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Efficient high voltage pulser for piezoelectric air coupled transducer

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ABSTRACT

The design of high voltage pulser for air coupled ultrasound imaging is presented. It is dedicated for air-coupled ultrasound applications when piezoelectric transducer design is used. Two identical N-channel MOSFETs are used together with 1200 V high and low side driver IC. Simple driving pulses' delay and skew circuit is used to reduce the cross-conduction. Analysis of switch peak current and channel resistance relation to maximum operation frequency and load capacitance is given. PSPICE simulation was used to analyze the gate driver resistance, gate pulse skew, pulse amplitude influence on energy consumption when loaded by capacitive load. Experimental investigation was verified against simulation and theoretical predictions. For 500 pF capacitance, which is most common for piezoelectric air coupled transducers, pulser consumes 650 μJ at 1 kV pulse and 4 μJ at 50 V. Pulser is capable to produce up to 1 MHz pulse trains with positive 50 V–1 kV pulses with up to 10 A peak output current. When loaded by 200 kHz transducer at 1 kV pulse amplitude rise time is 40 ns and fall time is 32 ns which fully satisfies desired 1 MHz bandwidth.

1. Introduction

Application of composite technologies in transport industry, especially airspace, sports and bioengineering is now making a significant part [1]. Thanks to ultrasound being the only technique directly sensitive to mechanical properties [2] the ultrasonic testing is a standard procedure for most composites inspection [3,4]. Air-coupled ultrasound [5] is preferred in field inspection. Use of the water as a couplant is not favored at some technology processes. Even food industry is switching to air-coupled ultrasound [6,7].

Because of the large difference of the acoustic impedances of the test part and the air the transmission loss is significant. To overcome this problem, powerful transmitters and low noise receivers are demanded [1]. The design of the pulser is complicated by the high electrical impedance of the ultrasonic transducer – high voltage is needed to supply the sufficient power [8]. The maximum working voltage of ultrasonic transducer according to [9] is a function of the piezoelectric transducer's thickness: 2 kV per mm of thickness. If PZT ceramics is used then 1 MHz natural frequency [9] transducer has 2.3 mm thickness which corresponds to 4.6 kV maximum working voltage. In general voltage applied is about 1 kV [10]. It can be concluded that for frequencies below 1 MHz the 1 kV pulse voltage is required. Such voltages are unusual in conventional electronics and therefore choice of components is limited. Square pulse, continuous wave (CW) burst, phase-manipulated sequence or chirp pulse train generation is aimed to attain large signal energy. Pulse voltage is high therefore design was aimed for low energy consumption, close to available economy limits. This paper aims to present the design of simple, energy-efficient, high voltage pulser for pulse trains or single pulses generation for up to 1 MHz frequencies.

2. Pulser configuration selection

The equivalent circuit of the transducer if based on Butterworth–Van-Dyke (BVD) model [11] is represented by the electrical capacitance of the transducer C_0 and series resonant circuit L_m, C_m, R_m describing the mechanical part. The mechanical boundary conditions are modeled by R_m, and C_m, while the mass of the mechanical system is described by inductance L_m. It can be assumed that the resistance R_m is presenting mainly an acoustic emission though it may include losses in transducer too. Few representative transducers' parameters are given in Table 1.

The essential load that piezoelectric transducer is presenting for the pulser is a capacitance C_0. This capacitance is the major drawback: it has to be charged during the pulse but only energy reaching R_m is useful. The charge has to be removed before the next excitation cycle. The frequency for air-coupled ultrasound inspection is relatively low, 100 kHz–1 MHz [1–5,16,17] and pulse trains are needed to raise the pulse energy. Conventional pulser topology, where only one active element is used [18–21] is not suitable here: return resistor (R_2 in Fig. 1) draws current during the pulse.

Resistor R_2 is essential since it is responsible for signal return to zero after pulse. Power consumed by R_2 can be calculated as:

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Table 1
Parameters for selected air-coupled transducers.

Transducer	F_c (kHz)	R_m (kΩ)	C_m (pF)	L_m (μH)	C_0 (pF)
Tr1 [12]	400	9.3	1758	88.7	3333
Tr2 [12]	500	410	173	561	480
ATK200 [13]	200	–	–	–	500
AT300 [14]	300	–	–	–	450
ARK41 [15]	41	–	–	–	5000
Tr3 [16]	800	1800	26	1600	65
Tr4	200	2300	140	9000	200

$$P_{R2} = \frac{\mathrm{PRF} \cdot V_{\mathrm{HV}}^2 \cdot N}{2R_2 \cdot F_c}, \quad (1)$$

where F_c is the transducer frequency or CW burst carrier frequency; V_{HV} is the excitation voltage; PRF is the pulse repetition frequency and N is the number of pulses is a burst. For 10 pulses train with 100 kHz frequency, 1 kV amplitude and 10 Hz PRF 5 W average power will be dissipated when R_2 is 100 Ω. Ultrasonic transducer with R_m 1.8 kΩ [16] will consume only 0.27 W.

If one more switch is used (Fig. 2) to return to zero (instead or R_2 Fig. 1), power consumption during the pulse is reduced: ultrasonic transducer impedance is mainly capacitive, only small fraction of it representing the mechanical energy consumption therefore energy is only consumed when charging/discharging capacitor C_0.

