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Designing and Simulation of Various Class-F Radio-Frequency Power Amplifier

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Designing and Simulation of Various Class-F Radio-Frequency Power Amplifiers

A thesis submitted in partial fulfillment

of the requirements for the degree of

Master of Science in Electrical Engineering

By

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B.Tech., Uttar Pradesh Technical University, Lucknow, India, 2014

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WRIGHT STATE UNIVERSITY

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May 24, 2016

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY <u>Varun Pundhir</u> ENTITLED <u>Designing And Simulation Of Various Class-F Radio Frequency Power Amplifier</u> BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF <u>Master of Science in Electrical Engineering</u>.

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Abstract

Pundhir,Varun. M.S.E.E, Department of Electrical Engineering, Wright State University, 2016. *Designing and simulation of various Class-F radio frequency power amplifier.*

In this thesis, the various kinds of Class-F radio frequency power amplifiers are discussed. The Class-F_3 RFPA is the one which has been designed and analyzed. It consists of an RF choke, blocking capacitor and a loading network. The loading network consists of a tank circuit resonating at fundamental operating frequency and also a parallel resonator circuit tuned to third harmonic.

For a better understanding of the operation of Class-F_3 amplifier, we go back to Class-C amplifier and discuss it briefly. Here the design remains same, operating at conduction angles less than $180°$. The design equations were used to derive required circuit parameters on MATLAB. The designed circuit is implemented on SABER circuit simulator and resulting waveforms and frequency spectrums are also presented. The dependence of Class-F_3 operation on gate-to-source voltage of a MOSFET is presented by varying it and showing the changes in the drain-to-source voltage and drain current. The frequency spectrum helps understand the harmonics in both signals. A design of the Class-F_3 RFPA is presented with drain-source capacitance. A design for Class-F_3 amplifier was produced where the MOSFET is forced to work in linear operating region and it is simulated in SABER.

The plotted SABER simulation results are in agreement with the theoretically derived results. The simulated circuit efficiencies are a little less than what was calculated theoretically. The spectrums help clarify the results obtained.

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Aknowledgement

To start of, I would like to express my immense gratitude to my advisor Dr. Marian K. Kazimierczuk , whose motivation, support and wisdom has helped me through out my research. I would also like to thank my thesis committee members Dr. Yan Zhuang and Dr. Michael A. Saville for their insightful comments and suggestions. I am grateful to the Department of Electrical Engineering and the Department Chair, for giving me this opportunity to obtain my MS degree at Wright State University. A sincere thanks also goes to my fellow colleagues Agasthya Ayachit and Ankit Chadha, whose support and experience built the confidence in me. Last but not the least I would like to thank my family, who stood by me on every decision I made and who have always showed me the right path.

1　Introduction

The first steps taken in the world of audio amplification were by Lee De Forest in 1906, who invented an electronic amplifying vacuum tube called Audion[5]. It was a triode based amplification device. The triode was a three terminal component with a control grid, which could modulate the flow of electrons. We have come far ahead from the days when vacuum tubes dominated the electronics industry. Electronics was advancing its steps to the future, but yet there was something missing. The circuitry was advanced and the operation was good but it acquired large space. This gap was filled in 1947, when the first transistor was invented at Bell Labs, by John Bardeen, Walter Brattain and William Shockley[23]. It revolutionized the world of electronics but also affected the field of amplifiers as now the circuitry would be reduced in size and would become potentially cheaper to build.

Experiments with "Wireless Telegraphy" had begun after the first quarter of the 17th century. These experiments used inductive and capacitive inductions and transmissions using water and ground. Such experiments became the foundation for wireless communication. But it wasn't until 1864, when James Clerk Maxwell[1] mathematically presented that electromagnetic waves could propagate through free space, that the real push was given to this field of science. In 1888, Heinrich Rudolf Hertz conclusively proved Maxwell's theory of electromagnetism by transmitting electromagnetic waves in an experiment[2].

The experiments in the wireless communication field continued through out 1890s till the 1920s. In 1894, British physicist Oliver Lodge, transmitted and received "Hertzian waves" at a distance up to 50 meters[11]. Next year, Indian physicist, Jagdish Chandra Bose[3], performed experiments regarding radio microwave optics. Alexander Stepanovich Popov, a Russian physicist constructed a radio based lightning detector, in 1895. The inventor of radio, Guglielmo Marconi, was also working

on the phenomenon regarding wireless communication. On 13 May 1897, he demonstrated his first prototype to the British Post Office engineers[12]. He later developed his prototype which after many iterations and improvements was commercially produced in 1920[13]. Until then the problem with radio transmission was the distance between which this transmission could be done. But these problems only led to more inventions and improvements in the design of amplifiers themselves. Together, these inventions led to the advancement of the field of wireless communication.

1.1   What are Amplifiers?

Amplifiers are considered as one of the most important circuits in all of electrical engineering. If there were no amplifiers, then it would be impossible to carry signals through long distances, which means no communication systems would be possible. The reason is pretty simple. Amplifiers, as the name suggests, means it is a circuit which amplifies one of the key attributes of a signal, amplitude.

As we transmit a normal signal, the signal loses its strength in the process. The power of the signal is reduced in the transmission and by the time it reaches its destination the signal has become too weak to be used directly. To make the signal usable again, its power level must be increased. This is when amplifiers come into the picture. An amplifier circuit amplifies the power of the signal, in most situations. The input currents, output currents, input voltages and the output voltages are some important factors for designing an amplifier. These factors help us understand various gains (voltage gain, current gain and power gain) related to that amplifier. The decibel, a logarithmic unit, is the most common way of quantifying the gain of an amplifier.

1.2 Need for Amplifiers

In today's world we are always involved with our mobile phones, computers, tablets and other communication technologies. We try to be updated with everything that is happening around the world in real time. We don't want to miss out on anything and the accessibility has been increased with innovations of noble techniques in communication technology. But if we think about it, all these things are incomplete without amplifiers. Amplifiers are found in most of the devices we use for everyday tasks. From the phones in our hands, which we use to access Twitter or Facebook for news and keeping in touch with friends, to complicated radar systems, which are used in air traffic control systems to monitor the route for different flights in air and on the airport, all these use amplifiers. If amplifiers were not there, it would become inconvenient for a countries defense organizations as well as a normal daily consumer of news and entertainment.

The amplifiers are a important part of radio communication. Today's long distance radio communication involves amplifiers on the transmission end as well as on the receiving end. Amplifiers help reduce the power load and the cost of broadcasting these signals. The audio amplifiers are used in headphones and stereo systems to bring up the low power audio signals to a level suitable for driving these speakers.

The signals need to be amplified for communication systems, especially long distance communication. These amplifiers are weak-signal amplifiers and are a key component for the communication and broadcasting industry, along with power amplifiers. It helps to maintain high efficiency and low cost for the system of transmitting as well as receiving sections of the system. They can be used for both audio or video signals. These are some of the applications of power amplifiers.

1.3 Motivation for Thesis

For every amplifier or for that matter every electronic circuits, main output characteristic(s) to think about are its efficiency, along with others. In case of radio frequency power amplifiers, the main output characteristics to think of are the system efficiency and linearity of the circuit[4]. The classes of amplifiers are differentiated on the basis of changes in these characteristics. An amplifier is designed keeping in mind the property of linearity along with efficiency. A good circuit tries to maintain the balance between these, so as it is more useful for practical purposes. As we move from Class-A to Class-D amplifier, we see that efficiency of the circuit improves at the cost of reduced linearity[10]. In the modern industry, as the technology improves everyday, we try and seek new ways to improvise the efficiency of systems, without damaging the linearity of the system.

As a young student, when electronics was introduced to me, it was fascinating to discover how such small electrons which we cant see, are able to move in these components and make it perform different operations. They could govern how the circuit would perform in different situations[8]. It was difficult to understand this without actually seeing a model showing its results, until I entered the field of electrical engineering. Here I have been able to work with many circuit simulation software which have helped me understand the working of many circuits and their characteristics and, results obtained from those. This has made my interest grow in the field of simulations.

These two reasons, together, helped me get involved in this topic as I could understand designs and their results at the same time. It made me think about the circuit and helped me realize on the fact that there may be a way to improve the efficiency of these kind of circuits even further.

1.4 Thesis Objectives

The thesis objectives are divided into two parts, as highlighted below:

Learning Objectives are to:

- understanding various types of radio frequency power amplifiers.

- study Class-F_3 RF power amplifier and understand its working.

Research Objectives are:

- to explore the idea of Class-F RFPA and compare it with Class-C RFPA to see the changes in the waveforms.

- to design a Class-F_3 RF power amplifier.

- to simulate this design of Class-F_3 RF power amplifier and present the characteristic waveforms.

- to design a Class-F_3 RFPA in which the MOSFET is working in the linear region.

- to simulate the above design and present its resultant waveforms.

- to present the results of this amplifier at higher frequencies and lower frequencies to see the change in the output.

1.5 Thesis Outline

This thesis is written in the following order:

Chapter 2: In this chapter, the different classes of amplifiers are discussed. It helps understand the evolution of amplifiers from Class-A to Class-F RFPA. We also understand how important are harmonics and how they are used in Class-F RFPA.

Chapter 3: Description of the software used for the thesis, that is, SABER sketch and Cosmoscope is done.

Chapter 4: A design and simulation of Class-C amplifier is performed and the similarity between this and Class-F RFPA is shown.

Chapter 5: Class-F_3 RFPA is designed and is simulated using SABER sketch.The waveforms and the frequency spectrum of the signals is shown and compared. Also conduction angle of the amplifier is varied and the effect of it on the waveforms and spectrum is discussed.

Chapter 6: A drain-to-source capacitance is added to the ideal MOSFET and the effect of varying this capacitance is shown.

Chapter 7: A conceptual design of Class-F RFPA is presented with MOSFET working in the linear region. Simulations of the design are shown and it is seen if the efficiency can be improvised.

Chapter 8: The thesis is concluded with the summary and contribution. Also future work is discussed.

2 Types of Amplifiers

There are certain properties to keep in mind which define an RF power amplifier.

