Z- Source Network Coupled Power Amplifier for Low Frequency Sonar Transmitter

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Abstract

Z Source (ZS) network is a new and attractive topology for power conversion, which is coupled between power source and converter circuit to provide both buck and boost properties. In this paper, Z source network coupled power converter that gives variable amplitude variable frequency conversion which can be used for low frequency sonar application is examined. Duration of Shoot through time and pulse widths of unipolar PWM waveforms are employed to control the output voltage in boost mode and buck mode respectively. Simulation is done using MATLAB/SIMULINK and the Digital controller dsPIC30F series is used for generation of PWM signal for variable frequency input signal. A prototype of 1kW Power Amplifier (PA) that can give a frequency response of 1 kHz to 10 kHz and a dynamic range of 27dB is developed in the laboratory and the results are presented.

Keywords: Microcontroller, Sonar, Unipolar PWM, Z-source inverter

1. Introduction

Power Amplifier (PA) is an integral part of active sonar systems which amplifies the sonar signal to the levels required by the transducer element. There are two kinds of amplifiers are used in sonar transmitter namely linear PAs and switch mode PAs.

In earlier days linear PAs were used for sonar transmission. In those PAs, power consumption is mainly 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. After the invention of power MOSFET's and IGBT's the PAs are developed using switch mode technology. The switch mode technology basically uses Sine Pulse Width Modulation (SPWM) for modulating the transmission signal into high frequency signal.

Block schematic of a typical high power sonar signal amplifier is given in Fig1. The first block is a HTDC, normally a general purpose AC-DC converter which can work as a high efficiency rigid voltage source. The next block is an inverter which is basically a variable gain and variable frequency inverter.

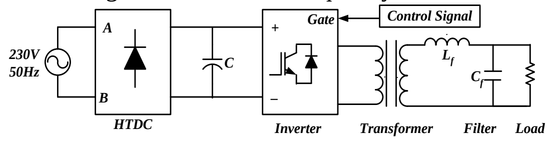

Figure 1: Block Schematic of Typical Switch mode PA

Since the power required for exciting the transducer elements are high of the order of kilovolts, the sonar PAs are huge in size and in sonar systems with multiple PAs which occupy huge size. Since the size of the PA is very important for sonar application, it is important to analyse different topologies that makes the system compact, reliable, efficient and easy to use.

2. Principle of Operation

The inverter generally uses Unipolar SPWM voltage modulation type 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.

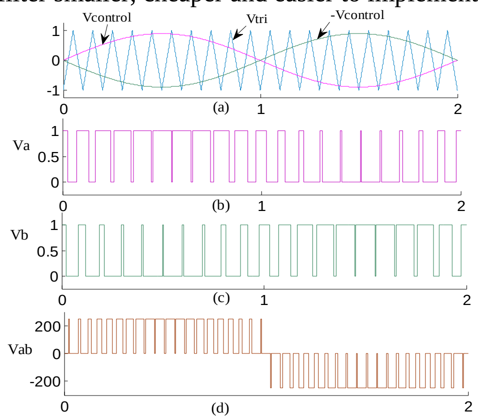

Figure 2: Waveform for SPWM with unipolar voltage switching

(a) Comparison between reference waveform and triangularwaveform (b) Gating pulse for H1 (c) Gating pulse for H2 (d) Output waveform

In unipolar PWM scheme applied to a single-phase full bridge inverter shown in Fig 3, the gate signals are generated by comparing a triangular waveform (Vtri) with a sinusoidal modulating signal (Vmod) as shown in the Fig 2. The carrier frequency is even number multiplication of modulating frequency. Higher value of carrier frequency shifts harmonics to high frequency side which can be easily filtered out with small filter components.

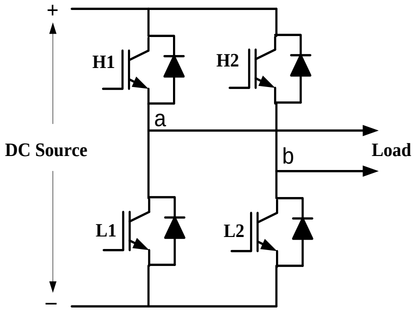

Fig 3: Single phase full bridge inverter.

Generally frequency of sonar signal lies in the range of 1 kHz to 10 kHz. Since the modulating frequency is in the range of kHz range the carrier frequency should be greater than 12 kHz for 1 kHz and 120 kHz for 10 kHz. A dead band is given in VSI PA to avoid shoot through as the switching frequency is more. A typical dead time given in PA is given in fig 4. Sufficient dead band which avoids shoot through adversely decreases the amount of power transfer and increases the distortion in the output waveform. Higher powers need to select IGBT as power switch where switching frequency is limited. The dead band is the solution to avoid shoot through in these cases.

