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Traveling wave piezoelectric transformer for multi-level insulated gate-driver power supply

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Abstract

The traveling-wave piezoelectric transformer (TWPT) is a new topology of piezoelectric transformer providing a multi-phases system of voltages at its output. The inherent galvanic insulation of piezoelectric transformers makes them particularly suitable for insulated gate-drive power supply applications. In this paper, we use the TWPT with several phases to generate the different insulated voltage rails required for the driving of a multi-level inverter leg. The insulated gate driver power supply including the TWPT is presented and experiments are performed to drive the power MOSFETs of a half-bridge. The TWPT and the circuit associated generates a bipolar voltage level +15 V/-15 V up to 500 kHz switching frequency.

1 Introduction

Strong emphasis is put currently on the development of multi-level cascaded power inverters. By reducing the constraints on switching elements, it allows replacing high-voltage transistors by multiple lower voltage ones [1]. However, with the number of transistors increasing, the number of gate drivers and their complexity also increase. Especially, the need for insulated power supply for the driver is of particular importance.

The galvanic insulation for gate-drive circuits is generally provided by magnetic coupled transformers [2]. However piezoelectric transformers have found a particular interest thanks to several inherent advantages: low electro-magnetic radiation, high efficiency and for the application considered: high voltage withstand and strong galvanic insulation [3].

The interest of piezoelectric transformers in gate-drive circuits has focused on standing wave piezoelectric transformer to convey the electro-mechanical conversion [4], [5]. This type of behavior limits the transformer to three electrodes and in practice we need one piezoelectric transformer to perform insulation for each gate-

drive circuit which limits their application to multi-level converters.

We have proposed a new topology of piezoelectric transformer that uses a traveling wave instead of a standing wave [6] as shown in Fig.1. The limitation of standing waves in piezoelectric transformer arises from the fact that the wave present nodes and antinodes that limits the number of position of

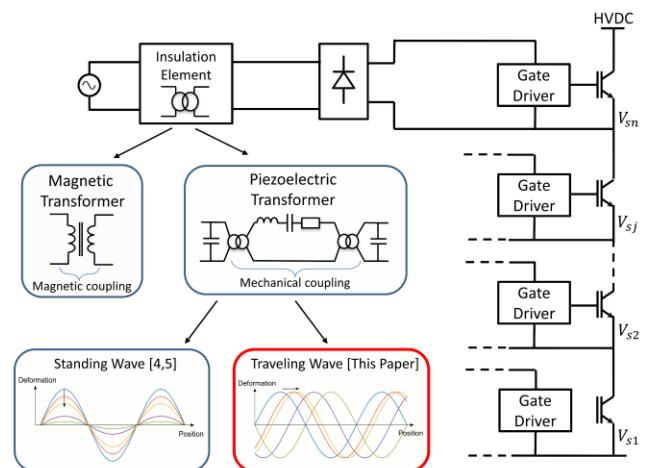


Fig. 1: Solutions for the insulation of multi-level gate-drive power supply

electrodes usable on the transformer for maximum power conversion. In the case of a traveling-one, the mechanical wave presents the same maximum amplitude but propagates. Thus, when the wave passes over electrodes, the voltage amplitude will remain the same for all electrodes but with phase-shift depending on their position. Thus, we can obtain a polyphaser system of voltages at the output of the transformer with a travelling wave. These different phases can then be rectified at the secondary side to generate the multiple insulated power supply for the gate-drivers. There are no theoretical limits to the number of phases and output voltages obtainable with this topology apart from the power considerations. Thus, the traveling-wave piezoelectric transformer (TWPT) can be suitable for multi-level converters drivers.

In this paper, we will firstly present the traveling wave piezoelectric transformer, its operating principle and its performances. Secondly, we will focus on the topology of the insulated gate-drive power supply using the traveling wave piezoelectric transformer. In the following part, we will present the experimental results obtained with this structure on a resistive load and supplying directly drivers. Finally, we will discuss the results and present perspectives of improvement.

2 Operating principle of the traveling wave piezoelectric transformer

2.1 Geometry and generation of the traveling wave

In order to generate a traveling wave in a piezoelectric ceramic, a solution mainly used in ultrasonic motors is to use a cylinder or ring geometry [7]. As the traveling wave propagates along the circumference of the ring, there will not exist any reflection on the boundaries of the medium that would allow the generation of a standing wave. The interest of using this geometry is also to work at the resonance of the ceramic element to benefit of low-loss conversion and maximize the power transfer. In Fig. 2 we show the chosen geometry which consists in a hollow thin cylinder. The electrodes on the interior and exterior surface allows to apply the input voltages for the wave generation and to obtain the output voltages. In the following, we will consider one voltage is applied between two electrodes directly

facing each other on the interior and exterior surface.