- Output Power

- Gain

- Linearity

- Stability

- DC Supply Voltage

- Efficiency

- Ruggedness

There are different classes of amplifiers. Some of the main ones are described as follows:

2.1 Class-A RF Power Amplifier

Class-A power amplifier are the most basic type of amplifiers. They are highly linear in operation, but they are not very efficient. Theoretically, the Class-A amplifier can become 50% efficient, at maximum. Linear amplification is required, when the envelopes of the modulated signals are not constant, hence it is useful with signals undergoing amplitude modulation. The conduction angle of the transistor is 360°. This means that the transistor conducts for the full cycle of the input signal.The process of the amplification of this type of amplifier is quite linear, hence increasing the dormant current or decreasing the input signal level monotonically decreases intermodulation and harmonics. The efficiency of this type of amplifier is low because of the on-state resistance of the transistor. It can also be low because of the load reactance.
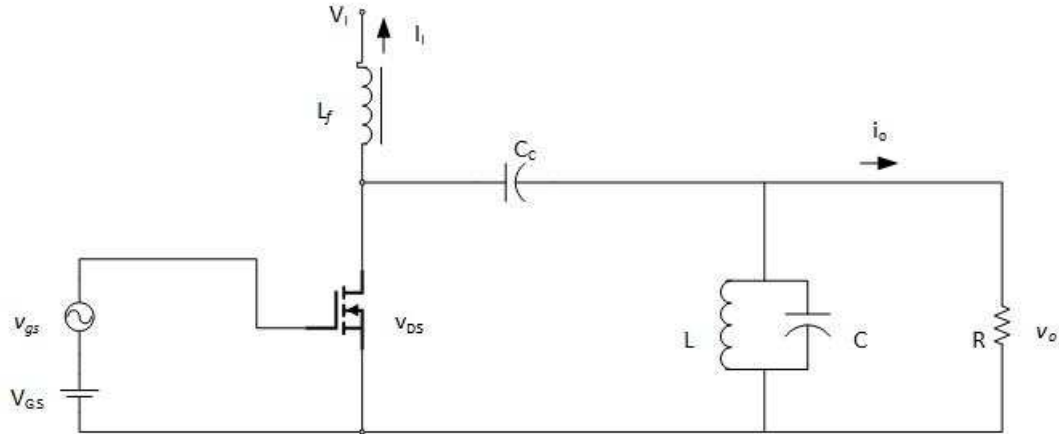
Figure 2.1: Circuit of Class-A RF power amplifier

2.2 Class-B and Class-C RF Power Amplifiers

Class-B power amplifier is the next category of RF power amplifiers. Theoretically, the maximum efficiency it can have is about 78.12%. The conduction angle, 2θ is 180°. This means that the transistor is conducting half cycle of the input signal. This half cycle can be either positive or negative. The Class-B amplifier produces quite a bit of harmonic distortion as well. The power gain of a Class-B amplifier is around 6dB.

The most commonly used configuration is the push-pull. This type of configuration helps manage the harmonic distortions introduced in the system. It also helps in high power amplification circuitry. So with this, the even harmonics are canceled, but the odd harmonics are added. Because of this only, the fundamental is seen on the output side.

Class-C power amplifiers are similar to the Class-B amplifiers, the current waveform is more rectified as compared to Class-B RFPA. The conduction angle 2θ is less than 180°. It is the least linear amplifier. Its efficiency can be any where between 78.5% to 85%. This makes it quite similar to a Class-B amplifier, but it has a lower threshold to input. This introduces large negative swing in the input voltage signal. This

leads the transistor to its worst operating condition. The power gain is less than 6 dB. Another thing to be noted is, we need a higher input drive level to produce a comparatively lower output power level.

2.3 Class-D and Class-E RF Power Amplifiers

Class-D power amplifiers are basically switching type of amplifiers. It produces half-sinusoidal current waveform and a square voltage waveform. Its is configured to use two or more transistors. The figure presented represents the circuit with two transistors being used.

This type of amplifier suffers from certain problems, especially at higher frequencies. The first problem is the availability of a suitable device for switching type operation is limited. Also, since it is a switching type of operation, device parasitic can cause a large amount of losses. The higher the frequency, the greater the loss. Amplifiers of such kind can reach 100% efficiency, theoretically.
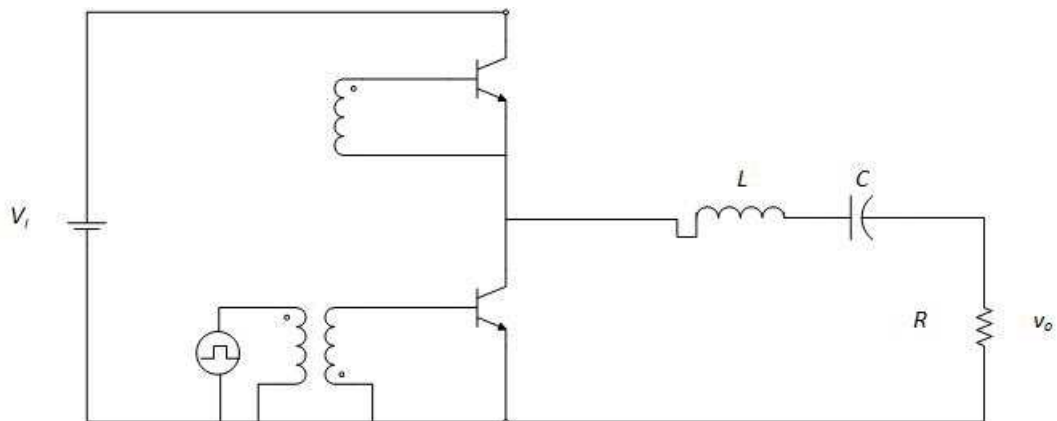

Figure 2.2: Circuit of Class-D RF power amplifier

In a Class-E amplifier, a single transistor is working as a switch. So this makes the Class-E amplifier a switch mode operated amplifier. The drain voltage is formed as a result of the sum of DC and RF currents charging the drain shunt capacitance, which is in parallel to transistors internal capacitance[6].

It can also be 100% efficient, theoretically, since there is no period, where the voltage and current signal overlap. It has lesser losses as compared to a Class-D amplifier due to lower parasitic capacitance and lower switching losses. Ideally, the transistor works as a perfect switch. The filter in the circuit helps remove the harmonics.

2.4 Class-F Power Amplifier

The Class-F amplifier are different from all the above described amplifiers[4]. The operation of a Class-F amplifier is based on the harmonics produced in the circuit. In fact, we try to produce more harmonics in the circuit, by using different components tuned to certain frequencies. The Class-F amplifier will be further discussed in the upcoming chapters.
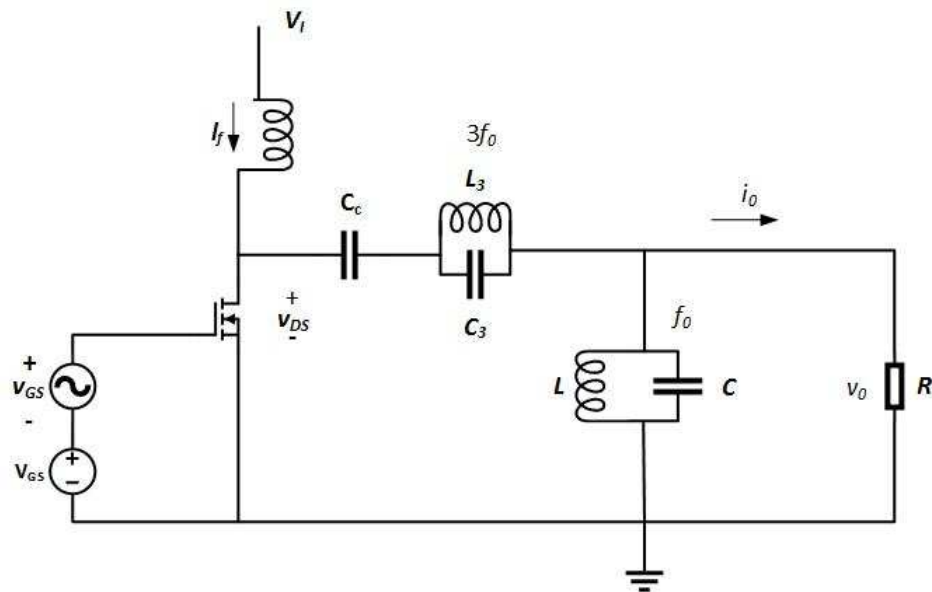

Figure 2.3: Circuit of Class-F_3 RF power amplifier

2.4.1 Introduction of Harmonics

Class-F RF power amplifiers use multiple-harmonic resonators. Basically, these are parallel or series based RLC circuits that are tuned to perform at certain frequencies.

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These frequencies are harmonic multiples of the circuit. The Class-F amplifier circuit that we design contains these elements. The resistance placed in here is working as a compensating resistor.

The Class-F amplifier can also use dielectric resonators instead of the RLC lumped circuit[19]. These are resonating circuit designed usually with ceramic puck.

2.4.2   What Effects Do Odd And Even Harmonics Make?

Class-F amplifiers can use both odd and even harmonics based upon what kind of resonators are placed in the circuit. Both kinds work in different ways.

In the odd harmonic based Class-F amplifiers, drain-to-source voltage contains only odd harmonics and the drain current has only even harmonics [10]. So, the input impedance of the load network represents open circuits at odd harmonics and short circuit at even harmonics. The voltage is symmetrical for the lower and upper halves of the cycle for this kind of amplifiers.

The even harmonic based Class-F amplifiers have drain-to-source voltage that contains only even harmonics. This makes the drain current to be comprised of odd harmonics. The drain-to-source voltage is not symmetrical in these kinds of amplifiers.

This has been a reason why industry prefers using a Class-F amplifier configured with odd harmonics rather than even harmonics, as it can help reduce power dissipation on the output. Also it is easier to handle symmetric voltage and switching of voltage level is easily handled, as compared to currents of the amplifier.

3   SABER Sketch

SABER sketch is a design creation, editing and simulation environment which helps in creation of schematics quickly. We can comprise our circuits with analog, digital and mixed-technology elements. It is used to produce the waveforms for the circuit schematics designed.

3.1   Cosmoscope and Signal Spectrum

With the help of Fourier transform any waveform can be presented as a sum of number of sinusoids, each with certain phase and amplitude. These are referred as signal spectrums. They are useful as sometimes they can provide certain aspects of a signal that are not revealed with time-domain representation. SABER circuit simulator is a program where we are able to simulate a circuit and produce waveform results for it. But along with it, we can also do Fourier transform on signals with this simulator and produce spectrum for all signals. It helps understand the waveform results better as you get to know what all frequencies are present in each signal.

Similar to waveform production, SABER uses Cosmoscope for production of spectrum. First we need to do a transient analysis of the circuit. Once that is done, then SABER uses those transient analysis plotfiles to do Fourier transform. We have to provide the fundamental frequency and how many harmonics we want to see in the final plots. Once the SABER has analyzed these, it produces spectrum files. In the thesis, we have used these plots to understand the harmonics and how they are helping in the result formation.

