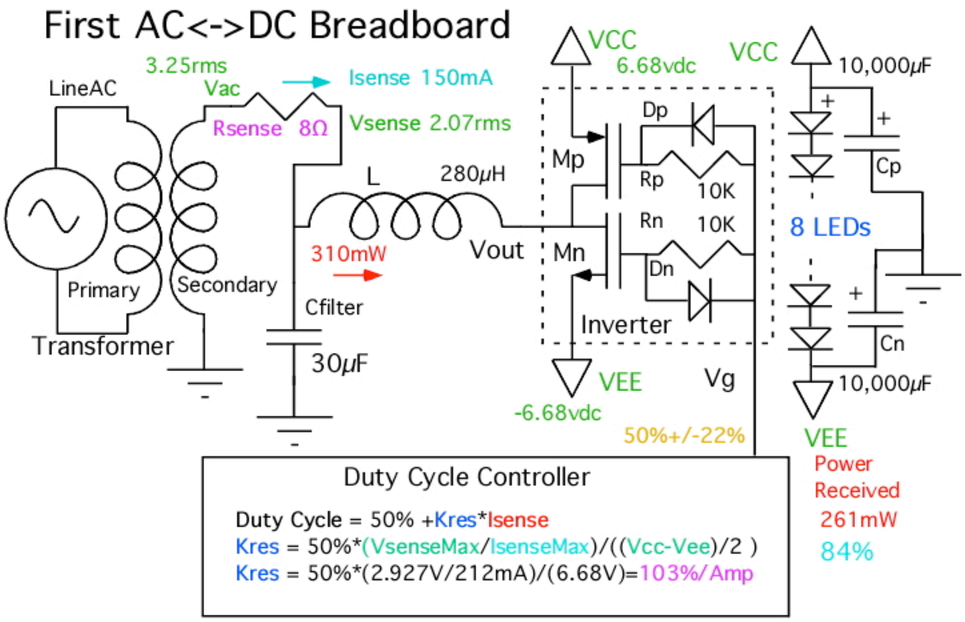
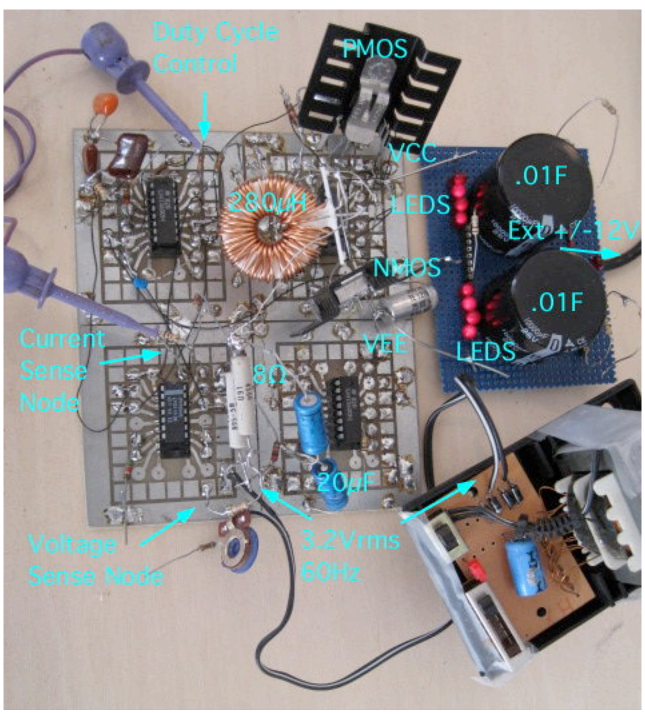
A RECTIFIER LESS AC<=>DC CONVERTER

12/945,704 filed 011-12-2010



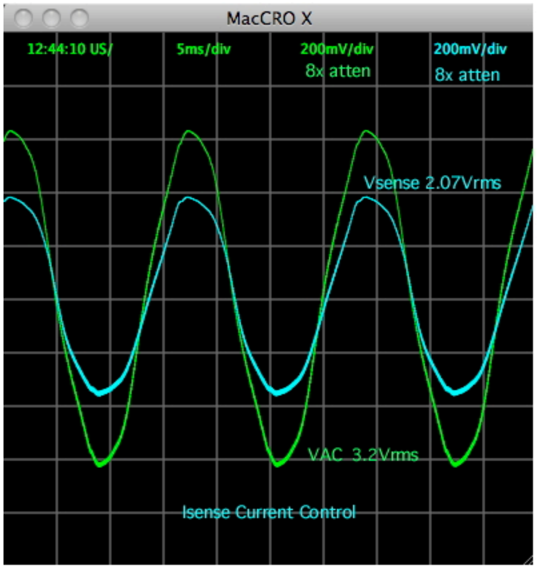
A Rectifier-less Bidirectional AC to DC converter is just a simple DC to DC being used differently. The duty cycle of a DC to DC converter defines an output voltage. If this output node instead gets connected across a secondary of an AC transformer, and if the duty cycle gets defined to track secondary current, then the secondary will be seeing a simulated resistor across it. This simulated resistor will absorb energy and transfer it to the split supplies. It is based on using the Energy Harvesting Resistor described here.

