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Simulation Study of High Frequency Power Amplifiers

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***Abstract*—Impedance Source inverter is a new and attractive topology for the power electronics interface. These inverters uses a unique impedance network, coupled between power source and converter circuit to provide both buck and boost properties which cannot be achieved with conventional VSI and CSI. In this paper, Voltage source and Z source inverter based high frequency power amplifiers are examined. Unipolar PWM technique is employed to control the output voltage magnitude and frequency. Analysis, design and simulation results are presented to demonstrate the buck boost features of z source inverter in high frequency power amplifiers.**

Index Terms—**CSI, VSI, Unipolar PWM, ZSI**

I. INTRODUCTION

High frequency power amplifiers are used in application such as Sonar systems where Power Amplifier (PA) is an integral part of active sonar systems, and amplifies the sonar signal to the levels required by the transducer element. There are two kinds of amplifiers used in sonar transmitter namely linear power amplifiers and switch mode power amplifiers. Linear power amplifiers include Class A, B, C and AB. In linear power amplifiers, most of the power consumption is caused by the linear operation of the power devices, in other words, the devices that handle the output current and voltage at the same time. Switched mode power amplifiers include Class D, E, F, H, S etc. In switching amplifiers, the power devices are working in either 'ON' or 'OFF' states. When the power devices are working in the 'ON' state, the voltages across the devices are low, so the devices' power consumption will be low. On the other hand, when the power devices are working in the 'OFF' state, there will be no current flow through the devices; thus the power consumption will also be low. By modulating the duration of the 'ON' and 'OFF' periods, the output of the switching amplifier (either voltage or current) can be controlled to follow the input reference signal, and thus the circuit can work as a power amplifier, and the expected efficiency will be higher than the linear power amplifiers. After the invention of power MOSFET's and IGBT's most of the power amplifiers are developed using switch mode technology. The switched mode technology basically uses Sine Pulse Width Modulation (SPWM) for modulating the transmission signal into high frequency signal. A typical switch mode power amplifier circuit is given in fig1.Though switched mode technology is advantages in respect of power dissipation and hence the heat dissipation, the same cannot be used for high frequency above 15 kHz. The linear power amplifiers gain upper hand in the higher frequency >15 kHz. In the lower frequencies, properly designed power amplifiers can be compact and energy efficient. The existing power amplifier block diagram is shown in the fig 2. Inverter can be either half bridge or full bridge that uses class D PWM technique.

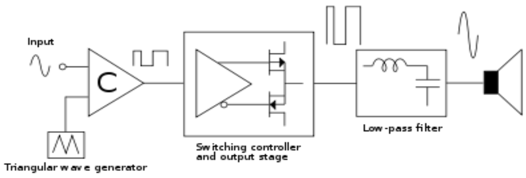

Fig. 1 Block Schematic of switch mode power amplifier

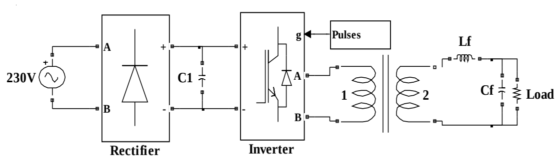

Fig. 2 Block Schematic of Typical Power amplifier

Traditional inverters are voltage-source inverter (VSI) and current-source inverter (CSI). VSI input is dc-voltage source: battery, fuel-cell stack, diode rectifier, and/or capacitor [1, 2]. CSI input is dc current source fed by converter main circuit [1]. The dc current source can be a large dc inductor fed by a voltage source such as a battery, a fuel-cell stack, a diode rectifier, or a thyristor converter. VSI and CSI have these problems [2]:

- Neither can be a buck–boost converter, i.e., the obtainable output voltage range of each is limited to either greater, or smaller, than the input voltage.
- The VSI main circuit cannot be used for the CSI, and vice versa

Z-source converter (ZSC) is a problem-solving option. The Z-source converter overcomes the above-mentioned conceptual and theoretical barriers and limitations of the traditional V-source converter and I-source converter and provides a novel power conversion concept. The Z-source network comprises split inductors L_1 and L_2, and X connected capacitors C_1 and C_2, for coupling of the inverter network to the dc source as shown in Fig 3.

