DESIGN AND MODELING OF THE STEP DOWN PIEZO TRANSFORMER

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Abstract

The energy conversion and the step down voltage waveform of the piezo transformer are required to achieve optimal working condition of the resonant frequency. To meet this requirement, a reliable and precise instrument is needed to scan the resonant point of the piezo transformer such that its output power performance can meet the required specification.

In this paper, the design and model of a new step down piezo transformer deployed in NSRRC is described. This step down piezo transformer is capable of delivering energy conversion with high efficiency performance, which is better than traditional transformer, and the voltage transfer ratio is correct. Using the simulation circuit model to develop driver circuit of it is also included in the design of this new step down transformer. It has been tested and proven to be working well in power conversion with excellent efficiency and reliability.

INTRODUCTION

The plan developed in our research is hoping to improve the control power stage of the magnet power supply: it changes the way of conversion energy in the power supplies with traditional 60Hz current transformer to the switching mode ones using the step down piezo transformer. This is a technique that converts the AC line source to the setting voltage as we expect, also analyses, and applies the characteristic of the piezo transformer. Various kinds of characters of piezo transformer are needed to understand in this study. For example, we need to calculate the resonant point of its circuit model with different behavior analysis to the entity, and then design the driver circuit of the step down piezo transformer. It somewhat differs from the common study of the booster piezo transformer, so all the essentials are considered in detailed discussion in this paper.

In order to improve the efficiency in this research, we have utilized a novel equipment to measure the resonant frequency and response point of the piezo transformer in frequency spectrum domain and calculate its equivalent circuit model and coefficient. According to the data mentioned above, we can smoothly design the switching mode PWM driver circuit. In this way, it can make the whole conversion efficiency significantly increase; however, these narrations are the main point of this paper.

MANUFACTURE AND TESTING

According to the physical characteristic of the piezo material, we make the prototype of step down piezo transformer, and its fundamental structure shows as figure 1. Its step down ratio is about 10:1, via design and test. In this suitable resonant region, it can produce the isolated energy power. If the way of figure 1 is connected via power amplifier, it frequency response is about at 50 kHz. The input and output resonant frequency response and testing diagram of the step down piezo transformer show as figure 2.

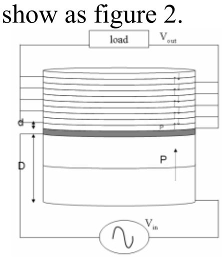

Figure 1: The prototype of the step down piezo transformer.

From figure 2, the diagram shows the input voltage of channel 1 is 21.6V (Vpp), and the operating frequency of the power amplifier is 49.46 kHz. The output voltage of channel 2 is 2.16V (Vpp) that the proportion is 10:1, and the operating frequency is the same as the input signal. There are no time delay and phase lag.

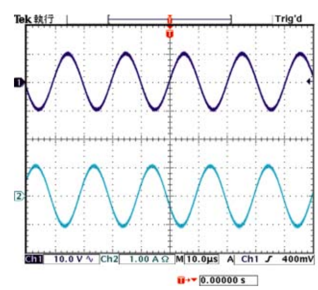

Figure 2: The resonant frequency-testing diagram of the step down piezo transformer.

The precision of the input frequency is quite important, especially in measuring the resonant reactions of the step down piezo transformer. Reading from the material reports and papers: the Qm value of piezo transformer is very high, but resonant region is very narrow. From the experiment, we understand the frequency response range being about 100Hz, and this is fairly different from traditional transformers. From the experimental method of figure 2, it can also verify that the energy is unable to produce any conversion if the non-resonant frequency excites the input of this transformer. Therefore, we can regard it as a band pass transformer. For that reason, it is more complicated to design the control circuit; nevertheless we can control the output power quality and noises. And there is no output power when frequency is out of the resonate band. This is another important advantage of using the piezo transformer.

RESEARCH AND MEASUREMENT EQUIPMENT

Viewing from the systematic research to analyze and measure the step down piezo transformer, the essential equipment is:

(1) Signal Generator: NF WF1946A
(2) High Precision Power Amplifier: NF HAS4052
(3) Oscilloscope: Tektronix TPS 2024
(4) Impedance Analyzer: Agilent 4294A

Agilent 4294A is an instrument measuring impedance relative to the change of frequency of the piezo transformer. It can make us find the impedance changing value in the frequency range we established. What we will look for is the minimum of impedance value Z produced by the piezo transformer, and it is also the maximum value of Y=1/Z. That is the resonant frequency of the piezo transformer and the optimal point of efficiency to produce energy.