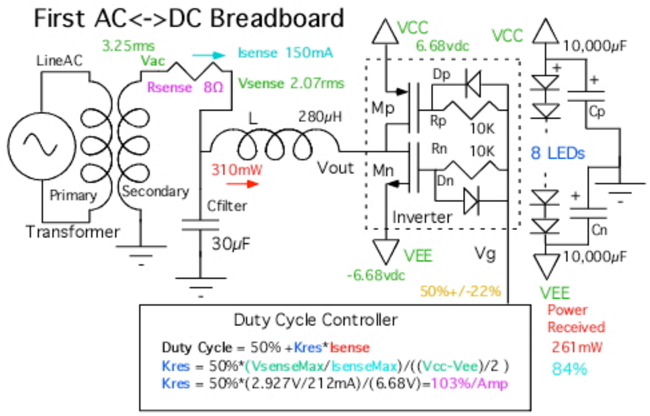
The circuit and equations are shown above. The working breadboard is shown below.



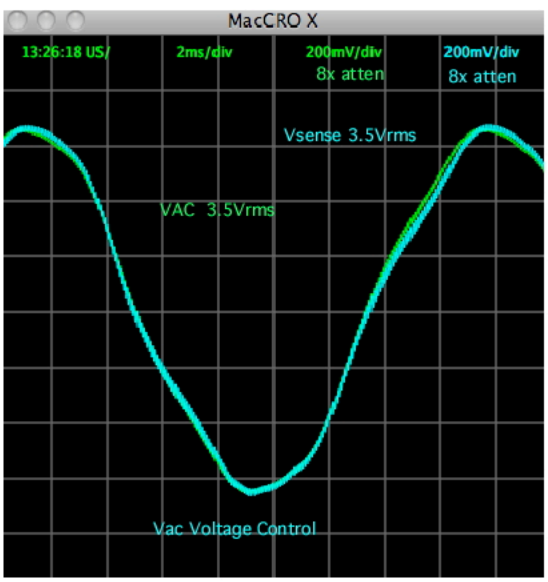
This breadboard takes a 3.2Volt rms 60 Hz input directly off a secondary of an ac line transformer, and transforms it directly into +/- 6.7 Volt splits supplies to drive 8 LEDS. Most of the circuit is for duty cycle modulation experiments.

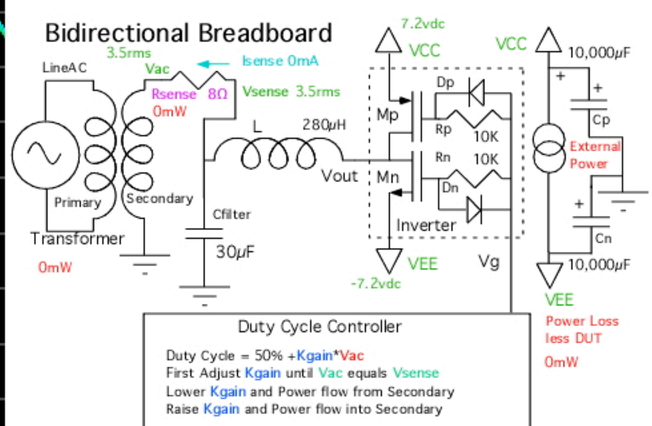
And this is all being done using analog circuitry.
The full schematic is included at the end. Everything appears to be working as expected.





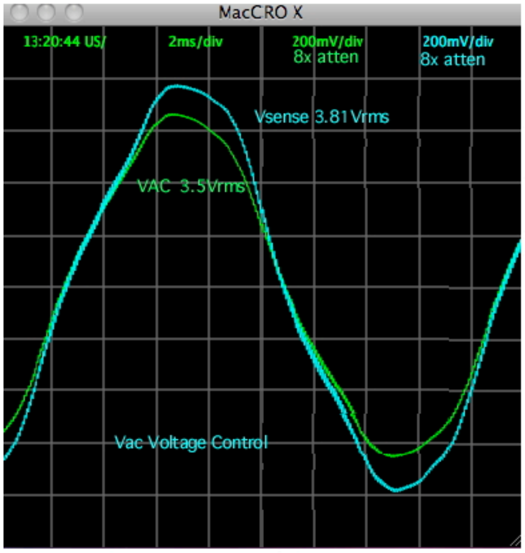
There appears to be two main modes of operation. The first mode is to measure the secondary current, and then use it to modulate the duty cycle of a simple DC to DC converter above and below 50%. In the breadboard, this causes the secondary to think it is seeing a 22 Ohm resistor across it. The modulating duty cycle is multiplexing the 150mA rms input current to the two supplies. The actual AC waveforms of the secondary voltage Vac and the Vsense voltage are shown above. Both waveforms are on the same scale. The current flowing across the 8 Ohm sense resistor is the secondary current.

