Piezoelectric Transformers to the Future Integrated IGBT Gate Drivers

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Abstract
In the coming area of ubiquitous computing, nanotechnology, increasingly compact or miniaturized power sources and preferably mobile & satellite systems are expected. In this paper, the application of piezoelectric transformer as a recent complementary gate driver for field-effect transistors with metal oxide and insulated gate bipolar transistors is presented. The proposed piezoelectric transformer has a high integration ability. A new design method has been mentioned based on an analytical Mason model in such a way to enhancing working efficiency, the available power at the transformer secondary ends, and the overall volume of the system. Proposed method of design considered mechanical losses and heating of the piezoelectric material. It can be comprehensive to forecast the quality of the PT: gain, transmitted power, efficiency, and heating of piezoelectric materials as changes of resistive load.

Index Terms : IGBT, PET, IIGBT, PT.

1. INTRODUCTION
At present, the inclination in Power electronic hardware is to incorporate the segments on a solitary substrate with a specific goal to reduce the volume of equipments and especially its thickness. The electrical protection limitation of gate drive circuits for present day power electronic switches turns out to be, therefore, extremely solid. Normally, transformers are utilized to accomplish this protection. Their assembling requires a winding procedure, which expands the assembling cost, as well as denies the full automation of the mounting procedure. This is advantage has prompted research efforts on planar electromagnetic transformer and inductor wound on a printed circuit board [1]–[2].

In any case, the assembling of these structures is intricate, and sometimes the galvanic insulation is achieved by air circulation. Circulation of air can limit the rigidity of dielectrically material. In addition, the winding acts like a receiving wire and transmit electromagnetic (EM) fields, which actuate electromagnetic instruction (EMI) issues.

This work focuses on to explain the utility of piezoelectric transformers for obtaining efficient and integrated electrical insulation. PTs have several inherent advantages over conventional magnetic transformers: low profile, low cost, low EMI, no winding, high efficiency, high power density, high operating frequency, and they suited for automated manufacturing.

The use of a high rigidity dielectric material means it has very high insulation quality. The dielectric breakdown field can be greater than several kV/mm. So that, a Piezoelectric transformers send electric energy through a coupling of electromechanical (i.e., acoustic wave) between the primary for step-up or step-down or vice versa of voltage.

In a classical magnetic core transformer, this function is done by the magnetic flux, where secondary winding coupled with primary winding magnetically. Therefore, a piezoelectric transformer is advantageous regarding the
EMI. In a first approach[3], presented electric isolation of circuit drive the gate circuit used in the power electronic switches by use of Piezoelectric transformers such as metal oxide semiconductor field-effect transistors (MOSFET) and also for insulated gate bipolar transistors (IGBT) circuit. Feasibility was proved in the case of a single switch structure in such a way that the gate drive circuits are assumed to the ground of the power structure. The purpose of this complementary gate driver circuit is to get improved switching ability for both turn-on and turn-off operations in an inverter-leg structure. Schematic structure of the gate driver is presented in Figure 1.

The piezoelectric transformer is supplied at a steady frequency which is its mechanical resonance frequency. The driving signal is transmitted by pulse square wave balance. Signal is demodulated in the optional part of the driver by a demodulator circuit (full wave rectifier) which drives the force transistor matrix. In this paper, the outline technique for a PT gate driver is displayed. Taking into account an explanatory Mason demonstrate, this outline technique gives the insignificant geometrical size of a multilayer PT.

This analytical method is applied to predict the characteristics of the PT: gain, transmitted power, efficiency, and heating according to load resistance.

Results obtained from successful implementations of the PT in a complementary gate drive circuits in a low profile power converter are included.

Figure 1 Structure of gate driver [3]

Figure 2 Structure of the piezoelectric transformer match to the gate driver [5]