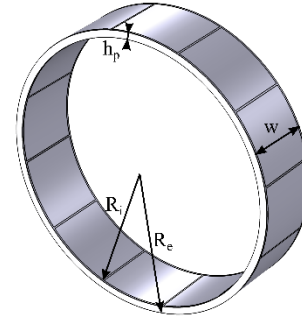


Fig. 2: Geometry of the traveling wave piezoelectric transformer

The generation of the traveling wave needs a particular electrode scheme. Indeed, mathematically, a traveling wave is the sum of two standing waves with a $\pi/2$ phase shift and a $\lambda/4$ displacement between them as shown in equation (1), λ being the wavelength of the wave.

$$\begin{aligned} h(x, t) &= U \cos(\omega t) \cos\left(\frac{2\pi x}{\lambda}\right) \\ &\quad + U \sin(\omega t) \sin\left(\frac{2\pi x}{\lambda}\right) \quad (1) \\ &= U \cos\left(\omega t - \frac{2\pi x}{\lambda}\right) \end{aligned}$$

Thus, in order to obtain the traveling wave, we must generate those two standing waves. The generation of a standing wave is done by applying voltage between electrodes. The electrode scheme is shown in Fig. 3. This electrodes scheme allows for the generation of the third mode of resonance shown in Fig. 4 with a minimum of 12 electrodes. The electrodes are separated into three sets. The input electrodes A are responsible for the generation of the first standing wave while electrodes B generate the second wave. The remaining electrodes are outputs. The number and size of outputs determine the number of phases at the secondary side. In this case, we will obtain a four-phase system.

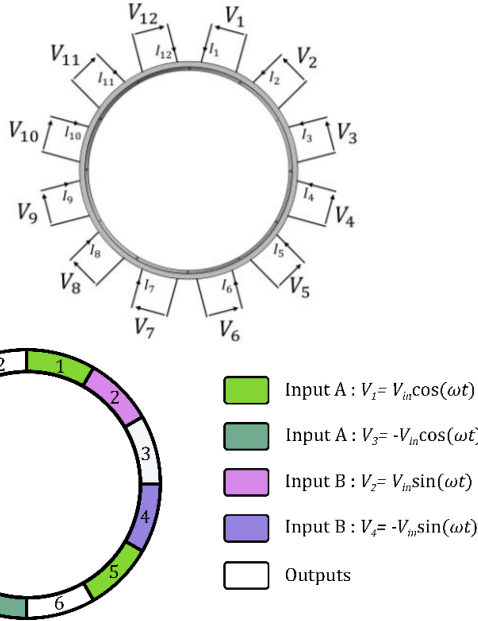


Fig. 3: Electrode scheme for the generation of the traveling wave

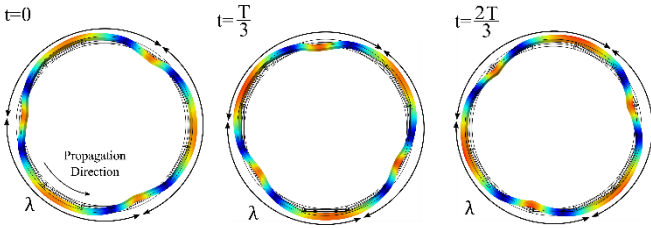


Fig. 4: Third mode of resonance

2.2 Experimental results of the traveling wave piezoelectric transformer

The designed piezoelectric transformer is shown in Fig. 5 with its PCB interface. This piezoelectric transformer was designed for the validation of the concept of TWPT. Thus, it was not optimized for the particular operation of gate-drive power supply. The piezoelectric material is PZT and the geometric properties are summarized in Table 1.