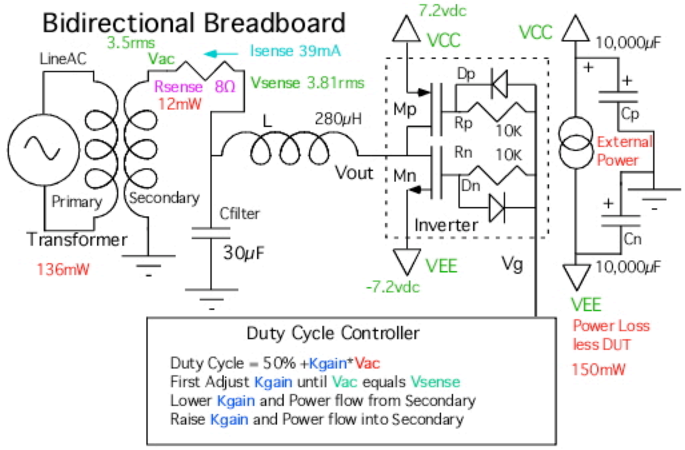




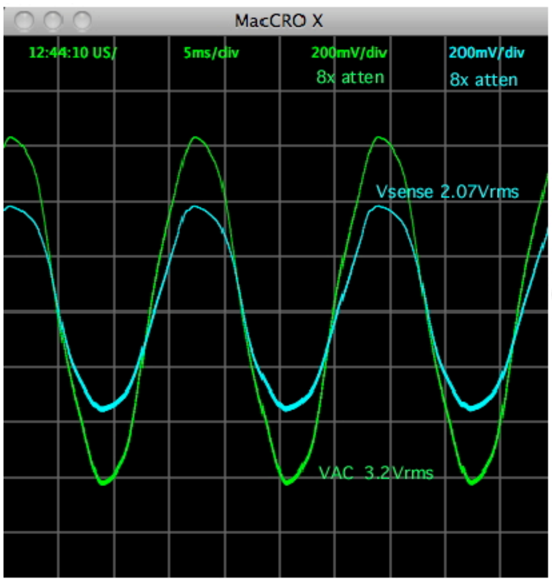
The bidirectional mode of operation involves monitoring the the secondary's voltage instead. In this case the secondary voltage times some constant Kgain is used to modulate the duty cycle.

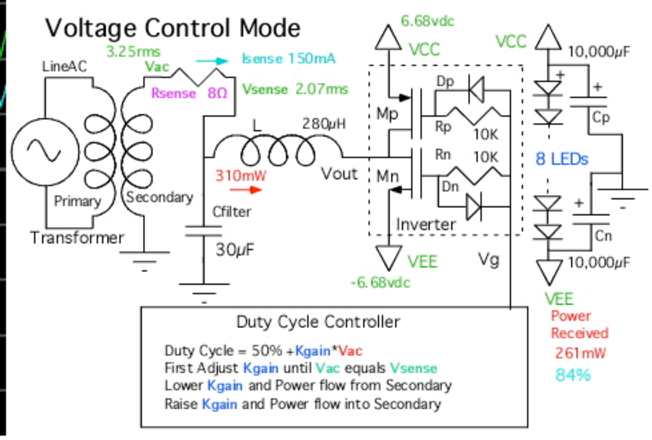
There will be some value for Kgain where the Vsense voltage equals the VAC input voltage. Under this condition, little power should flow. The two AC waveforms off the breadboard are shown above. This should raise some questions as to how close can the duty cycle get to reflect the voltage that will appear at Vsense.





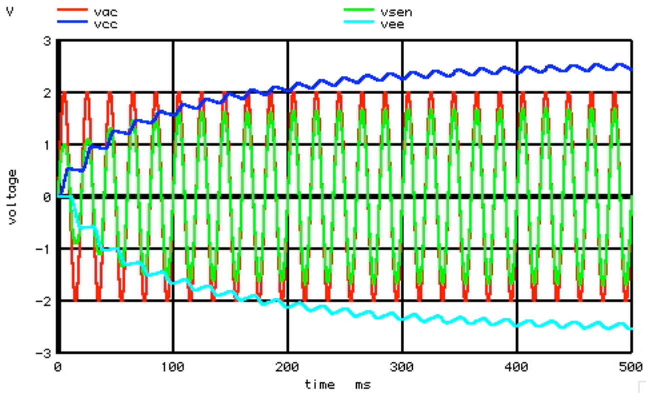
Now if this value for Kgain is increased, then the vsense voltage can get larger than Vac, and now power is flowing into the 60Hz AC socket. Unlike normal AC inverters, this is transferring power from the split supplies as a negative resistor. The waveforms above show that Vsense is larger than Vac. An external power source needs to be applied to VCC and VEE to do this test. It appears that the power drain on the external supply is what would be expected.



