ULRASONIC GENERATOR POWER CIRCUITRY

Will it fit on PC board

MAJOR COMPONENTS

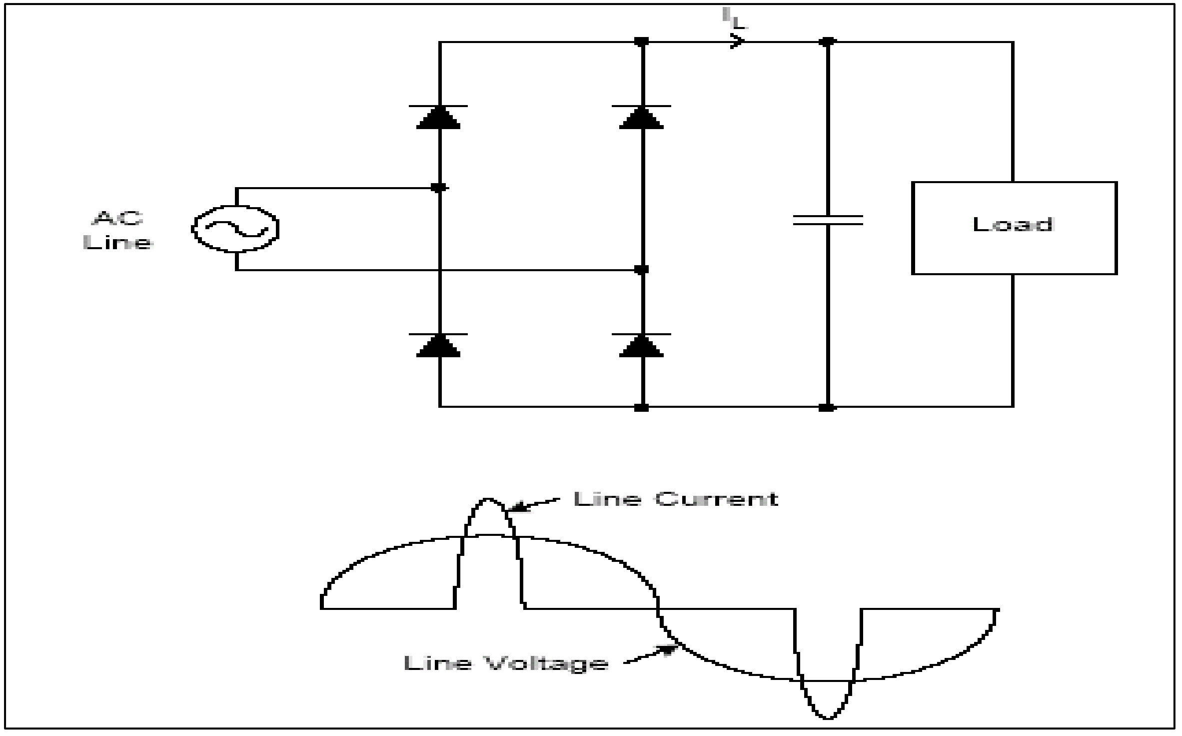
- HIGH POWER FACTOR RECTIFIER
  – RECTIFIES POWER LINE
- RAIL SUPPLY
  – SETS VOLTAGE AMPLITUDE
- INVERTER
  – INVERTS RAIL VOLTAGE
- FILTER
  – FILTERS HARMONICS

WHY HAVE A HIGH POWER FACTOR RECTIFIER

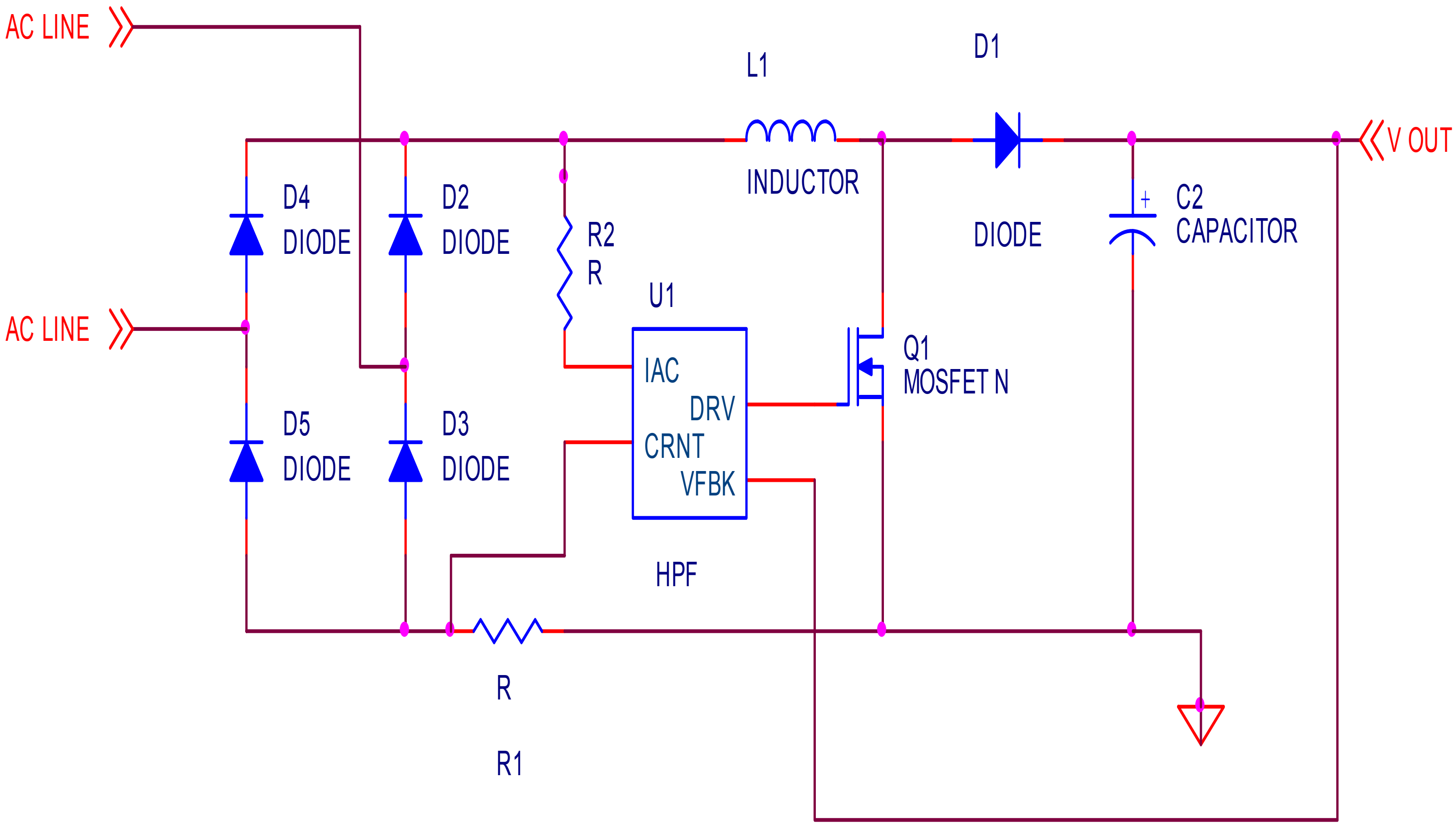
- TO COMPLY WITH IEC
  - IEC 60601-1-2 MEDICAL ELECTRICAL EQUIPMENT, TABLE 201
  - IEC-61000-3-2 HARMONIC EMISSIONS
- EFFECTS OF HARMONIC CURRENTS
  - POWER LINE POWER CAPACITY
  - MOTOR VIBRATION
  - EQUIPMENT BURN OUT

