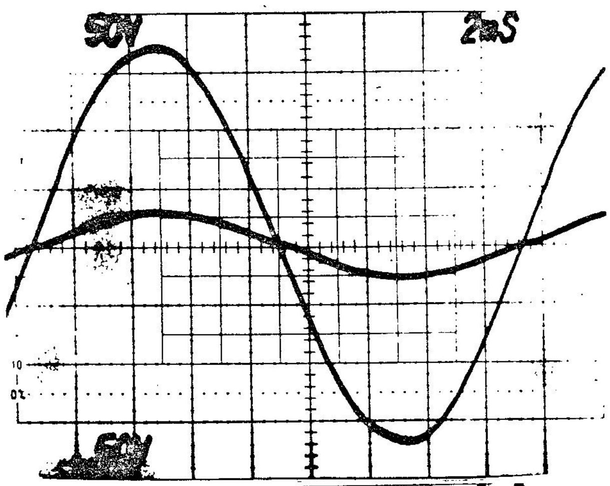
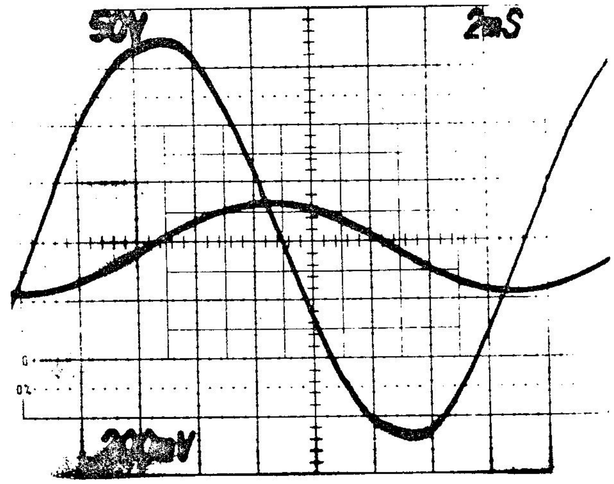
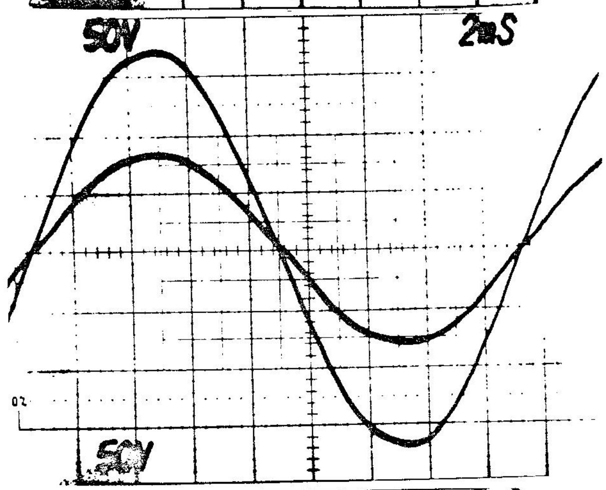


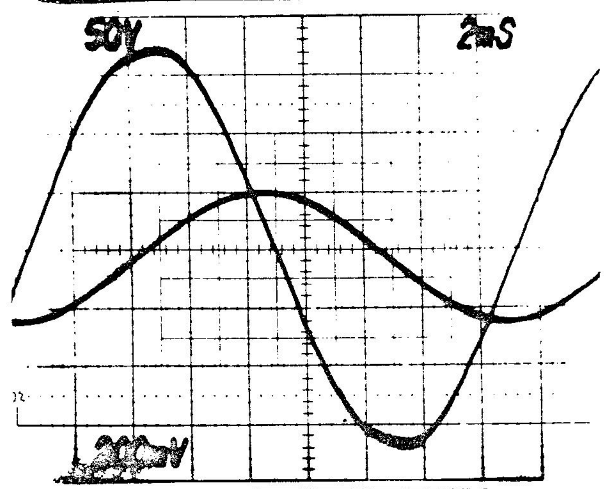
Figure 4B.

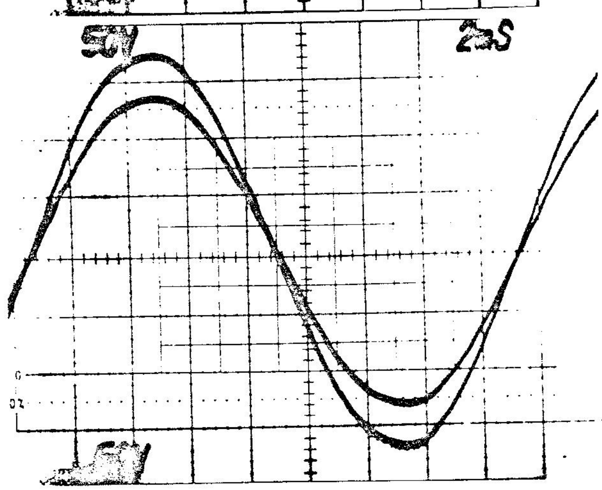
Perhaps the only thing interesting about the scope photos below is that there is nothing interesting in them. The row on the left is from the second test stand (timed recovery design) driving a 200 watt lamp. The voltage remaining constant is the input while the output is being varied. The row of photos on the right is of the same test stand driving a 2 henry load. The output is taken from across a 10 ohm resistor in series with the inductor.