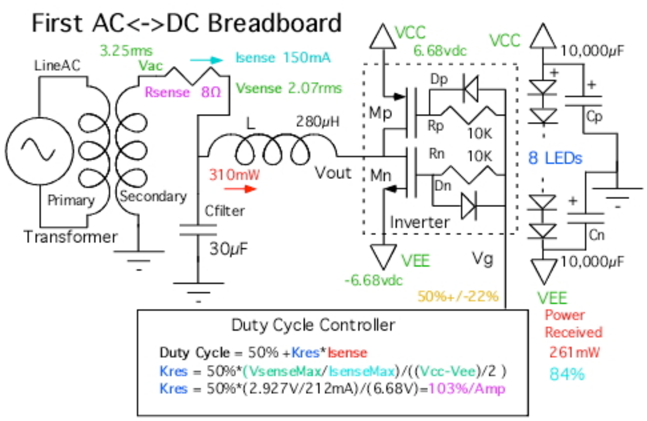


Lower the value of Kgain enough, and now the power is flowing from AC to DC. This method of voltage driving the duty cycle mode appears to be ideal for bidirectional AC<->DC power transfer since the circuit goes to an open circuit between the power flow directions.

**In this breadboard, the efficiency appears to be around 84%.
It is not obvious how this invention is little more that just using a simple DC to DC converter in a new application. If that is so, then the same efficiencies for DC to DC converters should be possible.**



This breadboard is actually self starting. When the AC first turns on, it forward biases the drain bulk junctions of both power MOSFETs. This turns on the duty cycle controller which drives the split supplies to a level higher than the AC input voltage.



When the breadboard is doing the job of a full wave rectifier, it loads the AC line exactly like a resistor. According to some recent articles in EDN and Power Electronics Technology, things like having a high power factor is becoming important.

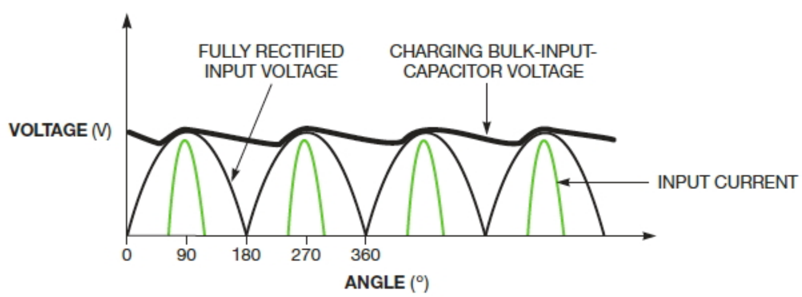


Figure 2 Superimposing the current over the voltage for the circuit in Figure 1 shows the need for a PFC to shape the current.

Apparently the nonlinear loading of full wave rectifier circuits is starting to create a need to raise the power factor of AC to DC convertors.

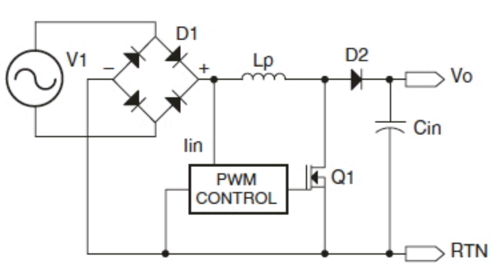


Figure 8. PFC Boost Pre-Regulator

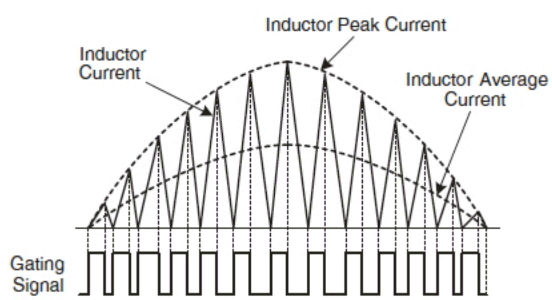
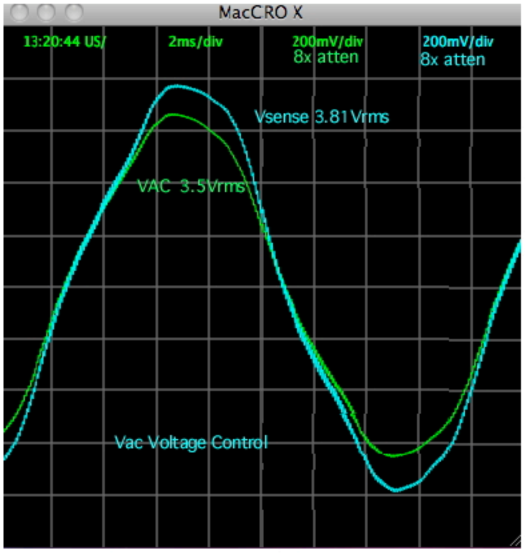
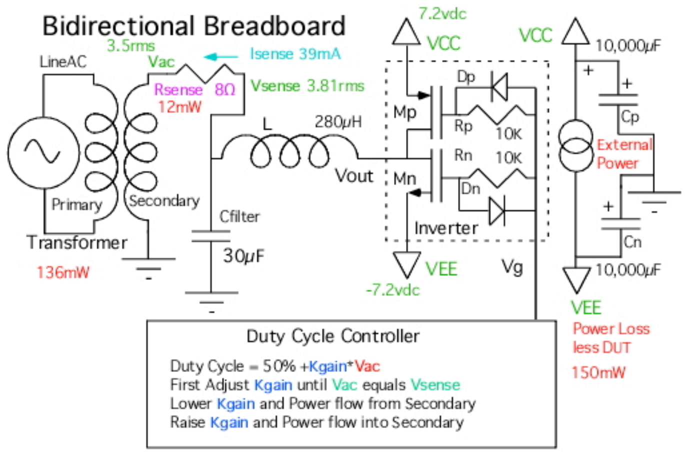