PRIMARY CAUSE OF HARMONIC CURRENTS

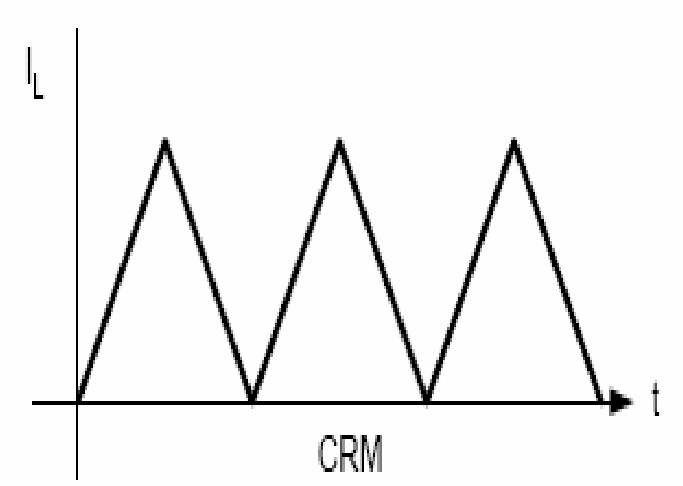
- CAPACITOR INPUT FILTERS

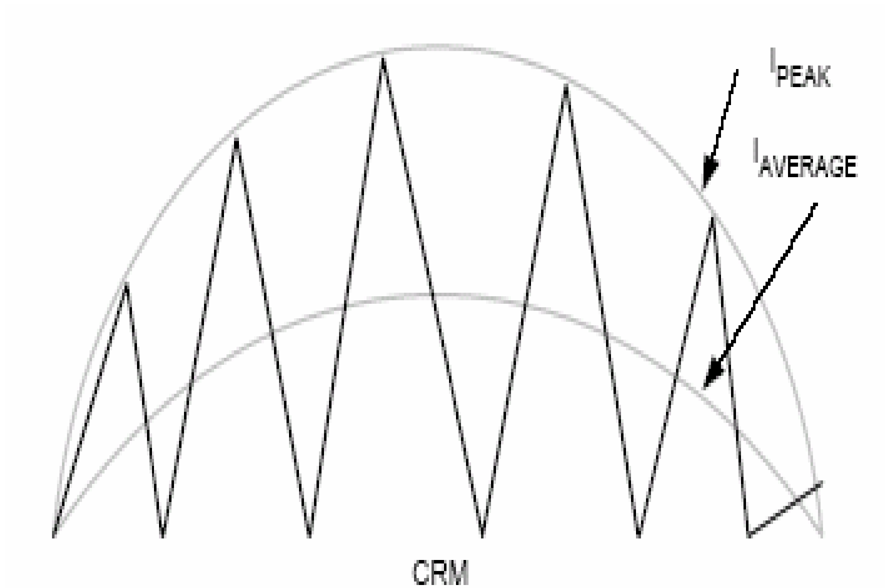


BOOST CONVERTER



CRITICAL CONDUCTION MODE





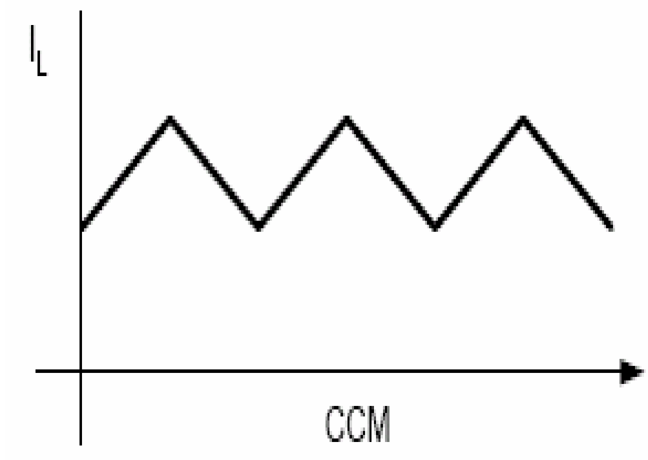
LIMITATIONS CRM

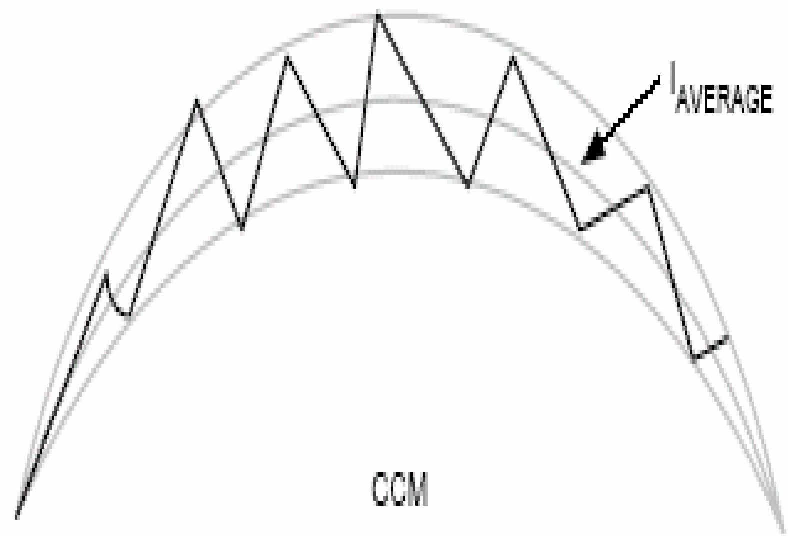
- LIMITED TO 200 WATTS
  - LARGE CONDUCTION LOSSES
  - INDUCTOR CURRENT EXCURSIONS
- HIGH EMI
  - RF CURRENT AMPLITUDE

ADVANTAGES

- VERY SIMPLE CONTROLLER
- LOW LOSSES AT LOW POWER
  - TRANSISTOR TURNS ON WHEN DIODE CURRENT IS ZERO
    - NO DIODE CHARGE
    - NO CURRENT IN TRANSISTOR WHEN IT TURNS ON

