A Study on Properties of Piezoelectric Ceramic Transformers

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압전 세라믹 변압기 특성에 관한 연구

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Abstract   In this paper, it is reviewed is to acquaint a circuit design with features of piezoelectric ceramic transformers(PT) and to show the general approach to the design of inverters utilizing PT as a circuit element. The description of the piezoelectric effect is not present here and can be easily found in numerous publications as well as complex equations and formulae. What is the most important to understand is that "they are different" ¬one cannot just change an electromagnetic transformer (EMT) for a piezoelectric one. Several examples of PT-based circuitry will help to start and use PT's advantages most effectively.
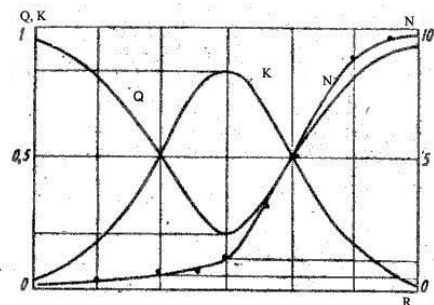
요 약   본 논문은 압전 세라믹 변압기(PT)의 특징과 회로 설계를 제시하였다. 그리고 회로 요소로써 사용하는 PT는 인버터 설계의 일반적인 접근법을 보여주기 위한 것이다. 또한 압전기 영향의 기술(記述)은 다수의 연구에서 복잡한 방정식과 공식도 쉽게 찾을 수 있다. 특히 압전기 세라믹 EMT가 변화하지 않으며 PT기초 전기소자의 여러 가지 예는 더욱 효과적인 PT의 강점을 이용하는데 도움이 될 것이다.

Key Words : Electromagnetic Transformer(EMT), High-Voltage, Piezoelectric Actuator

1. Introduction

Piezoelectric transformers can be used in the same applications as usual electromagnetic transformers but the most perspective are high output voltage low power applications and low output voltage, low and middle power (up to 50W) applications. Further on we will speak mostly about high-voltage piezoelectric transformers (HVPT). In comparison with electromagnetic transformers (EMT) they have some inherent features which should be kept in mind while developing schematics of inverters using HVPT. The most important for a circuit designer is the resonant frequency response of a PT. The Q factor, step-up ratio N, resonant frequency and efficiency K of a PT vary with the load resistance. Typical dependences are shown at fig.1 and fig.2.
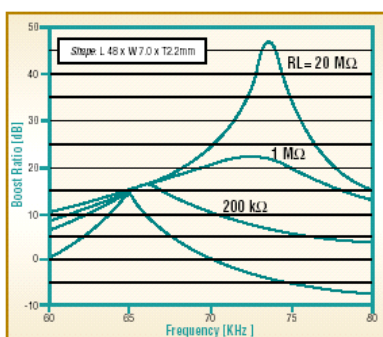

[Fig.1] Typical dependences of Q factor, efficiency K and step-up ratio N from the load resistance [1].
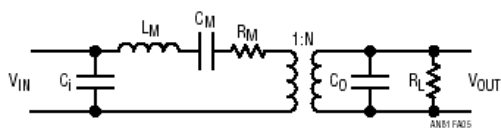
[Fig.2] Typical dependences of step-up ratio on frequency [2].
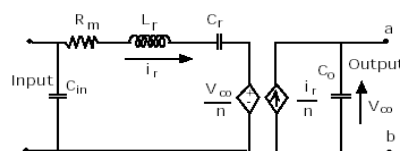
1.1 Main features of PT

Therefore there are two main problems facing a circuit designer. The first is that the inverter has to operate close to the resonant frequency of the PT even when the load resistance may change. It is necessary to obtain maximum step-up ratio and efficiency. The second is that maximum efficiency for a given PT (the dimensions of the PT are fixed) can be obtained only in a certain range of load resistance. In other words for different loads different PT should be developed. The equivalent circuit model of a PT is shown at the fig.3.

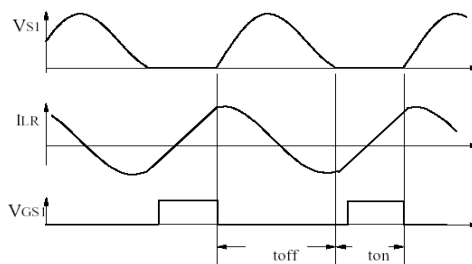[Fig.3] Piezoelectric transformer equivalent circuit model.