Figure 9. Discontinuous mode of operation

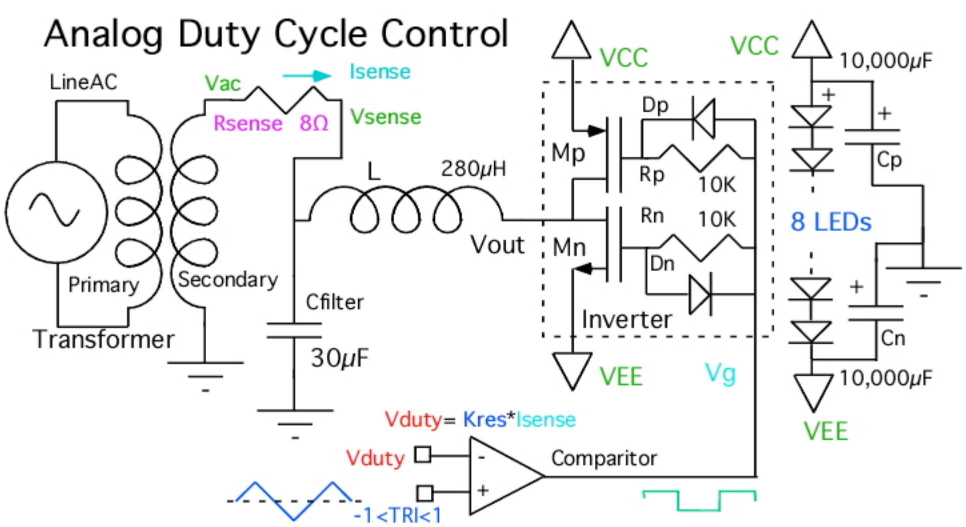
The figures above are from a Fairchild application Note about Power factor correction. The attempt is to be able to draw power off the ac line like a resistor. Not very many power factor reduction methods however lack rectifiers in the power signal path.





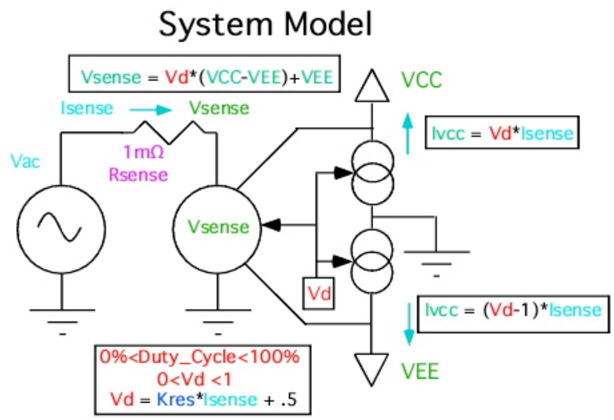
The breadboard sure does look like it can load the ac line like a linear resistor. And even as a negative linear resistor. If solar power becomes more widespread, would it generate a need for a high power factor DC to AC convertor?

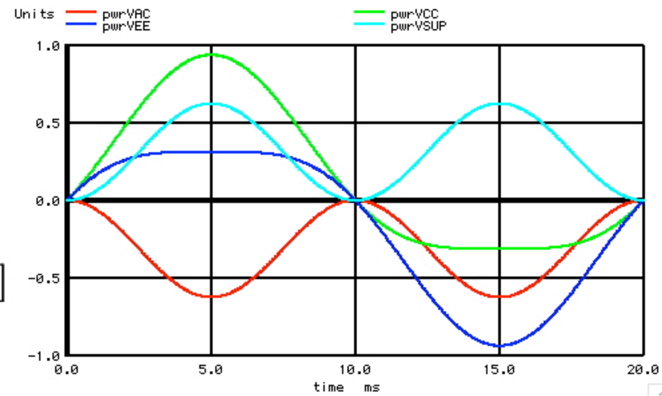
The power companies are installing smart meters in peoples homes. This might allow power companies to charge customers at different rates over the day. Could it be economical someday to store AC power into home batteries during the time when rates are low, and then reconvert it back to AC for use when rates are high?



The invention is mainly just a DC to DC converter with differences in terms of input/output ports, and in how the duty cycle gets defined. The easy way to do the duty cycle in analog is to build up a triangle waveform, and stick it into one input of a voltage comparator. An analog signal voltage on the other input will modulate the duty cycle.