CONTINUOUS CURRENT MODE

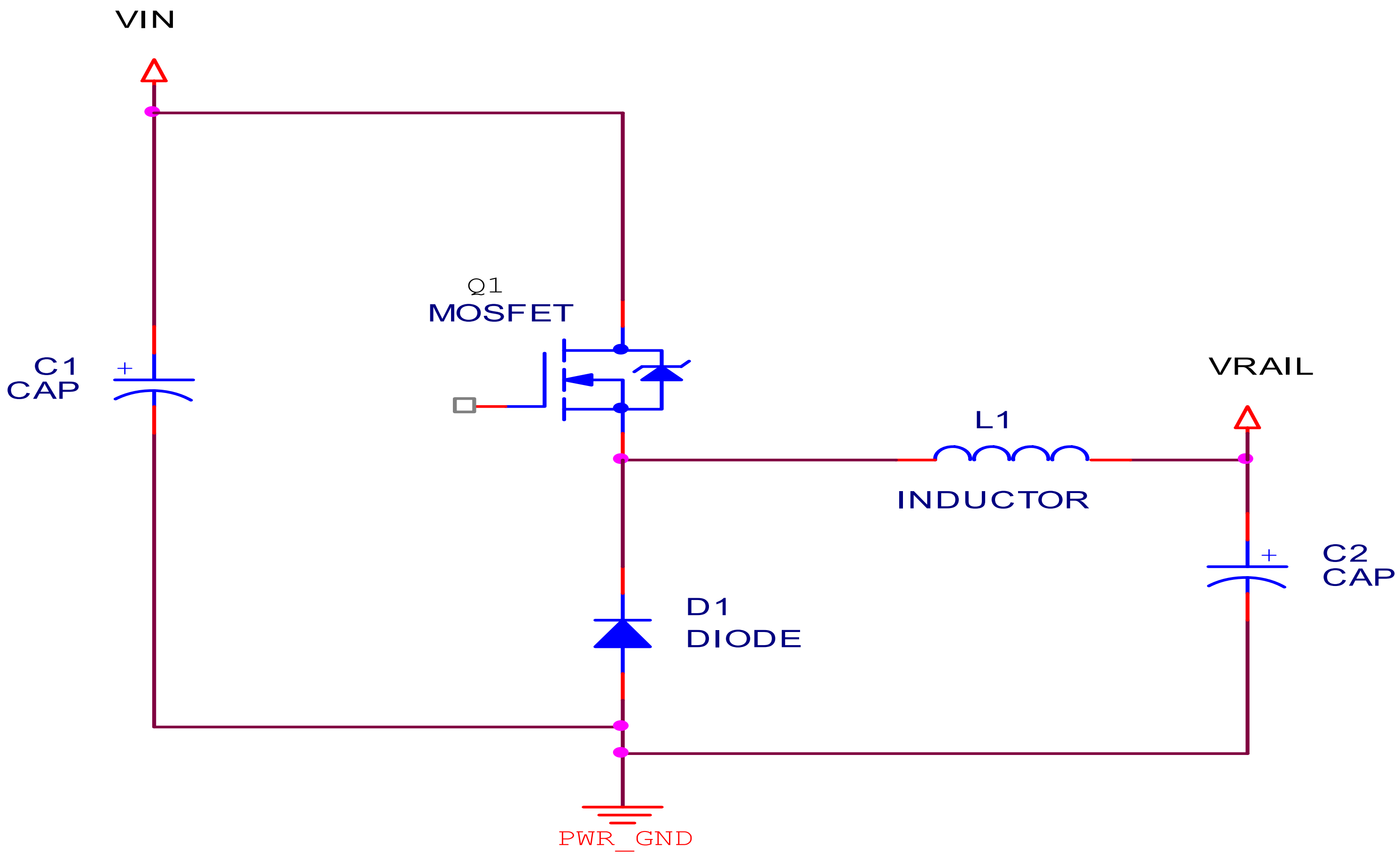




ADVANTAGES

- LESS HIGH FREQUENCY RIPPLE
- MUCH SMALLER INDUCTOR CURRENT EXCURSIONS
- SMALLER CONDUCTION LOSSES

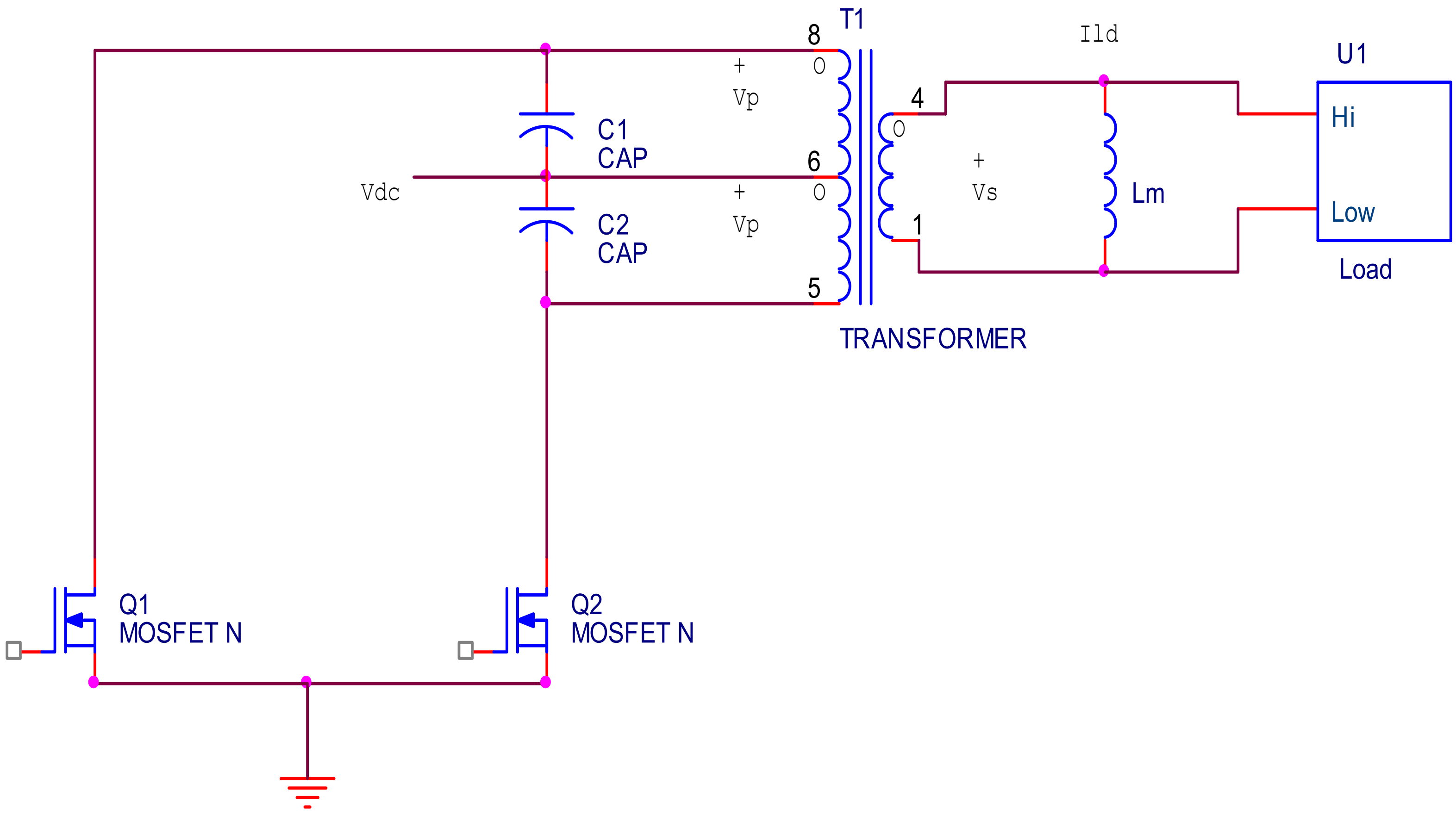
AMPLITUDE CONVERTER



BUCK CONVERTER

- OUTPUT VOLTAGE EQUALS INPUT VOLTAGE TIMES DUTY CYCLE
- POWER IN EQUALS POWER OUT
  - OUTPUT CURRENT EQUALS 1/DUTY CYCLE TIMES INPUT CURRENT
- ALWAYS STEP DOWN
- DYNAMIC RANGE GREATER THAN 20 TO 1