After finding out the resonant frequency from the scan frequency by impedance analyzer, we can set the resonant frequency to the signal generator. Under the operating mode, specific energy waveform produced by power amplifier delivers to the primary connection of the piezo transformer. From the oscilloscope, we can observe the waveform and amplitude of the primary and secondary behavior for the piezo transformer. Certainly, the resonant frequency may drift a little, because high-energy excitation results in non-linear mode for the piezo transformer. Another situation, it's the influence produced by the load effect. These are what we should look for while measuring.

EQUIVALENT CIRCUIT MODEL AND SIMULATION

We use Agilent 4294A impedance analyzer to get the parameter of the equivalent circuit model. At first, we short the secondary characteristic, and then sketch the diagram of scan frequency versus impedance response of the primary characteristic for the piezo transformer. We can find out the maximum value for Y =1 / Z, which is the resonant point, as figure 3 shows.

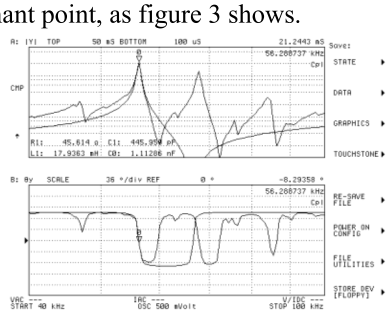

Figure 3: Impendence response diagram of the primary characteristic for the step down piezo transformer.

The main resonant point is at the position of 56.289kHz. The equivalent resonant circuit model is the most appropriate selection, which accords with Type E of the Agilent 4294A LCR simulation model, as figure 4 shows.

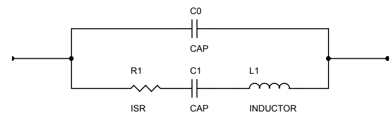

Figure 4: Type E of the Agilent 4294A LCR simulation model.

We calculate the parameter of the model via Agilent 4294A. At the same resonant frequency point, calculate out Y value and draw their simulation frequency response, the results show as figure 3 and in the following:

R_{1P}=45.614 ohm
C_{1P}=445.959 pF
L_{1P}=17.9363 mH
C_{0P}=1.11286 nF
Resonant Frequency: 56.289 kHz

Among them, the resistance R_{1P} in series is the internal resistance of the primary behavior for the step down piezo transformer. If we use the current about 0.1 amperes to pass the primary connection, it will produce the thermal energy above 0.456 W. So the energy loss is very large. If we want to raise the efficiency, we should redesign the internal resistance R_{1P} to decrease its value to improve the question of energy consumption.

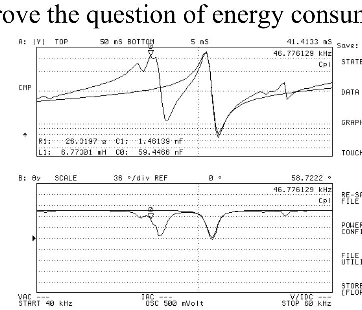

Figure 5: Impendence response diagram of the secondary characteristic for the step down piezo transformer.

By undergoing the experiment of scan frequency via power amplifier, we can find that the effective resonant point is not only one. So we short the primary connection to observe, calculate, and simulate parameters of the secondary connection for piezo transformer, as figure 5 shows, using the Agilent 4294A impedance analyzer.

Namely it is the relation diagram of the resonant point versus frequency of the secondary connection. We can get the coefficient from these measurement and calculation:

R_{1S}=26.3197 ohm
C_{1S}=1.46139 pF
L_{1S}=6.77301 mH
C_{0S}=59.4466 nF
Resonant Frequency: 46.776 kHz; **49.46k Hz**

Resonant frequency has two points; one of them is 49.46 kHz. It's close to the resonant frequency from the experiment tested at the beginning using the power amplifier. It proves the correction of the above experimental methods.

