Modified Unipolar Switching Technique for PWM Controlled Digital Sonar Power Amplifier

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Abstract — A modified unipolar switching technique for PWM controlled sonar power amplifier is proposed in this paper. In general, the sonar power amplifiers should possess high power density, high linearity, high power gain, high efficiency, reliability in performance and minimum THD over the entire operating bandwidth of interest. In comparison to other SPWM controlled sonar power amplifiers, the proposed sonar power amplifiers has the maximum output RMS value with significant reduction in output distortion. The principle of proposed modified unipolar switching technique is described. A low cost dsPIC microcontroller is used for generating the switching signals using proposed method for sonar power amplifier. Simulation and experimental results are given to demonstrate the validity and features of the modified unipolar switching technique.

Index Terms — dsPIC Microcontroller, Dead time, Sonar, Power amplifier, Unipolar PWM

I. INTRODUCTION

SONAR, an acronym derived from SOnund Navigation And Ranging, is the only effective method for underwater detection. The basic principle of sending a packet of energy and finding the time delay of the reflected signal received, to get a measure of range, as in radar, is used in sonar also. Sea water behaves as a low pass filter for the acoustic waves; hence the choice of frequency for transmission is limited to audio band, with the actual frequency being a compromise based on the permissible transducer size. In the design of power amplifiers, unlike other electronic equipment, great premium is placed on operating efficiency, because of both the loss of useful transmitted power and the difficulty of dealing with the heat generated in the transmitter. In some underwater acoustic applications, high power of the orders of tens of kilowatts is required to be delivered out of each unit. Several such units occupy prohibitive volume, where space is premium in a ship, and is very critical in the case of a submarine. Hence, highly efficient, compact in size switch mode power amplifiers, with flexibility in controlling parameters like frequency, power, pulse length and pulse repetition interval is a real boon in this scenario.

A. Importance of PWM Controlled Digital Sonar Power Amplifiers

The application of digital control techniques to PWM controlled digital sonar power amplifier has always been considered very captivating, mainly because of the several advantages a digital controller shows, when compared to an analog one. Of course, the most relevant one is the possibility that it offers for implementing sophisticated control laws, taking care of nonlinearities, parameter variations or construction tolerances which are very difficult or impossible to implement in analog form. Another very important advantage is the flexibility inherent in any digital controller, which allows the designer to modify the control strategy, or even to totally reprogram it, without the need for significant hardware modifications. Higher tolerances to signal noise and minimize the ageing effects or thermal drifts are also very significant [1]. In addition, in this modest era of digital sonar power amplifiers, we must consider the importance of the presence of some form of sonar operator interface which can ease testing procedure, fault localization, operational parameter finding, like operating temperature of power devices, log information of the power amplifier etc.,. Its implementation is almost impossible without having some kind of embedded microprocessor. The utilization of the computational power, which thus becomes available, also for lower level control tasks is almost unavoidable. For these reasons, the application of digital controllers has been widespread, and has become the only effective solution for the digital era power amplifiers for sonar applications. The increasing availability of low-cost, high-performance, microcontrollers and digital signal processors stimulates the diffusion of digital controllers in areas where the cost and size of the control circuitry is a truly critical issue. The research efforts towards digitally control sonar power amplifier applications need to be focused on the design of custom integrated circuits, rather than on algorithm design and implementation. Issues such as occupied area minimization, scalability and power consumption minimization play a key role.

B. Importance of Dead Time in Full Bridge VSI Configuration

In general, the widely used topology for SPWM (Sinusoidal Pulse Width Modulation) based sonar power amplifiers are VSI (Voltage Source Inverter) configuration. In ideal VSIs, input voltage is maintained constant and amplitude of the output voltage does not depend on the load. However, the waveform of load current as well as its magnitude depends upon the nature of load impedance.