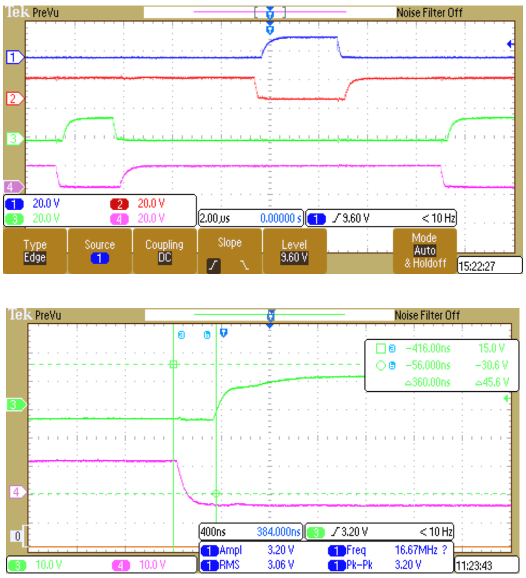

Fig 4: Gate signals with 360 nano seconds dead-time

The MOSFETs can be switched at higher frequencies but the operating voltage is limited. As the output of the sonar PA is of the order of kilo watts range the selection of power electronic device and operating frequency is critical.

The problem worsens with the variation of the load. The dynamic range with variable load limits the HT DC. For example, if the load impedance varies from Z to 2Z (assuming 100% variation), obtaining power of P watts in 2Z needs higher voltage than power of P watts in Z. The Z source network provides a solution to above problem with limited ranges. 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 5.

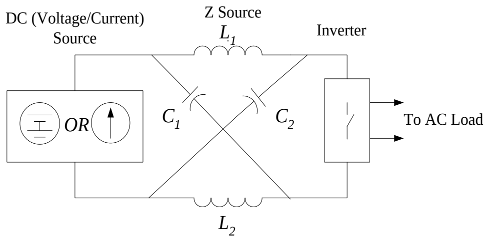

Fig5: Z Source network

A special feature of ZS network that it allows both power switches of a phase leg to be turned on simultaneously 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.6). 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.

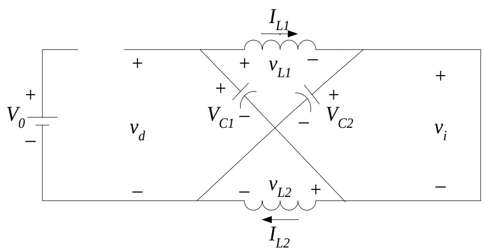

Fig 6: Equivalent circuit during shoot through state

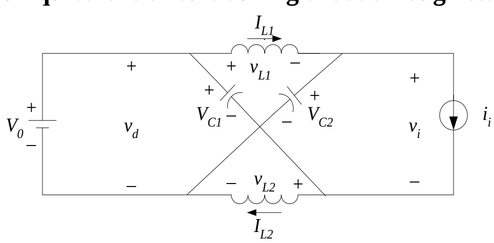

Fig 7: Equivalent circuit during non shoot through state

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 7. The following equations thus result:

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

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

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

3. Simulation Verification

A case study is carried out to understand the effects of above parameters.

A PA of 1kW needs to be designed for a resistive load of 100 Ω to 200 Ω (Reactive components are neglected). Random frequency of 5 kHz is chosen and it is required to achieve a power range from 1kW (0dB) to 1.8W (-27dB). MATLAB/Simulink model of VSI mode PA circuit is given Fig 8 and Z source coupled PA's model is given in Fig 9. V_{dc}=200V, Switching frequency = 60kHz, Fundamental frequency = 5kHz and filter components at the output of PA are, L_f = 4.5mH, C_f = 0.225μF, The design values for Z source circuit L_1= L_2 = 144.8μH, C_1 = C_2 = 1.01μF

