Design of Highly Efficient RF Frequency Class E Push-Pull Amplifiers with Low Harmonic Content for the Driving of Fusion Reactors

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Need an abstract

Abstract-

In the Princeton Field Reversed Configuration fusion reactor, ions in the plasma are heated by an antenna operating at RF frequencies. This article presents how push-pull class E amplifiers can be used to efficiently drive this antenna in the MHz range, from 0.5MHz to 4 MHz, while maintaining low harmonic content in the output signal. The paper presents theoretical values and breadboard results for various configurations that have a tradeoff between simplicity, harmonic content and efficiency. For a practical design, multiple amplifiers would be linked in parallel and would power the RF antenna at around 1MW. These designs provide multiple different options for reactor systems that could be used in a variety of applications, from power plants on the ground to rocket engines in space.

1. Motivation:

This amplifier was designed specifically for the purpose of achieving efficient RF heating of the plasma in the Princeton field-reversed configuration experiment (PFRC). In this reactor, an RF power amplifier is used to drive an antenna which in turn heats the plasma to desired temperatures. The current rendition of the fusion reactor, PFRC 2, utilized a Class C power amplifier to accomplish this. However, with a theoretical efficiency of 70% and a significantly lower operating efficiency, it was necessary to consider other designs. This is especially relevant in the context of fusion power, where a small change in the output power to input power ratio can mean the difference between a viable power source and a science experiment. In order to accomplish this goal, we chose to utilize the Class E power amplifier topology, which has a theoretical efficiency of 100%. It also has the potential to vary the harmonic content of the output, trading off with efficiency, which is important for research purposes as the effects of harmonics on the plasma in this particular reactor are not well understood.

2. Description of Class E Amplifier:

An example of a single basic class E amplifier can be seen in the figure 1.

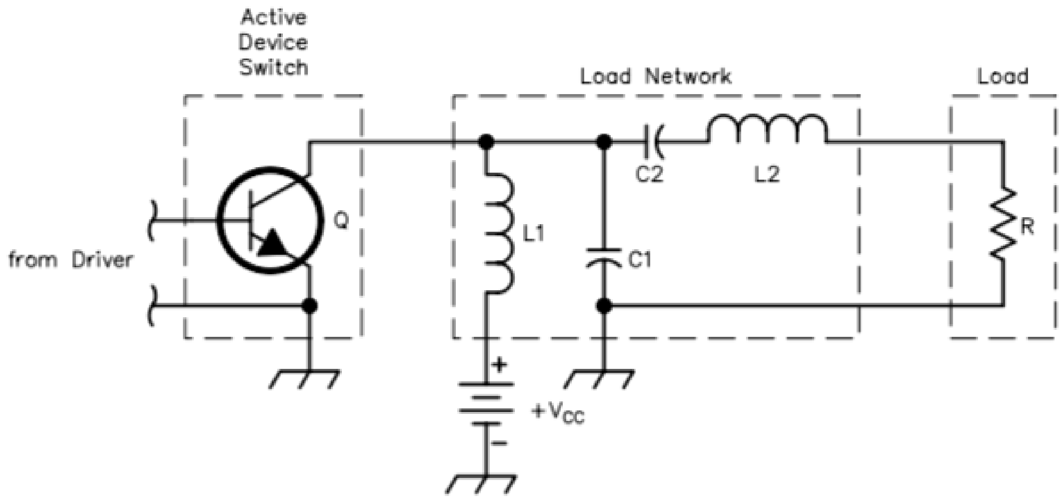


Fig. 1 **Caption needed**

The device is composed of a transistor driven by an pulsed power source, a shunt capacitor in parallel with the transistor, a DC voltage source connected to the rest of the circuit by a choke inductor, an LC tank circuit and a resistive output. The transistor is driven in the saturation regime, so it essentially acts as an on-off switch. This is a significant difference from linear amplifiers which operate in the active regime, and thus incur power losses from continuous current through the transistor. The on-off operation of the switch in class E allows the circuit to be designed so that current and voltage are not nonzero simultaneously, thus giving the circuit a theoretical efficiency of 100%. The choke inductor blocks RF frequencies to make sure the DC voltage input is as DC as possible. The DC voltage from the voltage source is converted into a sinusoid by the tank circuit. The tank circuit also serves to maximize power output at the first frequency by resonating at the fundamental frequency and to minimize other harmonics. As a voltage drop across a capacitor is not instantaneous, the shunt capacitor prevents the formation of a sharp voltage drop across the transistor when it is opened, making the transition more gradual as it charges up. This protects the transistor from damage.