PUSH PULL INVERTER



PUSH PULL INVERTER

- ADVANTAGES
  - TWO TRANSISTORS VERSUS 4 FOR FULL BRIDGE
  - GATE DRIVES ARE REFERENCED TO GROUND

POWER

- INPUT POWER TO GENERATOR IS POWER INTO THE TRANSDUCER PLUS LOSSES
- EVEN THOUGH FILTER PRESENTS A LARGE VOLT-AMP LOAD
  - LOW POWER FACTOR
- POWER INTO BUCK REGULATOR EQUALS TRANSDUCER POWER

SEMICONDUCTOR LOSSES

- DIODE FORWARD VOLTAGE DROP
- MOSFET CONDUCTION LOSSES
- MOSFET SWITCHING LOSSES
  - TURN-ON TURN-OFF
  - DIODE STORED CHARGE
  - CAPACITOR STORED ENERGY

CONDUCTION LOSSES

- LOSS IN CHANNEL RESISTANCE
  - I SQUARED TIMES R
  - SILICON RESISTANCE INCREASES WITH TEMPERATURE

TURN-ON TURN-OFF

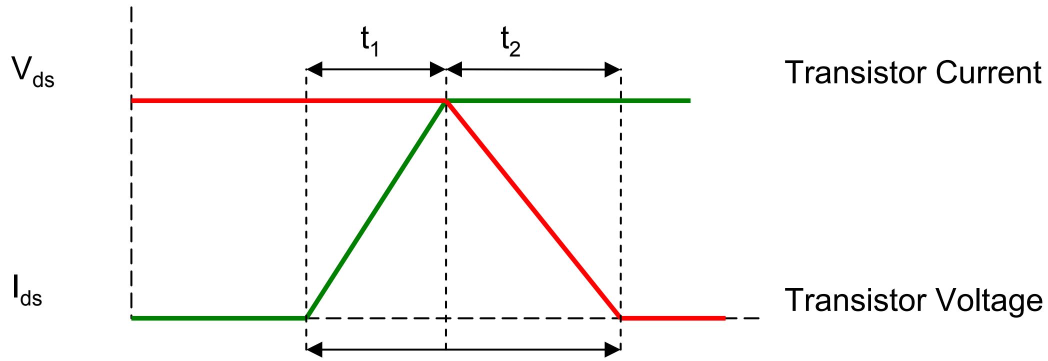


Figure 6a: Turn ON time

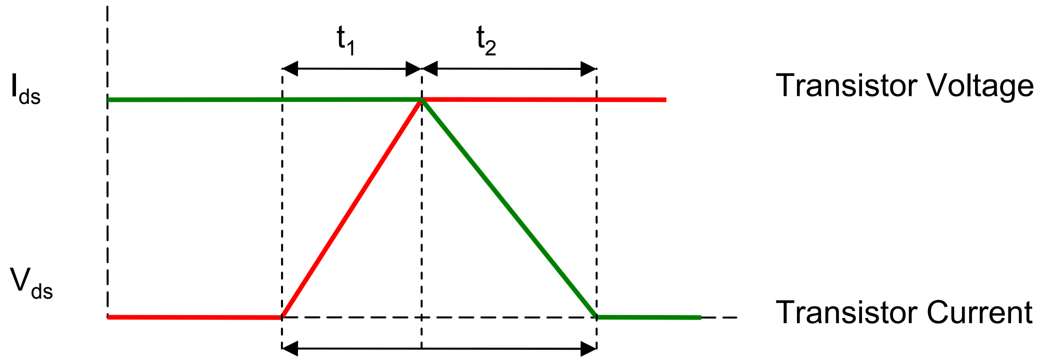


Figure 6b: Turn OFF time

BOARD MOUNTED HEAT SINKS

- DEPENDS UPON EFFECTIVE AREA AND AIR STREAM VELOCITY
- WAKEFIELD 657
  - TO-220, T0-247
  - 1.65 BY 1 INCH, 2 INCHES HIGH
  - 5.3 DEG C PER WATT
  - 2.9 DEG C WITH 200 LINEAR FT PER MINUTE
  - 5.5 DEG C PER WATT JUNCTION TO AMBIENT

LOSSES BUCK CONVERTER 8 WATT

- CONDUCTION WITH 1.2 AMPS
  - 1.3 WATTS (DUTY CYCLE 0.8)
- SWITCHING
  - 1.9 WATTS
- DIODE
  - 4 WATT
- CAP
  - 0.8 WATT

BOOST CONVERTER

- REQUIRES TWO TRANSISTORS AT 85 VOLTS (TO-247)
  - FOR 500 VA CURRENT IS 5.9 AMPS RMS
  - INDUCTIVELY CLAMPED EACH TRANSISTOR 12.5 WATT
  - TEMPERATURE RISE 62.5

EMI

- CONFINED TO BOX
- INTERFERENCE BETWEEN CIRCUITS
- GUIDELINES
  - PWM CHIPS ON GROUND PLANE
  - MINIMIZE AREA WITH HIGH CURRENT
  - MINIMIZE WIRE RUNS AT VOLTAGE NODES WITH HIGH DV/DT
  - MINIMIZE WIRING DRAIN, SOURCE AND GATE

PC BOARD SURFACE AREA

- HEAT SINKS
  - 5 WITH 1/4 BOARDER 16 SQUARE INCHES
  - 2 DIODES 6 SQUARE INCHES
  - MAGNETICS 3 @ 2 INCHES SQUARE = 8
  - OTHER CIRCUITRY
    - CONNECTORS, IC, PASSIVES INCLUDING CAPACITORS,

ULTRASONIC GENERATOR

POWER CIRCUITRY

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Table of Contents

1. INTRODUCTION

The block diagram, in Figure 1, shows the power subsystems in a modern-generic ultrasonic generator. Listing them from left to right in the direction of power flow, they include a power line interface, high power factor rectifier, amplitude converter, inverter, low pass filter, and transducer. This paper is concerned with the design of the high power factor rectifier, HPF, amplitude converter, inverter, and low pass filter. It is particularly concerned with defining the losses in this circuitry because along with some of the magnetic elements these control how well the circuits fit on a printed circuit board. These circuits along with the feedback controllers, not discussed, make up the bulk of circuitry on the generator PC board.