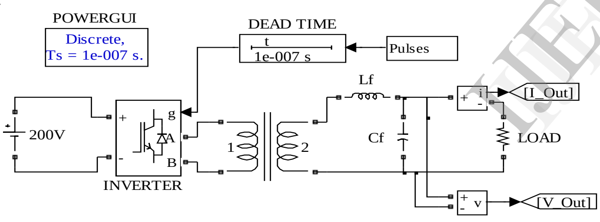

Fig 8: MATLAB/SIMULINK model of VSI based PA

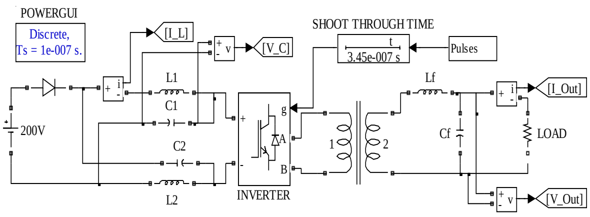

Fig 9: MATLAB/SIMULINK model of Z Source coupled PA

Table.1 shows the simulated values of output for different power level of VSI and Z Source Inverter (ZSI) circuits. THD is also provided to show that the distortion is less than 5% for ZSI which is the IEEE permissible limit. It is observed from the table that, for the modulation index greater than 0.4 the ZSI gives higher power than VSI and for modulation index less than 0.4 the power values are less.

Fig 10 is simulation results of both the configuration for two different loads (100Ω and 200Ω) with 1.26μsec shoot through in case of Z source coupled PA. It is evident from the figure that the output voltage for a different modulation index is not linear in Z source coupled PA where as the VSI based PA gives the linear result. However the lowest power as well as the highest power can be achieved in Z source coupled PA. This helps in achieving many levels (higher dynamic range) of power in sonar applications. The impedance source network avoids the shoot through problems inherently present in PAs.

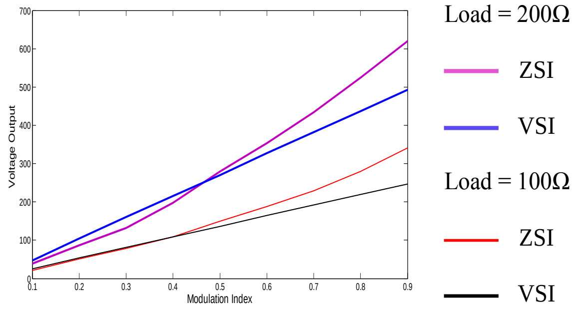

Fig 10: Voltage outputs of VSI PA and Z source coupled PA at two loads

Table1: Comparison of VSI and ZSI based PA

MI	ZSI(Load = 100Ω)		VSI(Load= 100Ω)	
	V_{rms}	THD(%)	V_{rms}	THD (%)
0.9	340.8	2.06	247.3	0.162
0.8	279	1.26	219.5	0.21
0.7	229.5	0.93	192.3	0.26
0.6	187.5	0.8	164.5	0.27
0.5	149.3	0.67	136.2	0.29
0.4	109.3	1.12	108.4	0.48
0.3	78.02	2.04	81.41	0.5
0.2	51.16	2.82	53.67	0.77
0.1	21.86	5.01	24.66	1.24

MI	ZSI(Load = 200Ω)		VSI(Load = 200Ω)	
	V_{rms}	THD (%)	V_{rms}	THD (%)
0.9	620	2.15	492.2	0.09
0.8	524.6	1.12	437.1	0.08
0.7	433.8	0.32	382.4	0.13
0.6	353.5	0.4	327.3	0.13
0.5	279.6	0.56	270.3	0.15
0.4	197.4	0.53	215.2	0.24
0.3	131.8	0.67	160.8	0.35
0.2	86.47	1.23	104.8	0.4
0.1	39.51	2.95	47.72	0.73

4. Experimental Verification

A proto type of hardware of 1kW that uses a Z Source network for the PA was fabricated in the laboratory. The block schematic of the prototype is given in Fig 11.

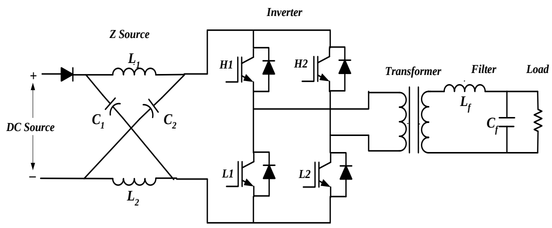

Fig 11: Block schematic of Z source coupled PA

The shoot through is given by simple inversion of signals using opto-coupler driver and this converts the dead time into shoot through. The gate switching pulses with shoot through signals are as shown in the Fig 12. The system consists of microcontroller circuit for generating SPWM pulses, opto-isolator or isolation circuit, gate drivers, inverter circuit or full bridge circuit step up transformer and filter circuit. SPWM signal generated by microcontroller needs to be isolated for protection from high power electronics. The outputs are then fed to high speed gate drivers.