2. PIEZOELECTRIC TRANSFORMER (PT)

A. Principle

The optimal structure of the piezoelectric transformer for the gate driver is the multilayer one operating in thickness mode, as presented in Fig. 2. The functioning principle is based on a double electromechanical conversion of energy (reverses and direct piezo-electric effect). If we impose an alternating voltage on primary electrodes, an alternating vibration of the structure is generated which induces an alternating voltage at the secondary electrodes. An alternating vibration of the structure is generated which induces an alternating voltage at the secondary electrodes. Since PT depends on the transmission of an acoustic wave, it must work near the mechanical quality of the structure. The decision of the choosing of resonance model is depends upon the performance of the PT. An acoustic wave, proliferating from one end along the thickness of the structure toward the flip side will be reflected and will go back toward its source. On the off chance that different waves have as of now been made, the main wave will meddle with them as it goes through. At specific frequencies (called reverberation frequencies
or modes), this impedance produces standing waves. At particular purposes of the PT’s thickness, named hubs, the medium is dependably very still and at antinodes the wave large quantity is greatest. Hence, only the standing waves exist are obtained when the structure’s thickness is a whole number of the half-wave length $\lambda$. In the first mode called $\lambda/2$, the antinodes of the stress wave $T$ (i.e., maximum stress) is located in the insulation coating. In favour of the second form called $\lambda$, a maximum stress point exists in the middles of the two piezo-ceramic parts; a node is located between the insulation layers. While the existing energy is approximately proportional to the stress in the piezoelectric material, a highest stress has to be reminding in active parts for maximum efficiency [5]. In the case of the $\lambda/2$ mode the maximum energy is not used effectively. In addition, in the second mode, the base anxiety is arranged at the protection layer. Subsequently, vitality is created proficiently. Subsequently, we will pick operation in this mode. Fig. 3 demonstrates the vibration uprooting and pushes dispersions for the thickness-extensional vibration in second reverberation mode.

The piezoelectric material utilized for the essential and auxiliary plates is lead titanate polarized along the thickness. This material has the favourable position to display a high electromechanical coupling element in the thickness reverberation mode. The coupling is less noteworthy in pairing mode, which makes it conceivable to diminish the parasitic modes that may exist superposed to the principle mode. The second advantage of this material is that the Curie temperature is $490^\circ$ C compare to the PZT which is in the request of $328^\circ$–$365^\circ$ C.

Figure 3 Mechanical displacement and stress distribution for the second thickness mode [5]

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<tr>
<th>S. no.</th>
<th>Symbols</th>
<th>Name of symbols</th>
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<tbody>
<tr>
<td>1</td>
<td>$C_{33}^D$</td>
<td>Young Modules(N/m^2)</td>
</tr>
<tr>
<td>2</td>
<td>$\varepsilon_{33}^S$</td>
<td>Permittivity</td>
</tr>
<tr>
<td>3</td>
<td>$\varepsilon_{33}$</td>
<td>Piezoelectric coefficients</td>
</tr>
<tr>
<td>4</td>
<td>$\rho$</td>
<td>Density(Kg/m^3)</td>
</tr>
<tr>
<td>5</td>
<td>$A$</td>
<td>The Layer Area(m^2)</td>
</tr>
<tr>
<td>6</td>
<td>$e$</td>
<td>Layer Thickness(m)</td>
</tr>
<tr>
<td>7</td>
<td>$Q_m$</td>
<td>Mechanical Quality Factor</td>
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The accepted equivalent circuit model for PT has been developed [7]. This model is an electrical circuit, illustrative of properties displayed by two layers of piezoceramic physically coupled together. Figure 3 demonstrates the streamlined proportionate circuit model basic to every piezoelectric transformer. The RLC arrangement circuit speaks to the motional branch; it portrays the mechanical motions of the material. The input capacitance $C_1$ and yield capacitance $C_2$ describe the dielectric conduct of the piezoelectric layers of the transformer. The coupling between the electrical and mechanical branches is spoken to by the proportionate transformer (proportion $\psi$: 1).

**B. Transformer Design Equations**

Owing to the equivalent circuit model described above, heating considerations and material properties, the PT’s dimensions, and its electrical performances can be calculated. Table I contains the definitions of the various material coefficients. Equations (1)–(4), show the relationships between each material characteristic and geometrical dimension: input and output capacitances $C_1$ and $C_2$, the coupling ratio $\psi$, the mechanical branch capacitance $C_m$ and RLC series circuit, where $C$ is the total equivalent capacitance [7].

The last equation required in the design process is the heating equation. It defines the relationship between the transformer heating and the losses, is the PT efficiency

$$ R = \frac{1}{Q_m \sqrt{\frac{L}{C}}} \quad (6) $$

Transmitted power and efficiency are depending on the PT’s load [6] [7]. It is proposed to introduce variables representative of the quality of energy conversion. These new variables are shown in Table II. $Q$ is the electric List Item-1 quality factor, it is inversely proportional to the load resistance $R_L$. $Q_m$ is the mechanical quality factor, which characterizes the mechanical losses and “c” is a capacitance ratio, which characterizes the ratio between mechanical energy and electric energy that can be converted to secondary. It can be regarded as being the inverse of square of the secondary effective electromechanical coupling coefficient $K_{eff}$.