4 Class-C RF Power Amplifier

Class-C amplifier is considered an amplifier, which has high linearity. This means the output is very similar to the input. The circuit of Class-C RFPA has a transistor, RF choke, a blocking capacitor and a loading network. The conduction angle used for these amplifiers is less than 180°. The equivalent circuit and the predicted waveforms are presented below

The circuit parameters include ac component of the gate-to-source voltage which is 1.4 V. The DC component of the same is 1.5 V. The design is suppose to deliver 10 W. The operating frequency is 1 GHz and the bandwidth of the circuit designed is 100 MHz. The conduction angle is 110°. The circuit schematic is shown in figure 4.1.
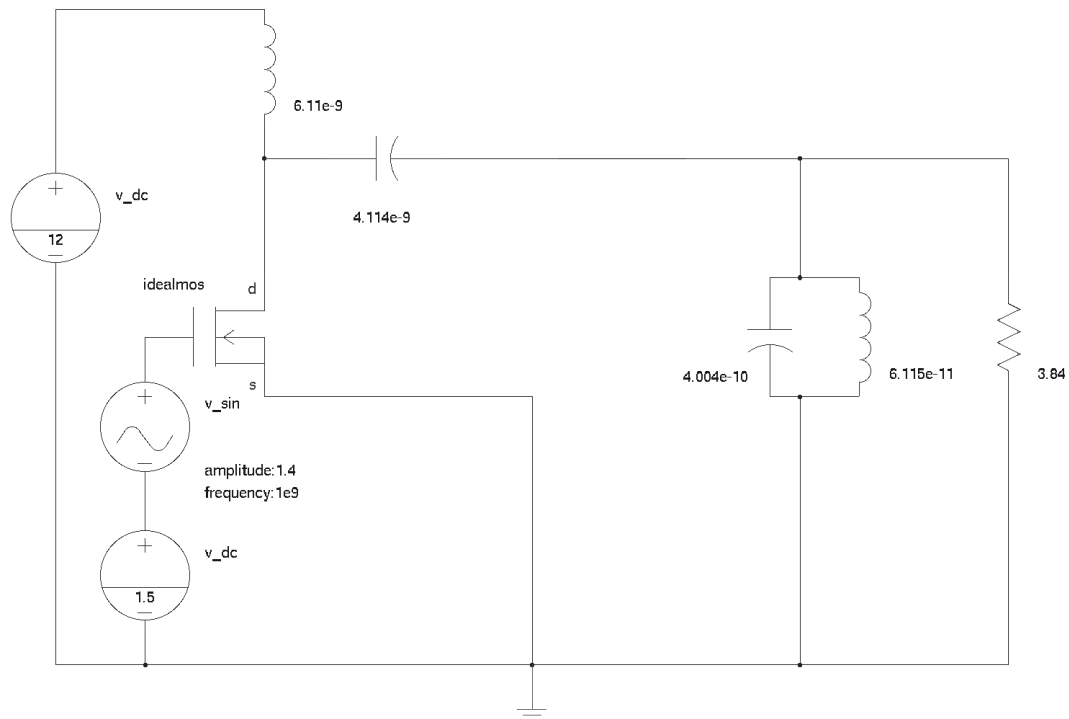

Figure 4.1: Circuit Schematic of Class-C RF power amplifier

4.1 Waveforms

In figure 4.2, we present the drain-to-source voltage and drain current of the Class-C amplifier. The amplitude of the drain current is 4.21 A. The maximum amplitude of the drain-to-source voltage found from simulation is 11.06 V. The theoretical values calculated for the design were similar to the values obtained in simulation.
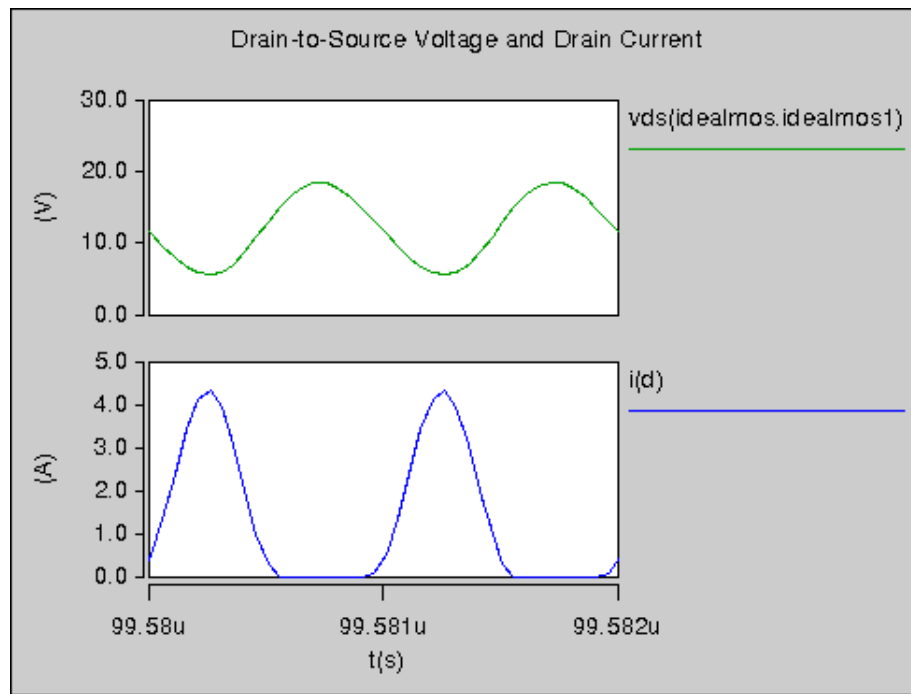

Figure 4.2: Waveform of drain-to-source voltage and drain current of Class-C RFPA

The above case is when we simulate the design in normal conditions.If we increase the drain-to-source voltage we can see certain changes happening to the waveforms. This is achieved by changing the gate-to-source voltage. These are also presented. In figure 4.3, the circuit is still in resonance, but the gate-to-source voltage has been changed which increases the drain-to-source voltage and this leads to a dip in drain

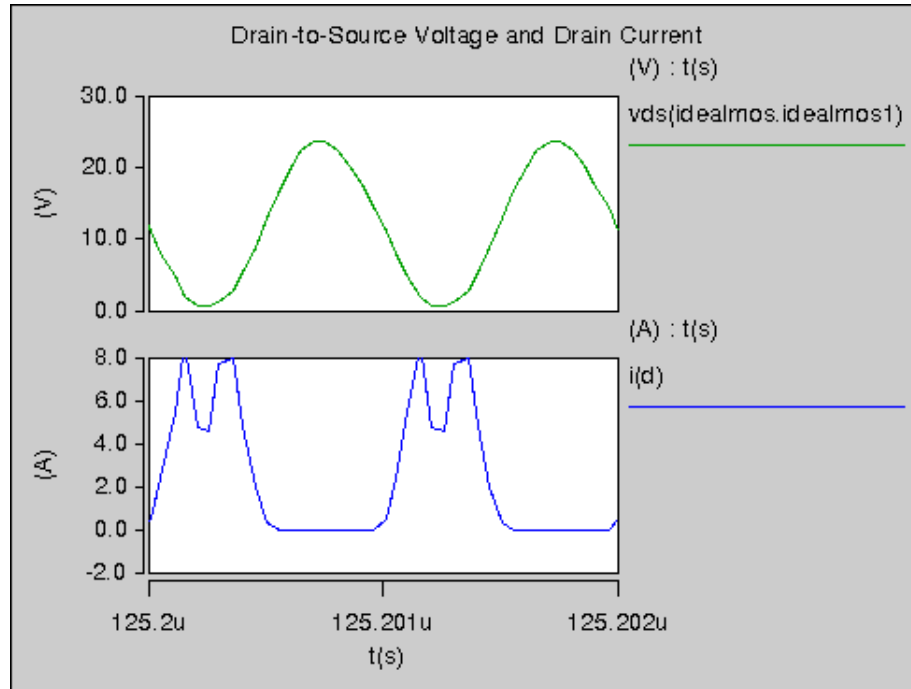current, instead of a smooth wave. This also changes the power obtained and the efficiency of the system.

Figure 4.3: Waveform of drain-to-source voltage and drain current of Class-C RFPA with high gate-to-source voltage

To explore this theory, certain change in the network capacitance was made to bring the circuit out of resonance at higher drain-to-source voltage. This produces certain changes in the waveforms. In figure 4.4 and figure 4.5, the two cases are presented with the waveforms for the signals. In both cases the capacitance was changed to see the differences.
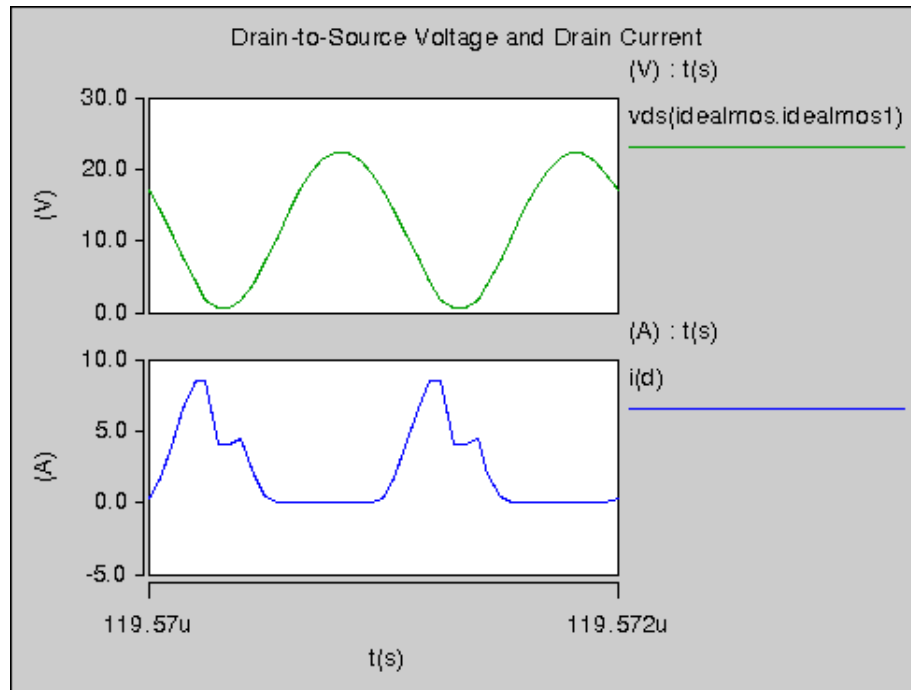
Figure 4.4: Waveform of drain-to-source voltage and drain current of Class-C RFPA with high gate-to-source voltage and increased network capacitance
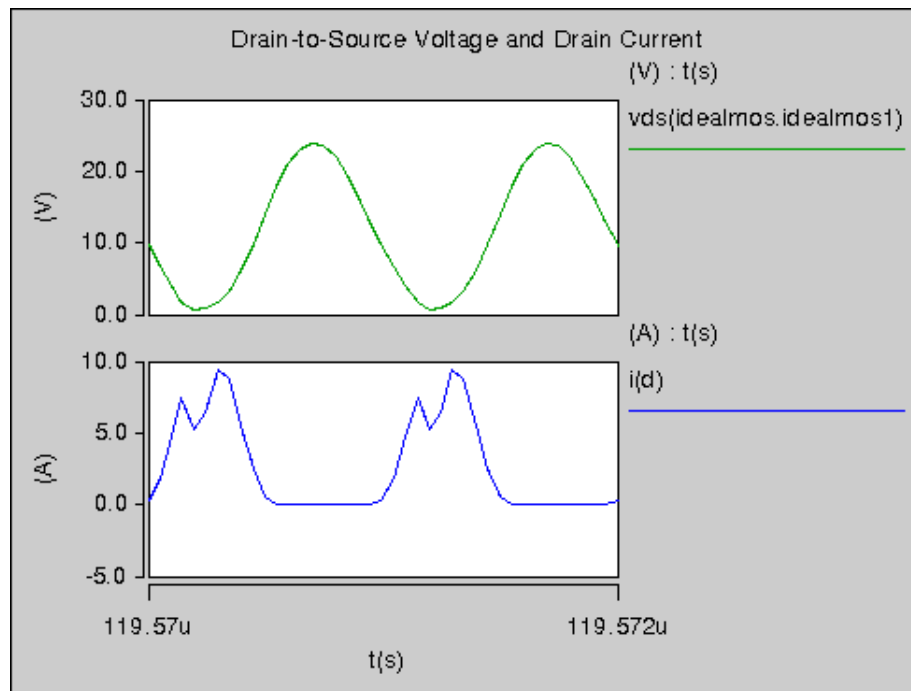

