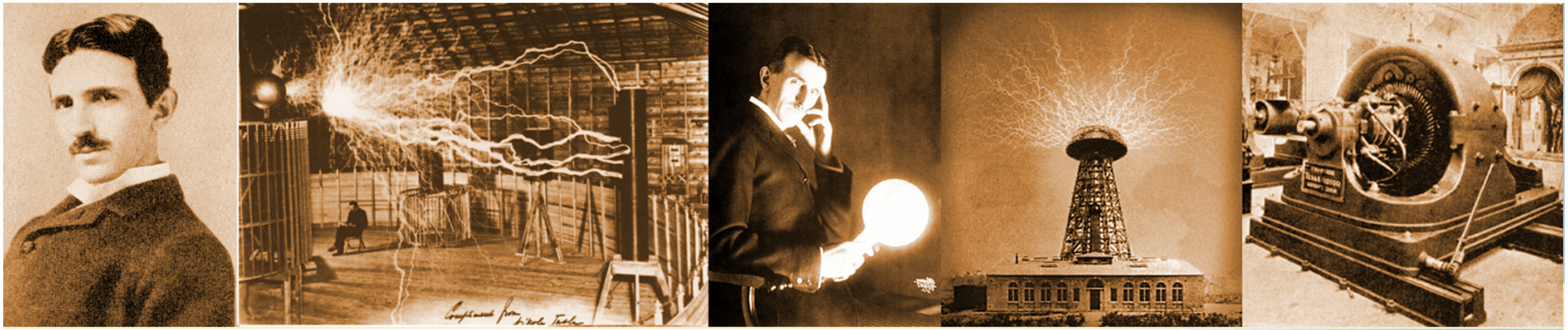
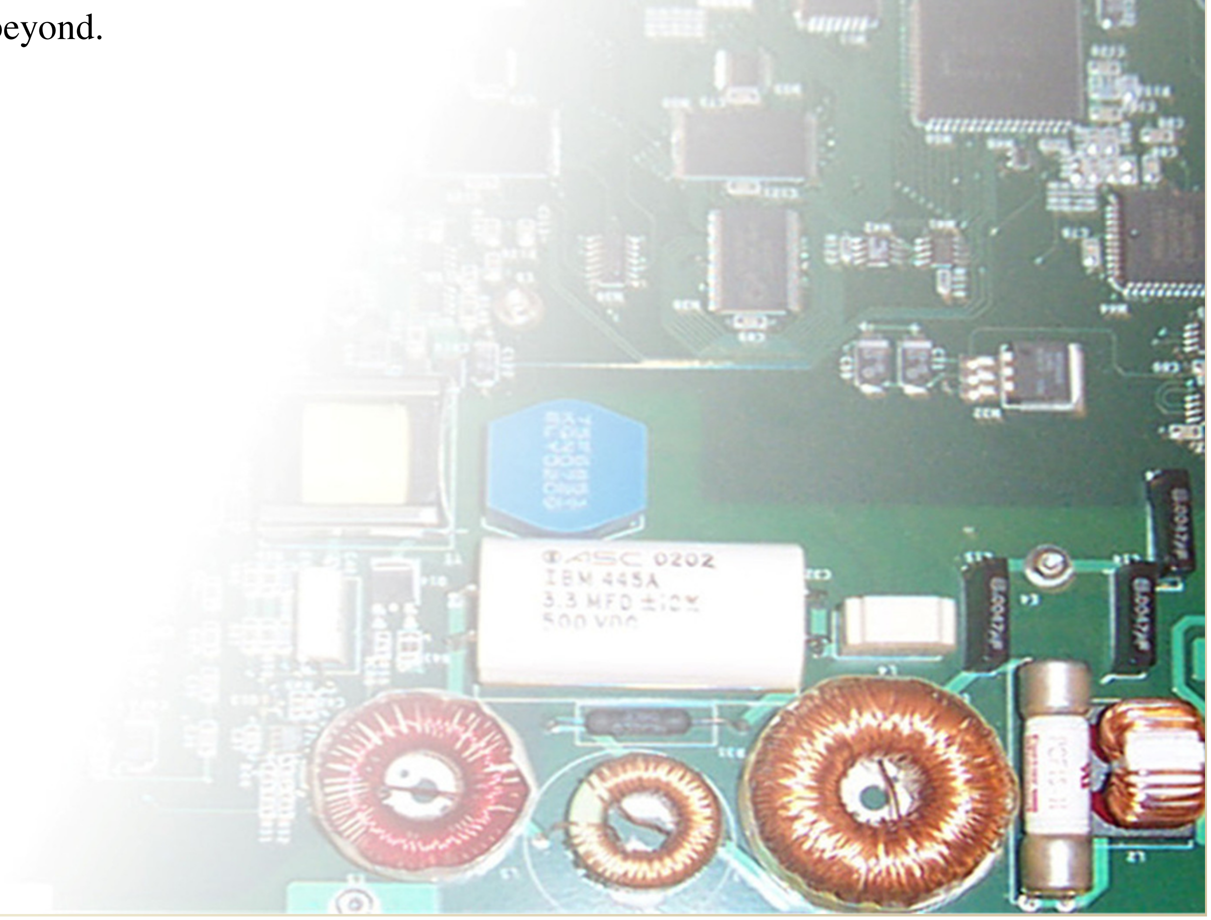


Introduction to Solid State Tesla Coils

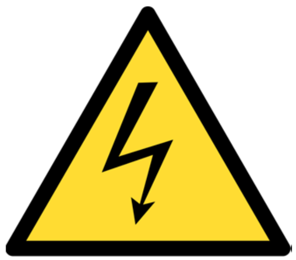
Concepts, implementation, debugging, and beyond.

presented by:

Staci “GrizzlyPanda” Elaan
Power electronics geek
youtube channel: stacielaan



¡IMPORTANT SAFETY WARNINGS!



Tesla coils often present fatal electrocution hazards. This is especially true for solid state designs!

Tesla coils emit massive RF power capable of causing painful and humiliating burns. This RF can break your stuff!

When power semiconductors and capacitors are used in solid state Tesla systems they represent a significant explosion hazard.

High power RF plasma can ignite flammable materials and vapors. Exploding power transistors can spew glowing metal chunks resulting in secondary fire(s).

Why play with solid state Tesla coils?

- Educational!
- Less expensive than dating.
- Impress random strangers.
- Charge your stuff without wires.
- Most interesting way to learn power electronics.
- You like the smell of burning electronics and ozone gas.
- You're tired of lugging around 100lbs of iron and copper from your spark gap based coil!
- A great reason to download LTSPICE for free and play with it.

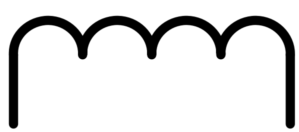
"Building a Tesla coil is something everybody should do at least once“. - *Some guy at Albany Spinjam*

Fundamentals of Resonance

A resonant circuit happens when capacitive and inductive reactances equal each other.

Inductor

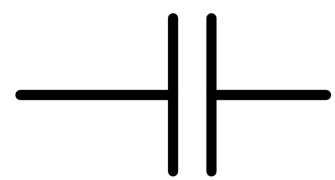
(units: Henrys)



$$X_L = 2*pi*f*L$$

Capacitor

(units: Farads)

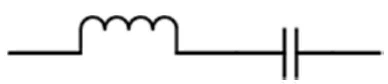


$$X_c = \frac{1}{2*pi*f*C}$$

Fundamentals of Resonance

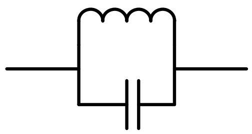
Two kinds of resonance:

series resonant



When X_L=X_C this circuit appears shorted.

parallel resonant



When X_L=X_C this circuit appears open.

Resonance Equation: $$f = \frac{1}{2\Pi\sqrt{LC}}$$

Where the heck did this come from?!?!

Fundamentals of Resonance

Set $X_L = X_C$ and solve

$$2\pi f L = \frac{1}{2\pi f C}$$

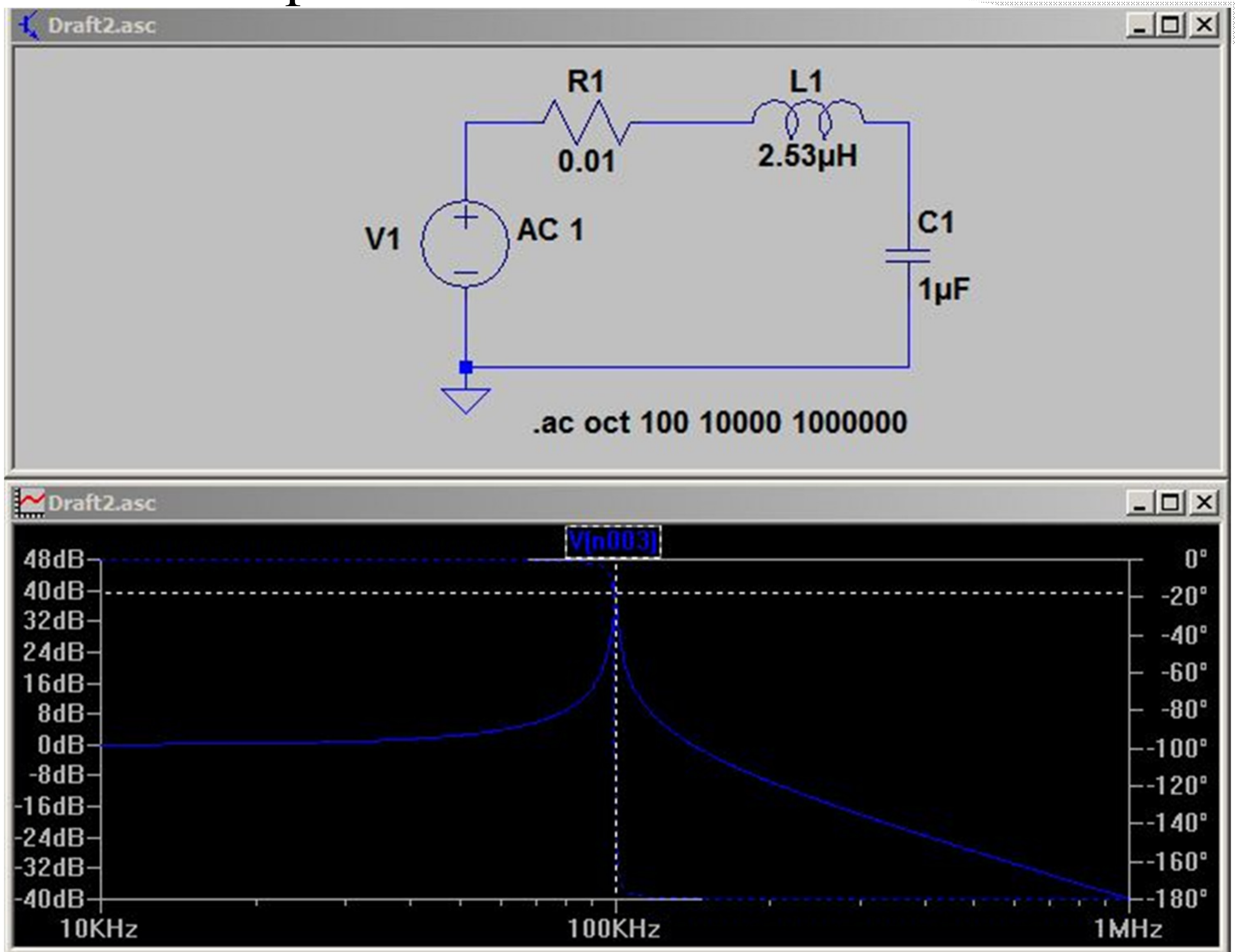
$$f^2 = \frac{1}{(2\pi)^2 LC}$$

$$f = \frac{\sqrt{1}}{\sqrt{(2\pi)^2 LC}}$$

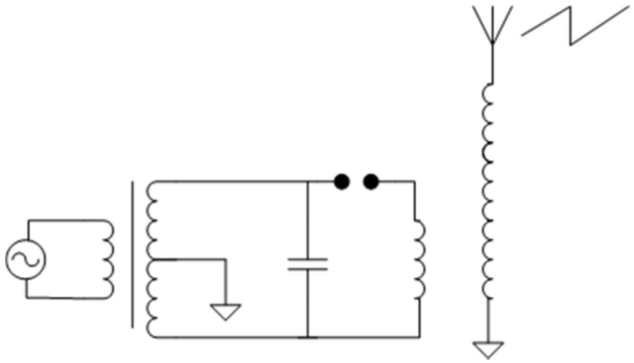
$$f = \frac{1}{2\pi\sqrt{LC}}$$

Fundamentals of Resonance

Simple simulation of a LC circuit:



Classic spark gap Tesla coil:



Simple spark gap Tesla Coil
Source: Wikipedia (GNU Free documentation licence)

Invented by Nikola Tesla around 1891

- Effectively a spark gap transmitter.