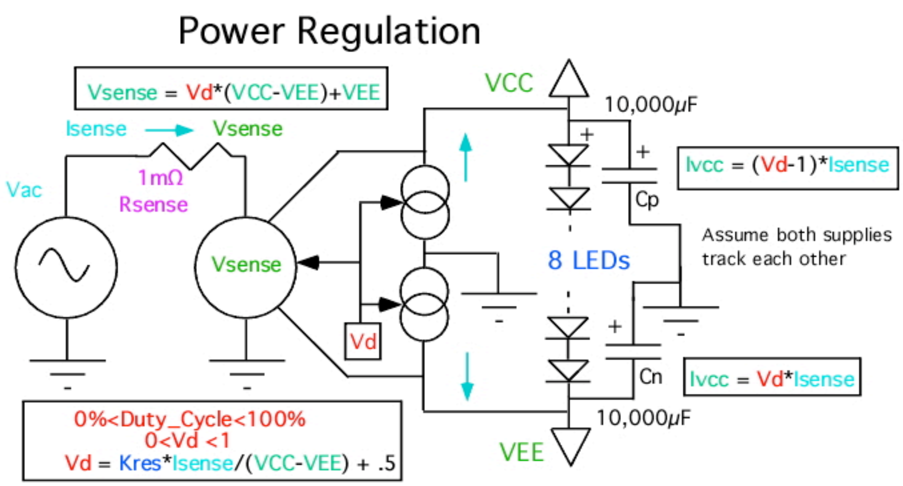
The analog signal and its effect on the duty cycle is doing two things. First it generates a voltage at Vsense which is scaled between the two supply voltages. Second, the duty cycle multiplexes any current through the sense resistor between the two power MOSFETs and their power supplies.





The system model above can show all the equations. For this system model, the analog voltage Vd is being defined to go from 0 to 1, which corresponds to a 0 to 100% duty cycle. This duty cycle Vd is being modulated by the Isense current at some gain. The Vd voltage will both define the voltage Vsense, and will multiplex any Isense current. Consider what happens when Vac and Vsense are identical. No Isense current will flow, and zero current will get multiplexed between the two MOSFETs.

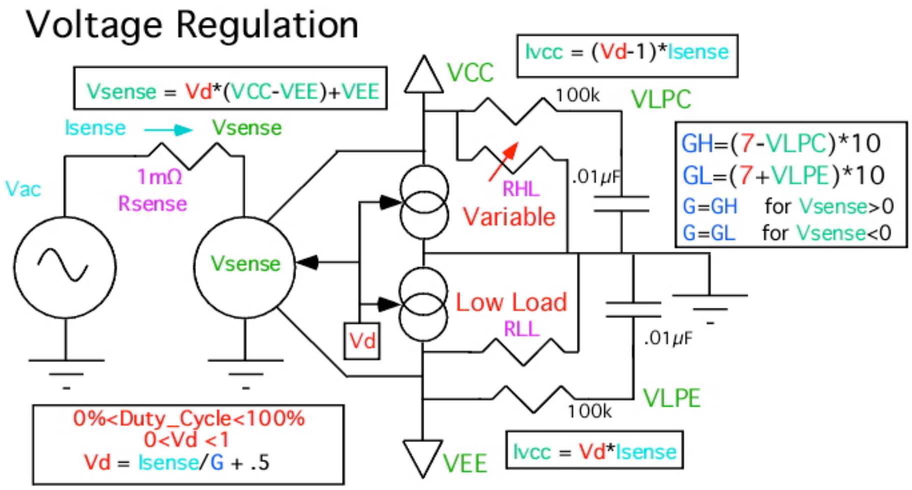
Because the Vd term, which defines the Vsense voltage, is being scale by the input current, the Vac voltage source will see a load looking like a linear resistor. Now the current multiplexing will always be charging up one of the supplies and discharging the other. But when the total power of both supplies are summed together, they are receiving close to the same power that the Vac source is being loaded with. Naturally any IR drop in the power path will reduce efficiency.



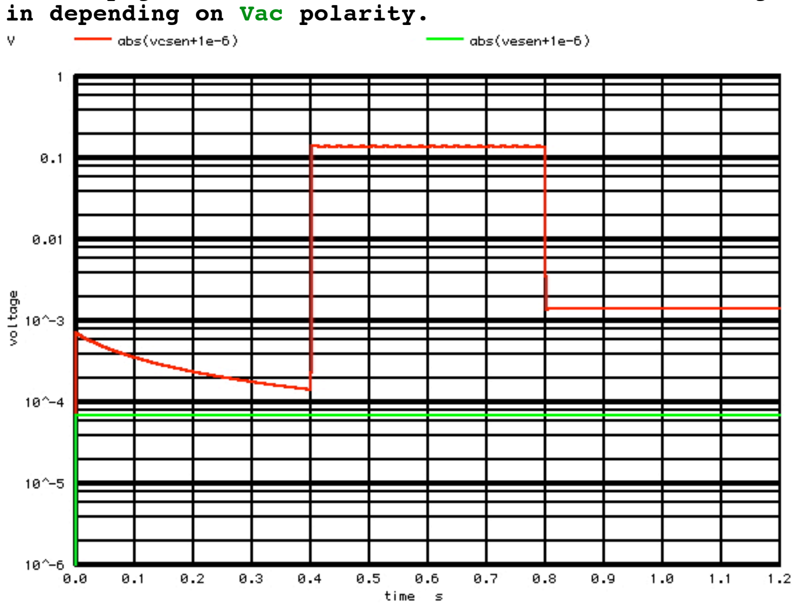
This invention tends to have a native output format of power regulation. For instance, if the output loads are LEDs, and if the voltage across LEDs can drift with temperature, the output current will auto-adjust itself the maintain the same output power.