Consider the case shown in Fig. 1 of full bridge VSI, where it consists of two ideal phase legs constituting four MOSFETS with anti parallel free-wheeling diodes, whose purpose is to make the switch bidirectional. In order to simplify the control, assume that the switch plus diode couple behaves as an ideal switch, i.e., one whose voltage is zero in the ‘ON’ state and
whose current is zero in the ‘OFF’ state. The control of a switching bridge usually involves a process of alternating the ‘ON’ time of two power switches connected in series between a high-voltage and a low-voltage. For example, the H-bridge of Fig. 1 can be operated by turning the upper left and lower right MOSFETs ‘ON’ and leaving the two remaining MOSFETs ‘OFF’, during the first half of the PWM cycle. In the second half of the cycle, the upper right and lower left MOSFETs are ‘ON’ and the remaining two are ‘OFF’. During the transition, between the first half and the second half of the PWM cycle, there is a very short period of time when both the upper MOSFET and the lower MOSFET in a leg could be ‘ON’. If both MOSFETs are ‘ON’, for this short period of time, they will effectively short the high voltage supply to ground, which is an undesirable situation [2].

In its analog counterpart, the unipolar SPWM controlled sonar power amplifier’s gate drive signals are generated by comparing the modulation signal at transmission frequency (both inverting and non inverting sinusoidal signals) and triangular signal at carrier frequency as shown in Fig.3a. Each PWM signal, with their inverted PWM signal, is fed to the respective gate of the full bridge VSI. In the transition period of switching time, if both MOSFETs on the same leg are ‘ON’, an undesirable situation of short the high voltage supply to ground can occur. In this particular unipolar SPWM switching, undesirable catastrophic failure situation arises 4 times the sampling ratio. It means, at every point where the amplitude of modulating waveforms and carrier waveform are equal, there is a chance of catastrophic failure. The valuable deadband introduction in SPWM control signals as shown in Fig.3b avoids the chance of cross conduction by guaranteeing that both MOSFETs in a leg are ‘OFF’ for a minimum time during a transition period. The value of deadband should be based on the device characteristics, ambient operating conditions, parasitic parameters of switching devices and load conditions. Though deadband introduction increases reliability of the sonar power amplifier, it will reduce the...
achievable output power by reducing the RMS output to a certain extent and increases the total harmonic distortion (THD).

D. Adverse Effect of Deadtime in Sonar Power Amplifier

If a little is good, a lot should be better - except with deadtime. Unfortunately, deadband in the switching output stage causes nonlinearity in the power amplifier circuit transfer function, which may be difficult for the control loop to remove. Normally, Sonar power amplifiers working in kilo hertz range and the output devices are switching at hundreds of kilo hertz. The introduction of deadband reduces the maximum achievable power output. Thus, the deadband introduction reduces maximum attainable power density and increases the THD of the power amplifier. Consider the practical case in Fig.4 which shows the adverse effect of incorrect deadtime over the control signals. In Fig.4b, the incorrect deadtime introduction, whitewashing the lower ‘ON time’ part of control signals, comparing to the control signals shown in Fig.4a. Unbalanced deadtime creates an offset in the PWM output stage transfer function, and can cause saturation of the output power transformer of the sonar power amplifier, if not corrected within a few cycles. This may lead to the failure of power switching devices and unwanted thermal concentration in the output transformer.

II. PRINCIPLE OF PROPOSED MODIFIED UNIPOLAR SWITCHING TECHNIQUE

The proposed scheme significantly reduces the adverse effects of dead time in sonar power amplifiers. Since frequency of operation is very high compared to general purpose inverters, and the dynamic range of gain (maximum output to minimum output) is at least 36dB, the proposed scheme has an upper hand as compared to SPWM with dead time insertion. As said earlier, ‘If a little is good, a lot should be better - except with deadtime’, this leads to thinking about an advance high frequency switching strategy. This reflects on the proposed ‘modified unipolar SPWM switching technique’. The proposed switching strategy is highly effective with some gate driver IC integrated half bridge packages and it allows the use of hybrid switching device topology for low frequency sonar power amplifiers. The control signals to the full bridge in the proposed scheme are given in Fig.5. In the modified unipolar SPWM switching technique implementation in full bridge configuration, two high side switching devices are switched at modulation signal frequency, which would be of the order of kilohertz range,
and two low side switching devices are switched at carrier frequency, which would be of the order of hundred kilohertz range. Though the proposed switching strategy has to be switched at double the carrier frequency compared to formal unipolar SPWM method, it allows flexible duty cycle variation from 0% to 100% in positive and negative half cycles. This leads to finite linear power level variation in dynamic range of gain.