- Relies on a AC mains transformer to step up voltage to several thousand volts.

- Typically uses neon or oil furnace. Transformer.

- Very heavy.

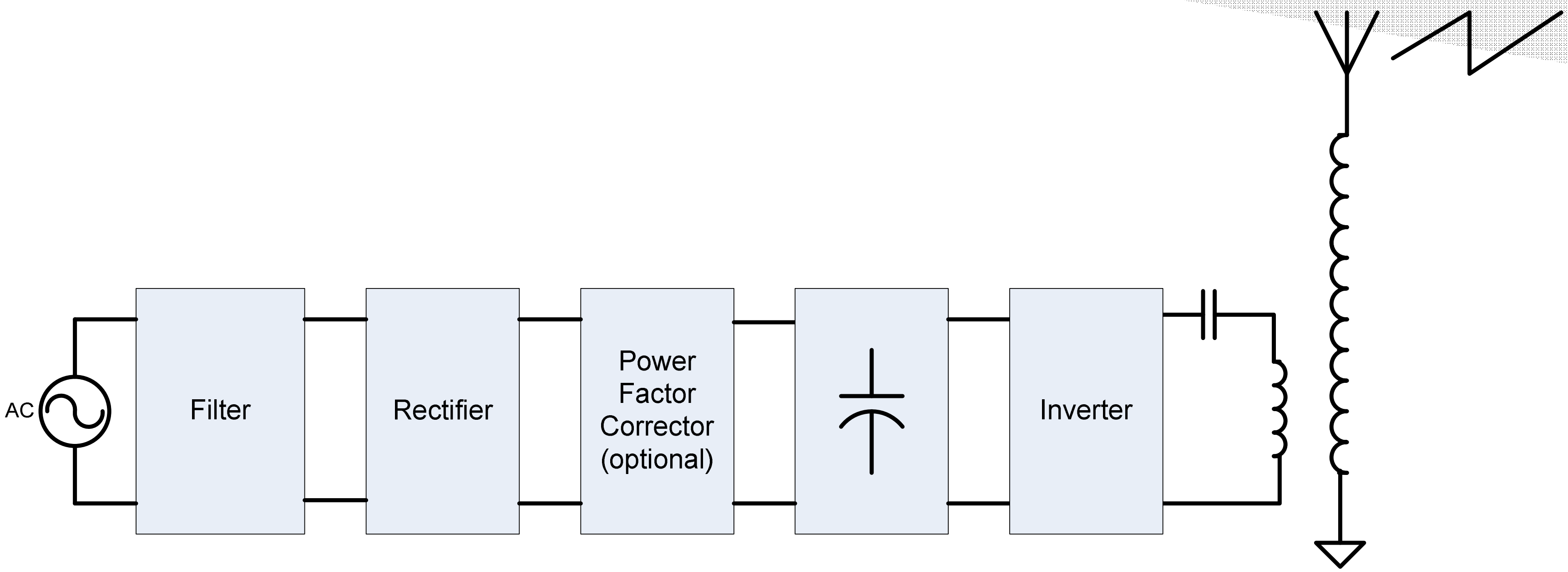
- High voltage capacitors are expensive.

- Most low power HV transformers fail due to high frequency energy from primary LC tank degrading insulation.

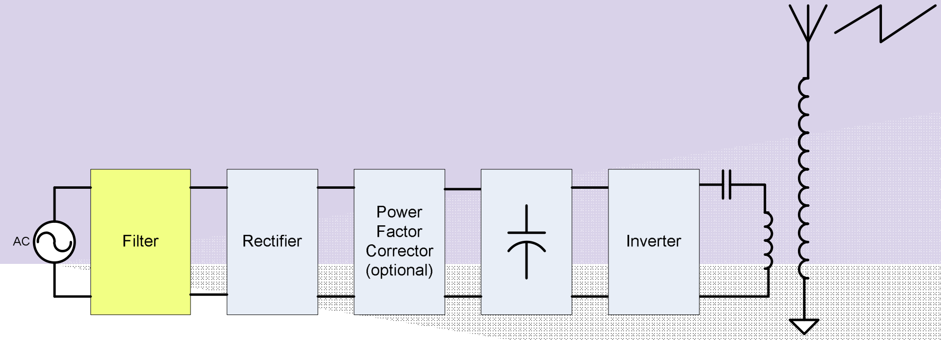
- Significant efficiency and performance limitations.


SOLID STATE TESLA COIL?
TELL ME MORE
memegenerator.net

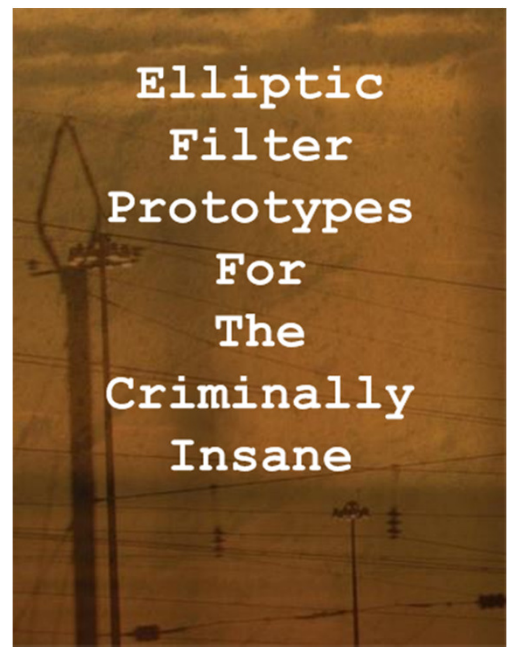
Solid State Tesla Coil Block Diagram



Input filter

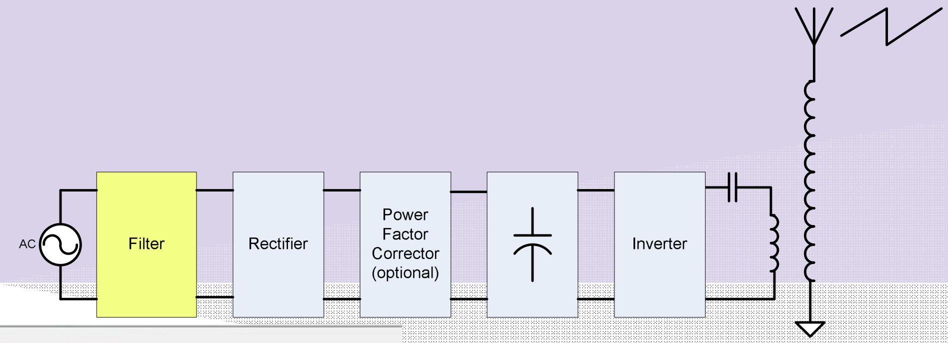


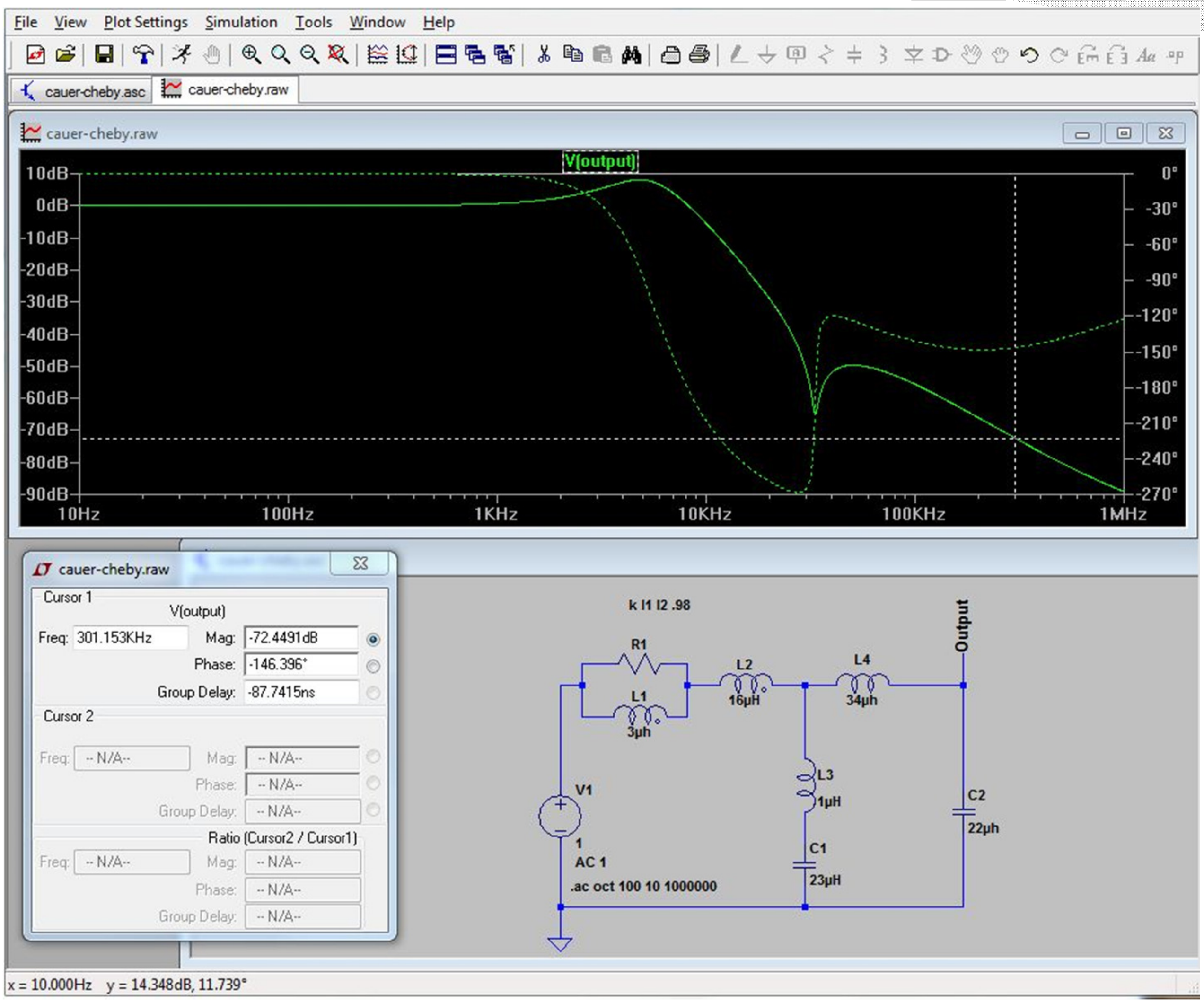
- Required to protect sensitive electronics from high energy transients.
- Typically more economical to buy than build.
- AC line filtering almost always requires non-standard L and C values.
- Custom filters can be designed using prototype topologies.
- Typical SSTC will run between 200KHz and 1MHz.
  - Choose filter accordingly.



Input filter continued

Cauer-Chebyshev example



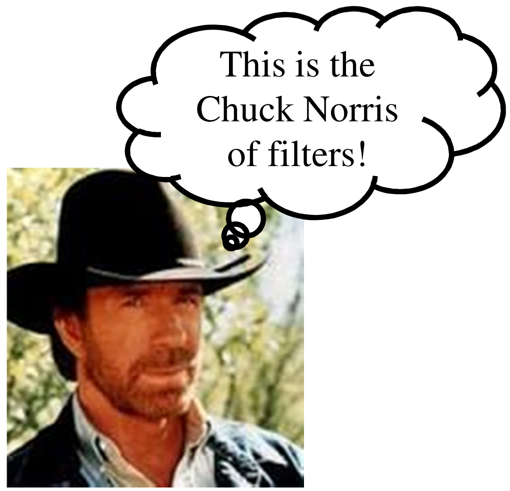


Attenuation of 72.45dB
At 301KHz.

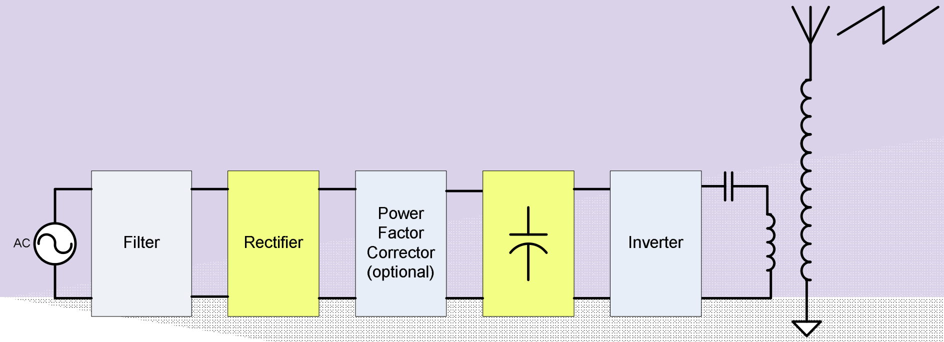
This corresponds to a voltage attenuation of 4192.