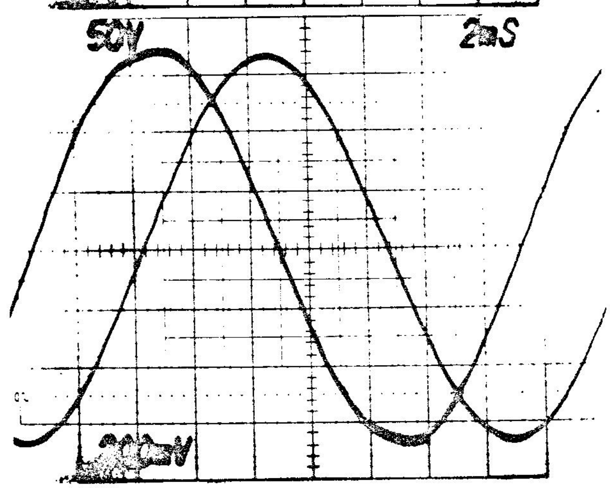












Two test stands were built to explore these two design concepts. The first test stand is shown in figures 4A and 4B. Both units ran directly off 117 vrms line voltage. Looking at Figure 4A one should note that power FETs were utilized in place of bipolar transistors. This simplified the driving circuit, allowing the use of both CMOS logic and operational amplifiers to directly drive the power FETs.

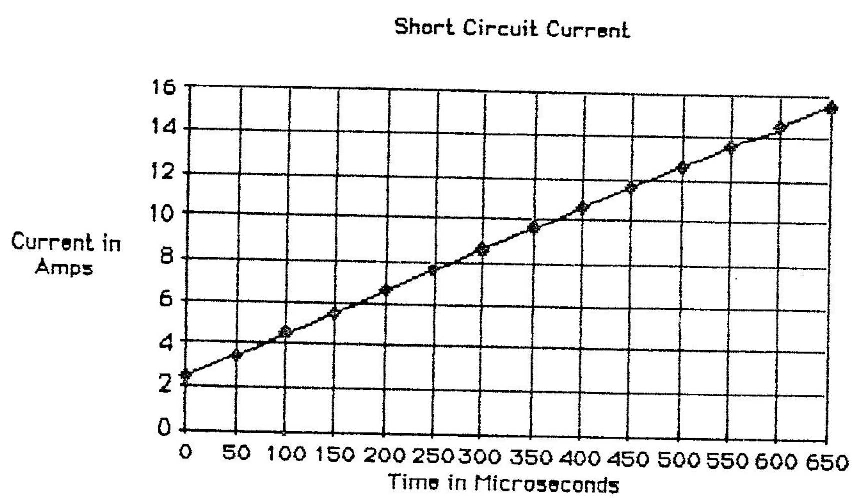
Also utilized in the test stands was full short circuit protection. The time delay given by the inductor L1, when combined with the very rapid shut down permitted with logic driven power FETs make short circuit protection quite easy. For example, let us consider a short occurring under a worse case condition.

(1) 200 watt (68 ohm) load
(2) Q1 at 100% duty, full on
(3) Voltage is at peak, 117 vrms=165 v peak
(4) Current through Q1 is at load peak, 2.43 amps
(5) Q1= MTP5N35
    Drain current continuous= 5 amps
    Drain current pulsed= 15 amps
(6) L1= 8 mh
(7) R1= 1 ohm

The equation describing the current upon short is:

$$i(t)= \frac{V - i(in)R}{R} \left(1-e^{-RT/L}\right) + i(in)$$

Graph 1



As can be seen from graph #1 it takes approximately 625 microseconds for the short circuit current to exceed the pulsed current limit of Q1. Assuming the circuit is designed to trip at 5 amps there is a 500 microsecond window in which to switch off Q1. This can actually be done in far less than 5 microseconds. It should also be noted that there is <u>no</u> inductive voltage surge associated with the switching off of Q1. The recovery circuit always provides a current path for L1.

In the test stands over current detection was used only to shut the output down. This is certainly not the only option available. The average current value can be monitored and used to control the duty cycle of Q1, in effect creating an AC current regulator. This could be combined with over current detection producing an AC current regulator with instant short circuit protection.

If, in the design shown in Figure 5, a step-up transformer is substituted in place of the load and a rms voltage feedback is added to the control circuit the design becomes an alternating current voltage regulator. The design would be capable of maintaining an constant output voltage Vout over an input range of 2/3 Vout up to the breakdown point Vceo of Q1.

What we have at this point is an AC power controller with an undistorted AC output; a true AC power source which can be both voltage and current regulated in the same manner as DC switching power supplies. Feasibility has been demonstrated on a laboratory scale and its use in numerous applications seems possible.

As a regulated AC voltage source this circuit could be used to ensure a constant AC voltage for any type of AC powered electronic equipment. This could be of particular benefit in areas plagued with wide voltage swings in the power delivered by the local utility. This design offers a decisive improvement in voltage regulation over ferroresonant transformers currently used in this function. A substantial cost savings is also likely.

As an regulated AC current source this circuit could replace the ballast used in gas discharge lamps such as mercury lamps. The benefits would be derived through the ability to control the lamp current in a precise manner; throughout start up and operation. This would promote longer lamp life and higher efficiency. It is possible (assuming integration of control circuit and volume production) that a cost savings over present lamp ballast could also be realized.