- The *HPF Rectifier* converts the AC power line, 50 or 60 Hz and 85 to 265 volts, and boosts it to regulated high voltage DC.
- The *Amplitude Converter* varies the DC bus that supplies the inverter under control of the ultrasonic amplitude controller, not discussed.
- An *Inverter* under control of a phase locked loop chops the DC bus into a square wave of the correct amplitude and phase to power the transducer.
- Finally, a L*ow Pass Filter* removes harmonics in the square wave.

Paragraphs that follow describe these circuits in detail. Since semiconductor losses mechanisms are the same through out, a separate section is devoted to calculating dissipation. Another section relates the calculated dissipation to available PC board heat sinks. A final section discusses the issue of circuit interaction and EMI.

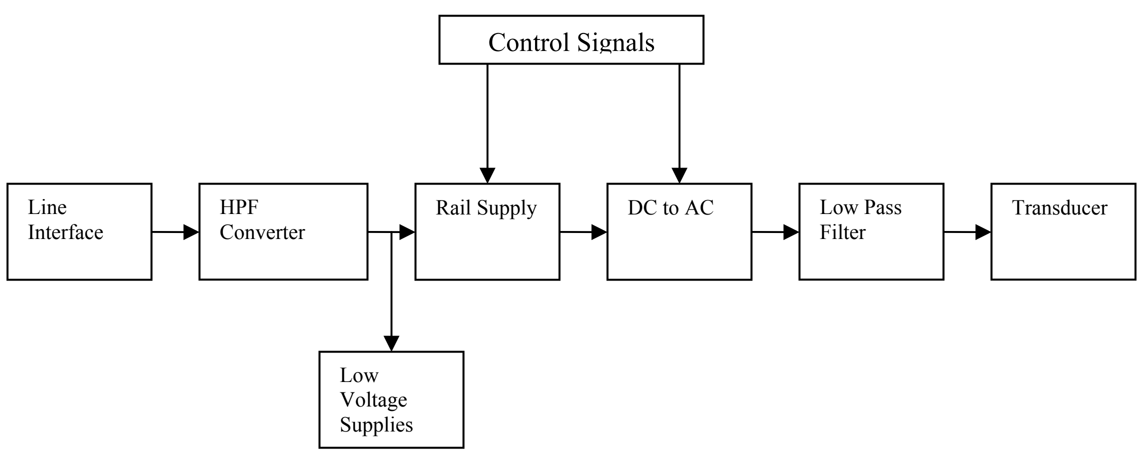
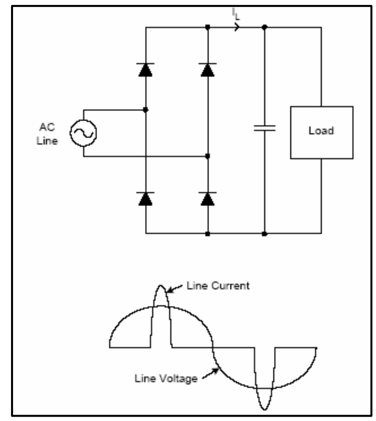


Figure 1: Block Diagram for Ultrasonic Generator Power Sub System

2. THEORY OF OPERATION

2.1 HIGH POWER FACTOR CONVERTER

Modern ultrasonic generators and consequently their power line rectifier must conform to IEC standard 61000-3-2 which limits input current harmonics. Current harmonics cause many power line and power plant difficulties, not the least of, reducing the power line's ability to transmit power without overheating. Before the wide spread use of high power factor rectifiers most electronic power supplies had capacitance input filters. These filters are simple enough consisting of a bridge rectifier which rectifies the AC line and a capacitor which peak detects the rectified voltage. Since the capacitor charges only when the voltage from the rectifier exceeds its own voltage it draws large charging currents each half cycle at the peak of the AC line voltage. The spectrum of these large input current spikes contains odd harmonics, the lower orders of which can be almost as large as the fundamental current.



On the other hand, the current drawn by a high power factor rectifier has the same phase and sinusoidal wave shape as the input line voltage. Most of these rectifiers take the form of a full wave rectifier followed by a boost converter, shown in Figure 2.

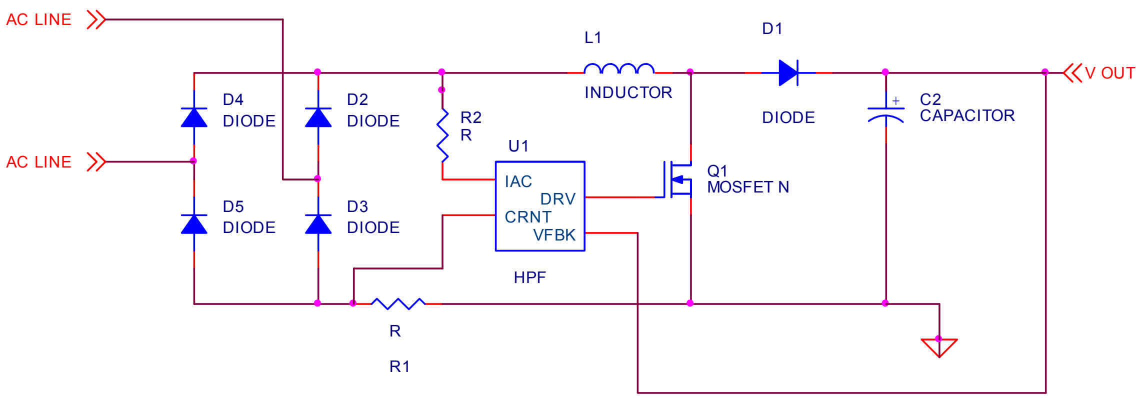


Figure 2: High Power Factor Boost Converter

A controller IC varies their switch on time to maintain the inductor current sinusoidal, which in turn ensures sinusoidal input current. Because its output voltage must be greater than its input voltage, an input voltage range of 265 volts RMS requires that the boost converter high voltage bus be around 400 volts. Several semiconductor manufacturers make IC control chips for control of HPF rectifier boost converters. They provide detailed application notes for their parts, referenced in the bibliography. The discussions below, concerns themselves with main categories of controller. The two most common types of HPF rectifiers are the Critical Conduction Mode (CRM) and Continuous Current Mode.

2.1.1 CRITICAL CONDUCTION MODE (CRM)

This works well at low power, up to about 200 Watts. It forces the inductor current to follow the input voltage by maintaining a fixed transistor on time when it charges the inductor. The inductor always charges to a current proportional to the average line voltage during the small time the transistor is on which is a fraction of a millisecond. The inductor then fully discharges into the output capacitor. The inductor current forms a series of triangular spikes whose peaks just touch the envelope formed by a sinusoid of twice the input current (see Figure 3). The time that the transistor is on varies in order to regulate the DC output bus voltage, but it is essentially fixed during any given power line cycle. Since the time to discharge the inductor varies during a power line cycle, frequency varies, turning the transistor on when the inductor current reaches zero, ensures a triangular current pulse. Since its average is just half its peak amplitude, the average inductor current is sinusoidal causing a sinusoidal line current.