Figure 4.5: Waveform of drain-to-source voltage and drain current of Class-C RFPA with high gate-to-source voltage and decreased network capacitance

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5   Class-F$_3$ RF Power Amplifier

The circuit has been given the name as it uses the third harmonic component of the operating frequency. It is one of the kinds of class-F amplifier. The circuit uses an ideal MOSFET to keep things simple.
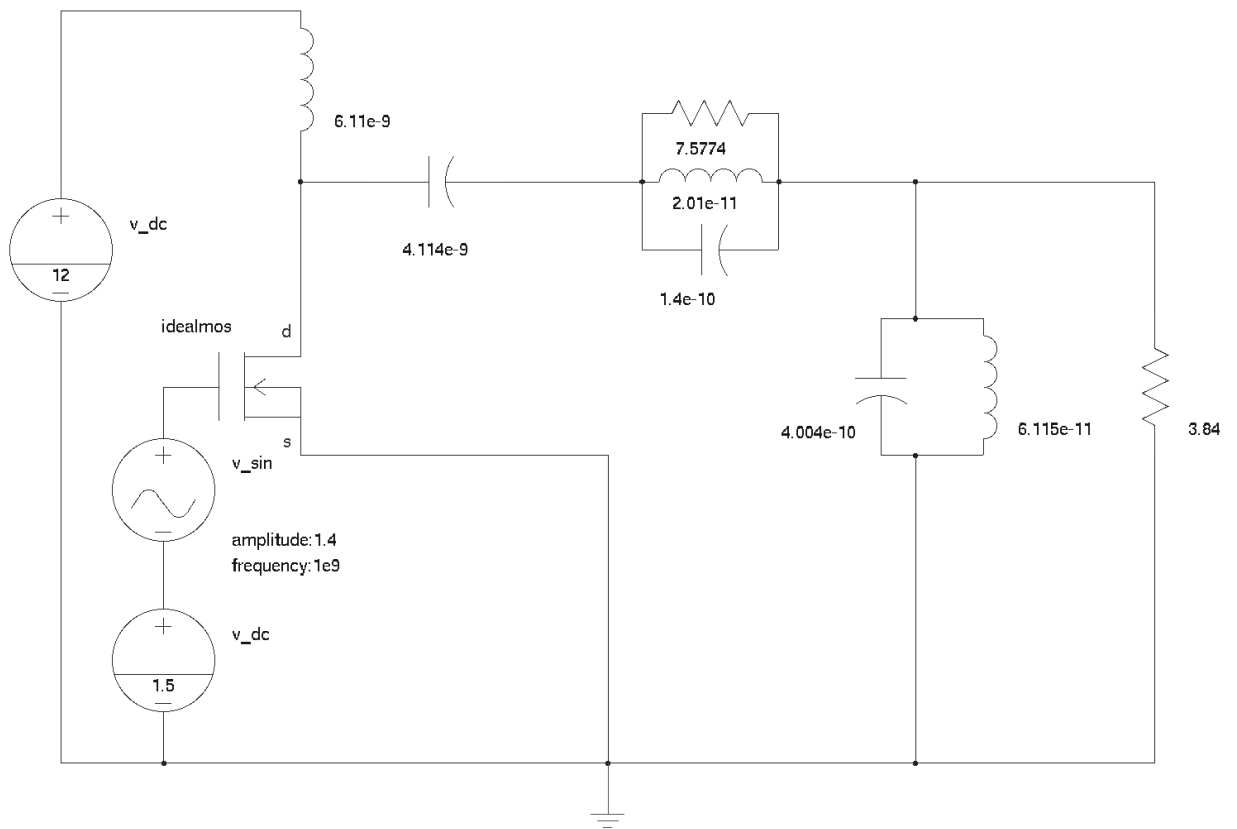

Figure 5.1: Circuit Schematic of Class-F$_3$ RFPA

The amplifier schematic shown in figure 5.1, contains a load network comprising of a parallel-resonant LCR circuit tuned to the operating frequency f_o. Alongside this, there is another parallel-resonant LCR circuit tuned to third harmonic component of the operating frequency. These both are connected in series.

Other components include, a radio frequency choke, a transistor and a coupling capacitor. The coupling capacitor is used to avoid the DC flow towards the load resistance[9].

The gate-to-source voltage of the MOSFET is used to control the output produced towards the output network. Third harmonic resonator helps produce the harmonic which helps shape the waveform of the drain-to-source voltage. The efficiency of the system is more based upon the shape of the waveform obtained. The blocking capacitor helps block the DC current flow to the output network. The technique used here for the design is maximum drain efficiency. Using this we are able to achieve higher drain efficiency. Along with it the power capability of the amplifier is also increased. Class-F amplifier is mainly used in broadcasting systems. The amplifier is implemented in the transmission stations on the ground. The efficiency required from the ground side needs to be high, so it is used here. The systems are working at high frequencies in this part of the system.

The main difference we see between the Class-C and Class-F amplifier is that the Class-C amplifier can reach a max efficiency of 78.4%[10]. But with Class-F RFPA we can achieve higher efficiencies, depending upon the type of RFPA. Theoretically, it is possible to achieve 100% efficiency. But when we move to real life applications we need to handle other problems which come with high efficiency. One of them is high non linearity, which produces a lot of losses and increases complications in the system and circuit design[17].

5.1   Design of Class-F$_3$ RFPA

The design used here is designed to deliver 16 W at switching frequency, $f_c = 1$ GHz[10]. The bandwidth for the system is 100 MHz and power supply is 12 V. The MOSFET used is ideal with threshold voltage $V_t = 1$ V and dc component of gate-

to-source voltage, $V_{GS} = 1.5$ V. Also, conduction angle $\theta = 110°$.

$$V_{gsm} = \frac{(V_t - V_{GS})}{\cos\theta} = \frac{1 - 1.5}{\cos 110°} = 1.462 \text{ V} \tag{5.1}$$

The max drain-to-source voltage calculated is 1.962 V. The maximum amplitude of the fundamental component of the drain-to-source voltage is 10.8 V, from equation 5.2. Also the amplitude of the third harmonic is 1.2 V.

$$V_m = \frac{2}{\sqrt{3}}(V_I - v_{DSmin}) = \frac{2}{\sqrt{3}}(12 - 2.4) = 11.08 \text{ V} \tag{5.2}$$

$$V_{m3} = \frac{V_m}{6} = 1.28 \text{ V} \tag{5.3}$$

The maximum drain current is 3.484 A and the DC supply current is 1.3189 A as shown in equations 5.4 and 5.5, respectively.

$$I_{DM} = \frac{I_M}{\alpha_1} = \frac{1.85}{0.5316} = 3.484 \text{ A} \tag{5.4}$$

$$I_I = \frac{I_M}{\gamma_1} = \frac{1.85}{1.404} = 1.3189 \text{ A} \tag{5.5}$$

The drain efficiency obtained is 61%, which is close to the calculated value, that is 63.2%. The system efficiency came out to be 43.7%

The values for the components calculated are shown in the figure. The waveform obtained from the simulation are shown.

5.2 Waveforms and Frequency Spectrum

In the figure 5.2, the waveforms presented are of the drain-to-source voltage and the drain current of the MOSFET.

The amplitude of the drain-to-source voltage is 15.42 V. Also the maximum drain-to-source voltage theoretically is 21.6 V and from the simulation, we found it to be
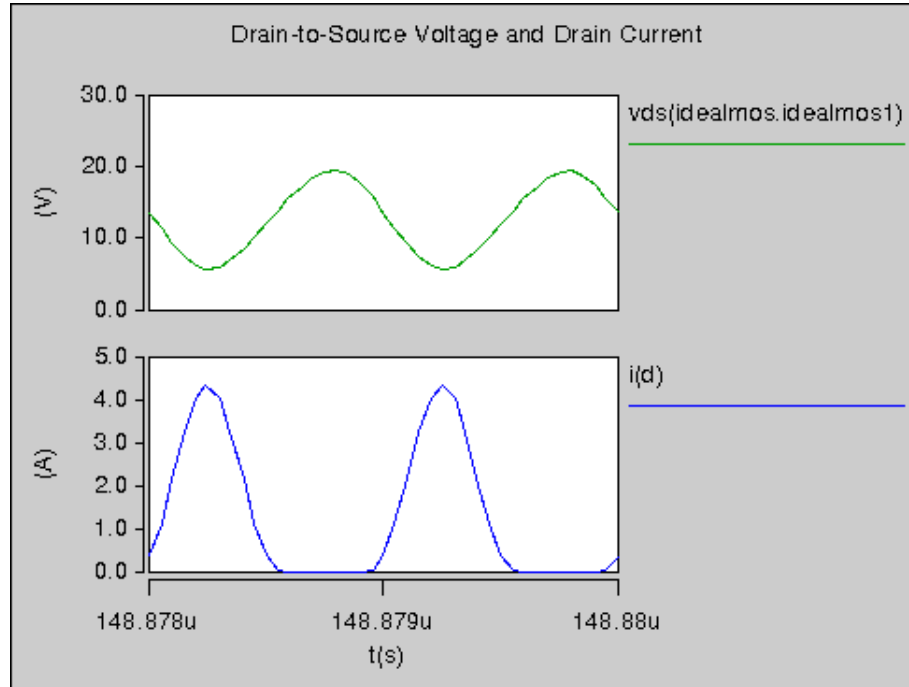
20.58 V.

Figure 5.2: Waveforms of drain-to-source voltage and drain current of the MOSFET

The waveforms in figure 5.3, present the voltages across different resistances. These include the fundamental voltage component and the third harmonic voltage component. Theoretically, the maximum fundamental voltage is 11.08 V. The amplitude of voltage across fundamental resistor is 12.32 V. In figure 5.4, the frequency spectrum of drain-to-source voltage and drain current of the MOSFET is shown. We can see the presence of the third harmonic component in the drain-to-source voltage signal. Also the current signal has prominent harmonics in it.
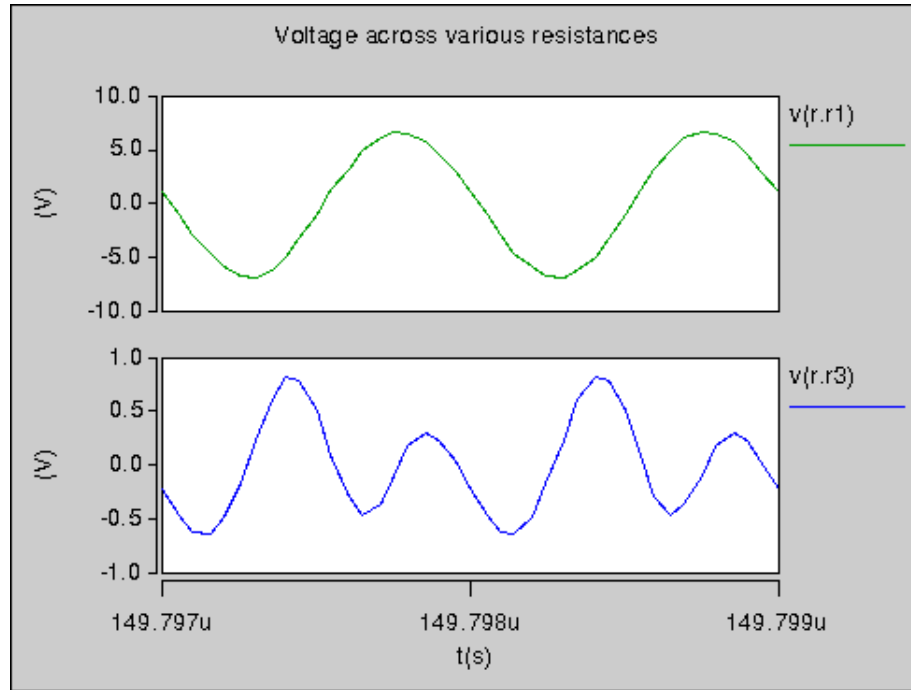
Figure 5.3: Waveforms of voltages across various resistances in Class-F_3 RFPA