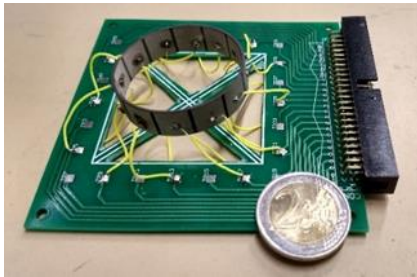


Fig. 5: TWPT with its interface PCB

Table 1: Geometrical parameters of the TWPT

Parameter	Value	Units	Notation
External Radius	20	mm	R_e
Internal Radius	19	mm	R_i
Width	10	mm	w
Thickness	1	mm	h_p

In Fig. 6 we show the circuit responsible for the generation of the input voltages. A function generator generates the two synchronized input signals with a $\pi/2$ phase shift to follow eq. (1). Operational amplifiers TL081 in inverting configuration allow to generate the opposite voltages. They are then amplified by linear audio amplifiers LM1876.

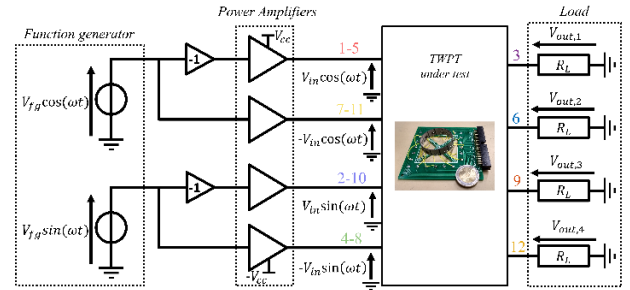


Fig. 6: Circuit for the generation of the input voltages

We represent in Fig. 7 the output voltages with the electrode command scheme of Fig. 3. The output electrodes are loaded with 2.2 k Ω resistors. The operating frequency is the resonant frequency $f = 84$ kHz. We see that we obtain the expected multi-phase system of voltages electrodes with the traveling wave behavior.

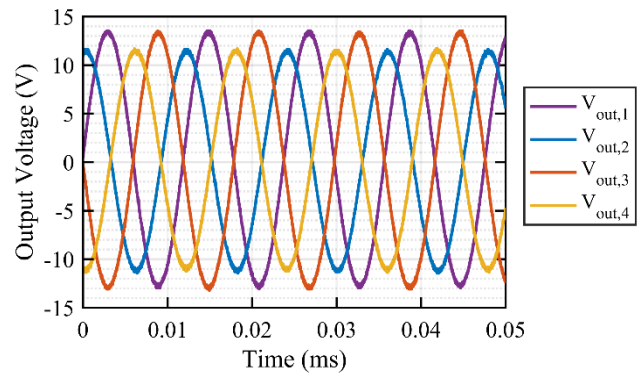


Fig. 7: Waveforms of the output voltages of the TWPT

3 Insulated Gate-Drive Power Supply Circuit Topology

The traveling wave piezoelectric transformer presents the same inherent advantages than classic topologies of piezoelectric transformer for insulated gate-drive power supply. However, the main interest of this topology is to output a multi-phase system of voltages at the output with each set of output electrodes insulated between each other. For this particular operation, it presents two main interests. In Fig. 8 we show the overall circuit for the generation of the insulated supplies. The first interest is thus to separate the different phases at the secondary side to supply different gate-drivers. In the example, we have four phases at the output but it is possible to increase either the number of phases available by dividing each output electrode in two or to obtain more instances of the same phases. There is a trade-off between the number of outputs and the power that the piezoelectric transformer is able to supply for a given topology of the device (height, diameter, thickness).

The second interest of the circuit proposed lies again in the number of phases available at the end. We choose to separate the four-phase system into two to have two phases for each gate-drive power supply. This separation combined to the proposed topology of two-phases full wave rectifier allows to generate the positive and negative voltages needed for the drive of the transistors. Furthermore, the use of several phases allow

limiting the size of the decoupling capacitors at the output of the rectifier.

4 Experimental results for the TWPT insulated power supply

For the test of the insulated power supply, we choose the same configuration for the generation of the traveling wave as presented in Fig. 3. Thus, we will obtain four output voltages that we separate into two to supply two drivers as represented in solid line in Fig. 8.

4.1 Measurement with a resistive load

Firstly, we tested the proposed topology with a resistive load at the output of the rectifier. The aim of this experiment is to determine the power that can supply the piezoelectric transformer to the driver. We set a power consumption of 1 W for each driver and the circuit must provide a bipolar voltage level of +15 V/-15 V. In order to emulate this power consumption, we plug a load resistance $R_L = 470 \Omega$ in parallel with each output capacitor. The generation of the TWPT input voltages is the same as presented in section 2.2.