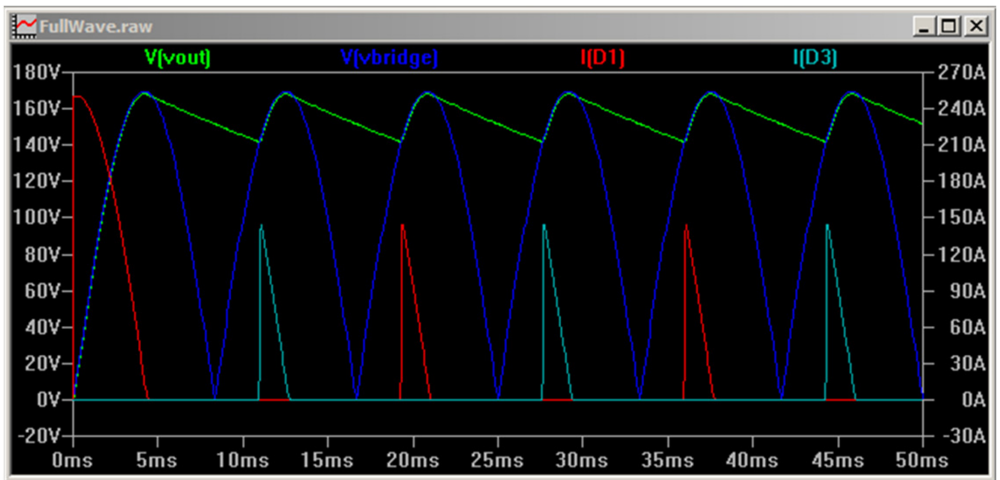
$-72.45=20\log(\text{Vratio})$
$-3.6335=\log(\text{Vratio})$
$10^{-3.6335}=\text{Vratio}= 0.0002385.$

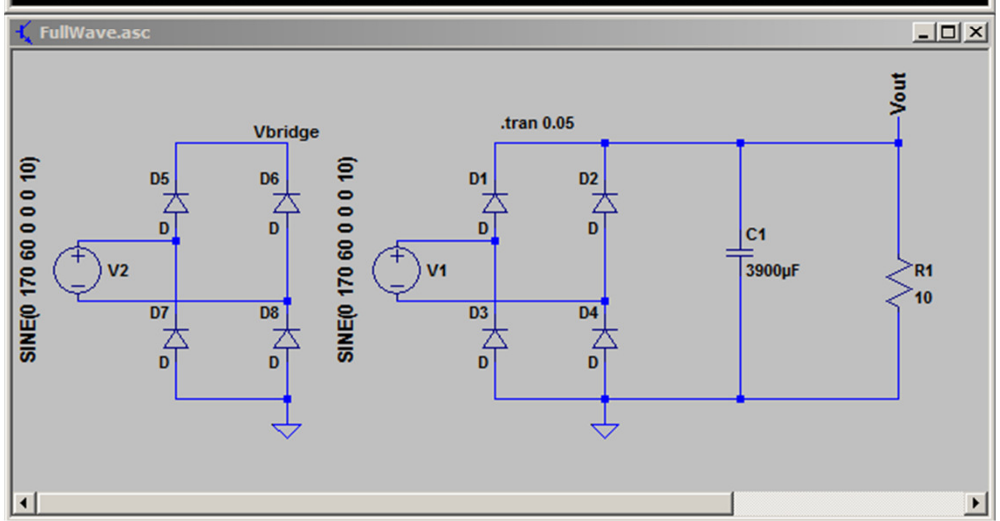
So multiply the voltage noise at 300KHz from your solid state Tesla coil emits by 0.0002385.



Rectifier
Full Bridge







• USE A FUSE AND CIRCUIT BREAKER!!!!

•North American AC Line is 120Vrms/60Hz.

• This corresponds to a 170V peak - sqrt(2)*120.

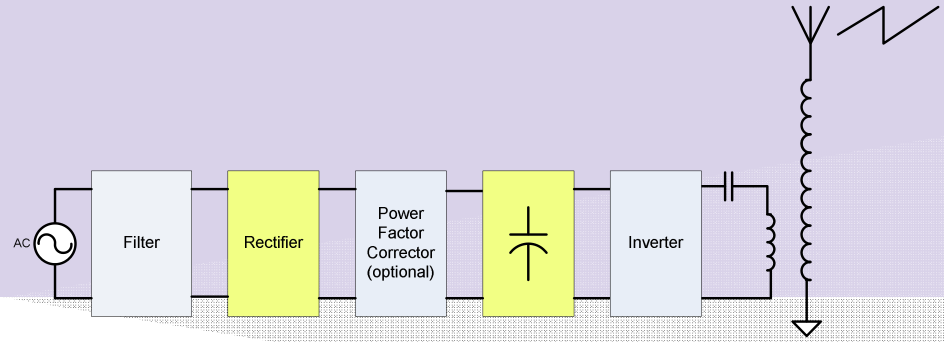
• A SSTC looks purely resistive at resonance so the 10 Ohm resistor is actually a good simulation of a real SSTC – (2500W is a tad high for a 120V circuit).

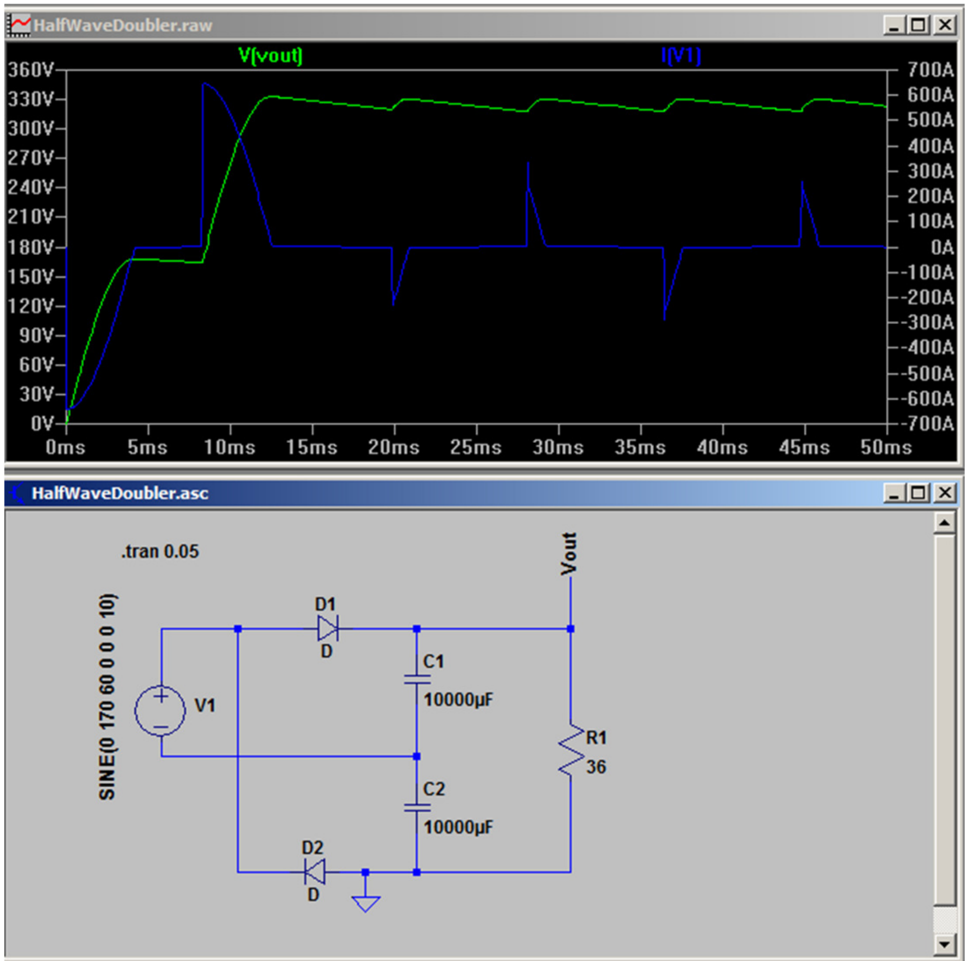
• If you do this, you will cause smoke. Note the peak currents drawn are nearly 150A per cycle. The RMS current is well below the 20A limit your house has on each breaker, but other electronics can die from induced voltage these spikes cause on the AC line. V=L*(di/dt). This is why filtering is so important.

•Note that a 3900uF capacitor still sees approximately 26V of ripple at this load. That's a huge and possibly lethal capacitor. On average it stores 50 Joules. 10 Joules can be lethal.

Rectifier

Half Wave Doubler

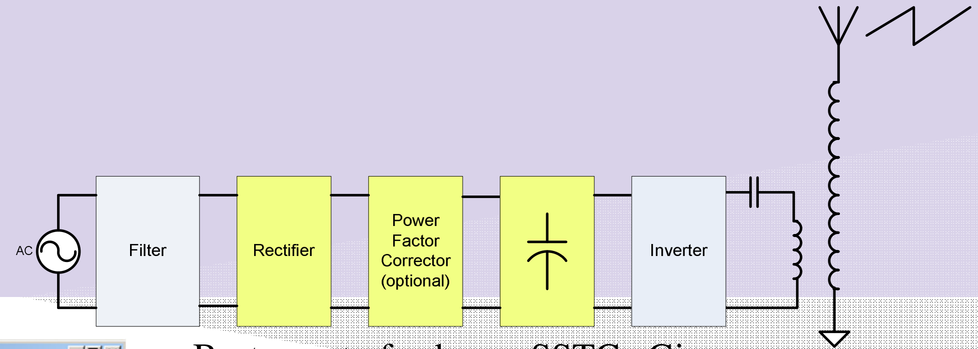


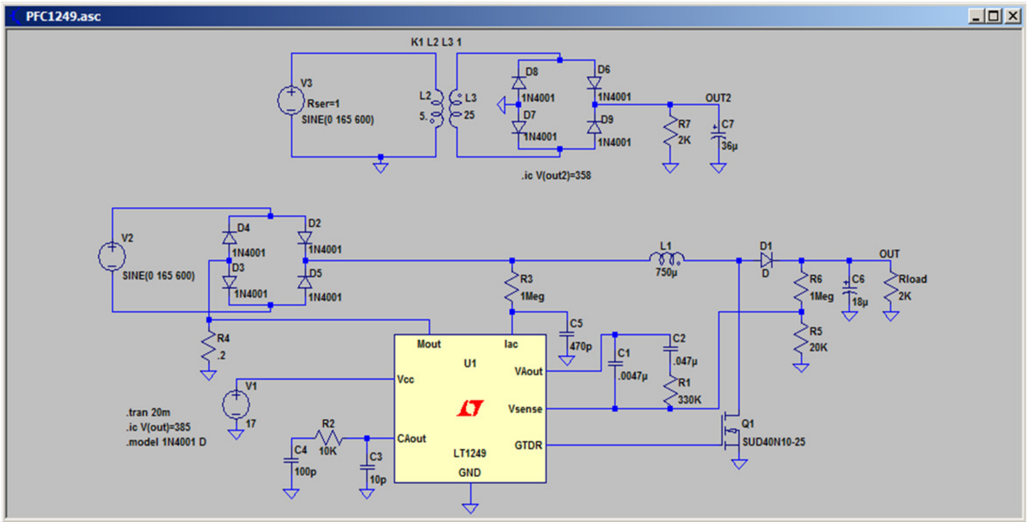


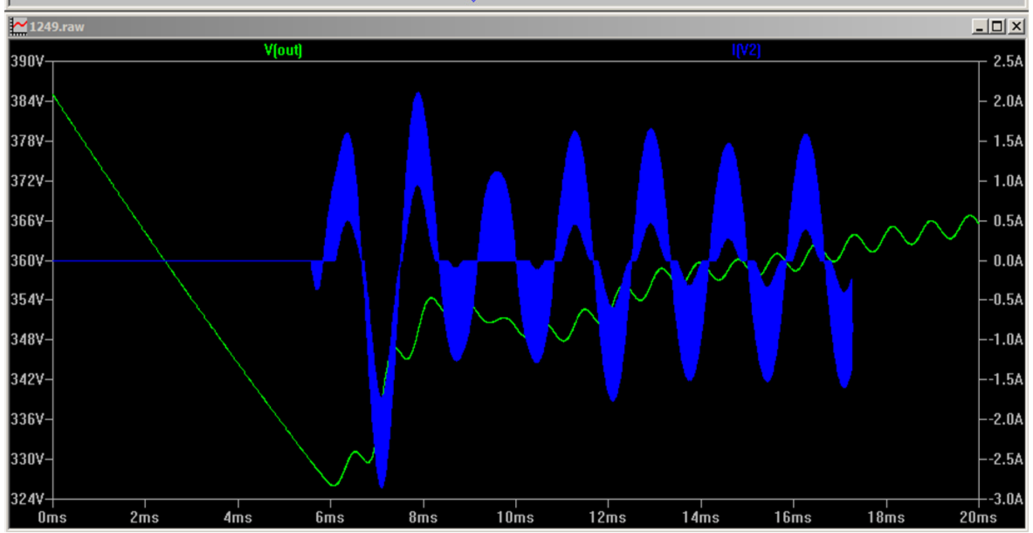
- Cheap way to get 300V DC from the AC mains without a transformer.
- Output capacitors roughly double in size due to series connection.
- Note that current peaks get very high. A tradeoff may be needed between allowable ripple voltage and RMS line draw.
- Most SSTCs are pulsed to limit line current.
- Load resistor is increased to 36 Ohms to simulate the same 2500W as in previous example if this gave a 300VDC bus.
- Keep in mind your input filter will do almost nothing for these current spikes as they are at line frequency.