<table>
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<tr>
<th>S. No.</th>
<th>Equations</th>
<th>Significations</th>
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<tr>
<td>1</td>
<td>$\omega_s = \frac{1}{\sqrt{LC}}$</td>
<td>Series resonance frequency</td>
</tr>
<tr>
<td>2</td>
<td>$\omega_p = \omega_s \sqrt{1 + 1/c}$</td>
<td>Parallel resonance frequency</td>
</tr>
<tr>
<td>3</td>
<td>$Q_m = \frac{1}{RC\omega_s}$</td>
<td>Mechanical Quality Factor</td>
</tr>
<tr>
<td>4</td>
<td>$Q_e = 1/RC_2\omega_s$</td>
<td>Electrical Quality Factor</td>
</tr>
<tr>
<td>5</td>
<td>$C = \frac{C_1 \psi^2}{e_2 C_m e_1^2}$</td>
<td>Capacitive Ratio</td>
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3. **DESIGN GUIDELINES**

This part will depict the general design process of a two layers PT corresponding to our application. However, the designing concepts developed in this procedure can be extended to many others applications of piezoelectric transformers. Assumptions: The assumption consists of
exploiting the Mason model which does not take into considered the insulating layer place between the two active layers. However, this cannot be precisely done, because losses in the material are difficultly predictable. Consequently, the mechanical quality factor has to be estimated. Our previous studies showed that manufacturer values would have to be divided by a factor close to five in order to take into account all extra mechanical losses. Given:

- Physical properties of the piezoelectric material.
- Transmitted power $P_2$ at the secondary $P_2 = P_{DEM} + P_{MOS}$.

Is composed of the power required by the demodulation circuit (noted $P_{DEM}$) and the power required by the MOSFET/IGBT grid circuit.

$PMOS = V_G Q_G F$ (Where $V_G$ is the supply voltage of grid, $Q_G$ is the gate charge, and $F$ is the switching frequency).

- PT operating frequency $f_R$
- PT voltage gain.
- Temperature rise $\Delta \theta$

To be evaluated: The geometrical dimensions: thickness $e_1$ and $e_2$, area $A$. The general design steps.

1) On the basis of the condition of the effective frequency, may be evaluate the total PT thickness $e_{TL} = e_1 + e_2$.

2) On the basis of losses considerations (4) and using the expression of efficiency (3), we calculate the PT load operation point with respect to the accepted temperature rise $\Delta \theta$ and to keep the minimal size [8]. The two values of the electric quality factor $Q$ corresponding to the optimal load operational points are obtained.

3) The determination of the area $A$ and the thickness ratio $\psi$ consists to express power $P_2$ and $V_2/V_1$ gain according to $A$ and $\psi$, and to solve these two equations.

In (5) and (6), we replace resonance pulsation $\omega_R$ by the one contained in (3) and the quality factor $Q$ by the solution of (6). In these new expressions of $P_2$ and $V_2/V_1$, $c$ is a function of $\psi$. The dissipating area $S$ and losses resistance $R_e$ are functions of the area $A$.

4) This system has solutions only if the initial conditions are realizable, i.e., if the authorized heating is not too small for the desired power or if the gain is not too great. The thickness ratio value of primary and secondary layers must lie between 0.8 and 1.2. Actually, the transformer would not be able to work properly: a too thin layer could not put into vibration a thick layer. Equation (6) gives two solutions. The resolution of this problem must be done for the two values. Finally, the solution which gives the thicknesses ratio $\psi$ in the range defined previously (closest to 1) must be retained.

4. CONCLUSION

This paper demonstrated the possibility of using piezoelectric transformers to realize an IGBT or MOSFET inverter-leg driver. First, we have highlighted the process to choose a PT structure well suited to gate driver applications. It was shown that the multilayered structure was preferred and that a suitable piezoelectric material is lead titanate. The PT must be supplied at its resonance frequency and must work at its loaded operating point. The choice of the PT second resonance mode has been carried out to minimize constraints in piezoelectric assembly layers.
REFERENCES


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