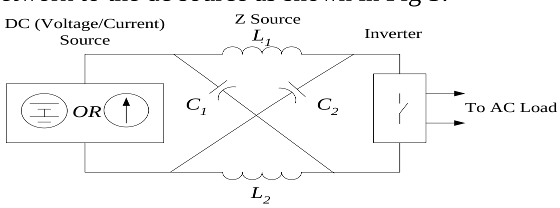

Fig3: Z Source network

A special feature of ZS network that it allows both power switches of a phase leg to be turned on simultaneously

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without damaging converter network (a scenario called shoot-through). The inverter's performance can be analysed via its equivalent circuits; In shoot through state, the ZSI is shorted (Fig.4). By assuming $C_1=C_2=C$, we get:

$$V_{L1}=V_{L2}=V_L \text{ and } V_{C1}=V_{C2}=V_C \quad (1)$$

$$V_O=V_L=V_C \quad (2)$$

$$V_i=0 \quad (3)$$

No energy is transferred to the load.

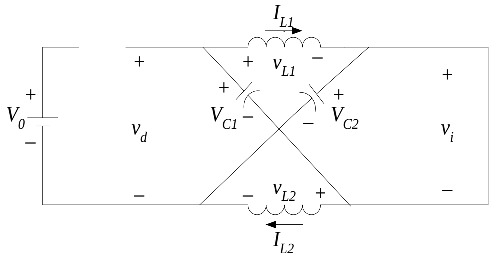

Fig 4: Equivalent circuit during shoot through state

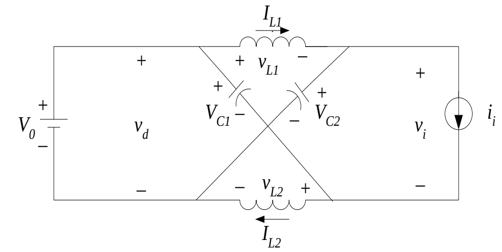

Fig 5: Equivalent circuit during non shoot through state

During non shoot through state, current flows from the Z source network through the inverter network, to the connected ac load. The Z-source network can now be represented by an equivalent current source; see Fig 5. The following equations thus result:

$$V_L = V_0 - V_C \quad (4)$$

$$V_d = V_0 \quad (5)$$

$$V_i = V_C - V_L = 2V_C - V_0 \quad (6)$$

II. PRINCIPLE OF OPERATION

A typical switched mode power amplifier generally consists of two important sections namely high power/voltage electronics and low power/voltage electronics. The high power electronic basically consists of Full bridge (made up of switches like MOSFETs or IGBTs), Power Transformer and power filter. The selection of the switching frequency, switching components, design of the duty cycle, designing of the inductor and capacitors are the key issues in optimizing the size and efficiency of power amplifier. A class D amplifier is a power amplifier where all power devices are operated in on/off mode. These amplifiers use pulse width modulation, pulse density modulation (sometimes referred to as pulse frequency modulation) or more advanced form of modulation such as Sigma delta modulation. The input signal is converted to a sequence of pulses whose averaged value is directly proportional to the amplitude of the signal at that time. The frequency of the pulses is typically ten or more times the highest frequency of interest in the input signal. The output of such an amplifier contains unwanted spectral components (i.e.. the pulse frequency and its harmonics) that must be removed by a passive filter. The resulting filtered signal is then an amplified replica of the input. The main advantage of a class D amplifier is power efficiency. Because the output pulses have fixed amplitude, the switching elements (usually MOSFETs, but valves and bipolar transistors were once used) are switched either on or off, rather than operated in linear mode. This means that very little power is dissipated by the transistors except during the very short interval between the on and off states. The wasted power is low because the instantaneous power dissipated in the transistor is the product of voltage and current, and one or the other is almost always close to zero. The lower losses permit the use of a smaller heat sink while the power supply requirements are lessened too. SPWM or sinusoidal pulse width modulation is widely used in power electronics to digitize the power so that a sequence of voltage pulses can be generated by the on and off of the power switches. The pulse width modulation inverter has been the main choice in power electronic for decades, because of its circuit simplicity and rugged control scheme. SPWM techniques are characterized by constant amplitude pulses with different duty cycle for each period. The width of this pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content. As explained earlier, a PWM in its simplest form has a comparator with inputs of (i)high frequency carrier wave and (ii) a constant or slowly varying signal called the control or the modulating signal. In PWM inverters the output voltage has to be sinusoidal with magnitude and frequency controllable. In order to produce a sinusoidal output voltage at a desired frequency, a sinusoidal control signal at a desired frequency is compared with a triangular carrier waveform. The triangular waveform is at switching frequency f_s, (carrier frequency) which establishes the frequency by which inverter switches are switched. The control signal $V_{control}$ is used to modulate the switch duty ratio and has a frequency f_1(modulating frequency) which is the desired fundamental frequency of the inverter output voltage. The important terms associated with the PWM scheme is Amplitude modulation ratio m_a which is defined as the