Rectifier

Active Power Factor Corrector (PFC Boost Regulator)







- Best way to feed your SSTC. Gives you rectifier, over current protection, and simpler filtering all at once.

- Active PFC is often a full semester graduate level course. PFC regulators have the dubious honor of either killing or getting more engineers fired than any other circuit. *

- AC line current is purely sinusoidal. The boost inductor current is controlled by a reference signal derived from the AC line.

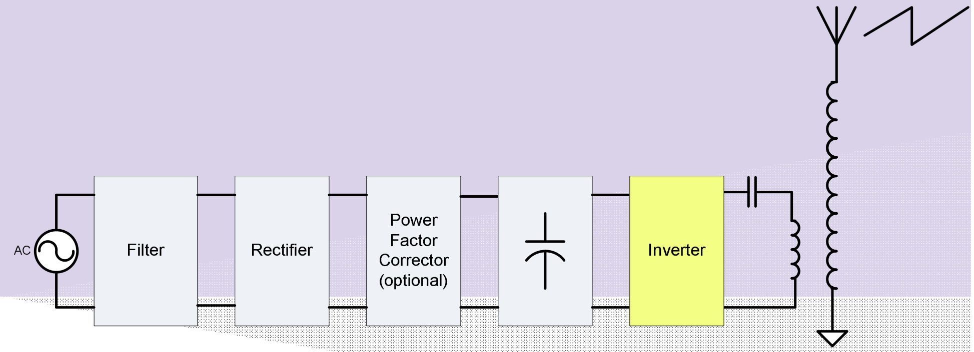
- The input filter is responsible for smoothing the current envelope out to look like a pure sine wave. This is the blue trace.

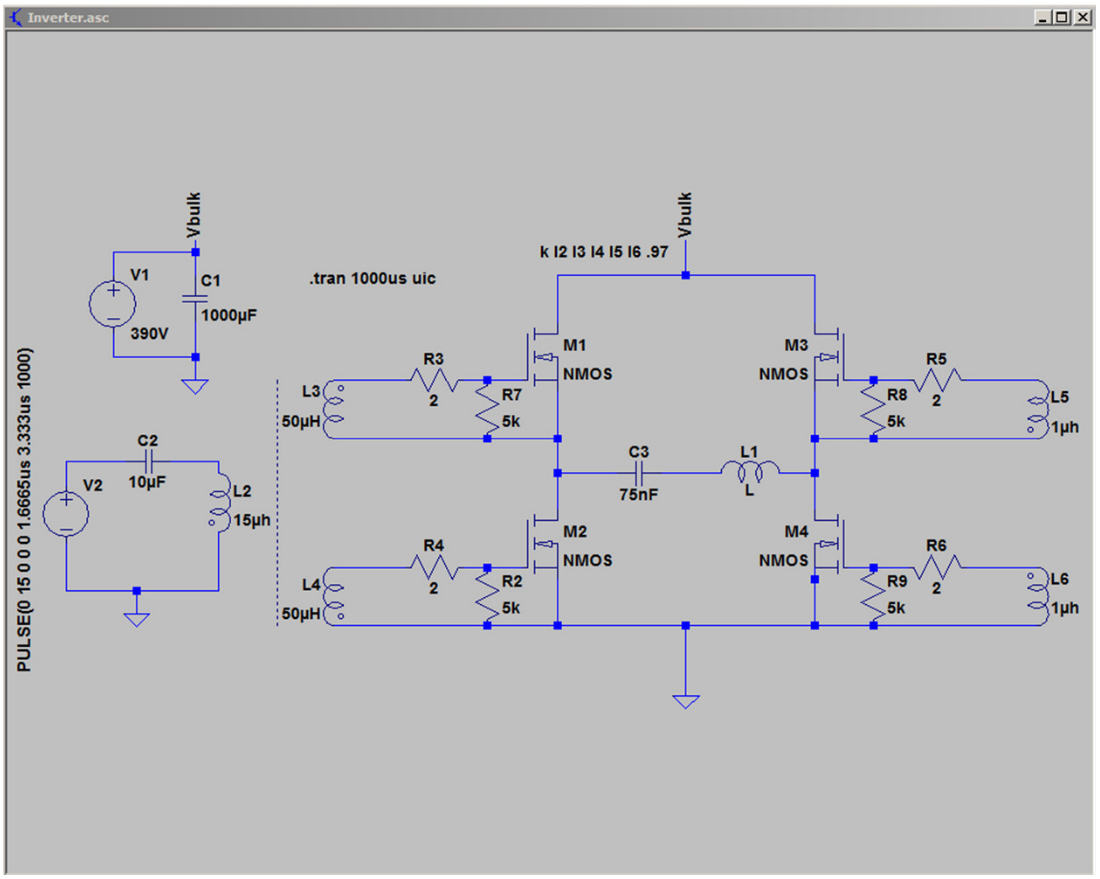
- These are absurdly difficult to build and stabilize. Buy a 1000W ATX power supply with active PFC and tap the 400V bus inside. Don't forget to hard-wire the enable signal(s).

* I made that up but it seems believable.

Inverter

(totally like my favoritest thing ever!)





• Converts HVDC to high frequency AC.

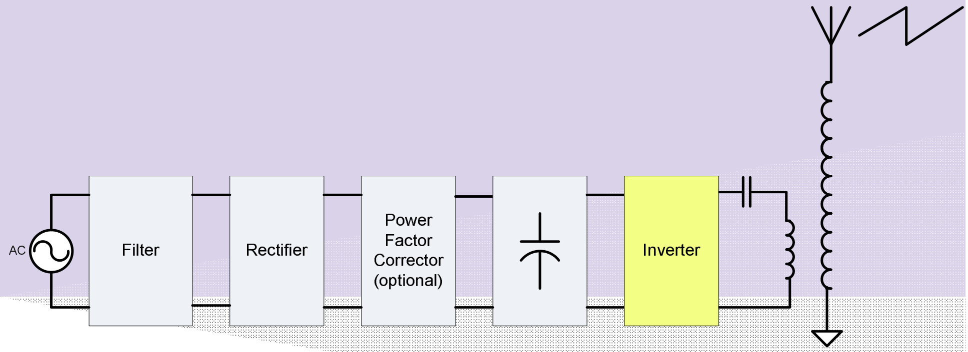
• Output is square wave, but current is sinusoidal due to resonant frequency of primary LC tank.

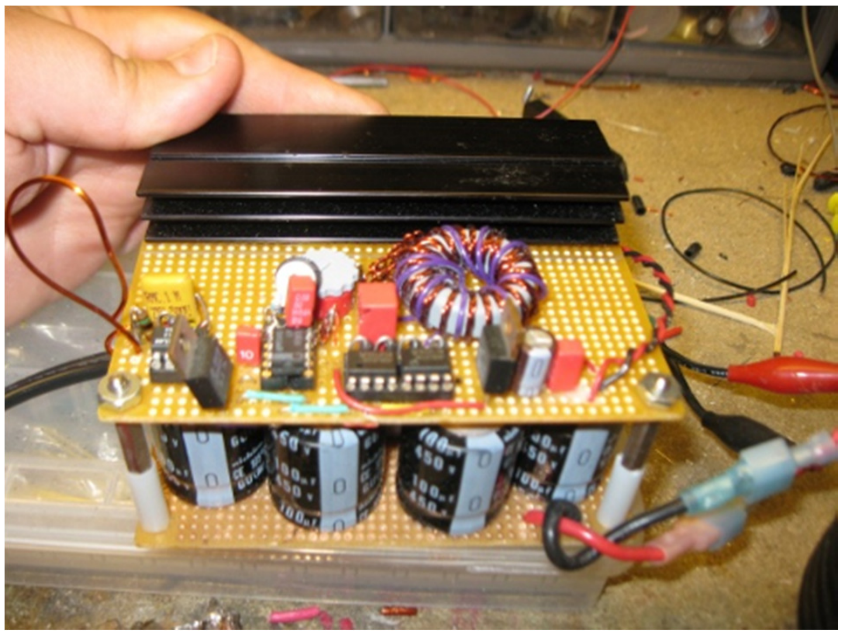
• Semiconductor switches are fragile and must be protected (more on this later).

• Transistors are always driven such that a top and bottom device on the same leg are never on.

•Very light weight. A 1000W inverter can weigh under 3lbs with a properly sized heatsink.

Inverter

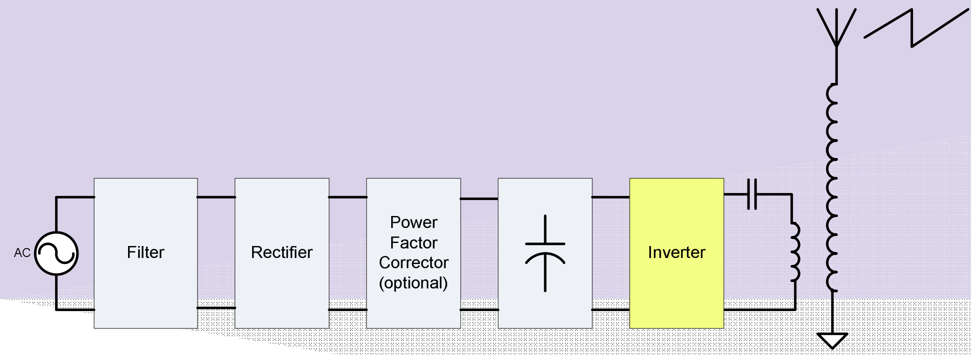




500W inverter from the 18V Tesla gun
(400VDC input IGBT inverter)

Inverter

MOSFETs



MOSFET Advantages:

- Very fast.
- Low gate voltage threshold.
  Typically less than 4V.
- Ease of drive.
- Ease of paralleling.
- No tail current.

MOSFETs were often used in early SSTCs because IGBTs of the time were not fast enough for small tabletop coils.

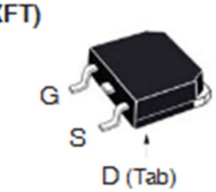
MOSFET Disadvantages:

- They do NOT current limit.
- The body diode is usually very bad.
- Substantially more costly than IGBTs due to larger silicon die required for comparable switching capacity.

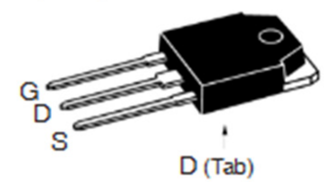
IXFT50N60P3
IXFQ50N60P3
IXFH50N60P3

V_{DSS} = 600V
I_{D25} = 50A
$R_{DS(on)}$ ≤ 145mΩ

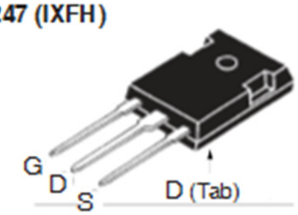
TO-268 (IXFT)



TO-3P (IXFQ)

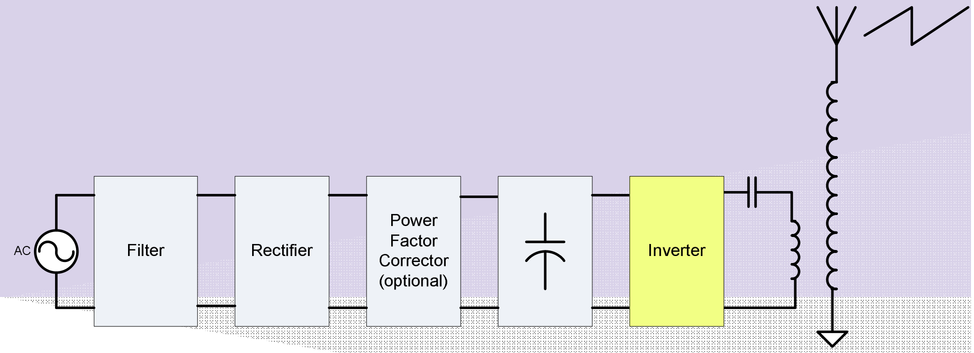


TO-247 (IXFH)



Inverter

IGBTs



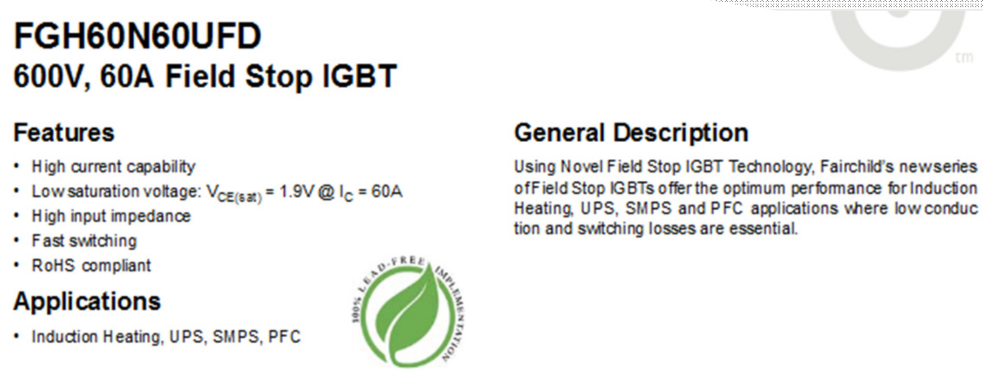
IGBT Advantages:

- Devices usually current limit based on Vg can be "short circuit rated".
- Can be run at much higher TJ than MOSFET.
- Diode is not parasitic, usually co-packaged.
- gives designer flexibility to choose a freewheeling diode.
- IGBTs are preferable for high voltage applications.