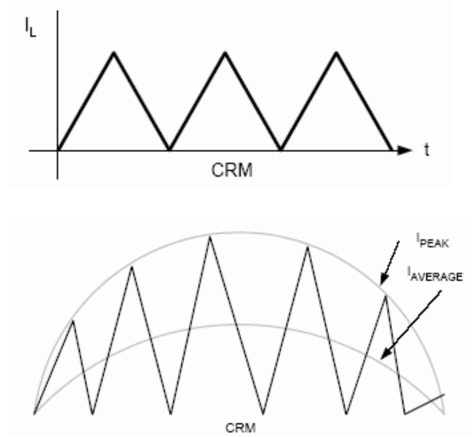


Figure 3: Inductor Current in CRM

There are good reasons why this type of simple rectifier should be limited to low power. Since the peak current in the semiconductor switch is twice the line current, and since MOSFET conductive dissipation grows as the square of line current, conduction losses become prohibitive with high line current. The triangular current pulses cause high frequency current, and consequently, EMI at the input that becomes more difficult to filter with increasing line current. EMI filter inductor size increase as the square of current. In addition, the large high frequency currents increases boost inductor core losses.

2.1.2 CONTINUOUS CURRENT MODE (CCM)

The second type of HPF rectifier also is a full wave rectifier followed by a boost converter. Its inductor current closely follows the input wave shape with a relatively small amount of high frequency ripple. The TI UCC2817 is one example. Because its peak current approximates the line current, rather than twice the current, this controller has lower conduction losses in the MOSFET and core losses in the boost inductor than the critical conduction one. It also produces significantly less high frequency ripple current at its input than the first type of controller (see Figure 4). Its disadvantage is its complexity and increased switching loss caused by forcing off the boost diode with current flowing. Nevertheless, because of the availability of ICs that contain all the necessary circuitry,

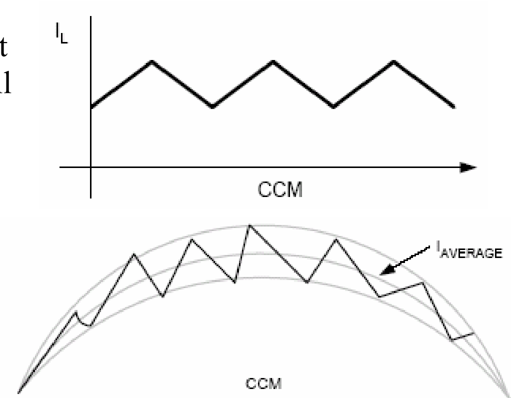


Figure 4: Inductor Current in CCM

complexity is not an issue. Use this type of rectifier above about 200 Watts.

These ICs derive their current programming signal by multiplying the input voltage on the AC line by voltage feedback formed from the difference of the voltage across the output capacitor and a voltage reference. Thus, the current drawn follows the line and their output voltages remains regulated. Both the current drawn by the boost inductor and line voltage signal itself are proportional to line voltage. Without some sort of correction, control loop gain would be a function of line voltage squared. Dividing the feedback by the average input voltage squared corrects the loop gain.

2.2 AMPLITUDE CONVERTER

The Amplitude converter, some times called a rail supply, consists of a Buck Converter that reduces the regulated voltage at the output bus of the HPF rectifier to the level needed to drive the square wave inverter that in turn powers the transducer (see Figure 5a).

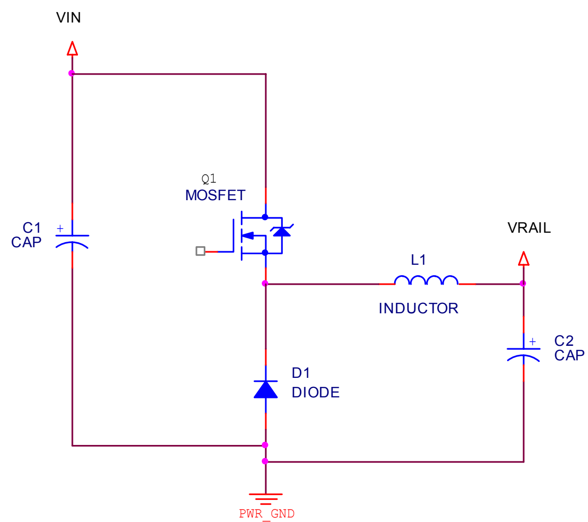


Figure 5a: Buck Converter

Two-step development of the transducer signal produces significantly less harmonics than pulse width modulating the AC signal to the transducer directly. Q1 varies its on time in response to control signal which is a pulse width modulated signal developed by the transducer feedback controller. The output voltage from the buck converter is its duty cycle, D, times its High Voltage Bus. Ignoring losses, the converter behaves like a transformer; power in equal's power out. Its output current is 1/D times the current drawn from its high voltage bus. Diode D1, called a commutating or free wheeling diode, continues the current flowing in the inductor. At low values of output voltage, the inductor current is discontinuous but this does not affect its transfer gain. The converter's dynamic range is limited by the MOSFET'S switching times at both high and low outputs.   At either end, it becomes nonlinear rather than simply falling off a cliff. Its useful dynamic range is greater than 20 to 1.   Section III: *Semiconductor Losses in Buck Converter* analyzes the losses caused by the switching action of Q1 and D1. These losses determine the size of heat sinks, which along with magnetic components are the largest components on the PC board.

2.3 SQUARE WAVE (PUSH-PULL) INVERTER

As shown in the block diagram the rail supply drives a transformer coupled square wave inverter. There are at least three forms for such an inverter, push-pull, half bridge and full bridge. This paper details the use of a push pull inverter.

Figure 5b shows a push-pull inverter of the type used in many ultrasonic generators. Its primary advantage is ease driving the transistor gates since their sources are in common and at ground potential. In addition, it only needs two transistors. Its disadvantage is voltage stress on the transistors.