The parameters of the model are usually given by the manufacturer or can be measured as shown in [3]. It should be kept in mind that this is the idealized model which is valid only in the vicinity of the resonant frequency. In fact a PT has several resonant frequencies, so-called harmonics. For every harmonic parameters of the model are different. Usually the first (so-called λ/2-mode, where λ is the sound wavelength in ceramic) or the second (λ-mode) harmonics are chosen, because the efficiency and step-up ratio is maximal in this case and decrease quickly with the increasing number of a

harmonic. In a practical circuit changes in drive level or load characteristics may induce "mode-hopping" that is jumping to other harmonics. So it is necessary to undertake special measures to avoid such jumping. Another important feature is the capacitive input and output impedances of PT. That means that DC current cannot flow through the input or output terminals of PT, though the equivalent circuit model shows it. The more correct model is proposed in [4] and shown at fig.4. The result is that different topology of input driver and output rectifier is used unlike EM transformer.

[Fig.4] Another equivalent circuit model proposed in [4].

The input driver includes an inductor as a rule. Another reason for this inductor is to match the driver with a PT for maximum efficiency as shown in [3]. The output rectifier which is usually built as a voltage multiplier must contain even number of diodes (2, 4, etc.). Finally it's important that PT has polarity. That means that if the input voltage contains DC component, like in the case of single-ended driver (fig.5), it is necessary that positive DC polarity be applied to the "+" electrode of PT. Otherwise the output voltage significantly decreases. Generally it is better to avoid applying DC voltage to PT. In the case of sine input voltage (no DC component) the polarity of PT does not matter.

[Fig.5] Single-ended driver wave forms (note that PT input voltage Vs1 contains DC component).
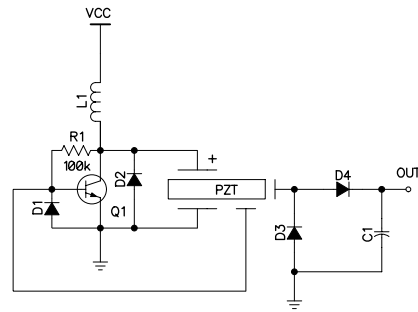
2. Piezoelectric inverters schematic examples

All high-voltage applications of PT may be divided into two groups. The first group has relatively high load resistance – more than tens and hundreds mega ohms. It is typical for image intensifier tubes, ionizers, air cleaners, low power ozone generators, photo multipliers, laser printers and so on. The output voltage can be $1 \sim 6kV$ and the load current not more than $0,1 \sim 0,5mA$. As the operating mode is close to "no load" the step-up ratio and Q-factor of a PT are maximal which can be seen from the fig.1. Another group are relatively "high-current"power supplies with output current several milli amps and output voltage $300 \sim 600V$. And the typical value of load resistance is $100 \sim 300kOhm$. The most popular application of PT nowadays is low profile power supplies for CCFL (cold cathode fluorescent lamp) backlight of LCD displays. Typical specifications of such kind of inverter are in the table 1 [2]. To achieve the maximum efficiency the piezoelectric transformer must be developed specially for every value of load (a lamp type). The step-up ratio is relatively small in this case $(5 \sim 10)$ and the Q-factor is minimal (fig.1).

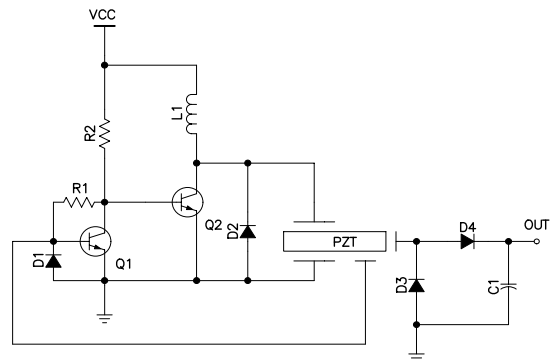[Table 1] Typical specifications of CCFL power supplies [2].