Because of this step down transformer, the working mode is that high voltage and low current for the primary connection equivalently converts to low voltage and high current for the secondary connection. Consequently the internal resistance in series is R_{1S}=26.3197 ohm for the secondary connection. The power lose produced by the current is far from the internal resistance of its the primary connection produced, which is about ten times larger. In addition, there are two resonant points, one is at 46.776 kHz and the other is at 49.46 kHz. Both of them aren't the same with main resonant point at 56.289 kHz of the primary connection. If we consider the energy loss produced by the internal resistance of the secondary connection: The working frequency of the optimal efficiency is 49.46 kHz as a base.

CONTROL CIRCUIT OF THE PIEZO TRANSFORMER

The TL494 PWM Controller is the core controller of the switching control circuit. It is an adjustable frequency of switching controller. We apply it to implement the PWM controller circuit of the piezo transformer, which regulates the output voltage.

Because this piezo transformer works around 50 kHz of resonant frequency, and its power stage needs to implement from half bridge topology. Hence, the half bridge topology block diagram shows as Figure 6.

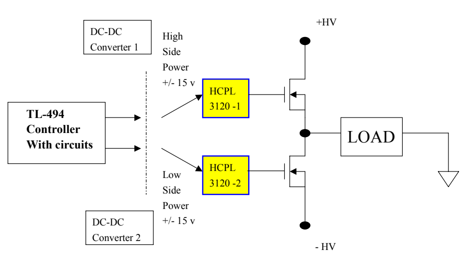

Figure 6: Half bridge driver and topology.

In order to implement the circuit of the controller to work smoothly, we will isolate it to the power circuit. So we design the optocouper MOSFET/IGBT driver, HCPL-3120, to isolate and drive the power MOSFET module directly. But what we should pay attention to be: The isolated power must separate from the power used by the controller. The working frequency is established according to the equation:

$$\text{Fosc}=\frac{1.1}{R_T C_T} \quad (1)$$

Because controller TL494 is set up at the control state of operation mode is dual channel output, the output frequency will be the half of the oscillation frequency. As a result working frequency set up at 100k Hz with adjustable mode. Please calculate in accordance with the equation 1, and define the value of C_T first, which is designed for the oscillation frequency of circuit at 100 kHz:

C_T=0.001uF

Through calculating R_T

R_T=11K adjustable +/-1K Ohm 10% range

Q1 and Q2's output frequency =50 kHz +/-500Hz

Regulating the design of close loop circuit and PWM output response, we must have to observe the time sequence relation of TL-494 controller. We establish error amp.1 within TL494 for the feedback amplifier to receive output the voltage, as figure 7 shows.

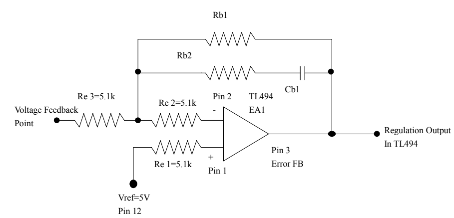

Figure 7: Circuit diagram for voltage feedback control loop.

ANALYSIS AND CONCLUSION

Our study purpose is the development of step down piezo transformer and their driver circuit producing the energy into the control power of the correction power supplies to solve the problems such as volume miniaturization, low weight and efficient enhancement. On the other hand, there is an inevitable problem that it produces much more noises. The high quality and low current ripple are desperately required to the correction power supply in the NSRRC. In this way, we should be prudent to develop this technology.

Certainly, information from the Aglient 4294A is a linear model, while really applying high voltage on the piezo transformer causes its operating frequency shifting. To show out a non-linear characteristic of the piezo transformer caused by the high working voltage. So we have already taken this factor into account while designing the circuit. We already find out the best linear operating point of energy conversion in the article. In the future, we combine the impedance analyzer linking with power amplifier to measure the non-linear model, and reach the best result of the entity measurement and analysis.

REFERENCES

[1] Rey-Lee Lin, "Piezoelectric Transformer Characterization and Application of Electronic Ballast", Ph.D. Dissertation, Virginia Tech, November 2001.

[2] George Chryssis, "High-Frequency Switching Power Supply Theory and Design", McGRAW-HILL Publishing Company, Second Edition, 1989.

[3] Agilent 4294A High Precision Impedance Analyzer Operation Manual, Fifth Edition, March 2002.

[4] Shih-chin Lin, "Piezo Transformer Prototype Manufacture", Y&Y Unictron Enterprise CO., LTD., September 2005.