For the sake of tying up any loose ends, one might be inclined to make the Vd value track the inverse of the supply voltages. Since the Vsense voltage is being scaled by the supply voltages, that means the Vsense magnitude should be insensitive to the supply voltages. If so, then the same input Isense produces the same Vsense. So the simulated load resistance across Vac will not change. So the power transfer will be independent of the split supplies voltages.

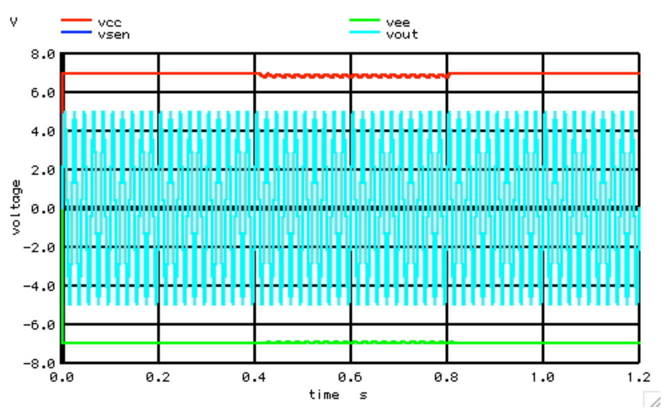
Suppose both VEE and VCC increase by 10%. The same Isense current should produce a Vd with a 10% decrease in modulation. But the Vsense is also scaled by the 10% higher VCC and VEE voltages. So Vsense comes out the same. But the multiplexing of Isense current has been reduced by 10%. So the two supplies are at a 10% higher voltage, but they are receiving 10% less charging up current.



Now normally the output power is formated in a voltage regulated mode. There is nothing stopping the voltage to current relationship to the input resistor from being adjusted in terms of both magnitude or asymmetry. Because VCC gets charged up when Vac is positive, and VEE when negative, it is possible to regulate both VCC and VEE independently. The system simulation above shows both VCC and VEE being regulated to 7 volts. The supply voltages are low pass filtered since feedback should have a one pole compensation. The loop gain is set to 10. Different values for G get switched in depending on Vac polarity.

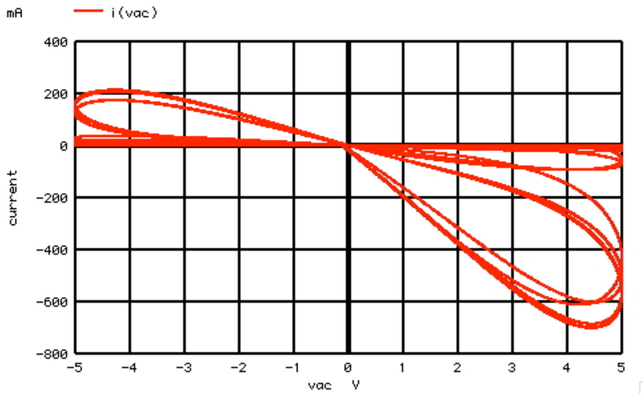


In this example, VEE will lightly load with constant 50uA load. But VCC will vary its load in steps over three orders of magnitude.



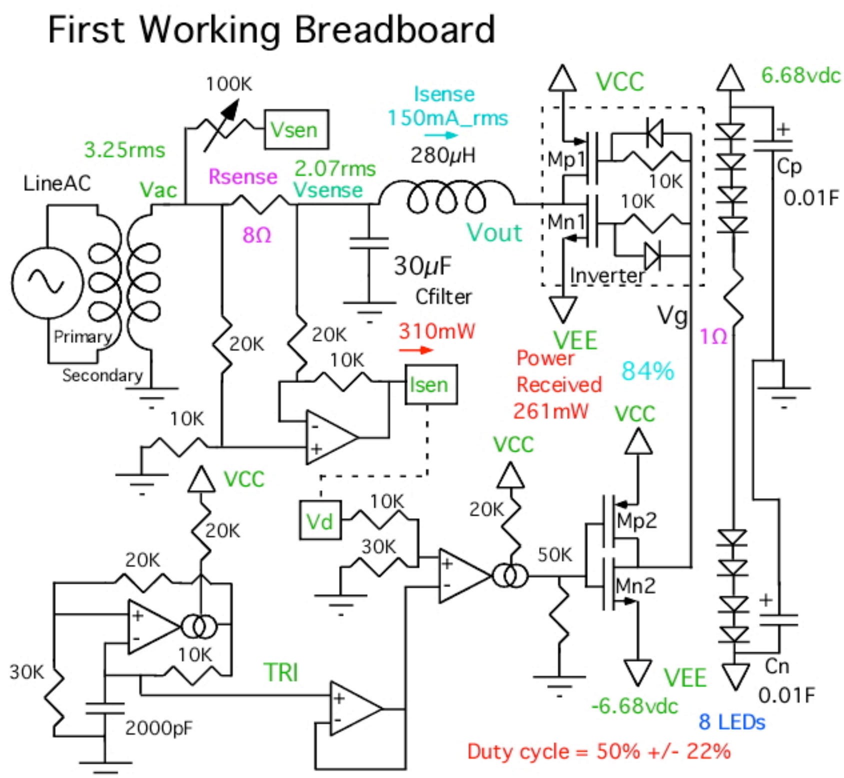
Under heavy load, one would expect VCC to develop some ripple. But VEE appears to develop ripple at the same time. This is