5.3 Variations of Class-F_3 RFPA by changing the Drain-to-Source Voltage

Their are certain changes which are observed as we try to vary the drain-to-source voltage. This variation is done by tweaking with gate-to-source voltage. These variations are presented below.
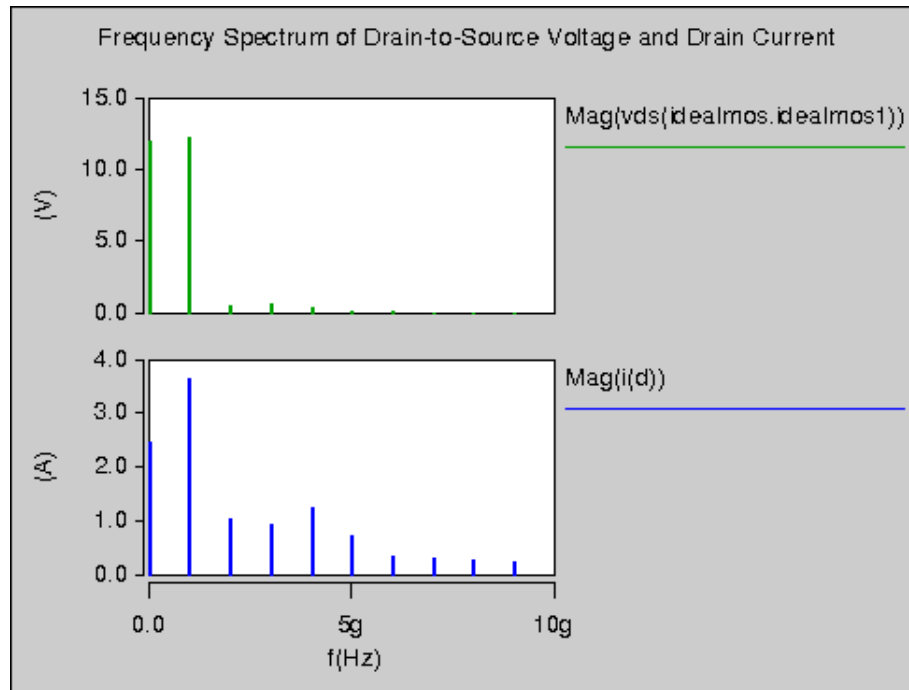
Figure 5.4: Frequency spectrum of drain-to-source voltage drain current of the MOS-FET

In the first case, we decrease the ac component of gate-to-source voltage. We pick it to be 0.7 V. The waveforms and spectrum are presented in figure 5.5, figure 5.6 and figure 5.7.

Here we can see, in the spectrum presented, the lack of presence of harmonics in the drain current along with the drain-to-source voltage of the MOSFET. This is also reflected by the signal waveforms.
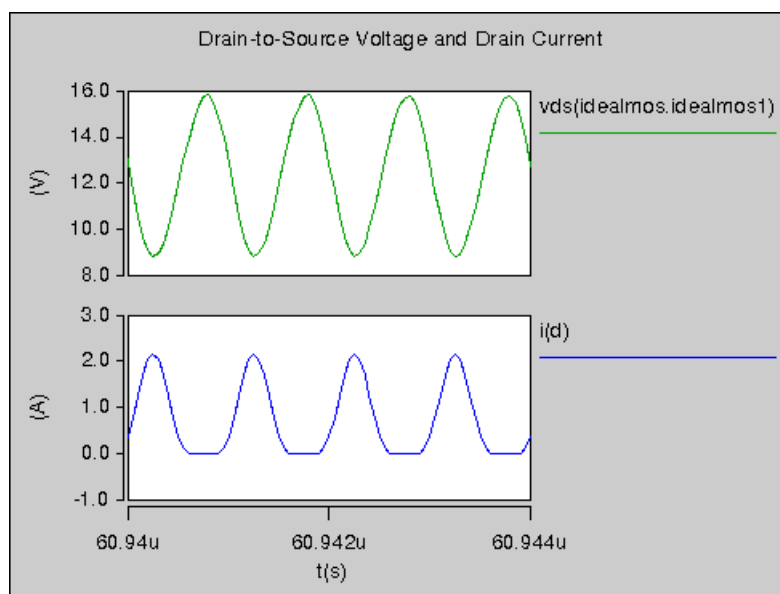
Figure 5.5: Waveforms of drain-to-source voltage and drain current of the MOSFET where AC component of gate-to-source voltage is 0.7 V

In the next case, we increase this component of gate-to-source voltage to 2.5 V. The drain-to-source voltage increases rapidly, and starts distorting the drain current as seen from figure 5.12.
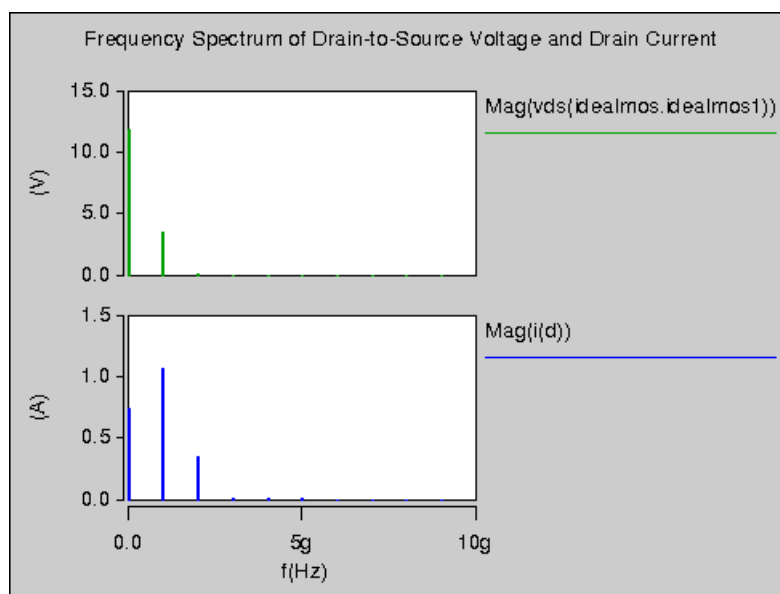
Figure 5.6: Frequency spectrum of drain-to-source voltage and drain current of the MOSFET where AC component of gate-to-source voltage is 0.7 V

Now we present the case where we show the difference when in waveforms when we either increase or decrease the DC component of gate-to-source voltage.
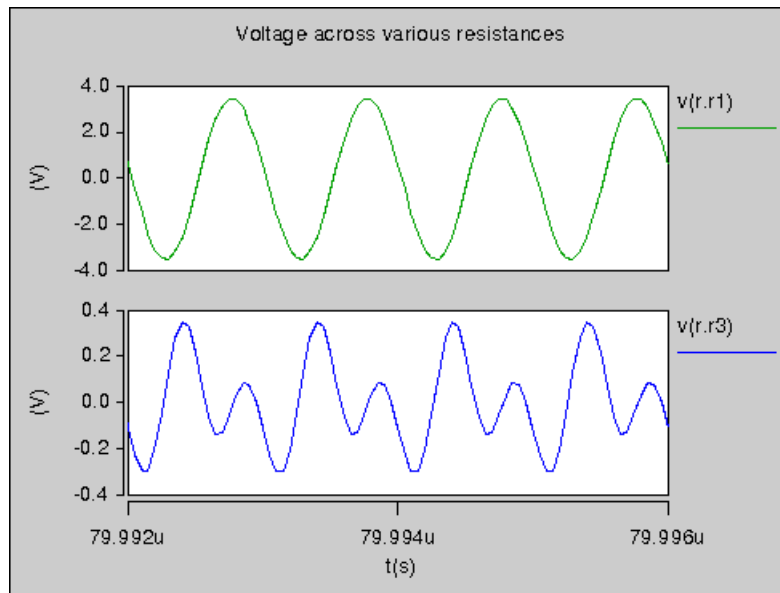
Figure 5.7: Waveforms of voltage across various resistances of Class-F_3 RFPA where AC component of gate-to-source voltage is 0.7 V
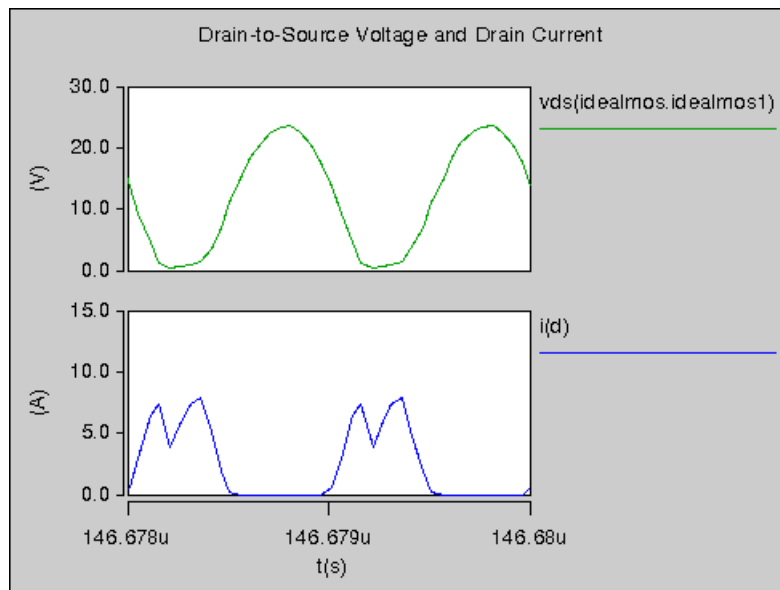