In order to reach the desired voltage level, we can adjust either the operating frequency of the piezoelectric transformer or the amplitude of the input voltages. We measured the input power directly at the input of the piezoelectric transformer after the electrode driving circuit (the efficiency of the amplifiers are not included). The output power is directly measured after rectifying. In Fig. 9 we

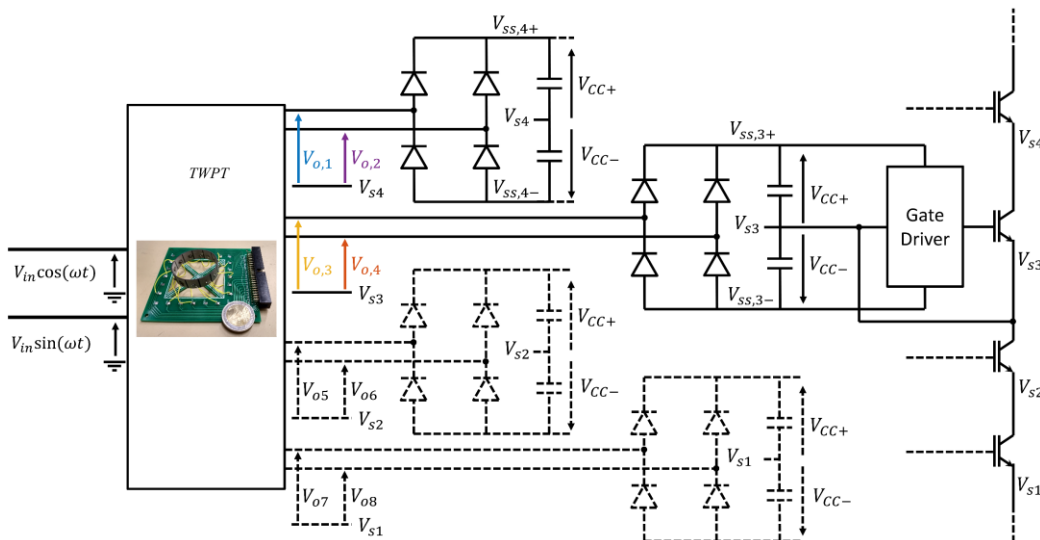


Fig. 8: Topology of the generic insulated voltage supply for the gate-driver.

represent the power at stake for different operating frequencies and the input voltage amplitude that allows to reach 15 V at the output.

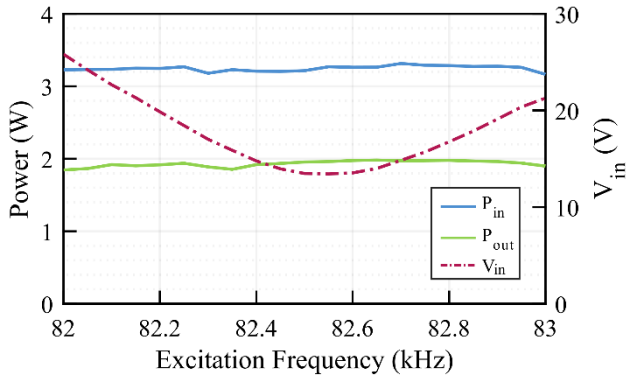


Fig. 9: Input and output power and input voltage amplitude of the TWPT + rectifier circuit.

The output power remains constant at 2 W whereas the input power is 3.3 W corresponding to the design constraints we set. This leads to an overall efficiency of the TWPT and the rectifier of 60 %. It is noticeable that variations of the excitation frequency around the resonance do not influence the power performances of the circuit. Only the input voltage can be controlled to insure the supply voltage reaches the aimed value. With this experiment, we show that the TWPT can provide the power needed to supply drivers. However, the input currents of gate drivers are not constant with peak during switching and we need to study the dynamic behavior of the insulated power supply.

4.2 Measurement on a half-bridge

Consequently, we tested the proposed topology to supply gate-drive circuits themselves responsible for the switching of a MOSFET half-bridge. The