III. SIMULATION RESULTS

To validate the modified unipolar SPWM switching technique, an H-bridge VSI configuration, as shown in Fig.1 has been simulated in Matlab simulink. The load is composed of an equivalent sonar power transformer, power filter and transducer impedance of 250 ohm resistor. VDC is set to 270V and the sonar amplifier is controlled by SPWM with switching frequency of 48 kHz (Case1 & 2) and 96 kHz (Case 3). The fundamental frequency of the output voltage is set to 4 kHz.

Table 1: comparison of output voltage and THD for Case 1: without deadtime, Case 2: with 1μsec deadtime, Case 3: with modified unipolar method.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>0.1</td>
<td>76.49</td>
<td>0.5107</td>
<td>76.12</td>
<td>0.46%</td>
<td>20.93%</td>
<td>0.46%</td>
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<tr>
<td>0.2</td>
<td>152.9</td>
<td>60.55</td>
<td>152.5</td>
<td>0.37%</td>
<td>9.54%</td>
<td>0.38%</td>
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<tr>
<td>0.3</td>
<td>229.4</td>
<td>135.3</td>
<td>228.9</td>
<td>0.33%</td>
<td>4.56%</td>
<td>0.33%</td>
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<tr>
<td>0.4</td>
<td>306.2</td>
<td>212.8</td>
<td>305.7</td>
<td>0.29%</td>
<td>2.87%</td>
<td>0.31%</td>
</tr>
<tr>
<td>0.5</td>
<td>382.7</td>
<td>288.6</td>
<td>382.6</td>
<td>0.26%</td>
<td>2.11%</td>
<td>0.27%</td>
</tr>
<tr>
<td>0.6</td>
<td>459.6</td>
<td>365.8</td>
<td>459.1</td>
<td>0.23%</td>
<td>1.65%</td>
<td>0.24%</td>
</tr>
<tr>
<td>0.7</td>
<td>536.3</td>
<td>441.1</td>
<td>536.1</td>
<td>0.19%</td>
<td>1.38%</td>
<td>0.20%</td>
</tr>
<tr>
<td>0.8</td>
<td>612.5</td>
<td>518.5</td>
<td>611.9</td>
<td>0.16%</td>
<td>1.16%</td>
<td>0.17%</td>
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<tr>
<td>0.9</td>
<td>689.6</td>
<td>595.7</td>
<td>689.1</td>
<td>0.13%</td>
<td>1.02%</td>
<td>0.13%</td>
</tr>
<tr>
<td>1</td>
<td>766.3</td>
<td>684.3</td>
<td>766</td>
<td>0.11%</td>
<td>1.21%</td>
<td>0.12%</td>
</tr>
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</table>
Table 2: comparison of output current and THD for Case 1: without deadtime, Case 2: with 1µsec deadtime and Case 3: with modified unipolar method.

<table>
<thead>
<tr>
<th>Modulation Index (MI)</th>
<th>Peak Output Current (Ip)</th>
<th>Output Current THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Deadband</td>
<td>With Deadband</td>
</tr>
<tr>
<td>0.1</td>
<td>0.4317</td>
<td>0.00289</td>
</tr>
<tr>
<td>0.2</td>
<td>0.865</td>
<td>0.3435</td>
</tr>
<tr>
<td>0.3</td>
<td>1.301</td>
<td>0.7674</td>
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<tr>
<td>0.4</td>
<td>1.740</td>
<td>1.207</td>
</tr>
<tr>
<td>0.5</td>
<td>2.172</td>
<td>1.637</td>
</tr>
<tr>
<td>0.6</td>
<td>2.607</td>
<td>2.075</td>
</tr>
<tr>
<td>0.7</td>
<td>3.042</td>
<td>2.502</td>
</tr>
<tr>
<td>0.8</td>
<td>3.475</td>
<td>2.941</td>
</tr>
<tr>
<td>0.9</td>
<td>3.911</td>
<td>3.379</td>
</tr>
<tr>
<td>1</td>
<td>4.348</td>
<td>3.881</td>
</tr>
</tbody>
</table>