due to the fact that whenever VCC is being charged, VEE is being discharged. The VEE feedback loop needs to recover this lost charge when Vac is negative. So even when VCC is the only supply being used, the Vac voltage can not be completely asymmetrically loaded.



The asymmetry of the current loading on the AC line is shown above. So this type of AC to DC converter cannot load the AC line like a one diode rectifier. The lowpass filtering is not at the moment low enough to reduce the looping in the current loading curve. These low pass filters will affect the voltage regulation response to load current spikes. The step response to a high load current appears to be fast attack, slow decay.

For single supply applications, it may make more sense to build up a second DC switching network as is shown on [figure 9 on this web page] to transfer charge from one supply to the next. This enables the resistive loading to be symmetrical.



The full circuit for the breadboard is above. A secondary sense current node and secondary voltage sense node are provided, and both have been checked out. A LM13600 is being used to provide an easily scaleable triangle wave, and it is also used as a voltage comparator. A LM6144 is being used to buffer the triangle wave, and to measure the current through the 8 Ohm sense resistor. A CD4007 is being used to drive the Power MOSFETS. These MOSFETs have large capacitances, and adding some diodes and resistors appear to reduce the shoot through current.

Most of the supply current is going to the LM13600. It draws in fact a little too much supply current. It is mainly being used just to check out some scaling concepts. The duty cycle controller mainly needs just a triangle wave source and a comparator. The gate resistor/diodes networks certainly could be replaced with something better in order to operate at higher frequencies. The sense resistor is set at 8 ohms in order to make the voltage across it obvious enough to show things like bidirectional power flow. The Triangle wave is running below 20KHz, so the 30uF cap (two 60uF electrolytics) is chosen just to make the Vsense signal look clean.

Other breadboard experiments are in the works. Running spice simulations side by side with a working breadboard has some crosschecking advantages. Some of the components used to build the AC<->DC converter hardware are shown below.

There appears to be a lot of recent patent activity in the area of building "bridgeless PFC convertors". The following are some of the patents.

11_584_983_Method_and_apparatus_for_high_efficieny_rectifier
11_204_307_AC_to_DC_power_supply_with_PF
11_302_544_Simple_partial_switching_power_factor_correction
11_474_712_BRIDGELESS_BI_DIRECTIONAL_FORWARD_TYPE_CONVERTER
11_480_004_High_efficiency_power_converter_system
11_706_645_AC_to_DC_voltage_converter_as_power_supply
12_401_983_BRIDGELESS_PFC_CIRCUIT_FOR_CRM
12_798_682_Bridgeless_PFC_converter

3295043_MASSEY_D_C__TO_D_C__REGULATED_CONVERTER
4183079_DC_AC_inverter
4523266_AC_to_DC_conversion_system
4943902_AC_to_DC_power_converter_and_method
5570276_Switching_converter_with_open_loop_input_regulation
5815380_Switching_converter_with_open_loop_Primary_regulation
5815384_Transformer_uses_bi_directional_synch_Rectifiers
6115267_AC_DC_converter_with_no_input_rectifiers
6157182_DC_DC_converter_with_multiple_operating_modes
6608522_DC_to_DC_converter_providing_stable_operation
7250742_Digital_control_of_bridgeless_power_factor_correction
7265591_CMOS_driver_with_minimum_shoot_through

And here is some more information for those who may be interested.

A_BIDIRECTIONAL_PWM_THREE-PHASE_STEP-DOWN_RECTIFIER
A_bidirectional,_sinusoidal,_high-frequency_inverter
A_DUAL_INPUT_BIDIRECTIONAL_POWER_CONVERTER
A_new_structure_for_bidirectional_Power_flow
BI-DIRECTIONAL_INVERTER-CHARGER_
Bi-directional_single-phase_half-bridge_rectifier_for_power_quality
BiDirectional_Converter

Bidirectional_UP_Inverter
Synthesis of Input-Rectifierless AC/DC

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