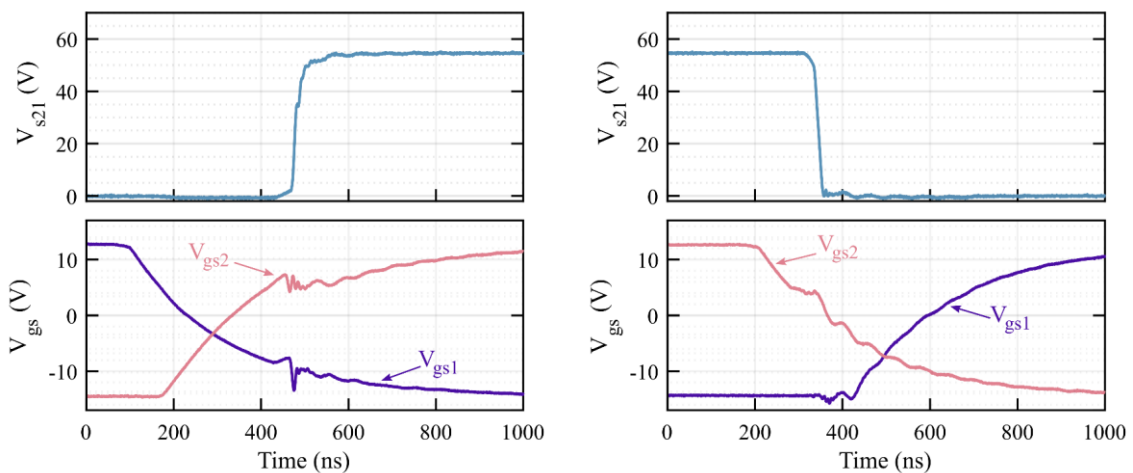


Fig. 10: Voltages V_{s21} and V_{gs} during the switching-on and off of the half-bridge.

complete scheme of the insulated gate-drive power supply is shown in Fig. 11. The inverter leg consists in an ITF14019 half-bridge package containing two 150 V voltage-ratings power MOSFETs. The insulation of the command of the gate is performed by optocouplers A3120 and the gate resistances R_g are 220 Ω . The supply voltage for the half-bridge V_{DD} is 55 V and the current I_L is 1.5 A.

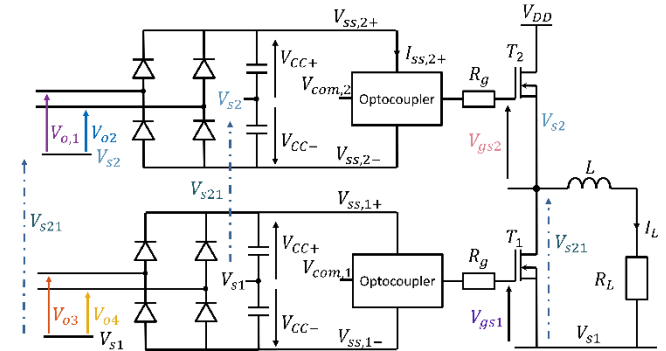


Fig. 11: Waveforms of the output voltages of the TWPT

Firstly, we focus on the behavior of the half-bridge at a switching frequency of the power MOSFETs of 150 kHz. The dead-times between the switching are fixed at 200 ns by an extra circuit on the board not represented on the scheme. The TWPT is operating at 83.5 kHz. This frequency is higher than representing in Fig. 8 as the output power of the rectifier is different, changing the resonant frequency of the TWPT. The amplitudes of the input voltages of the TWPT are set to obtain $V_{cc} = 15$ V. The experimental waveforms are presented in Fig. 10 for the switching from high-to-low and low-to-high of the voltage V_{s21} . The routing of copper tracks allows the limitation of the parasitic inductance to obtain clean waveforms (i.e. without ringings). During the switching-up the transistors

are subject to maximum $3.3 \text{ kV}/\mu\text{s}$, and to maximum $2.65 \text{ kV}/\mu\text{s}$ during the other phase with no critical influence on the gate voltages.

In Fig. 12, we also represent the voltages V_o directly at the output of the transformer. We find the multi-phase system of voltages that we expected. Moreover, compared to Fig. 7 the phases are better balanced, which leads to equivalent supply voltages value. Furthermore, we notice that when changing the power leg duty cycle, the changes on the supply voltage are negligible.