Tabular comparisons between the above mentioned Cases are shown graphically in Fig. 6 & 7; it shows that the adverse dead-time effect has been minimized when the modified unipolar switching strategy is used.

Fig. 7. Simulated output current and THD comparison with different values of MI

Fig.8 shows the simulated output voltage and current waveforms when the modulation index is 0.9. It is noticeable that the modified switching strategy regains the RMS value of output current and voltage, and hence the maximum achievable power.

Fig.8. Simulated output voltage and current waveforms with MI=0.9
Fig.9 shows that the RMS value of output voltage is only 421.22V when there is a 1μsec dead time. However, after the introduction of modified unipolar switching strategy, the output voltage RMS value increases to 487.27V, which is the maximum achievable RMS output, as far as the Case 1 is concerned.

Fig.10 simulated Fourier analysis comparison when the modulation index is 0.9. It shows that the modified switching strategy keeps the THD values comparable to the ideal unipolar SPWM without deadband (Case 1).

IV. IMPLEMENTATION OF MODIFIED UNIPOLAR SWITCHING IN SONAR POWER AMPLIFIERS AND TEST RESULTS

In order to validate the modified unipolar SPWM switching, a scale down version of unipolar SPWM based sonar power amplifier consisting of an H-bridge with supporting circuitry, as shown in Fig.11, has been built and the performance has been evaluated. Four IXYS MOSFETs (IXFK80N50P) have been used to configure the H-bridge.
topology, and loaded with equivalent transducer impedance in resistive form (250Ω), which has one same value as that used in simulation studies. The dsPIC30F2010 has been used to develop control signals for the H-bridge and to implement the control strategy of the power amplifier.

The experimental waveforms using unipolar SPWM without deadband (Case 1) as shown in Fig.12, consists of control signals, their expanded view and output voltage & current waveforms. The Fig. 12.2 validates the unipolar SPWM without deadband control signalling. The maximum achievable peak-peak output voltage is 1.02kV as shown in Fig 12.3.

The experimental waveforms using unipolar SPWM with 1μsec deadband (Case 2) as shown in Fig.13 consists of control signals, its expanded view and output voltage & current waveforms. The Fig. 13.2 validates the unipolar SPWM with 1μsec deadband control signalling. The maximum achievable peak-peak output voltage is 980V as shown in Fig 13.3, which is 40V less than Case1.

The experimental waveforms using modified unipolar SPWM (Case 3) as shown in Fig.14, consists of control signals, their expanded view and output voltage & current waveforms. The Fig.14.3 validates the proposed switching strategy and regains the maximum achievable peak-peak output voltage of 1.02kV compared to Case 2.
Table 3 gives an efficiency comparison for Case 1: unipolar SPWM without deadband, Case 2: unipolar SPWM with deadtime (1μsec) and Case 3: modified unipolar SPWM under mentioned test condition, which validates the upper hand of modified unipolar SPWM over other switching strategies used in PWM controlled digital power converters for sonar applications.

V. CONCLUSION

In this paper, a strategic switching technique has been proposed for increasing the reliable performance of sonar power amplifiers. As compared to the conventional deadband inserted unipolar SPWM controlled sonar power amplifiers; the proposed switching strategy regains the achievable RMS output with significant reduction in output distortion, reduces switching stress on switching power devices and allows finite linear power level variation in dynamic range of gain. The simple program implementation in existing systems can be carried out with minimum hardware changes, which makes it very attractive for increasing the efficiency of existing as well as future systems.

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