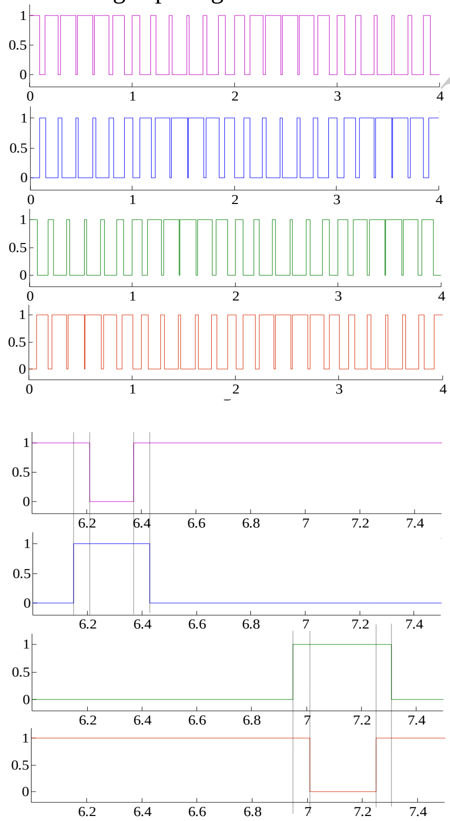

Fig 12: Shoot-through Pulses for Single phase full bridge inverter.

The unipolar signals at the end of gate drivers are as shown in Fig 13. The outputs of the gate drivers are then connected to power switches in full bridge arrangement. A step up power transformer designed to operate at modulating frequency was connected at the output of the H bridge legs. In order to get fundamental component of modulating sine wave a LC filter was used to reduce harmonic content.

Fig 13 shows the PWM output from the microcontroller. Marks 1 and 2 are the waveforms used for driving high side and low side power devices of leg 1 and marks 3 and 4 are the waveforms used for driving high side and low side power devices of leg 2. The low side power devices are driven using complement waveforms of respective legs. Wave form marked M is the waveform is the voltage available at the input of the power transformer.

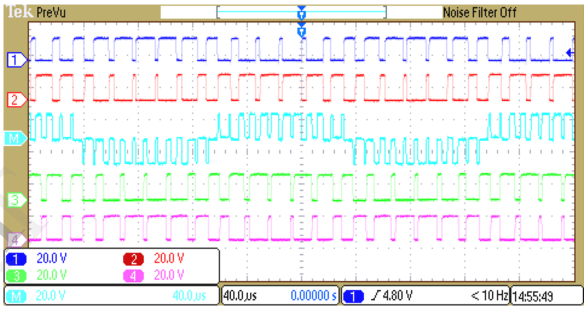

Fig 13: Pulses for the Full bridge inverter

In case of VSI, turn off time of the device will act as a shoot through and it causes high current to flow through the device which results in increased heat dissipation. So in that case, dead-time became necessary for the protection of device. Else failure of the device can happen due to high temperature. Figure 14 shows the gate signals of high side and low side devices of one leg without dead-time insertion.

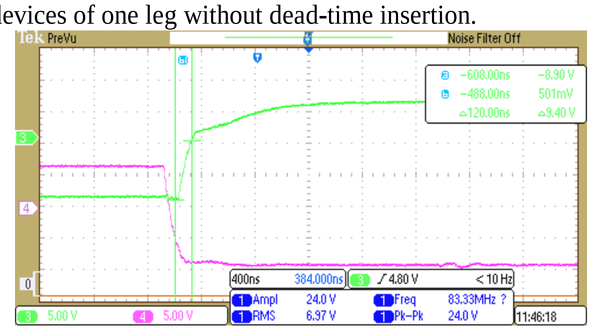

Fig 14: Gate signals for one leg of the H-bridge without any dead-time

The proto type developed in the laboratory uses dsPIC30F2010 for generating SPWM signals. When dead time is not given the gate drive signals of upper device and lower device has a small over lap i.e shoot through of 120 ns as shown in fig.14. This delay is due to the delay of the opto-coupler and high side low side driver. The gate signals of low side device and high side are reversed in hardware while isolating optically and hence the dead time becomes a shoot through in the actual hardware.

Z source coupled PA is free from problems due to shoot through condition due to the networks property. The boost operation of ZSI is controlled by controlling shoot through duration which is the dead time given in micro controller. Fig15 shows signal with shoot through of 336 nano seconds generated using the hardware.