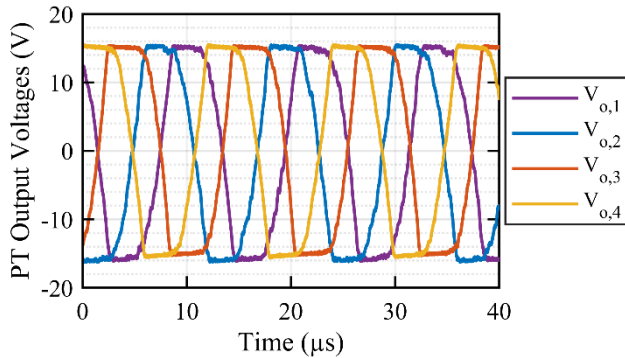


Fig. 12: Waveforms of the output voltages of the TWPT

After studying the behavior at a particular frequency, we wanted to test the performances of our TWPT insulated power supply. For this purpose, we measured the power at the input of the piezoelectric transformer and the power at the output of the rectifier supplying the optocoupler. Thus we can directly obtain the efficiency of the circuit TWPT+rectifier. In this experiment, we keep the same operating frequency of 83.5 kHz for the different measurements but we vary the power leg switching frequency of the power stage. For each measurement, the amplitude of the input voltages of the TWPT are set to provide desired supply voltage to the optocoupler. In Fig. 13, we represent the input and output power and the efficiency of the circuit. As expected, when increasing the power leg switching frequency, the power consumption increases. Up to 200 kHz , the efficiency remains constant around 73% with power consumption under 600 mW for the two gate-drive circuits. When the switching frequency increases more, the power grows then quickly and the efficiency drops down. Comparing to the results of Fig. 8, we see that the efficiency is very much related to the power provided by the TWPT.

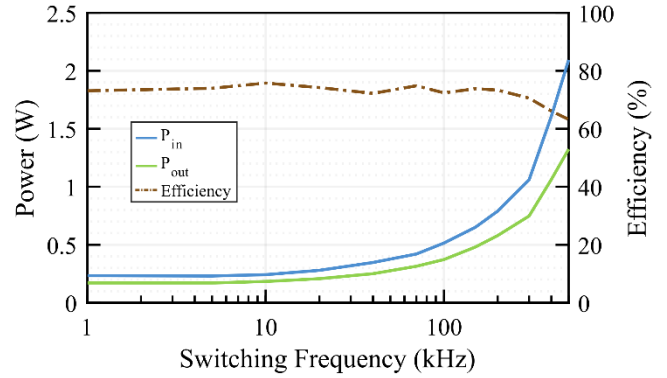


Fig. 13: Power and efficiency of the couple TWPT + rectifier as a function of the switching frequency of the half-bridge

5 Discussion and Perspectives

The experimental performances of the proposed circuit for insulated power supply are encouraging. Indeed, we tested the circuit for supplying the gate-drives of two transistors in a simple half-bridge. At the frequency tested of 150 kHz , the power consumed by the two drivers is equal to 500 mW . Moreover, we also proved that the circuit can provide up to 2 W to resistive loads. Thus, we can expect that the circuit could supply insulation and power for many more drivers simultaneously, e.g. for multi-level converter applications or a full-bridge. With this TWPT, the four outputs were combined to supply two drivers. However, it is also possible to use these four outputs to supply four drivers depending on the power considerations. The input/output configuration can also be modified with four inputs and eight outputs as shown in Fig.8 but the critical aspect is still the power that can provide the TWPT.

Nonetheless, a global optimization of the circuit still needs to be done. As we stated in section 3.3, the interest of the TWPT is to provide several phases to allow for polyphaser rectifying. Thus, a reduction of the size of the decoupling capacitance is possible that was not the point of interest here. As stated, the number of output phases can be much higher and thus the decoupling capacitances could be reduced further. Moreover, the transformer was firstly conceived to validate the concept of the traveling wave and not optimized for this application. Thus, there exists strong parasitic capacitances between side-by-side electrodes (up to 110 pF) Even in these conditions, the TWPT insulated power supply performs well thanks probably to the symmetrical configuration of the electrodes used in this application. However, this would need to be reduced. A global design of the transformer is possible to reduce its size and

increase the efficiency and power. Different parameters have an influence on the performances: the geometry, e.g. ring instead of cylinder, the piezoelectric material, the electrode scheme, the input/output configuration. A modelling of the TWPT has already been done in [8].

6 Conclusion

In this paper, we propose the use of the traveling wave piezoelectric transformer as an insulated gate-drive power supply. The circuit consisting of the TWPT and its rectifier has been tested and can supply a bipolar voltage level of +15 V/-15 V to the two drivers of a power half-bridge with switching frequency as high as 500 kHz. In these conditions the converter supply 1.3 W to the drivers but when supplying resistive loads, the power delivered is as high as 2 W.

The generic topology for the use of the TWPT in multi-level converters is also presented. Following the experiment results, we can expect the designed TWPT to supply at least four drivers for switching frequencies lower than 200 kHz. A global optimization of the circuit and especially of the TWPT is still yet to be done to increase the performances of the proposed topology.

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