Modern IGBTs are quite fast, and when used in resonant applications like SSTCs, you force commutate the device to the off state anyway.

IGBT Disadvantages:

- Can "latch up" if driven with too much current. This doesn't matter when you use ZCS.
- Higher gate threshold voltage.
- Some older devices require a negative gate drive (rare these days).



FGH60N60UFD
600V, 60A Field Stop IGBT

Features

- High current capability
- Low saturation voltage: $V_{CE(sat)}$ = 1.9V @ I_C = 60A
- High input impedance
- Fast switching
- RoHS compliant

Applications

- Induction Heating, UPS, SMPS, PFC

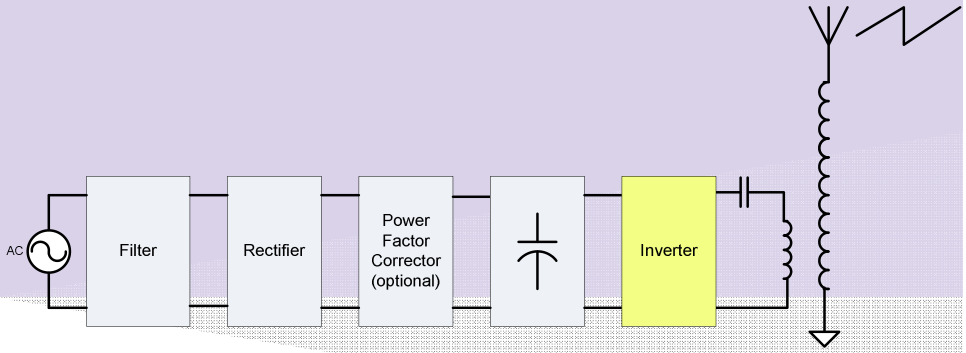
General Description

Using Novel Field Stop IGBT Technology, Fairchild's new series of Field Stop IGBTs offer the optimum performance for Induction Heating, UPS, SMPS and PFC applications where low conduction and switching losses are essential.

Modern IGBTs are almost always preferred over MOSFETs in SSTCs. They're cheaper, and speed is not so important when resonant topologies are used.

Inverter

Resonant link elements

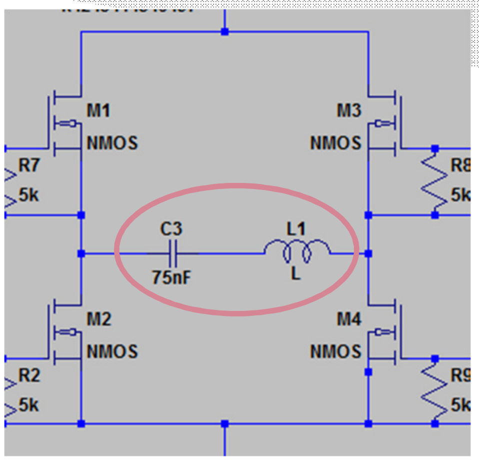


Standard SSTC:

• Typically primary LC circuit is not resonant.
• capacitor is for DC blocking only.

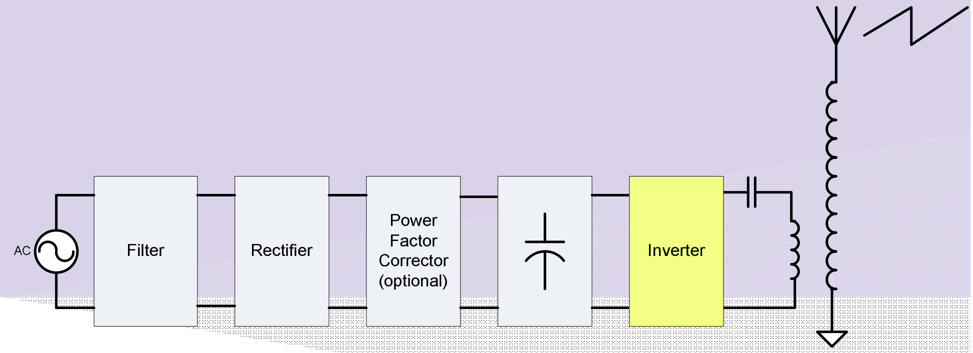
Dual Resonance SSTC:

• Invention generally credited to Jimmy Hynes.
*Specifically, interrupted dual resonance mode.
• Both primary and secondary LC are tuned to same Frequency.
• Tuned primary LC gives excellent Z-matching to secondary.
• Series resonance enables primary tank to circulate thousands of Volts at hundreds of Amperes.
• Can not be operated in continuous wave mode. LC ringup over 10-30 cycles can be hundreds of Amperes (in microseconds). CW mode would require kW to MW.
• Link capacitor must be high voltage rated, and have low enough ESR to work well with high oscillation currents.
• You'll want to use Litz Wire for your primary to keep losses down.
• Soft copper tube works but is not optimal.



Inverter

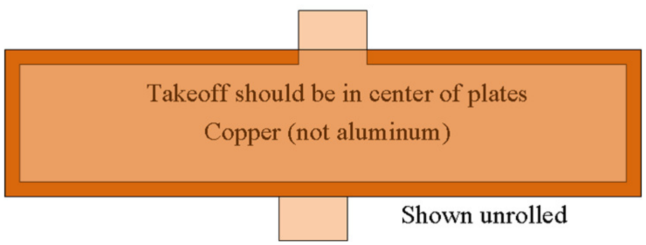
Resonant link elements continued



Making your own capacitors:

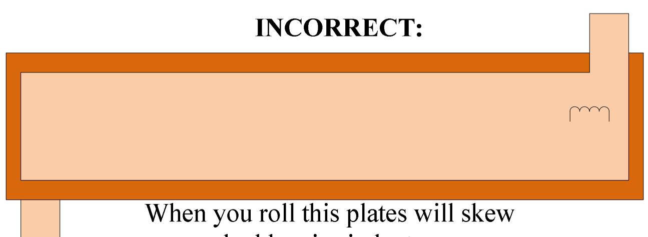
- Usually the capacitors for SSTCs are inexpensive.
- You should try to make your own anyway.
- Pot this with boiling paraffin.
- Epoxy the ends to form a seal.
- De-burr copper foils for best life.
- Use PVC pipe for capacitor enclosure.
  End caps are easy to get.
- This capacitor is self healing.

CORRECT:



Shown unrolled

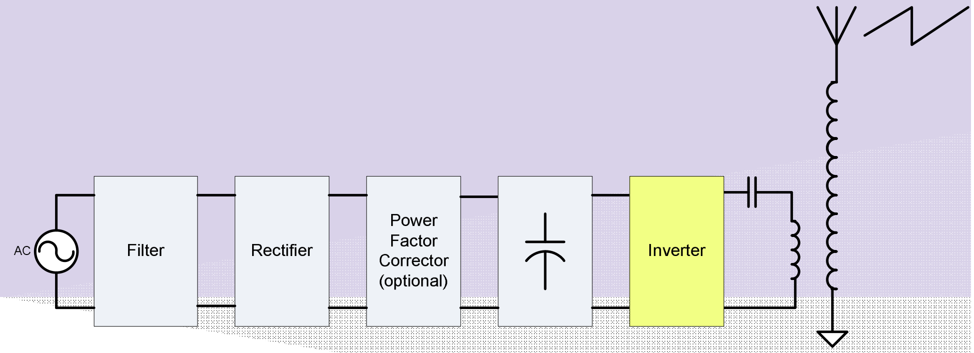
INCORRECT:



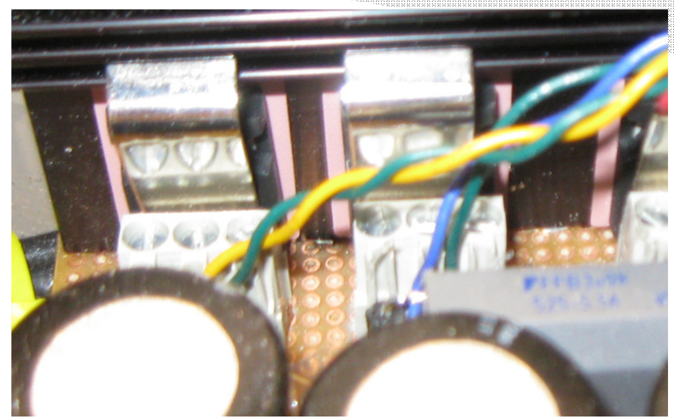
When you roll this plates will skew
and add series inductance.

Inverter

Thermal and mechanical considerations



Device packaging:TO-247 or ISOTOP?



TO-247:

• Easy to mount to heatsink with spring clip or M3/#6-32 screws.
• Back of transistor is almost always tied to drain/collector.
• Requires silicone elastomer thermal gasket material.

Adds thermal impedance.
Not a great idea for high power.
Fairchild devices are solder back rated. IR are not.

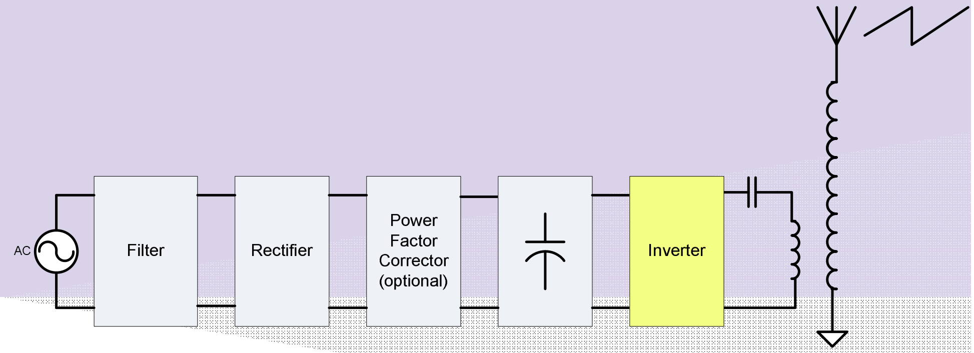
• Use of electrically isolated heatsinks can allow direct metal contact with device.

• ISOTOP (SOT-227):

• Expensive.
• Mounting surface is usually electrically isolated.
• Leadframe bonding rated for much higher current than TO-247.

Inverter

Gate drive transformers

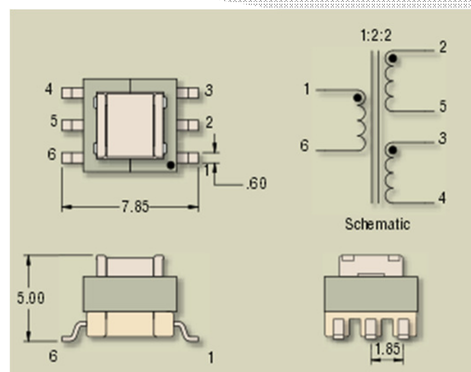


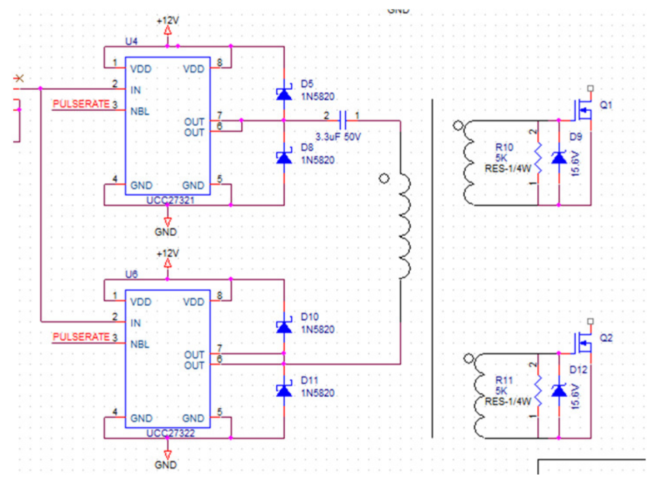
Top side devices on inverter can't be driven from ground. Wouldn't it be nice if we didn't need 3, or ideally 4 separate power supplies and isolation to drive each gate from our logic level controls?