$$m_a = V_{control}/V_{tri} \quad (7)$$

where $V_{control}$ is the peak amplitude of the control signal and V_{tri} is the peak of the triangular signal.

The frequency modulation ratio m_f is defined as

$$m_f = f_s/f_1 \quad (8)$$

There are many PWM techniques available. Two important PWM techniques used in power amplifiers are explained below.

A. *PWM with Bipolar Voltage Switching*

The basic idea to produce PWM Bipolar voltage switching signal is that it contains a comparator used to compare between the reference voltage waveform $V_{control}$ with the triangular carrier signal V_{tri} and produces the bipolar switching signal[3].

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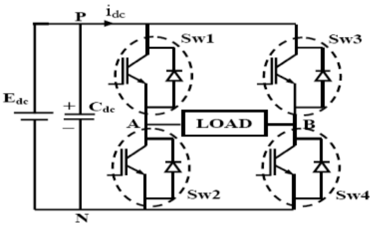

Fig 6: Single Phase Full Bridge Inverter

If this scheme is applied to the full bridge single phase inverter as shown in Fig 6 the output of leg A is equal and opposite to the output of leg B. The output voltage is determined by comparing the reference signal, $V_{control}$ and the triangular carrier signal, V_{tri}.

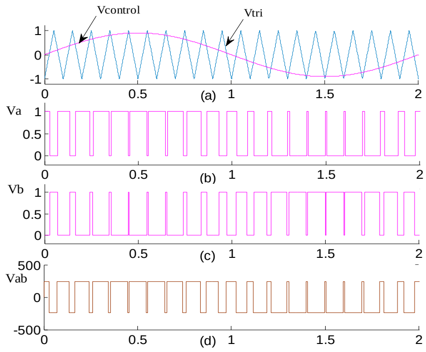

Fig 7: SPWM with bipolar voltage switching
(a) Comparison between reference waveform and triangular waveform (b) Gating pulses for S1 and S4(c) Gating pulses for S2 and S3 (d) Output waveform

In this technique a high frequency carrier signal is compared with a sinusoidal reference signal. Here the frequency of the carrier signal determines the output frequency and its peak amplitude controls the modulation index which in turn the rms output voltage. Here the sinusoidal voltage, has the following constraints,

1. The peak magnitude of the sinusoidal signal is less than or equal to the peak magnitude of the carrier signal. This ensures that the instantaneous magnitude of the modulating signal never exceeds the peak magnitude of the carrier signal.

2. The frequency of the modulating signal is several orders lower than the frequency of the carrier signal. Under such high frequency ratios, the magnitude of modulating signal will be virtually constant over any particular carrier-signal time period. Fig 7 shows the typical waveforms of bipolar sinusoidal PWM scheme. In this scheme we observe that the output voltage switches between $-V_{CC}$ and $+V_{CC}$ voltage levels. That is the reason why this type of switching is called a PWM with bipolar voltage switching.