3. Push Pull Class E Amplifier:

In our design, we combined two class E amplifiers in parallel and drove the ac voltage sources 180 degrees out of phase to create a push pull class E amplifier. This symmetrical design allows us to significantly reduce the degree to which even harmonics are present in the output signal. This is due to the destructive interference that results from the combining of the wavelength with the shifted version of itself that comes from the phase shift.

To prove this, we will take the two output current of the transistor at the drain, Id1 and Id2, with same amplitudes, but with one pi radians out of phase due to the inputs being pi radians out of phase. These currents include the harmonics. These need to be formatted as equations

Id1 = Io + I1*sin(wt) + I2*sin(2wt) + I3*sin(3wt) + I4*sin(4wt) + ...

Id2 = Io + I1*sin(wt+pi) + I2*sin(2wt + 2pi) + I3*sin(3wt + 3pi) + I4*sin(4wt + 4pi) + ..

Where w is the fundamental frequency and Io is the DC component of the current. The reason for the addition of multiples of pi in the phase is that each phase shift of pi shifts the signal one period. In order to properly line up the harmonics of the phase shifted signal in the same way that you would for the non-shifted signal, you need to shift each harmonic more as each has a smaller period than the fundamental, and thus needs more shifts to align properly while the fundamental only requires one. Since phase shifting a sinusoid by pi is the same as inverting it, and shifting it by 2pi results in the same signal, we get

Id2 = Io - I1*sin(wt) + I2*sin(2wt) - I3*sin(3wt) + I4*sin(4wt) +...

The output current is given by Id1 - Id2 = 2I1*sin(wt) + 2I4*sin(4wt) +...

You can see that the even harmonics have been cancelled.

4. Design of the Class E Amplifier:

We tested two different designs of the Class E push-pull amplifier. One, we label “Simple” and the other “Tank” as the simple circuit lacks a tank circuit.

For Simple, we start with a class E amplifier, but we remove the tank inductor and the tank capacitor from the design. We then put two of them together to form a push-pull amplifier, as we can see from Figure 2 from Reference 2.

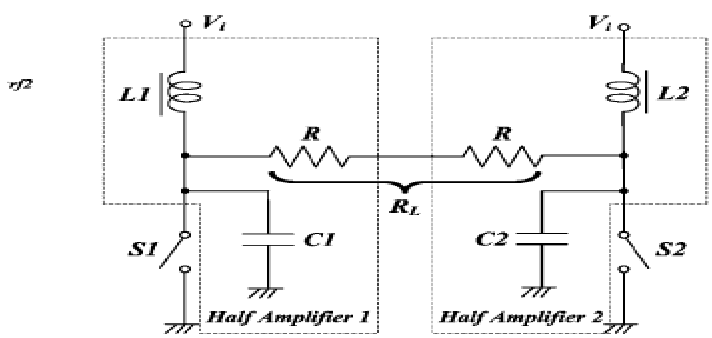
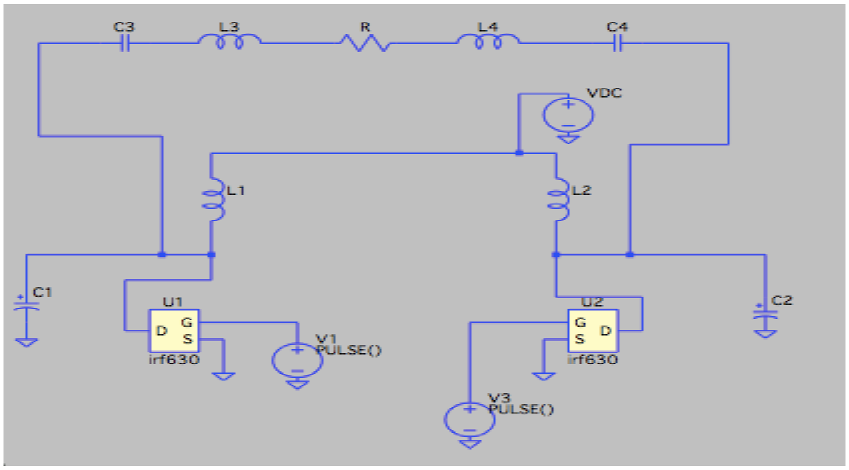


Fig. 2.Caption needed

We use the equations from Reference 2, to build this simpler circuit. We can pick the frequency, the load resistance R, and the value of Q (the quality factor of the circuit). A higher Q means the output is closer to the first harmonic, but it also means lower efficiency. The paper calculates numerically the values that Q and D (the duty ratio of the circuit) must take in order to maximize efficiency.