Figure 5.8: Waveforms of drain-to-source voltage and drain current of the MOSFET where AC component of gate-to-source voltage is 2.5 V
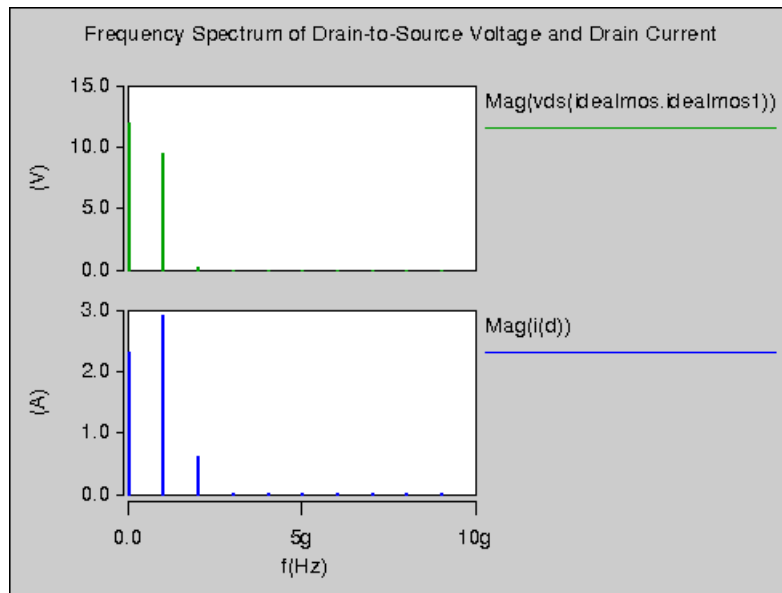
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Figure 5.9: Frequency spectrum of drain-to-source voltage and drain current of the MOSFET where AC component of gate-to-source voltage is 2.5 V

Figure 5.10: Waveforms of voltage across various resistances of Class-F_3 RFPA where AC component of gate-to-source voltage is 2.5 V

Figure 5.11: Waveforms of drain-to-source voltage and drain current of the MOSFET where DC component of gate-to-source voltage is 1 V

Figure 5.12: Frequency spectrum of drain-to-source voltage and drain current of the MOSFET where DC component of gate-to-source voltage is 1 V
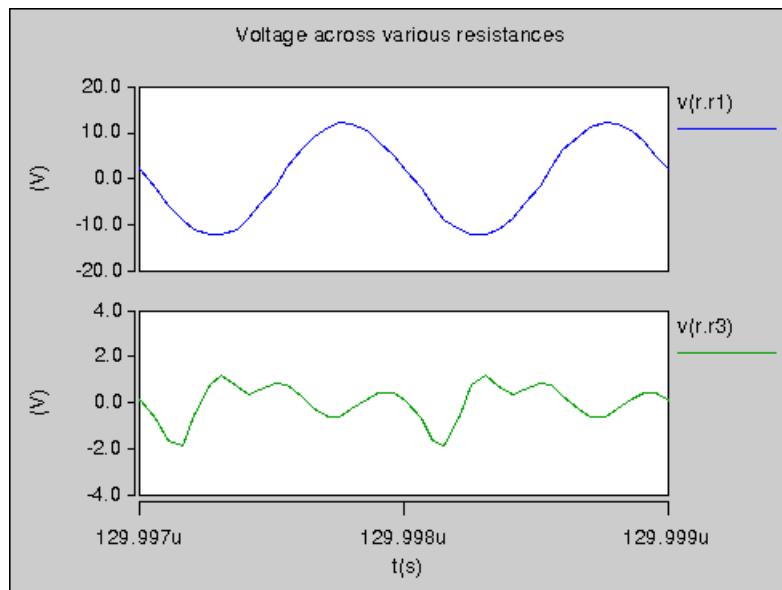
Figure 5.13: Waveforms of voltage across various resistances of Class-F$_3$ RFPA where DC component of gate-to-source voltage is 1 V
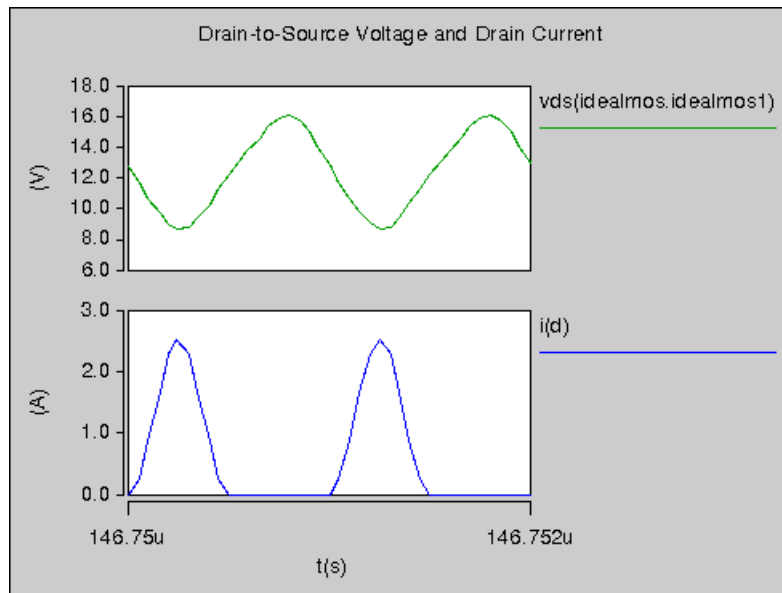

Figure 5.14: Waveforms of drain-to-source voltage and drain current of the MOSFET where DC component of gate-to-source voltage is 2.5 V
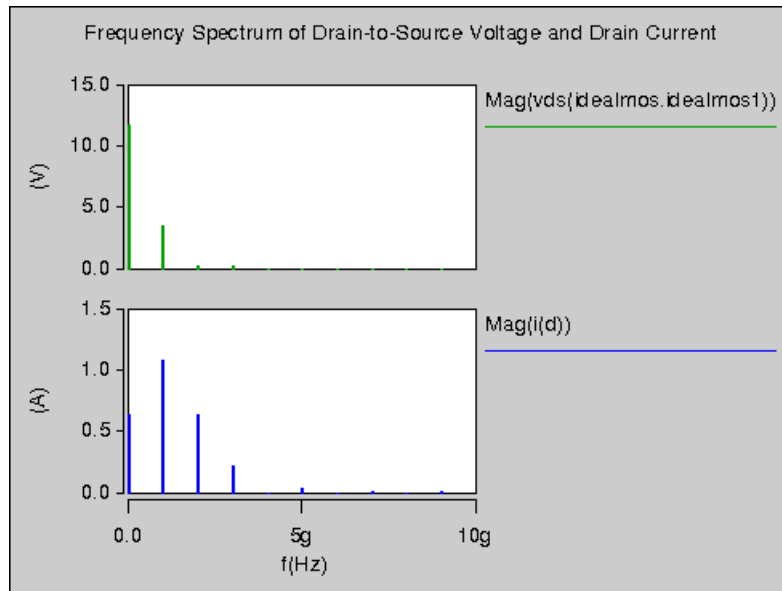
Figure 5.15: Frequency spectrum of drain-to-source voltage and drain current of the MOSFET where DC component of gate-to-source voltage is 2.5 V
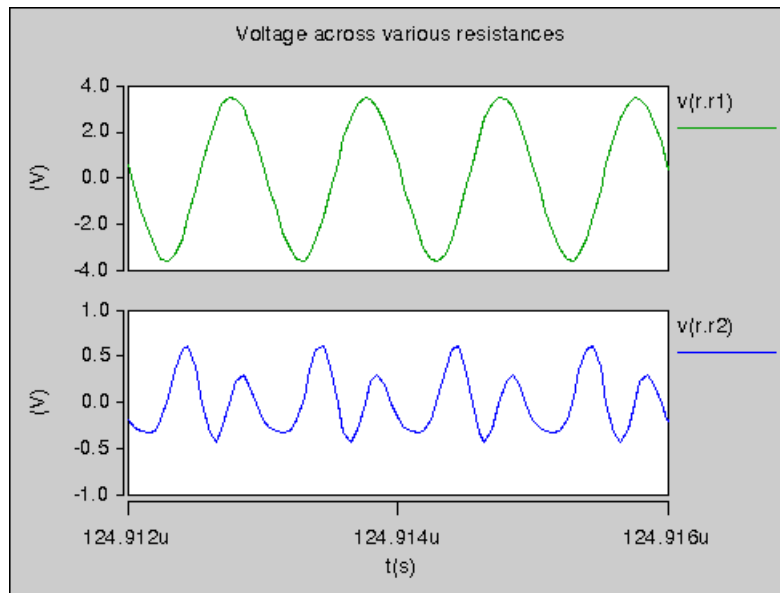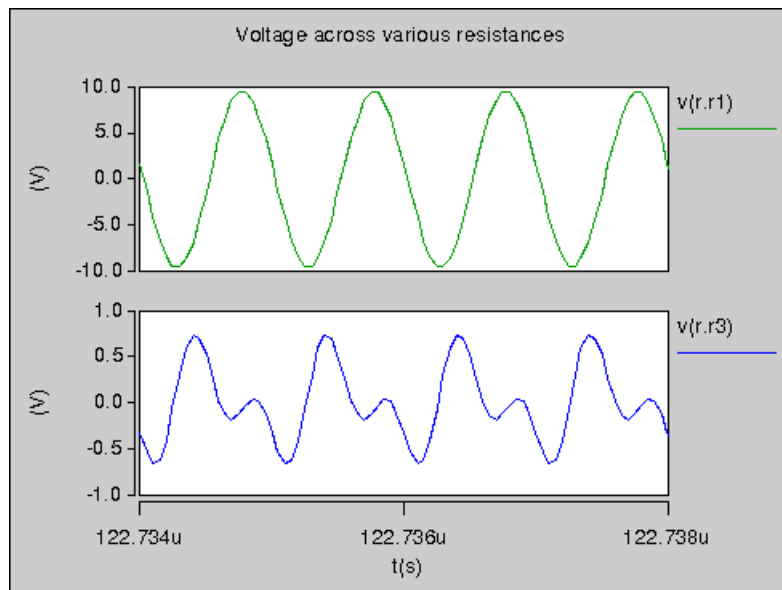

Figure 5.16: Waveforms of voltage across various resistances of Class-F$_3$ RFPA where DC component of gate-to-source voltage is 2.5 V
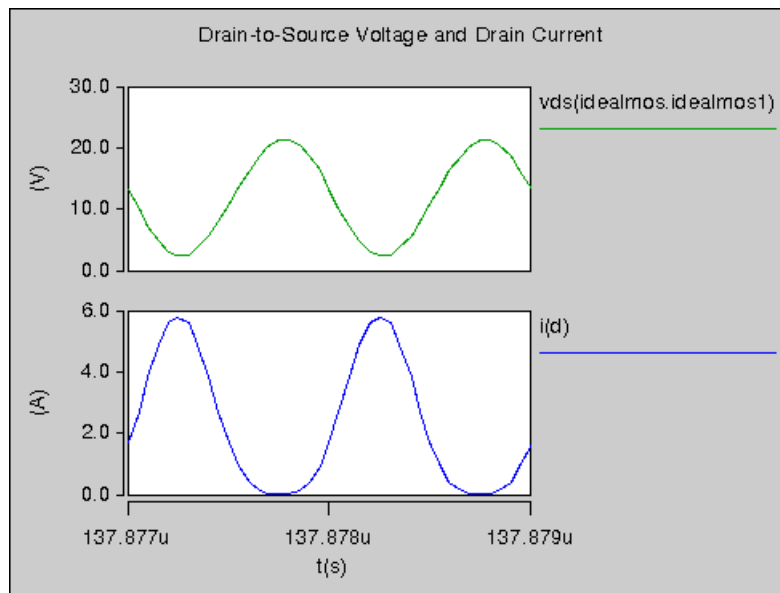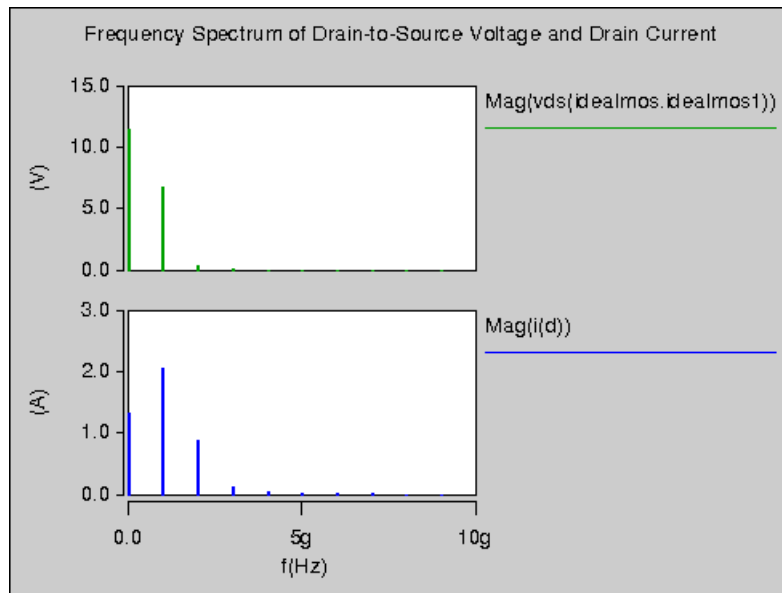
6   Class-F₃ RFPA Including Drain-to-Source Capacitance of the MOSFET