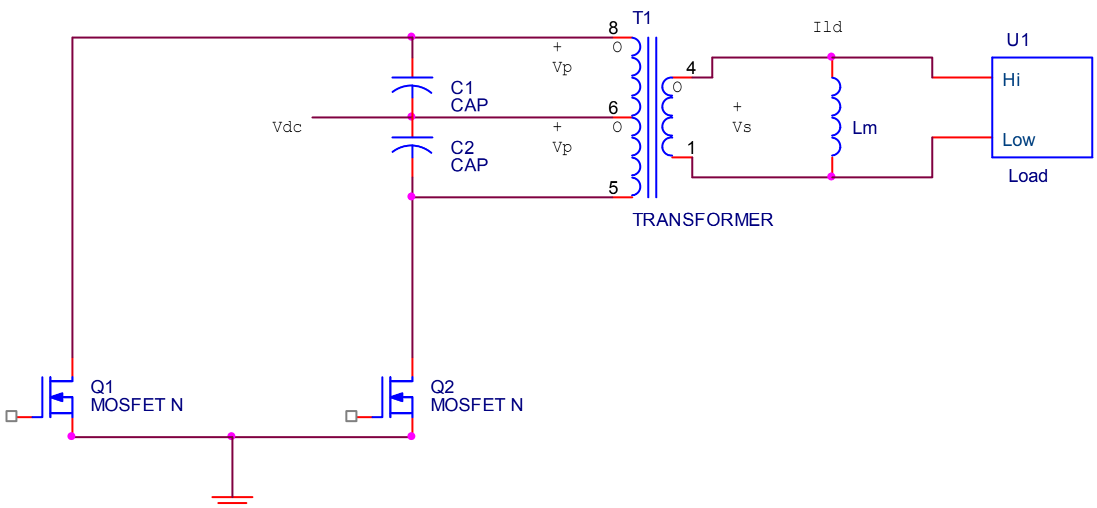


Figure 5b: Push Pull Inverter

Gate drive to the transistors turns them on alternately. When Q1 is on, the output is negative because the primary voltage at pin 5 of the transformer is positive. Current flows from pin 1 of the secondary into both the load and magnetizing inductance. In general, the magnetizing inductance is much larger than the load inductance. When Q2 is on just the opposite is true. Vp is positive and the secondary voltage on 4 is positive. Thus, the inverter converts Vdc into an isolated square wave voltage whose amplitude is equal to the turns ratio time the dc input voltage. The alternating action of the transistor switches charge and discharge capacitors C1 and C2. The voltage across the capacitors equals that across the associated transformer winding. These capacitors consist of the sum of MOSFET output capacitance and transformer primary capacitance. If both switches turned on simultaneously, the transformer would not support any voltage and simply short the supply. To prevent this, the on switch turns off before the other switch turns on. During the off time, current flowing in both the load and in the magnetizing inductance, Lm, acts to reverse the charge on capacitors C1 and C2. If the capacitors discharge fully, the anti-parallel diode in the transistor clamps the voltage to ground and the transistor turns on with zero voltage across it. Whether capacitors fully discharge or not depends upon the load parameters, current and the magnetizing inductance.

2.4 POWER LOAD

Although this discussion concerns a generator sized to withdraw about 500 watts from the AC line, the power drawn is that delivered to the transducer, plus component's dissipation and housekeeping power. The combined transducer and low pass filter present a volt-ampere load to the square wave inverter, but only the real power drives the transducer. The non-real portions of the Volt-Amps increases dissipation in the square wave inverter without increasing the power delivered to the transducer, the power delivered by the amplitude converter, or the power withdrawn from the AC line.

Examination of the fundamental current into the square wave inverter demonstrates this. Current that is in phase with the square wave produces a current wave shape at the inverter power bus that looks like a full wave rectified current wave shape with a DC component of two times the peak current divided by pi. Out-of-phase current has no DC component. It produces a half cosine wave of current each half cycle of the square wave. This wave starts at its peak negative or positive value and ends at the opposite value each half cycle. The capacitor at the output of the amplitude converter supplies this AC current without drawing any from the rest of the converter. The high voltage bus current remains unaffected and consequently so does the generator's input power.
If the phase locked loop maintains the transducer at resonance, it is possible to choose the filter components to yield maximum power transfer to the transducer. At this condition, the filter input impedance is real. The practicality of this depends on the variability of the transducer resonant impedance.

3. SEMICONDUCTOR LOSSES IN BUCK CONVERTER

3.1 Sources of Semiconductor Losses

To determine whether or not a particular MOSFET is suitable, you need to calculate its power dissipation. Resistive losses and switching losses mainly make up the dissipation.

$$PD_{DEVICE\ TOTAL} = PD_{RESISTIVE} + PD_{SWITCHING}$$

3.1.1 Diode Forward Voltage Drop

Although it varies slightly with temperature, current and other factors, a fast diode forward voltage drop is approximately 1.5 Volts around its rated current and as low as 1.2 volts at about half its rated current. Therefore, the approximate dissipation is its forward current times about 1.5 volts times its duty cycle.

3.1.2 MOSFET Resistive Losses

The MOSFET data sheet gives the on resistance, measured at 25 °C. Since the junction is always above 25 °C, and on resistance has a positive temperature coefficient, it is more accurate to plan on a junction temperature of 110 °C. The increase of resistance can be determined from the data sheet, which shows that it increases to approximately twice its value at 25 °C, $R_{DS(ON)\ HOT}$. The power dissipation due to resistive losses is as follows:

$$PD_{RESISTIVE} = (I_{LOAD})^2 \times R_{DS(ON)\ HOT} \times (V_{OUT/VIN})$$

Where;
I_{LOAD} = 1.2A
$R_{DS(ON)HOT}$ = 1.5 ohms @ 125°C
$V_{OUT/VIN}$ = 0.75 arbitrary duty cycle

$$PD_{RESISTIVE} = (1.2)^2 \times 1.5 \times 0.75 = 1.62W$$

3.1.3 MOSFET Switching Losses

This discussion concerns transistor losses that occur when the MOSFET switches between conducting and non-conducting states. The causes of these losses are illustrated by reference to the buck regulator. This discussion parallels similar discussions given in books and journal articles. see reference. Various processes during each MOSFET switch cycle consume energy. Since this happens once each cycle, the total dissipated power is that energy times switching frequency. Losses that are unimportant at 10 KHz overheat transistors at 30 KHz. The key mechanisms that cause switching losses are:

- Current flowing simultaneously with voltage across the transistor.

- Energy used to charge the MOSFET drain to source capacitance when it turns off and then dissipated in the MOSFET when it turns on.

- Energy used to remove stored charge in the free wheeling diode when the MOSFET turns on.

- The gate circuit also consumes energy but compared to that in the drain circuit is small.

3.2 Explanation of Losses

3.2.1 Switching Losses

MOSFET Turn OFF

Figure 6a shows idealized MOSFETS current and voltage turn off transitions for a circuit that has an inductor that continues the current flow. Current continues to flow through the MOSFET while its voltage increases. Current in the MOSFET starts to fall after the diode becomes forward biased. The voltage rise time is about 40 nanoseconds and the current fall time is somewhat less, about 20 nanoseconds. The energy dissipated in the transistor during this time is one-half the product of drain voltage and current times the sum of voltage and current fall times.