Winding your own on the appropriate ferrite is the best way to get exactly the gate voltage you want.

Must be designed with proper volt second product and primary inductance.

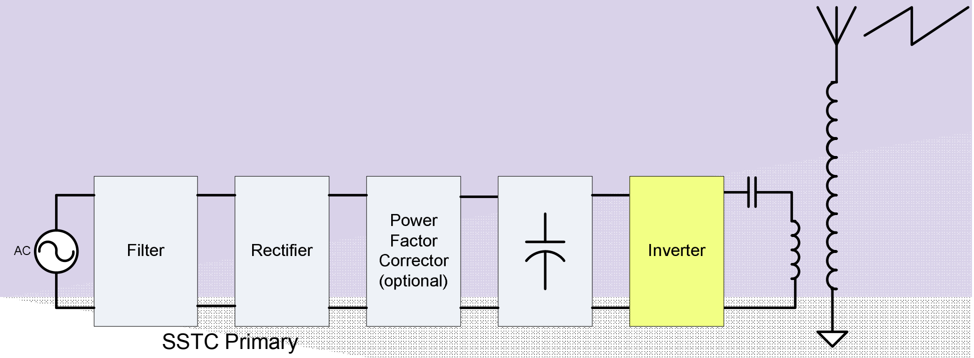
Use of Mircrel or Unitrode driver IC is not recommended for SSTCs over 1000W. A discrete push-pull MOS drive is better for high current drivers.



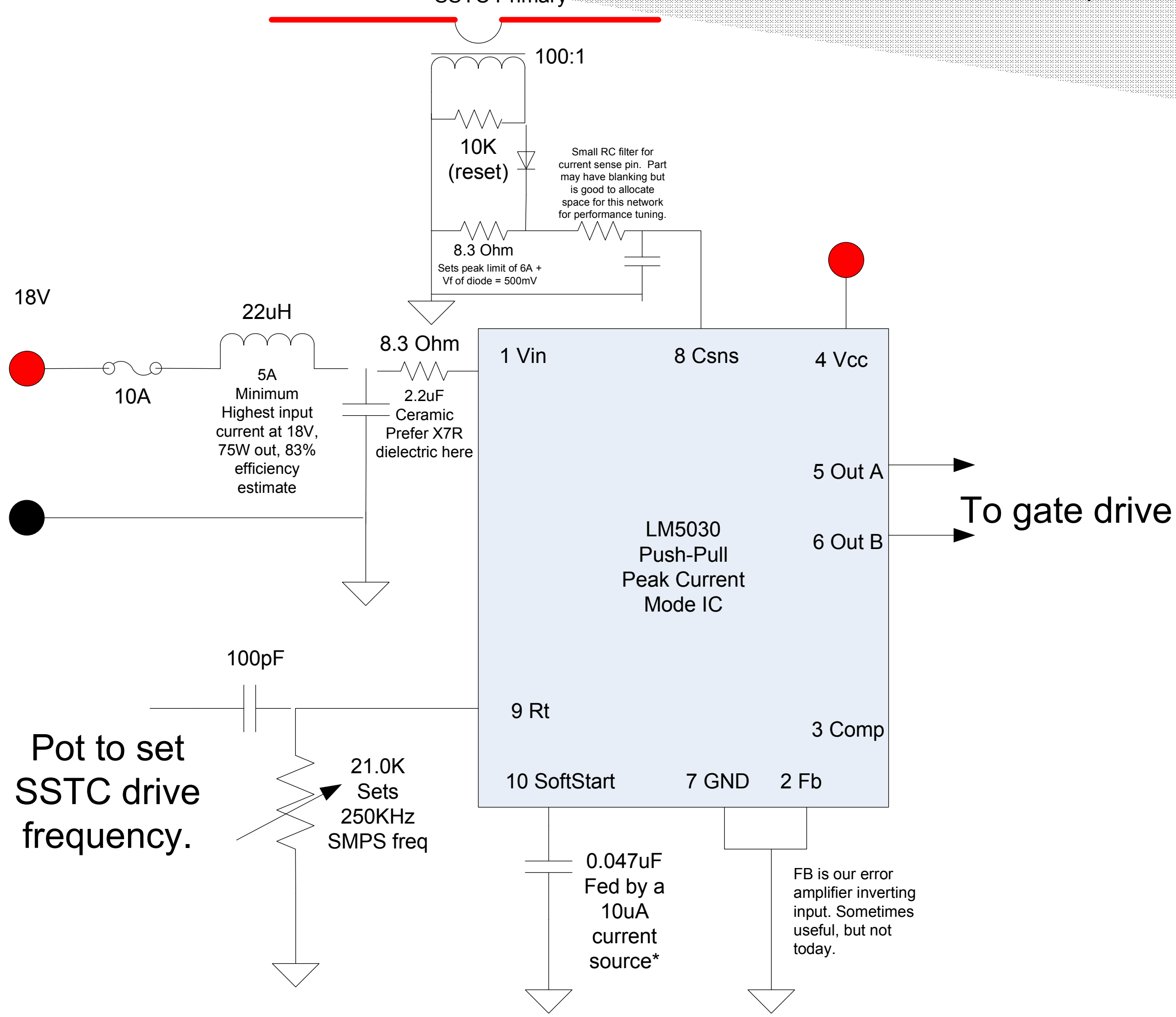


Inverter

Open loop control (useful for testing only)



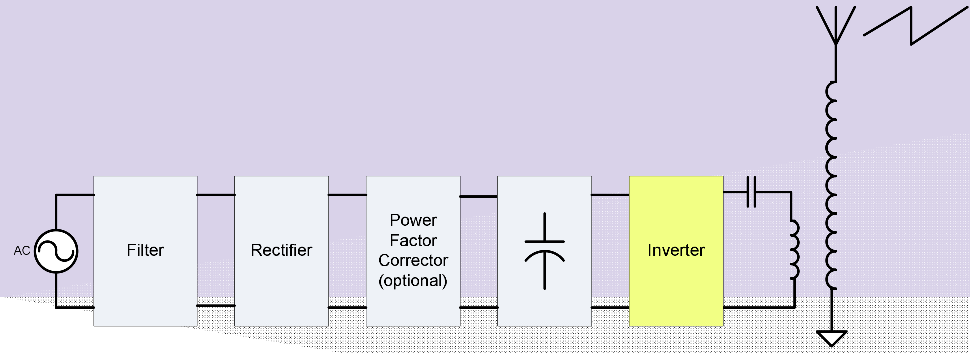
- Use a 555 timer, function generator, or any suitable SMPS IC you have laying about.
- Do NOT do this at line power, or at least use a variac.
- Useful for characterizing system resonances and other basic testing.



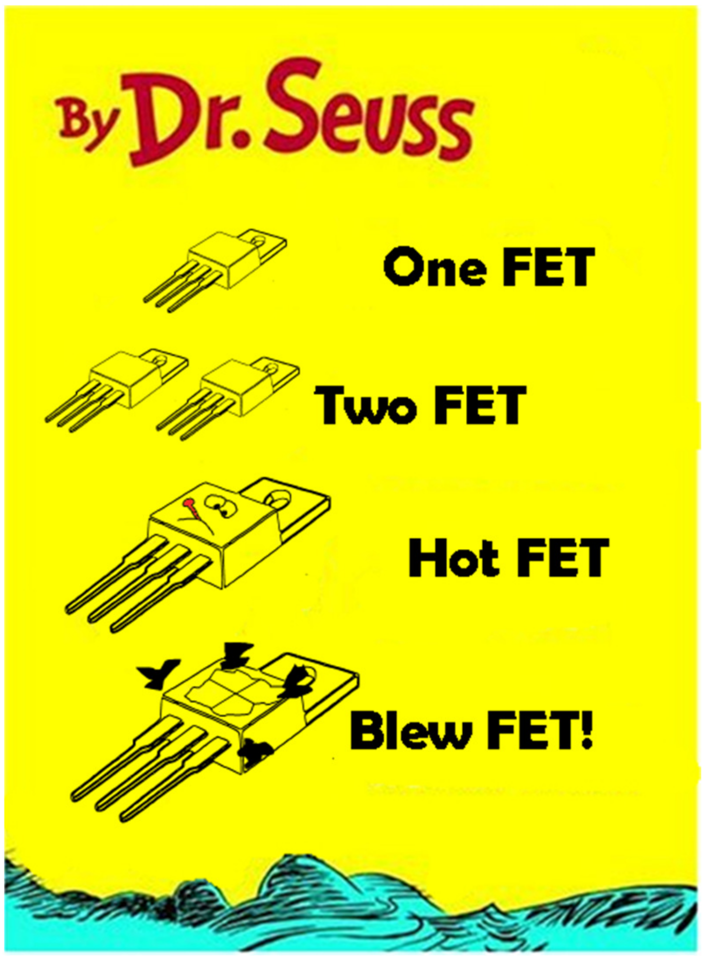
Inverter

Overcurrent protection of your inverter

(dead inverters make me cry)

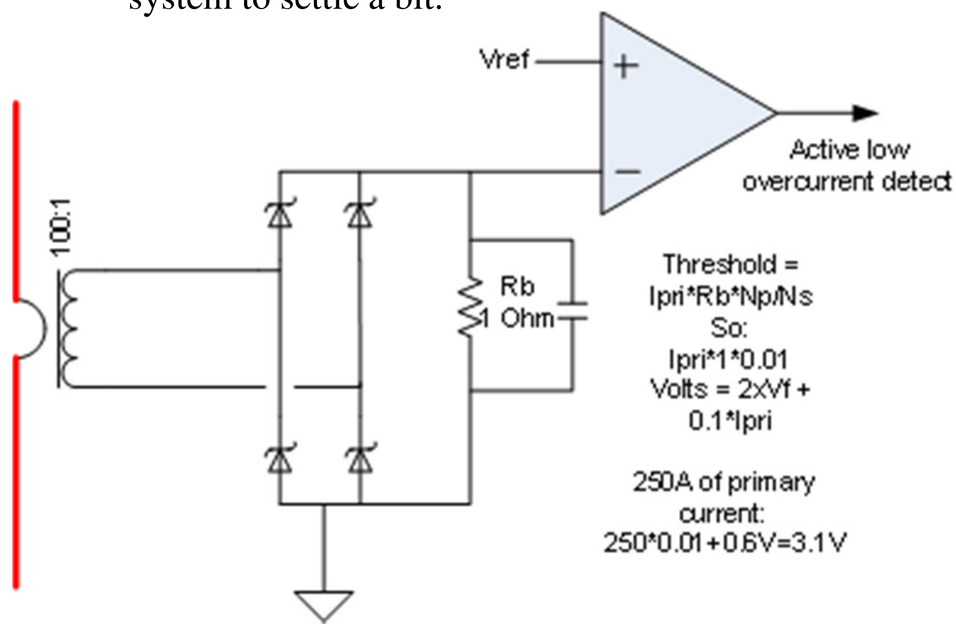


If you omit overcurrent protection, you might want to read this less popular book by Dr. Seuss.



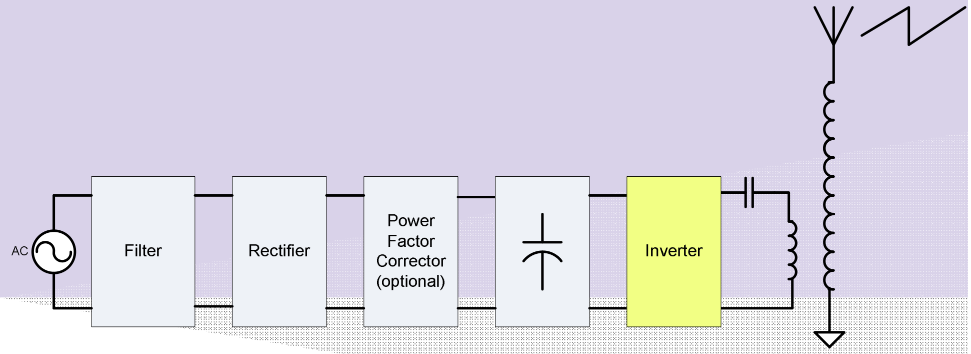
You may need some hysteresis depending on how clean your layout is.