The previous design was based on an ideal MOSFET. That means it has no parasitic capacitance to it. But in practical designs, the MOSFET's used have certain capacitance in them. These are between drain-to-source, drain-to-gate or gate-to-source of the MOSFET.

So for this part we have added a 10 pF capacitor between the drain pin and the source pin of the MOSFET. This added to see if it brings any effects to the waveforms. With each iteration, we increase this capacitance by 10 pF. The schematic is presented in figure 6.1.
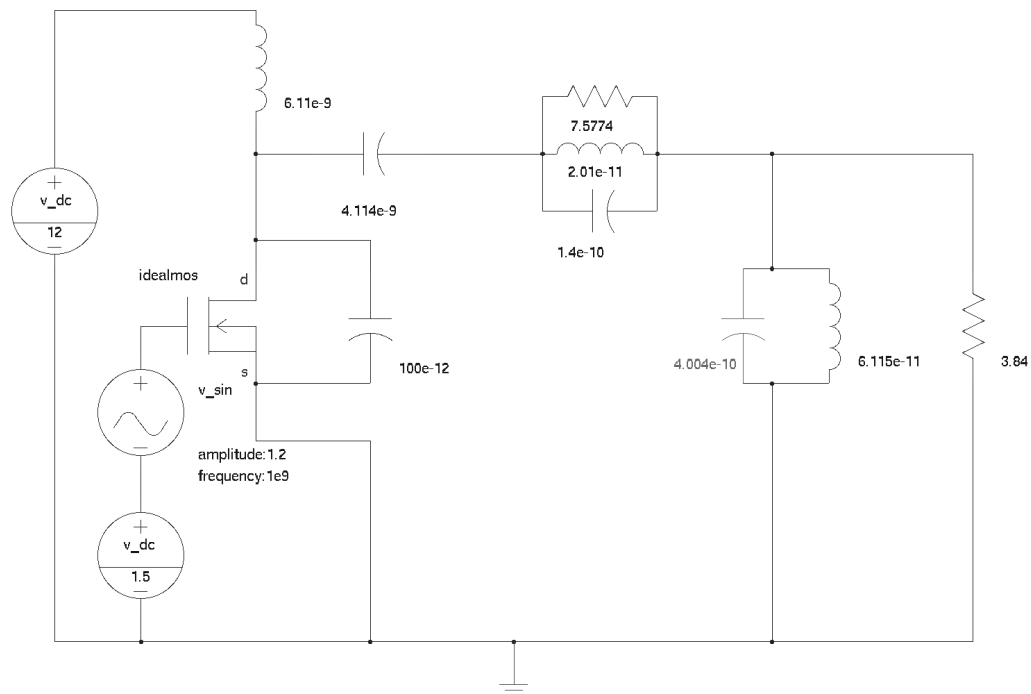
Figure 6.1: Circuit schematic of Class-F₃ RFPA with drain-to-source capacitance

6.1   Waveforms and Frequency Spectrum

On adding this 10 pF to the MOSFET, not much change is seen. The circuit acts normally as the previous case. It does so till we reach 70 pF. At this point, we start seeing changes in the waveforms, slowly and gradually, we see the harmonics in the drain current decreasing in magnitude. As we increase this capacitance further, we see that the waveforms start getting distorted. This can be observed from the frequency spectrum in figure 6.3.
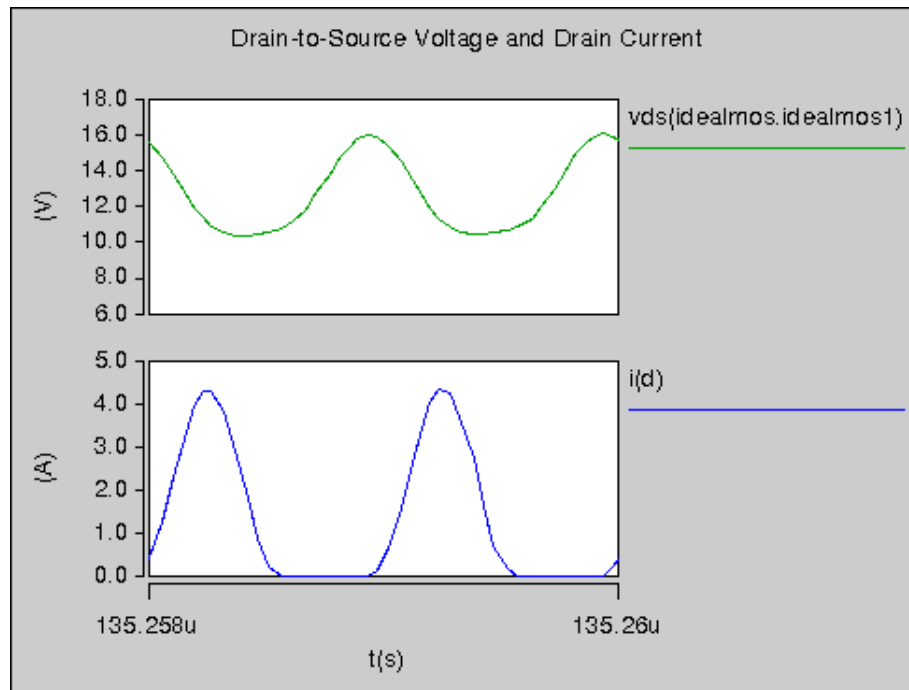
Figure 6.2: Waveforms of drain-to-source voltage and drain current of Class-F$_3$ RFPA with 100 pF drain-to-source capacitance

The waveforms of drain-to-source voltage and drain current are presented in figure 6.2. Also the voltage across third harmonic resistance and load resistance is presented in figure 6.4. We can see that the voltage across third harmonic resistance

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is not having any third harmonic instead the signal had more of second harmonic component in it. This translates towards the drain-to-source voltage which also gets distorted The transistor will stop working if we keep increasing this.

Figure 6.3: Frequency spectrum of drain-to-source voltage and drain current of Class-F_3 RFPA with 100 pF drain-to-source capacitance
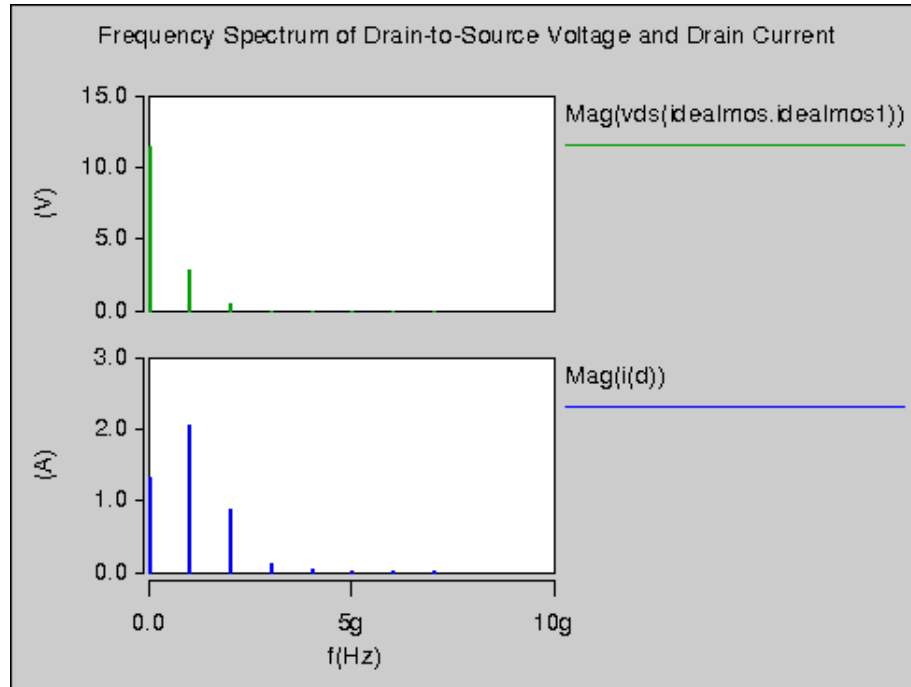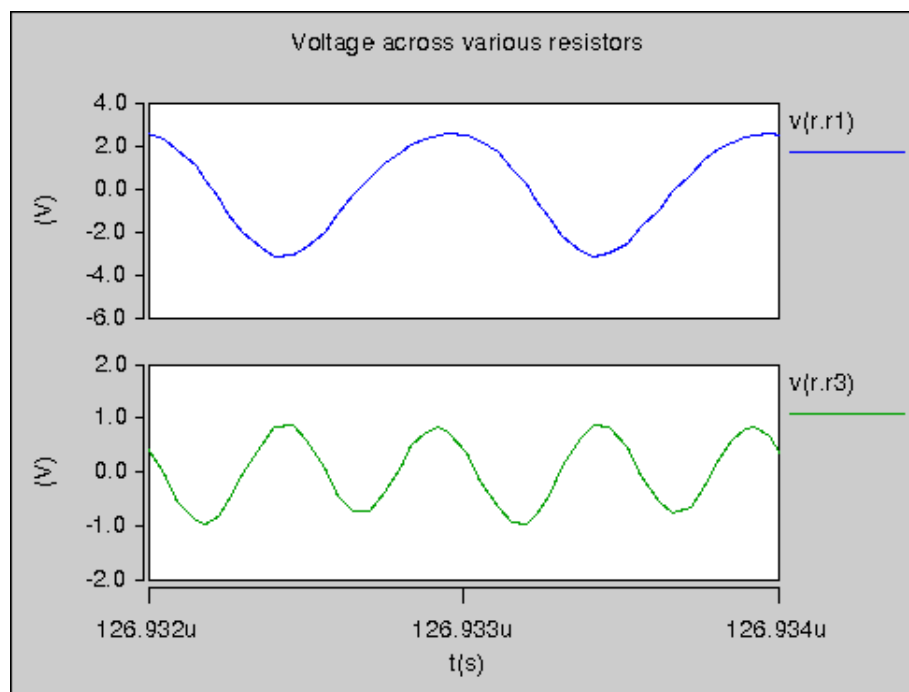
Figure 6.4: Waveforms of voltage across loading network resistances in Class-F$_3$ RFPA with 100 pF drain-to-source capacitance

7 Class-F$_3$ RFPA With MOSFET Working In Linear Region

The Class-F amplifier, generally uses a MOSFET working in saturation mode. This means that the minimum drain-to-source voltage of the MOSFET is greater than the saturation drain-to-source voltage. This principle is kept in mind, when designing a Class-F amplifier. To see how, this principle is important to the operation of a Class-F amplifier, a design is made where, the drain-to-source voltage can go less than the saturation region. This leads to a design with MOSFET working in the linear region. This is done to explore the possibility of increasing the efficiency of the amplifier.