For Tank, we start off with a basic class E amplifier. We use the equations from Reference 1 to calculate the values of the DC voltage source, the shunt capacitor, and the capacitor and inductor in the LC tank circuit. We chose the choke inductor to have a value that was a factor of 10 larger than that of the resonant inductor, however, it is only necessary for this value to be large compared to the resonant inductor so that it acts as a DC current source at the frequency of the RF signal. Our frequency range of consideration was 500kHz to 4Mhz. We then connected two of these Class E amplifiers together so that they share the same resistive load and couple the two choke inductors.



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We will use two parameters to describe the circuit: THD (Total harmonic distortions), which measures how much of the signal is contained in the first harmonic, and the efficiency of the circuit, which is influenced by how much heat is lost on the transistor and storage components such as the capacitors. For both circuits, we tried to see how introducing a notch filter for the 3rd harmonic would affect the efficiency and THD of the circuit.

5. Results of simulations:

We first simulated the circuits in LTSpice to see what efficiencies and THD's we can obtain with the two types of circuits and subsequently tried to match real components to these circuit designs. We measured the ideal efficiency given the limitations of real components.

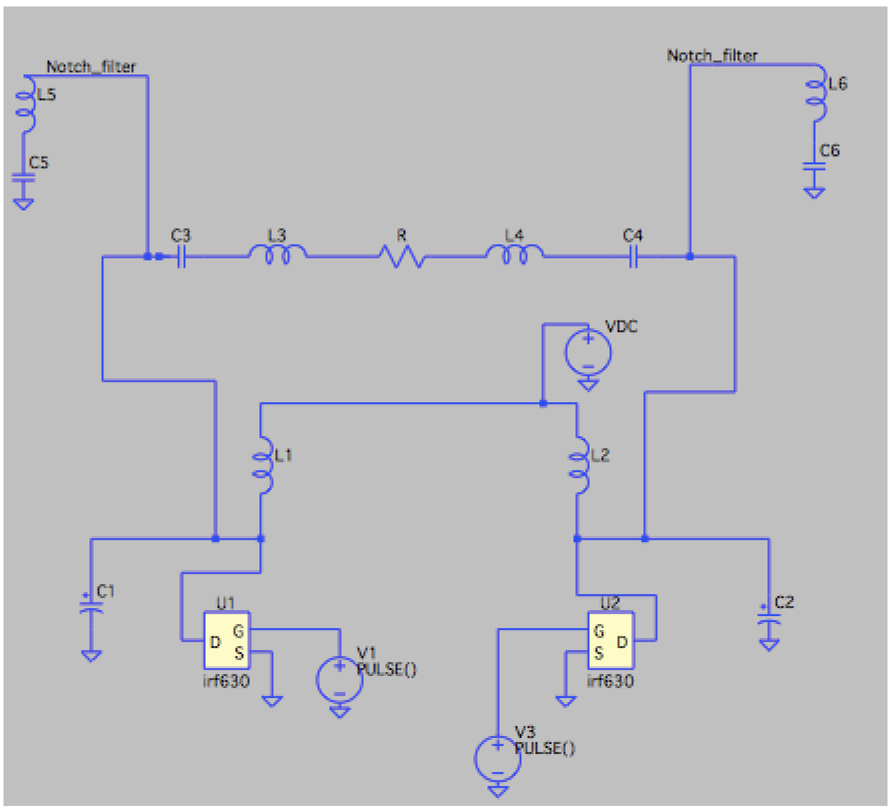
Circuit Name	**Frequency(MHz)**	**THD (%)**	**Efficiency (%)**
Simple Circuit	**.5**	**15.83**	**94.65**
	1	**16.81**	**94.92**
	2	**13.35**	**94.62**
	4	**13.77**	**93.17**
Tank Circuit	**.5**	**0.72**	**95.18**
	1	**1.02**	**95.18**
	2	**0.78**	**95.04**
	4	**0.45**	**90.96**
Simple Notch	**.5**	**5.69**	**96.15**