Energy stored in capacitor C_0 which is charged to voltage V is

$$E = \frac{V_{\mathrm{HV}}^2 \cdot C_0}{2}, \quad (2)$$

Same amount as (2) will be dissipated on active element M_1. If majority of load is the transducer capacitance, then pulser has to charge this capacitor and then take the same charge back. If there is no recirculation [22] of this energy, it is dissipated as heat in discharge switch (M_2 in Fig. 2). Then, power consumed by pulser generating bursts of N pulses over 1 s is:

$$P_{M1M2} = V_{\mathrm{HV}}^2 \cdot C_0 \cdot \mathrm{PRF} \cdot N, \quad (3)$$

Power consumed will be much smaller than (1). Generally air transducer has 50 pF (1 MHz transducer, [16]), 500 pF being the most common (200–500 kHz [12–15]) to 5000 pF (41 kHz, [15]) capacitance. Then, pulser loaded by same 1 MHz transducer as above which has 65 pF capacitance [16] will consume 0.0065 W at 10 Hz PRF for bursts 10 pulses long. In case of passive return (Fig. 1) this value would have been 5 W. Power economy is evident. In addition, since the power delivered to the mechanical part (radiation) is tampered by the capacitance C_0 efficiency can be further improved if C_0 is compensated or its influence reduced. Sources [23–26] are more extensive on transducer matching.

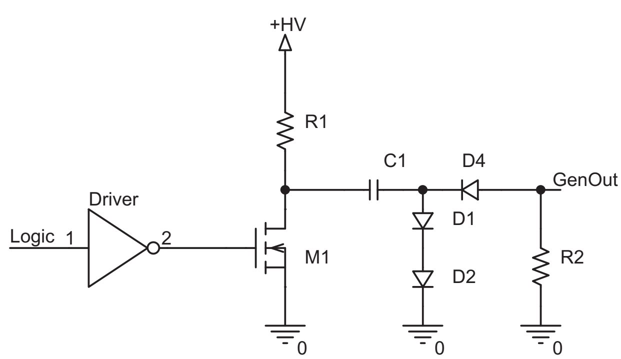

Fig. 1. Pulser with one active component.

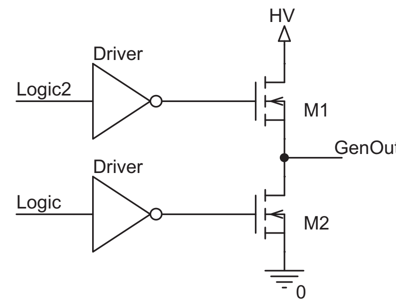

Fig. 2. Half bridge pulser contains two active elements.

3. Pulser design

If voltage to be delivered is relatively low (below 100 V), plenty of solutions [27–33] and even commercially available IC's exist [34–37]. But we need a 1000 V excitation voltage. Then number of unipolar solutions is limited [10,14,15,38]. Fortunately, modern MOSFETS and IGBT transistors are able to operate at such voltages and deliver sufficient current [39]. Analysis presented below was aimed to select the suitable switch elements.

Assuming that exciting signal bandwidth is limited only by signal rise time, t_r one can obtain maximum frequency for such generator operation [40]:

$$f_{\max} = \frac{1}{\pi \cdot t_r}. \quad (4)$$

When load is a capacitor the rise time is defined by two processes: constant current charge (beginning of the charging cycle, when MOSFET is above its peak current I_{Dpeak}) and constant voltage charge through drain-source resistance R_{DS} (when current is below I_{Dpeak}). Transition of these modes occurs at voltage

$$V_{tr} = V_{\mathrm{HV}} - I_{Dpeak} R_{\mathrm{DS}}. \quad (5)$$

Total rise time is constituted by time spent in constant current charging mode

$$t_{cc} = \frac{V_{tr} C_0}{I_{\mathrm{Dpeak}}}, \quad (6)$$

and time spent in constant voltage charging mode

$$t_{\mathrm{RC}} = -R_{\mathrm{DS}} C_0 \ln\left(\frac{V_{\mathrm{out\,max}} - V_{\mathrm{HV}}}{V_{tr} - V_{\mathrm{HV}}}\right), \quad (7)$$

where $V_{\mathrm{out\,max}}$ is the pulse convergence amplitude, 99% of V_{HV}. Solving (4), (6) and (7) for I_{Dpeak} and R_{DS} versus C_0 at 1 MHz maximum frequency (Fig. 3).

It can be seen that for 5 nF transducer it is complicated to achieve 1 MHz maximum frequency: such high voltage MOSFETs hardly achieve peak current above 10 A. Fortunately, such high capacitance is possessed by very low frequency transducers (41 kHz, [15]). The conventional, around 500 kHz frequency transducers have 500 pF capacitance. After Fig. 3 results analysis it was decided to use STW3N150 MOSFET which has 10 A peak drain current and 6 Ω typical drain resistance and can withstand 1500 V [39]. This switch will ensure good coverage for all transducers considered with sufficient reserve for temperature effects. The half bridge topology (Fig. 2) with both upper and lower switch using N-channel MOSFET is the best candidate for air coupled ultrasound pulser design. Problem associated with such topology is the MOSFET drive: upper switch has to be driven by middle-point referenced driver. Performance of low side MOSFET drivers is impressive [41]: rise/fall fronts of 1 ns order can be obtained. But performance of modern high side drivers is limited either by oper-