7.1 Design Components

The output power desired from the circuit is 10 W. The dc component of the gate-to-source voltage is 1.5 V. The minimum drain-to-source voltage is 1.6 V. The design of passive components is based on these values of voltages and currents. The schematic used for simulation is shown in figure 7.1.

7.2 Waveforms and Frequency Spectrum

The amplifier designed works in a way where, the MOSFET keeps switching between the linear region and saturation region as the drain-to-source voltage changes. This can be seen in the waveforms as well. As the gate-to-source voltage is increased, the shape of drain current starts to distort even further. This happens as the drain-to-source voltage starts going to zero. The power levels in the output are really low. The shape of the power wave is also not usable. This can be seen in figure 7.2

The spectrum of the drain-to-source voltage and drain current is also shown in figure 7.3. The drain current has a lot of harmonics. Also the drain-to-source voltage shows increase in the third harmonic component, as the drain current shape distorts.
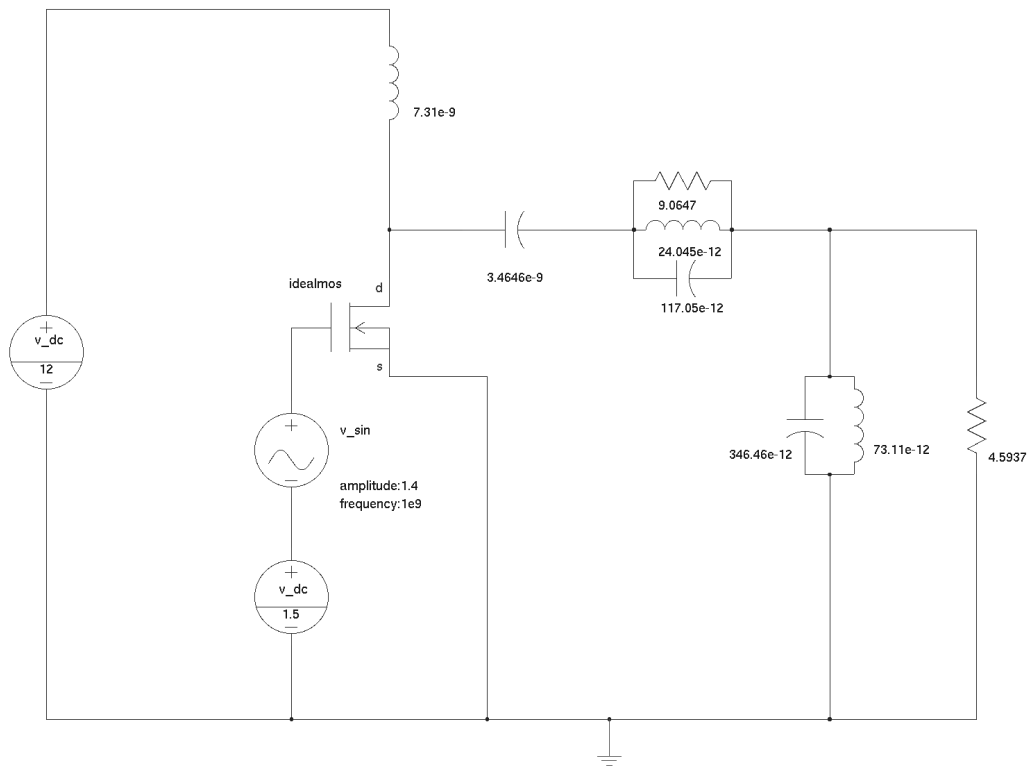
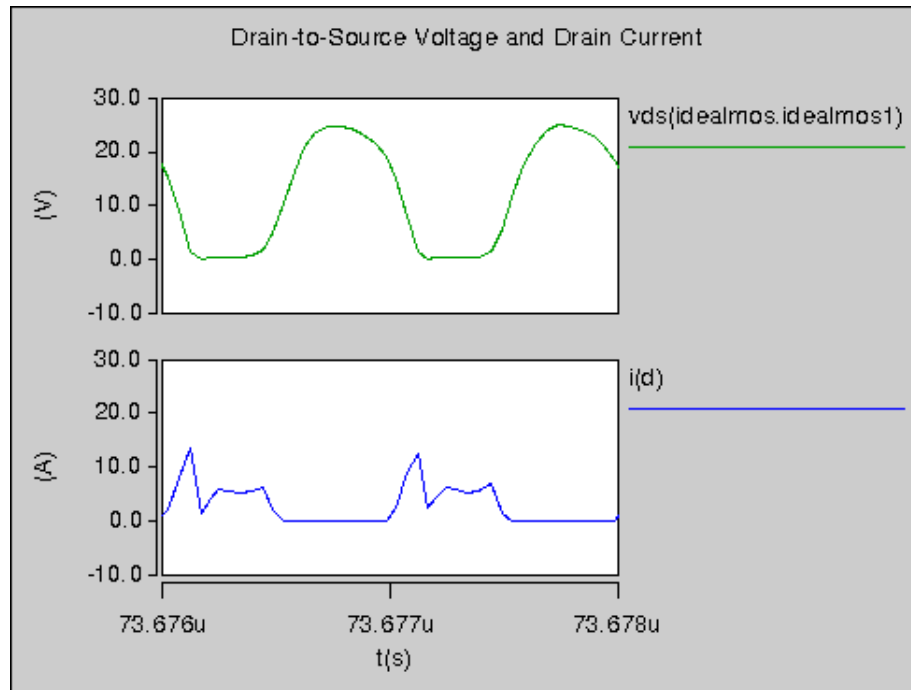Figure 7.1: Circuit schematic of Class-F$_3$ RFPA with MOSFET working in linear mode

Figure 7.2: Waveforms of drain-to-source voltage and drain current of Class-F_3 RFPA with MOSFET working in linear mode
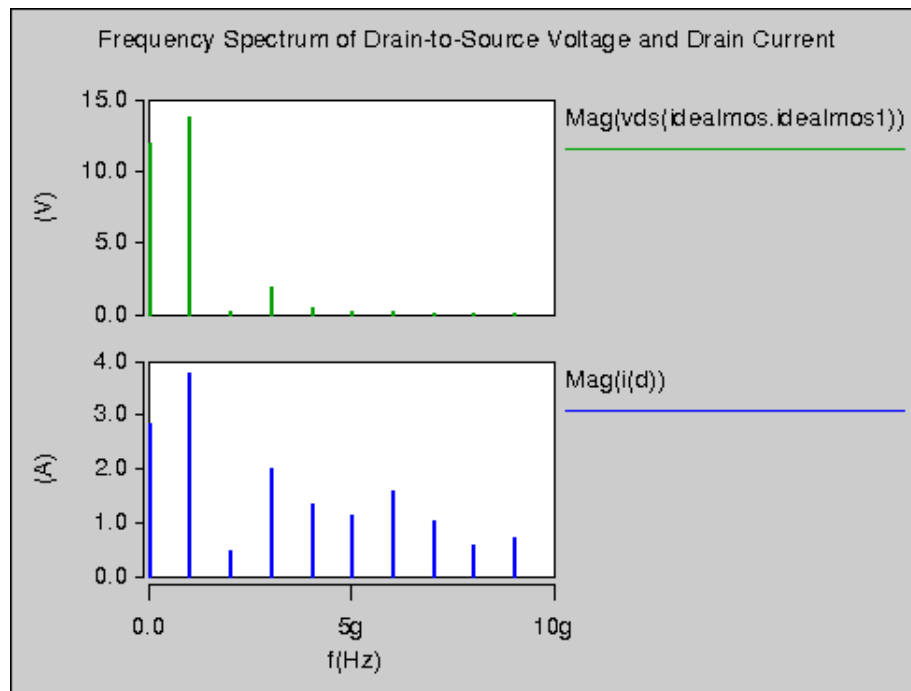

Figure 7.3: Frequency spectrum of drain-to-source voltage and drain current of Class-F_3 RFPA with MOSFET working in linear mode

8 Conclusion

8.1 Summary

- The radio-frequency power amplifiers are discussed, and what are the characteristics of these amplifiers are described.

- The different classes of amplifiers are mentioned and how they are different from each other is presented. Also the characteristics of a MOSFET is discussed as it is a key component of any radio frequency power amplifier circuitry.

- The functioning of generalized Class-F amplifier is explained including the effects of various types of harmonics on these amplifiers and how they can make a difference in the performance of these amplifiers.

- We have discussed about Class-C RFPA and how it can transform to a Class-F RFPA.

- The Class-F_3 amplifier is discussed including its working using a design. The simulations and fourier transform are performed for that particular design and the resulting wave forms and spectrum are presented.

- A design incorporating a 100 pF drain-to-source capacitor to the MOSFET is presented and the effects of increasing this capacitance are described.

- A conceptual design has been presented for Class-F_3 amplifier, where the MOSFET is operating in linear mode. Finally, a simulation has been performed on this design and the results have been presented.

8.2 Contribution

The Class-F amplifiers have been essential in the industry, simply because because of the high efficiency that is obtained, maintaining a good linearity in the output.

In chapter 3, a Class-F$_3$ amplifier is designed. These simulations have helped understand the working of this system. Also fourier transform is performed and the signal spectrum is presented for the design for better understanding the working of harmonics in drain current and drain-to-source voltage.

We have also tried to understand the effect of changing the conduction angle of the circuit and how it affects the signal spectrum. The introduction of capacitance in the MOSFET and recording the changes to the waveforms.

Also we have introduced a design of Class-F$_3$ RFPA where the MOSFET is working in the linear region. This was performed to see if the efficiency could be improvised in this or not. We have seen from our results that is not true, the efficiency is not improved.

8.3   Future Work

Using the results we have with these simulations. The concept of MOSFET working in linear mode, in higher order Class-F amplifier, could be explored further. This thesis has helped in understanding the formation of the harmonics in Class-F amplifiers and how their importance. Also It helped understand the role of MOSFET and how it effects the formation of these harmonics and which is the good region to operate it in, to get better efficiency.

Further expanding on the work performed for the conceptual design of the Class-F amplifier at higher harmonics is possible. It could help understand why the MOSFET keeps moving in that region between linear mode and saturation mode. By solving this problem, it might be possible to increase the performance of the amplifier.

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