MOSFET Turn ON

As shown in figure 6b, the reverse process occurs upon turn on. Until the current flowing in the transistor equals the load current, the forward biased diode clamps the transistor's source to ground. Once the transistor current equals the load current, the diode turns off and goes through its reverse recovery. The voltage across the MOSFET falls to its conduction value. Since the sum of these times is close to the sum during turn off, the total energy due to switching losses is as follows:

$$PD_{SWITCHING} = V_{DS} \times I_{DS} \times (t_{OFF} + t_{ON}) \times F_{SW}$$

Where;
V_{DS} = 350 V Supply
I_{DS} = 1.2 A
$(t_{OFF} + t_{ON})$ = 60 nanoseconds
F_{SW}= 100 KHz switching frequency

$$PD_{SWITCHING} = 2.52 \text{ watts}$$

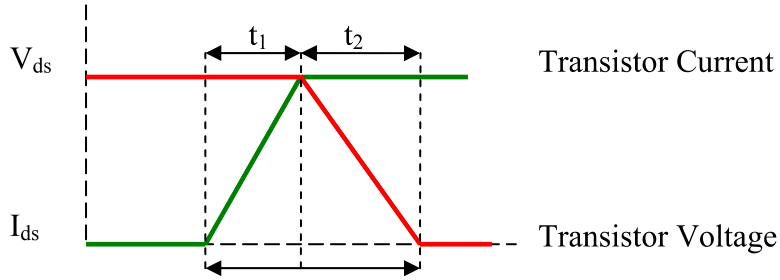


Figure 6a: Turn ON time

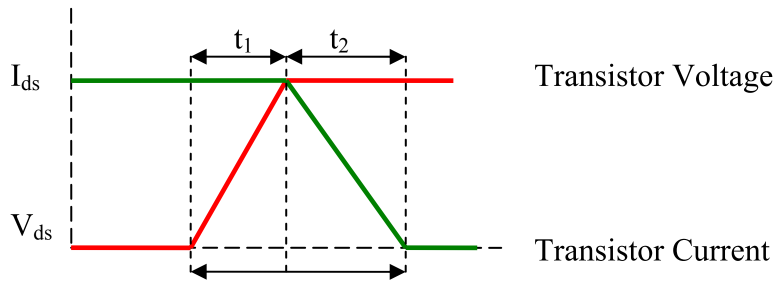


Figure 6b: Turn OFF time

3.2.2 MOSFET Drain to Source Capacitance

Each time the MOSFET turns off its voltage rises to the supply voltage charging its drain to source capacitance. The energy stored in the capacitance is ½ times the drain-source capacitance times the square of the voltage ($1/2CV^2$). Since the capacitance is highly nonlinear, it stores more energy than a linear capacitor. Several authors compensate for this effect by using a capacitance value of 4/3. For the MOSFET mentioned earlier this yields about 100 Pico farads and a dissipation of 0.8 watts @ 100 KHz switching frequency.

3.2.3 Charge in Free-wheeling Diode

Each time the MOSFET turns on it must extract the charge stored in the diode and raise it to the supply voltage, consuming an amount of energy equal to the supply voltage times the charge. According to manufacturer's data sheets, for an ultra fast diode rated at eight amps, the energy is about 100 nano coulombs. The energy required to turn off the diode is 35 micro-newtons which is 3.5 watts @ 100 KHz.

3.2.4 Total Losses

The total losses are: $PD_{DEVICE\ TOTAL} = PD_{RESISTIVE} + PD_{SWITCHING}$

Therefore, the total switching energy is approximately 1.62w + 2.52w +0.8w + 3.5w which equals 8.4 Watts.

4. SEMICONDUCTOR LOSSES IN PUSH-PULL INVERTER

The voltage across the transistors is a square wave, but the current flowing in them is nearly sinusoidal because of the reactive load at the input to the transformer. Accordingly, if the square wave amplitude is Vsq and the load VA is VA_{load} its RMS fundamental current is VA_{load} times (square root of 2 times pi)/(4 times Vsq).

Assume Vsq =350
VA_{load} = 400

I =1.27 A

Conduction losses each transistor = 1.5 x 1.27 squared x0.5 = 1.21

Switching losses vary with power factor. It is safe to use the worst case.
Without inductive clamping both current and voltage are transitioning together.
Switching Losses = Switching time x switching frequency x Vsq x I x square root of 2/6.
Assume a switching frequency of 60 kHz.

Switching losses = 0.25 Watts

The loss caused by the cap is a function of circuit conditions. To find a reasonable value, assume that the load and magnetizing current discharges the capacitors to approx 350 volts when the transistor turns on. Assume 1 nano farad capacitor.

Capacitor Power loss = ½ x 1 x 1EXP-9 x 350 x 350 x 60000 = 3.7 Watt

Total losses/transistor = 1.21 + 0.25 + 3.7 = 5.5 Watt

5. BOARD MOUNTED HEAT SINKS

Wakefield has several board-mounted heat sinks for the TO-220 MOSFET used in the calculation of transistor losses. Their 657 series heat sink, 2 inches high and footprint of 1.65 by 1 inch, has a thermal resistance of about 5.3 °C/ watt in still air and 2.9 °C/ watt with 200 linear feet per minute air velocity. Estimate 4 °C/ watt for this heat sink with the generator mounted in an enclosure with some moving air. The same heat sink supports either TO-220 or TO-247 transistors. As with all thermal data, verify it with tests.

5.1 Expected Temperature Rise Buck Regulator MOSFET

Assumptions:

Maximum Voltage 350 volts
Maximum current 1.2 Amps
600-Volt TO-220 MOSFET
Diode stored charge 100 nano coulombs

The thermal resistance from junction to ambient is given by:

$$Rja = Rjc + Rcs + Rsa$$

Where;

Rjc = thermal resistance from junction to case
Rcs = thermal resistance from case to sink
Rsa = thermal resistance from sink to ambient

First, the temperature rise for heat sink (Rsa) is 4 °C / watt and the rise in the junction to case (Rj-c) and in the transistor case to sink (Rc-s) is 1.5°C / watt total.

Therefore the total thermal resistance is 5.5 °C/watt from junction to ambient. This yields a total heat rise of 52 °C. This heat sink and transistor combination is safe in a 50 to 60 degree ambient.

5.2 Expected Temperature Rise BOOST CONVERTER MOSFET (High Power Factor Regulator)

The mechanisms that cause MOSFET loss are the same for the boost converter as the buck converter. The difference is in the voltage and currents. With 500 watts of input power and 85-volt RMS line, the RMS input current is 5.9 Amps. Two slightly larger TO247 transistors in parallel are required. The ones chosen have a Rdson equal to 0.4 ohms. With them in parallel, the conducted dissipation is 7 Watts and the switching loss calculated as above is 9.9 Watts. This dissipation yields a heat rise of 82 °C, which only works at slightly over room temperature. These calculations are worst case in that they assume maximum power, and lowest line voltage. At higher values of line voltage or slightly lower power, the design yields good results. For example at 85 volt line, and 400 VA input, the dissipation is 12.9 watts, and the junction temperature is 110 °C assuming a 45° ambient.

6. EMI CONSIDERATIONS

As long as the generator is in a reasonably good EMI enclosure with filtering on inputs and outputs it should meet requirements. The real issue is to keep internal circuits from interfering with each other. Layout is very important. Minimize all loops where high frequency currents circulate. Minimize the wiring length of voltage nodes with high dV/dT. Be aware that PWM chips are very sensitive to high frequency noise. They contain ramp generators and comparators. Noise here causes unstable behavior. Put these chips on their own ground plane with no high-frequency-high current flowing through the plane. Avoid parasitic oscillations by minimizing wiring in transistor drain and source circuits, between gate drivers and gates and between the drivers and the transistor sources.