	1	**9.16**	**96.24**
	2	**12.74**	**94.79**
	4	**22.76**	**92.28**

Need caption to say that this is SIMULATED data

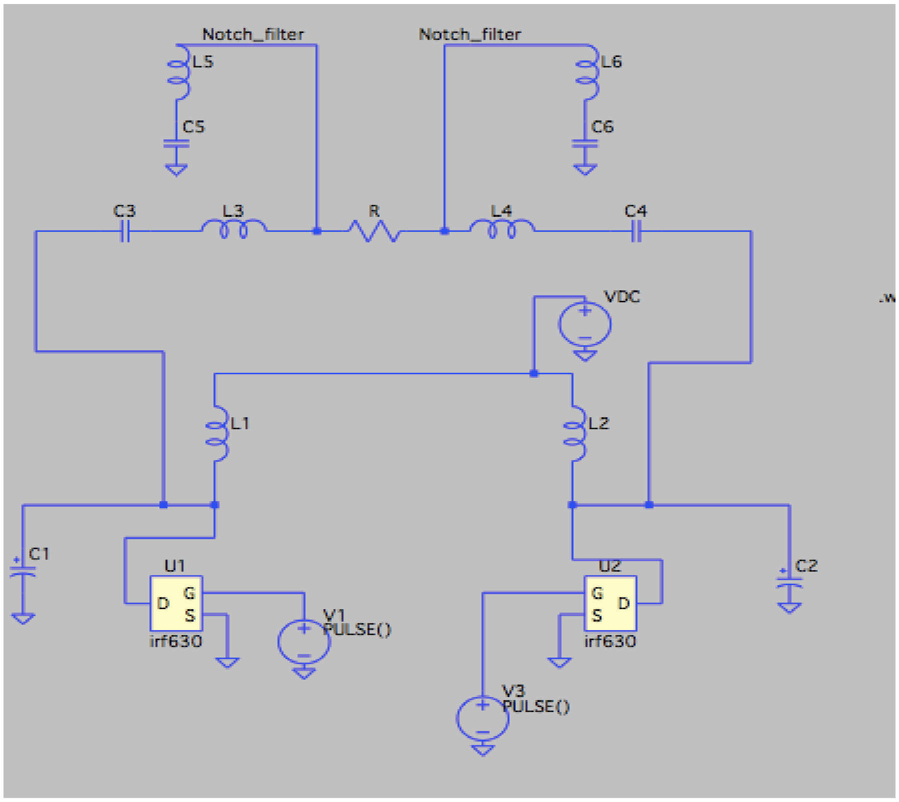
When we used a notch filter and a tank circuit in our simulations we noted that putting the notch filter after the tank circuit inductance and capacitance resulted in more efficient designs than putting the notch filter before the tank capacitor and inductor.

Notch filter before tank



Notch before Tank	Frequency (MHz)	THD	Efficiency
	0.5	0.89%	91.67%
	1	1.01%	64%
	2	0.55%	53.20%
	4	0.47%	10.80%

Notch filter after tank



Notch after tank	Frequency (MHz)	THD	Efficiency
	0.5	1.70%	95.32%
	1	1.01%	95.14%
	2	0.95%	91.08%
	4	0.45%	94.45%

We also tested the real parts we could buy to build this circuit and we found that parasitic capacitance in the inductors was one of the elements which caused the most problems with efficiency and harmonics. We tried to minimize the parasitic capacitance and the resistance of the inductors we bought.

6. Real Circuit Design

We first implemented a regular class E amplifier with a tank circuit at .5Mhz. We found that the transistor turn on time was too slow as if there was a large capacitance at the gate of the transistor (Figure X), and so we decided to utilize a gate drive between the input and the transistor. The gate drive effectively lowers the input impedance into the transistor which results in a lower charge up time so that the turn on time was much lower and the waveform much more square.

7. Real Circuit Results

8. Conclusions:

In this paper, we have outlined several options for power amplifiers that could be used to power the PFRC fusion reactor. They not only have extremely high efficiency, but also very low harmonic content.

9. Future Work:

In order for this approach to be a viable method to power the reactor, many of these reactors will have to be connected in parallel so that the power output is the correct magnitude. Furthermore, due to the variation of plasma conditions within the reactor, it will be necessary to determine how to utilize variable components to change the harmonic content and or power output of the circuit in real time. It may also be necessary to determine how to reduce stress on the transistor, or to find a transistor that can better handle the stress of operation.

10. Other Applications:

Although we specifically designed this technology for the purpose of driving the PFRC fusion reactor at PPPL, these amplifiers have applications in a variety of other fields. These include pasteurization and decontamination of food products, RF frequency communication systems, heating of fusion reactors that also rely on other heating methods such as neutral beams, and radar. We believe that this technology, through its high efficiency and minimal addition of unwanted harmonics, will also facilitate the development of these other areas of research.

11. References:

[1] N. O. Sokal, "Class-E RF power amplifiers ... ," *QEX*, No. 204, pp. 9-20, Jan./Feb.2001.

[2] F.-Y. Chen, J.-F. Chen, R.-L. Lin, "Low-harmonic push–pull class-E power amplifier with a pair of LC resonant networks", IEEE Trans. Circuits Syst. I Reg. Papers, vol. 54, no. 3, pp. 579-589, Mar. 2007.

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