B. PWM with Unipolar Voltage Switching

PWM with Unipolar voltage switching technique uses two inverted sine waves as modulating signals for the two legs of the inverter [3]. The generation of the PWM signal can be explained with the aid of the full bridge circuit shown in Fig 6. Here, the legs A and B of the full bridge inverter are controlled separately by comparing V_{tri} with $V_{control}$ and $-V_{control}$, respectively. Unipolar SPWM voltage modulation type is selected because this method offers the advantage of effectively doubling the switching frequency of the inverter voltage, thus making the output filter smaller, cheaper and easier to implement.

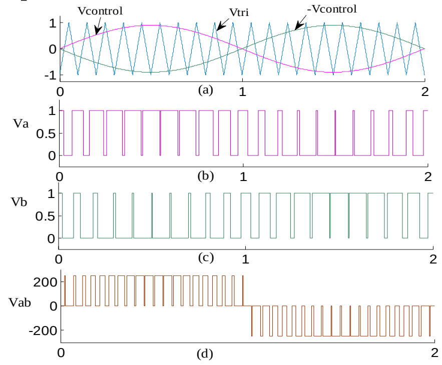

Fig 8: SPWM with unipolar voltage switching
(a) Comparison between reference waveform and triangular waveform (b) Gating pulse for S1 (c) Gating pulse for S3 (d) Output waveform

C. PWM Signal Generation

Class D amplifiers can be controlled by either analog or digital circuits. The analog method uses a signal generator system which generates sine wave of sonar frequency with a selected pulse length, pulse repetition rate and power level. This sonar signal (also called as modulating signal) of frequency fm is compared with a triangular wave (also called as carrier wave) of frequency fc which is generally many times greater than sine wave frequency to generate pulse width modulated (PWM) signals. The output of the comparator is pulse width modulated signal. The PWM output signal, now a representation of input signal is used to control the 'ON' duty ratio of power electronic switch in the full bridge circuit. Since the full bridge circuit is operated at high DC supply (HT supply), the voltage output of full bridge is amplified PWM signal. This amplified PWM signal forms the input of an isolation transformer. The isolation transformer output is connected to a power filter to filter out the carrier frequency components. The power filter output (the final output of the power amplifier) excites the sonar transmitter (projector). Digital method is the generation of PWM signal using microcontroller or PWM IC. The use of the microcontroller brings the flexibility to change real-time control algorithms without further changes in hardware. It is also low cost and has a small size of control circuit for the single phase full bridge inverter. This microcontroller based amplifier is highly efficient, compact, low cost and versatile since the control strategy of the amplifier becomes programmable.

III. DESIGN CONSIDERATIONS

At 0dB, ie, in order to get the rated power the load voltage should be 387.3 rms. The maximum rms that can be obtained using a 250v input is 353.55V. Therefore we need a boost operation for getting the rated power. For this purpose we are

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going for z source inverter where we will get the solution for this problem.

Table I: Specification

Input Voltage	250V dc
Rated Power	1Kw
Fundamental Frequency	5kHz
Switching frequency	60kHz
Load Resistance	150Ω
Modulation Index(M)	0.8
Transformer turns ratio	1:2

$$P = \frac{{V_{rms}}^2}{R} \quad (9)$$

$$I_L = \frac{P}{V_{dc}} \quad (10)$$

To get the rated power,

$$I_L = \frac{1000}{250} = 4\ A$$

$$V_{rms} = \sqrt{1000 * 150} = 387.29\ V$$

The boost factor required is,

$$MB = \frac{387.29 * \sqrt{2}}{2 * 250} = 1.09542$$

$$B = \frac{1.09542}{0.8} = 1.36927$$

$$B = \frac{1}{1 - 2D_0} \quad (11)$$

$$D_0 = 0.13484$$

$$T_0 = D_0 * T = \frac{0.13484}{60 * 10^3} = 2.2473\mu\ sec \quad (12)$$

Current ripple through the inductor is selected as 30%.