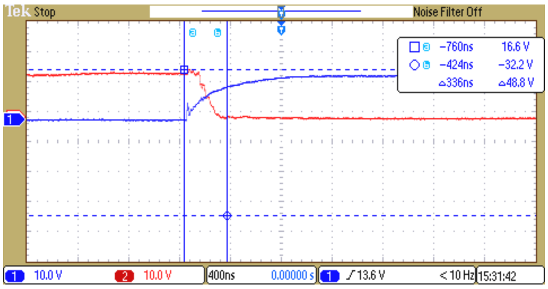

Fig 15: Gate signals with 336 nano seconds shoot through

The Table2 shows the effect of dead-time and shoot through in VSI and ZSI. The input voltage is 100 V dc, and MI is fixed as .707

Table2: Effect of dead-time and shoot through in VSI and ZSI

Converter Topology	Dead-time (Nano Sec)	Shoot through time (micro Sec)	V_{out} (rms)
VSI	200	0	120
VSI	0	0	121
ZSI	200	0	116
ZSI	0	0	121
ZSI	0	0.4	122
ZSI	0	0.8	130
ZSI	0	1.2	143

The figure 16, 17 shows the effect of dead time and shoot through in inverter. The parameters V_{dc} = 200, MI=0.95 z network, transformer, and filter are as per the design values. It is clear from Fig 16 and 17 that the boost operation is possible by increasing the shoot through period.

Since the components are less and the pulse are generated only when transmission is required, micro controller based power amplifier is compact and highly efficient. High power requirement also can be met with very small modifications only in program and modularity in power circuits. Fig 18 shows the output voltage at different power levels.

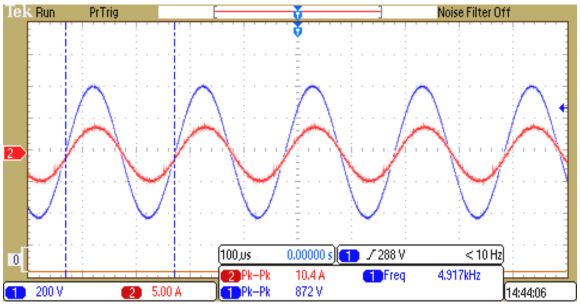

Fig 16: Output Voltage with dead-time of 200nSec, V_{dc} = 200, MI=0.95

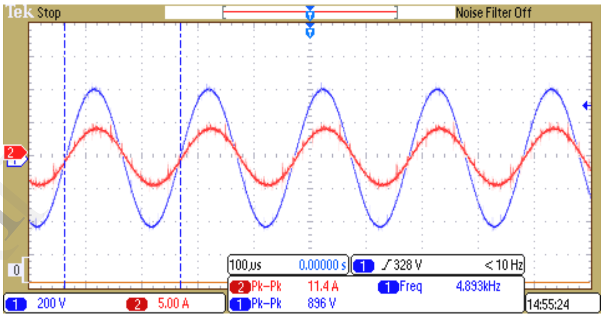

Fig 17: Output Voltage with shoot through of 0.5μSec, V_{dc} = 200, MI=0.95

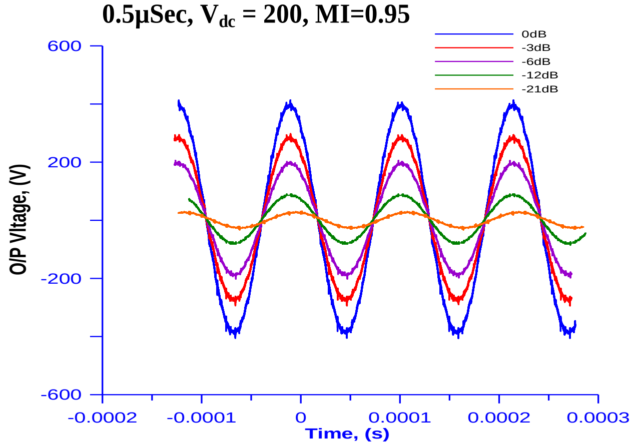

Fig 18: Voltages at different power levels by controlling modulation index

5. Conclusion

This paper has presented an impedance source inverter for sonar PAs. The buck boost capability of z source inverter provides a wide operating range for the PAs. By avoiding the shoot through problem as in the case of VSI, ZSI provides a safe operation condition, by reducing the heat dissipation at the device due to high current. Since there is no need of dead-time, the adverse effect of dead-time is also eliminated by using the ZSI. Using the coupled network, it is also made possible to work IGBT at very high switching frequency. Analytical, simulation and experimental results of the PA have been presented

6. References

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