A monostable fixed "off time" is recommended after this circuit to allow the system to settle a bit.



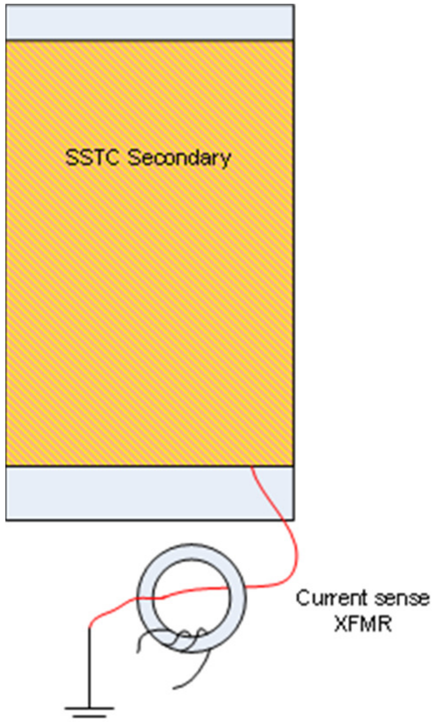
Inverter

Secondary Current Transformer feedback



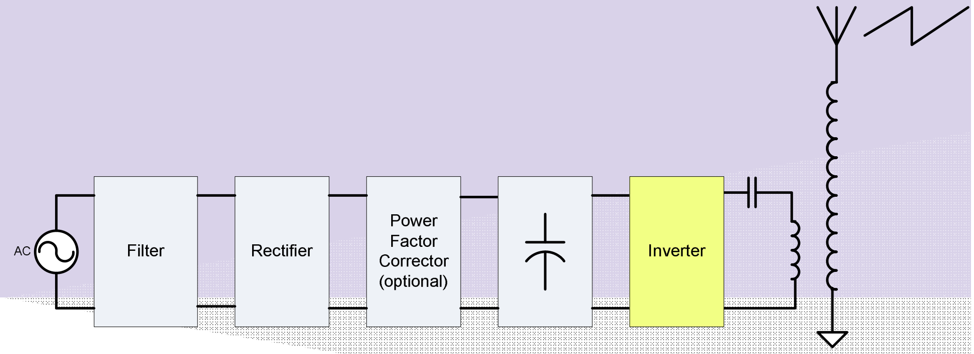
- Drive primary LC tank based on resonant voltage of secondary.

- Not really useful for dual resonance designs. Secondary may be ringing up and primary LC tank is not resonant resulting in poor performance.



Inverter

Primary Current Transformer feedback
(This is also one of Steve Ward's circuits)

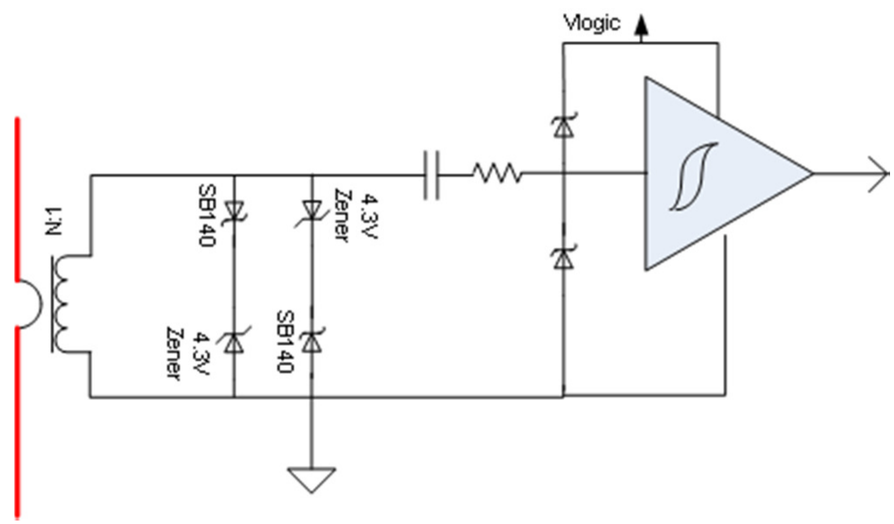


- Sense primary current, clamp it to the rails, square it up, and drive inverter.

- This forces perfect resonant switching of your primary.

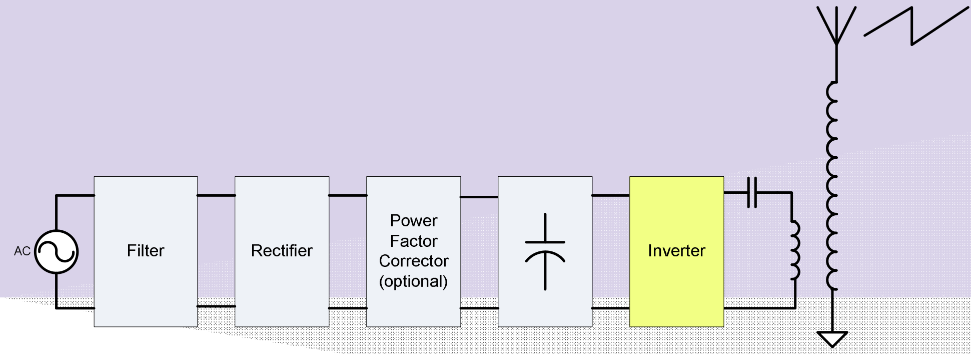
- Currents can climb to hundreds of amperes in a few RF cycles!

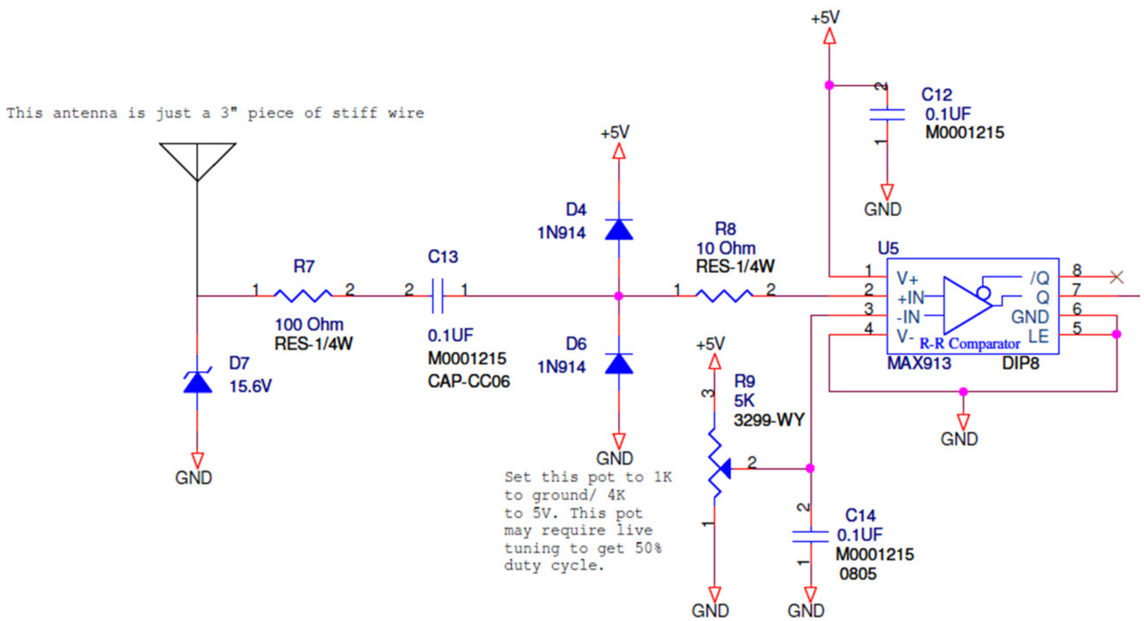
- Schmitt trigger adds some hysteresis to this signal. Hash on this signal is likely going to destroy your inverter or cause spurious overcurrent latch trips.



Inverter

Antenna voltage feedback





- Tesla secondary windings create massive voltage fields that can be picked up by an antenna.

- This sine wave signal needs to be clipped and squared up to re-drive the gates of the MOSFETs or IGBTs to maintain perfect tuning.

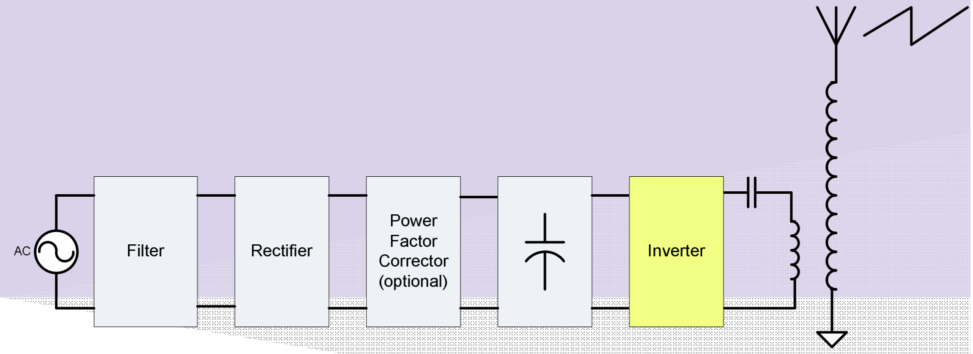
- Comparator MUST be VERY FAST.   The MAX913 is popular for this application, but the pin compatible LTC1711 is a little better (2ns risetime).

- These comparators are fragile and expensive. This method is only recommended for battery coils under a few hundred Watts. This feedback strategy is best for floating coils (no earth ground).

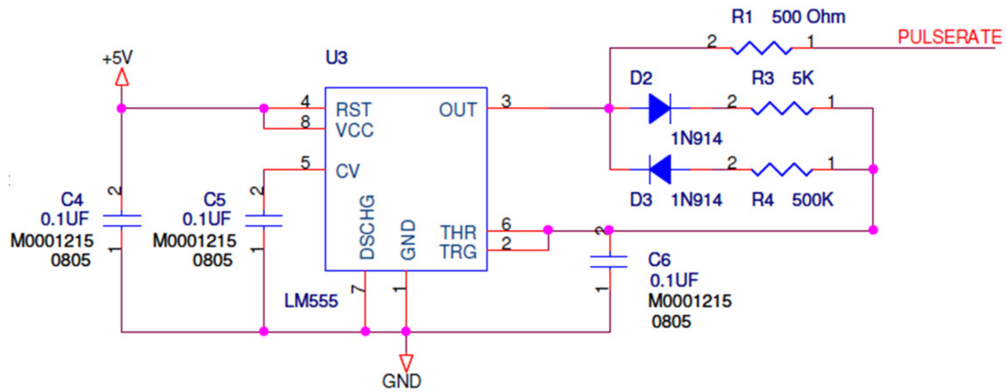
Inverter

Power considerations for SSTCs

Interrupter function



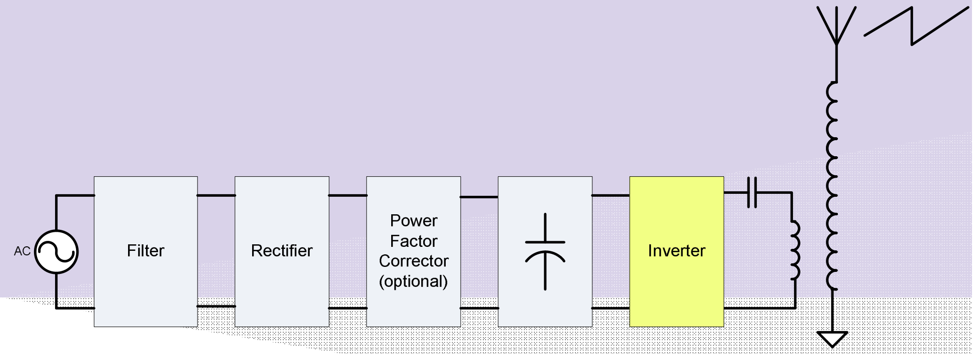
- Used to control total power of SSTC.
- Mandatory for DRSSTCs or you will blow up inverter.
- Works like a PWM controller.
- DRSSTC use low (<1%) duty cycle.
- ISSTC use any duty cycle your line cord can feed it.