$$\Delta I_L = I_{L,max} - I_{L,min} = 5.2 - 2.8 = 2.4 \quad (13)$$

$$Vc = \frac{V_{dc} + V_{dc\ max}}{2} = 296.16V \quad (14)$$

$$L = \frac{T_0 * V_c}{\Delta I_L} = 277.27\mu H \quad (15)$$

Let the peak ripple voltage across the capacitor be 3% then,

$$C = \frac{T_0 * I_L}{V_c * \Delta V_c} = 1.01\mu F \quad (16)$$

The power filter which suppresses the high frequency noise normally consists of inductors and capacitors. The filter used in sonar power amplifier can be second order which is designed using single inductor element and a capacitor.

$$L_f = \frac{1.414 R_L}{2\pi f} \quad (17)$$

$$L_f = 4.5mH$$

$$C_f = \frac{0.707}{2\pi f R_L} \quad (18)$$

$C_f = 0.1\mu f$

IV. SIMULATION VERIFICATION

To verify the proposed design strategies, a MATLAB/ SIMULINK model of single phase z-source inverter is presented as shown in figure ---

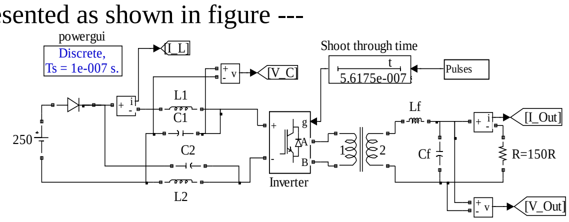

Fig 9: MATLAB model of Z Source coupled PA

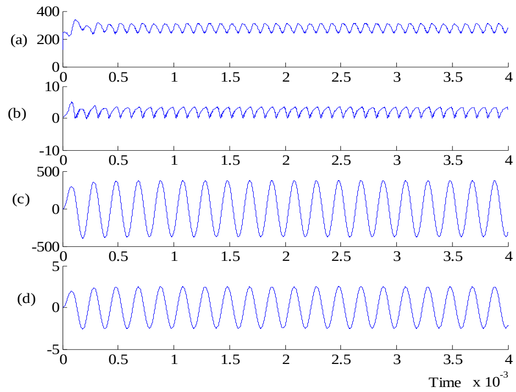

Fig 10:CapacitorVoltage, Inductor current , Load voltage, Load current at MI = 0.8, Shoot through is 10 nanoseconds

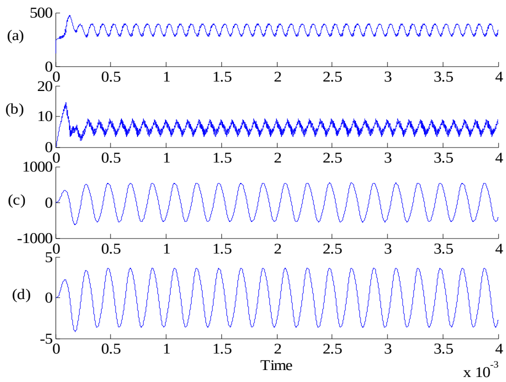

Fig 11:CapacitorVoltage, Inductor current , Load voltage, Load current at MI = 0.8, Shoot through is 0.8 micro seconds

Table II: Variation of voltage and current for different Modulation Index

MI	Load Voltage (rms)	Load Current (rms)	THD
0.05	11.9	0.079	3.536
0.1	25.12	0.1675	1.776
0.2	52.04	0.3469	1.2
0.3	79.43	0.5295	0.7956

0.4	112.7	0.7514	1.075
0.5	151.9	1.013	1.163
0.6	189.3	1.262	1.085
0.7	225.4	1.503	0.8855
0.8	264.6	1.764	0.7367
0.9	306.6	2.044	1.07

Table III: Effect on switching frequency

Switching frequency (kHz)	Load Voltage (rms)	Load Current (rms)	THD
60	264.6	1.764	0.7367
80	267.8	1.785	0.5693
100	269.8	1.799	0.5283
120	275.3	1.836	0.694
140	280.5	1.87	0.7443

V. CONCLUSION

This paper has presented an impedance source inverter for high frequency PAs. The buck boost capability of z source inverter provides a wide operating range for the PAs. Using the coupled network, it is also made possible to work IGBT at very high switching frequency. Design analysis and simulation results of the PA have been presented

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