TAMURA PART NO.	INPUT VOLTAGE RANGE	CONTROL VOLTAGE REQUIREMENT	MINIMUM NO LOAD OUTPUT VOLTAGE	OUTPUT CURRENT	MAXIMUM OUTPUT POWER	OPERATING FREQUENCY	DIMMING	H x W x L (mm)	Weight (grams)
HBL-0217	3.0V~5.5V	5V ± 10%	800Vrms	1.1mArms	0.4W	160 KHz	PROVIDED	9.0 x 9.4 x 103.95	4.46
HBL-0210	3.0V~5.5V	5V ± 5%	900Vrms	1.8mArms	0.38W	160 KHz	PROVIDED	8.9 x 9.0 x 59.5	4.14
HBL-0204	3.0V~5.5V	5V ± 5%	900Vrms	2.0mArms	0.65W	160 KHz	PROVIDED	8.9 x 9.0 x 59.5	4.14
HBL-0214	4.5V~5.5V	N/A	1200Vrms	4.0mArms	3.00W	70 KHz	PROVIDED	5.0 x 12.5 x 142.0	11.90
HBL-0215	4.75V~5.25V	N/A	700Vrms	1.5mArms	0.60W	160 KHz	PROVIDED	4.3 x 23.0 x 46.9	3.63
HBL-0218	5.0V~10.0V	N/A	1080Vrms	2.4mArms	1.20W	160 KHz	PROVIDED	6.4 x 9.0 x 56.4	2.61
HBL-0219	8.0V~14.0V	N/A	1300Vrms	3.8mArms	2.20W	100 KHz	PROVIDED	7.4 x 13.6 x 118.0	7.97
HBL-0216	9.0V~15.0V	N/A	1250Vrms	3.7mArms	2.5W	100 KHz	PROVIDED	5.0 x 12.0 x 138.0	8.77

Speaking about the first group of applications the easiest and cheapest way is to use a self-oscillating circuit like shown at fig.6. The positive feedback is provided by capacitive antenna (it may be a bracket or a printed trace located neat the output end of a PT). The inductor L1 should be matched to obtain the maximum output voltage. In this case it is in fact a single-ended quasi-resonant inverter. It's wave forms are similar to those at fig.5.
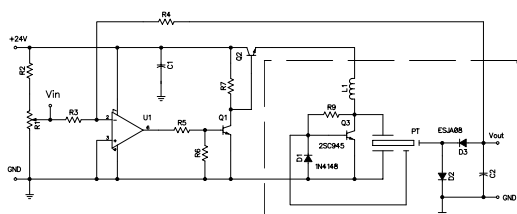

[Fig.6] Single-ended one-transistor inverter.

It should be noted that this simple inverter works well only when the Q-factor is high enough. In other words – when the load is $40 \sim 50$ MOhm and more for the most often used PT's. Changes in load resistance (for example a breakdown in an air cleaner) may cause mode-hopping that is oscillation at the other harmonic with low output voltage. The next two-transistor inverter (fig.7) behaves a little bit better due to the higher amplification in the feedback loop. The other advantage of this circuit is that the antenna should be placed not near the end of PT but at the L/4 distance from the end, where L is the length of PT. So it is easier to provide the high-voltage isolation. In some cases the mounting bracket may serve as an antenna.
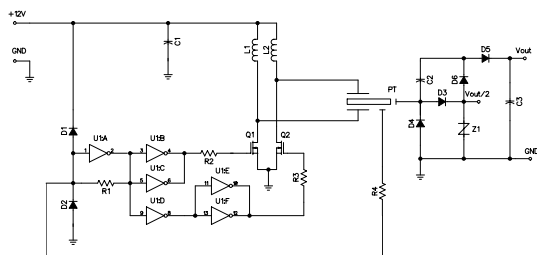

[Fig.7] Two-transistor inverter.

For stabilizing and regulation of the output voltage or current usual voltage/current feedback circuits can be used. The regulating element may be linear as shown at fig.8 or pulsed boost converter

[Fig.8] Regulated self-oscillating inverter.

To improve the load characteristic of a PT-based inverter a push-pull or totem-pole drivers can be used. In this case the input voltage of PT is almost sine which also improves the efficiency. The circuit shown at the fig.9 includes the push-pull drive stage and the pre-amplifier built on the CMOS gates (CD4069). Another feature of this inverter is the varistor Z1 which is used for the stabilizing of the output voltage. As its capacitance is high enough (about 100pF) there is no need in a capacitor connected to the Vout/2 output.

[Fig.9] Push-pull inverter for air cleaner.

The pre-amplifier together with the high-side driver is built on the IR2109 microchip. The transformer T1 solves tree problems at once:

1. It's inductance is necessary for the matching.
2. The step-down voltage ratio helps to apply necessary input voltage to the PT (310Vp-p is too high for the PT used).
3. It enables galvanic isolation of the ozone generator from the power line.

3. Conclusion

At last the third approach is to use voltage controlled oscillator(VCO). In this case two tasks are solved simultaneously. The voltage or current feedback controls the VCO frequency so that an inverter operates as close to the resonance as it necessary to obtain the desirable value of voltage/current. Such inverters have two modes of operation. The first is the search ofthe resonance – initial frequency at start-up is usually higher than the resonant one and then it gradually decreases until the preset value of output parameter obtained. Since then the inverter operates in the normal mode when the feedback compensates possible changes of output voltage or current by means of changing the operating frequency.

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