Inverter

Pulse Registration Drive

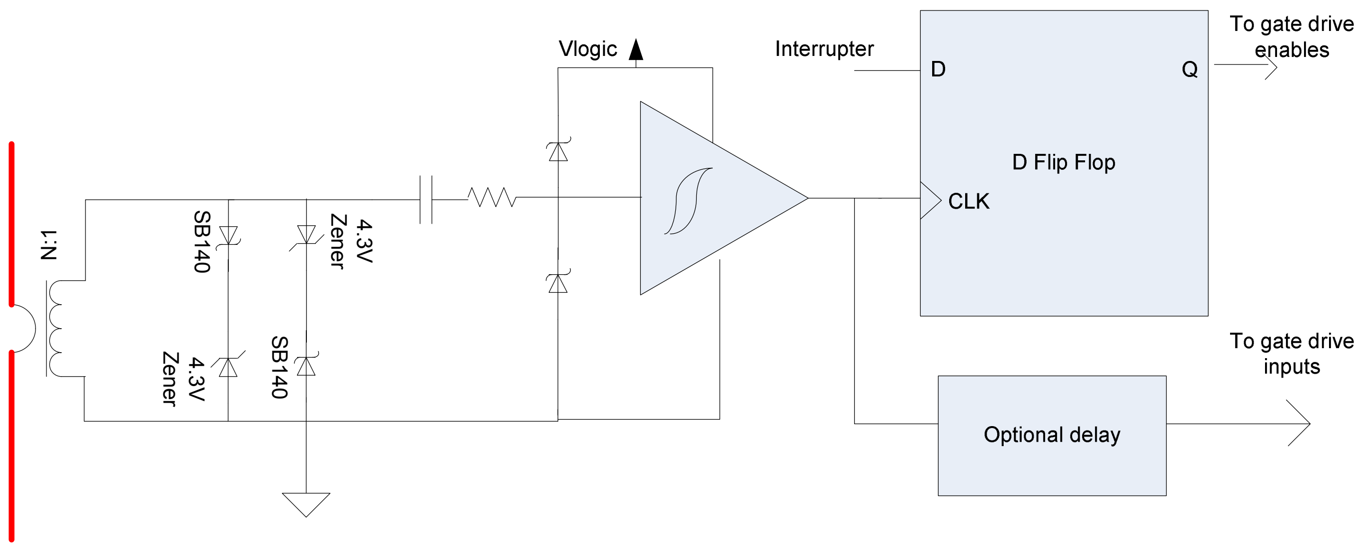
(Credit to Steve Ward for first introducing this)



- Bad for power inverter to hard switch mid RF cycle.
  Recall that IGBTs can latch up…

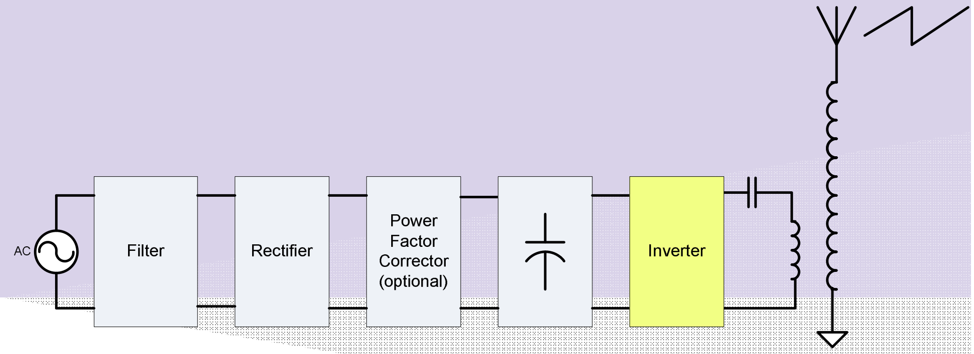
- Use a register to align the enable pulse with next RF cycle.

- Delay tuning may be necessary for very fast oscillation.



Inverter

Musical modulation



- It's possible to vary interrupter frequency to make SSTC play music.

- DRSSTCs best used with single tone music.
  Can use a microcontroller to convert MIDI into interrupter frequencies.
  Duty cycle can then be computed based on MIDI data volume.

- Be sure to set a maximum duty cycle clamp in software in addition to hardware overcurrent.

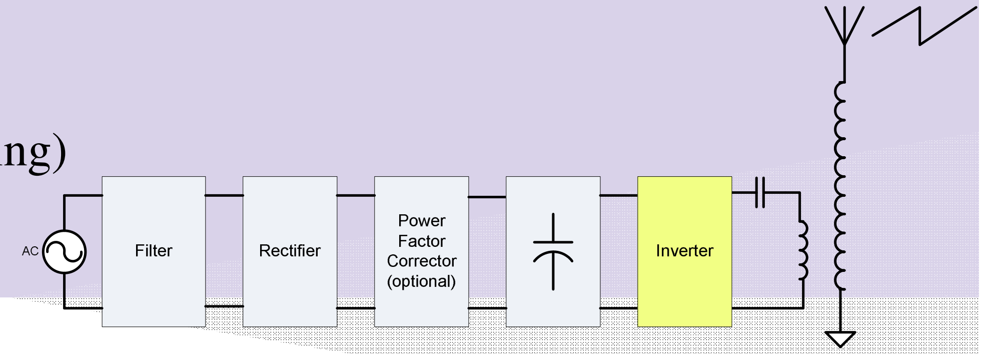
- ISSTCs can be used as plasma speakers.

```
const float notes[128]=
{8.1757989156
,8.661957218
,9.1770239974
,10.3008611535
,10.3008611535
,10.9133822323
,11.5623257097
,12.2498573744
,12.9782717994
,13.75
,14.5676175474
,15.4338531643
,16.3515978313
,17.3239144361
,18.3540479948
,19.4454364826
,20.6017223071
,21.8267644646
,23.1246514195
```

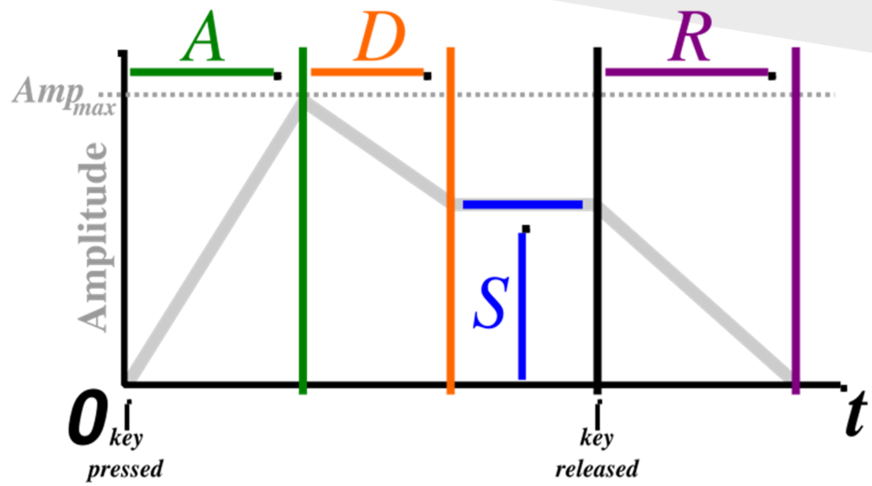
Snippet of MIDI note frequency
Indexed by note number.

Inverter

Modulation continued (ADSR envelope + tuning)

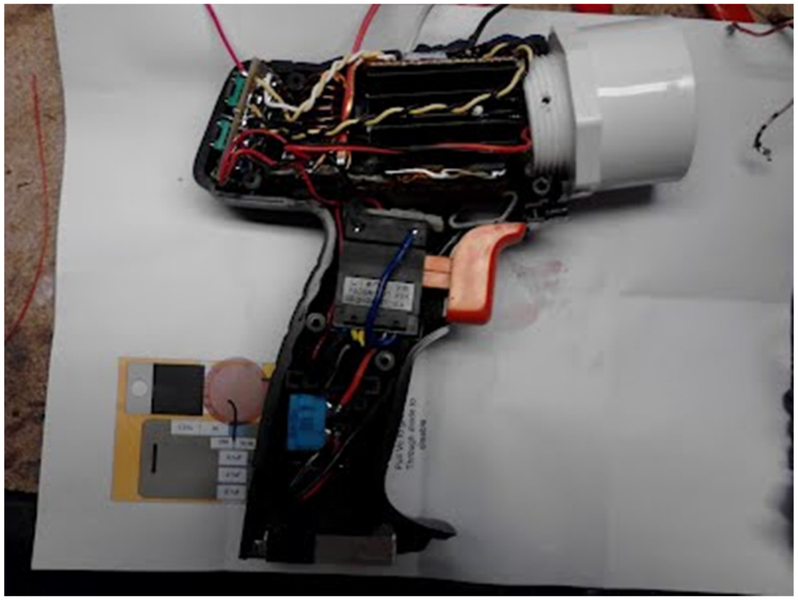


- SSTC inverter can fail or over current if turned on into high duty cycle at high break rate.
- Typically decay term is not necessary.
- SSTC will emit a loud "POP" if you abruptly turn it off. This is fine for normal interrupted operation, but causes audible distortion when playing music.
- Software must compute the length of the MIDI note and compute the attack and release time on the fly.
- Software should parameterize these as a percentage of total note time.
- Experiential tuning required and is usually most specifically affected by system resonant frequency.

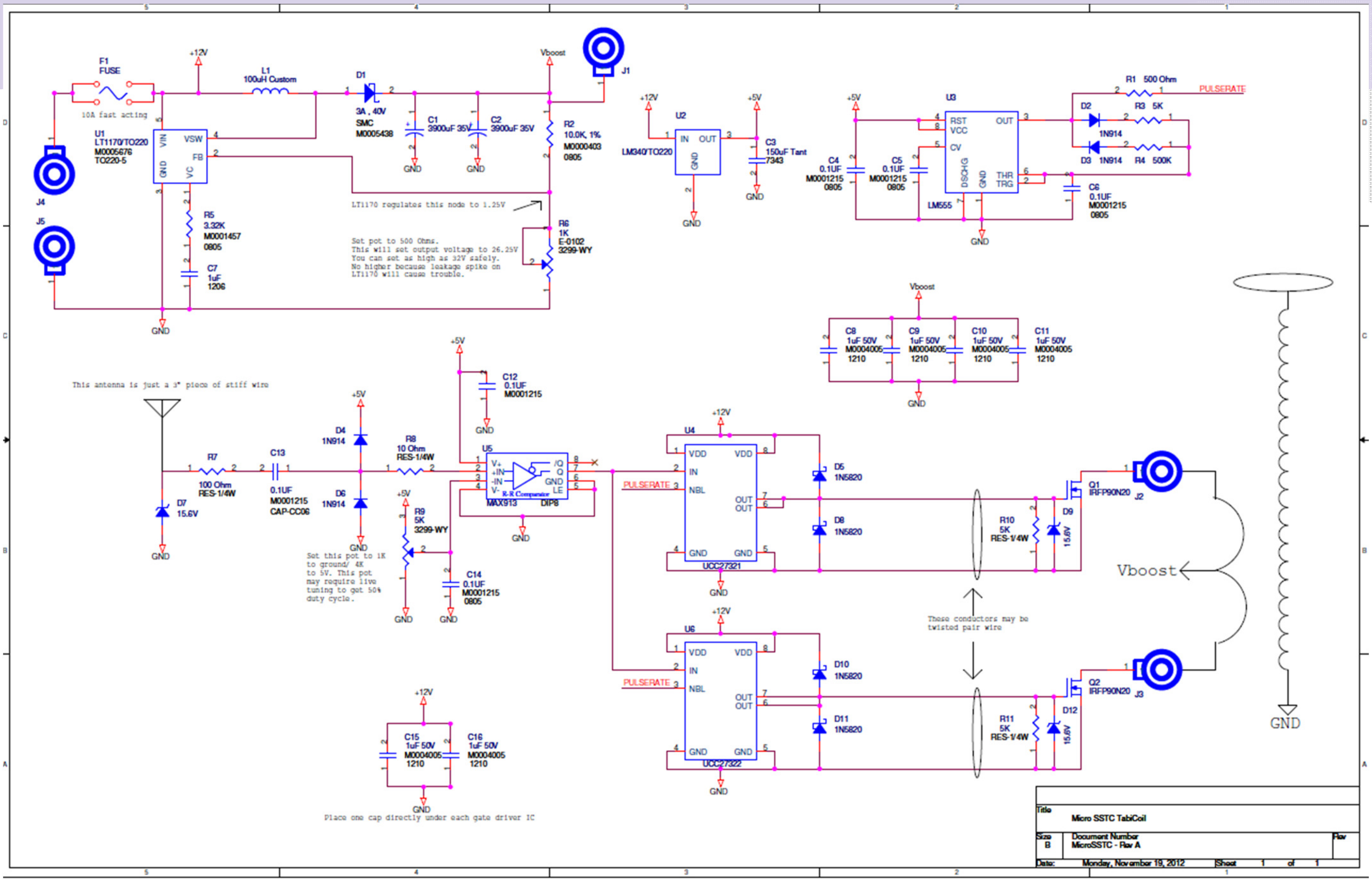


Source: Wikipedia (GNU Free documentation licence)

Micro 12V power coils!



Micro 12V power coils!



Micro 12V power coils!
PCB layout