Piezoelectric Transformer with Pulse Dropping Technique for High Voltage Generation

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Abstract*— This paper describes implementation design and analysis of piezoelectric transformer with pulse dropping technique to produce high voltage. The main contribution is the implementation of pulse dropping mode in inverter switching mechanism to decrease heat of piezoelectric transformer during the high voltage generation. Piezoelectric transformer fed by inverter in this work is dedicated to generate high voltage in high frequency. How ever, load current drawn from the transformer causes temperature rise and deterioration of internal elements of piezoelectric. As operating temperature reach the maximum limit, the output voltage of piezoelectric becomes non sinusoidal and decreases in magnitude. In pulse dropping technique, there are two modes in period of inverter switching. The first mode is called as power injection and the second is called as relaxation period. The experiments was carried out by a high frequency inverter, power MOSFET as power electronic switch, KW06-559 infra red thermometer to detect temperature of piezoelectric transformer, and resistive-capacitive component as a load. Without the use of pulse dropping technique during experiment, the temperature of piezoelectric reached the maximum limit at 70ºC, voltage output was unstable and the piezoelectric was easy to crack. It was found that first mode maintained high voltage output at 2.45 kV peak to peak and the second mode successfully maintained the average temperature of piezoelectric in the range of 35 – 40ºC.

***Keywords*— piezoelectric transformer, pulse dropping technique, high frequency inverter, high voltage generation.**

I. INTRODUCTION

High voltage generation in small dimension is widely demanded as power supply for various applications such as electric lighting, plasma generation and electronic display. For portable application, bulky and heavy iron transformer is impractical to use. Piezoelectric Transformer (PT) has been known to replace the conventional transformer to generate high-voltage [1, 2]. It was developed from ceramic material in form of $Pb(Zr\ Ti)O_3$ which makes PT provides electric insulation and matches for high voltage application. PT becomes more attractive as part of a power electronic converter due to its compact size and higher efficiency than conventional magnetic transformer[3].

PT is designed to convert low voltage in high frequency to higher voltage at the same frequency of input. To fed PT, high frequency inverter is required. The simple topology of inverter is single switch inverter which is developed from class E resonant inverter [4, 5]. PT has internal equivalent circuit modelled from resistive, inductive and capacitive element as resonant tank. By considering the present of internal resonant tank inside PT, a single switch inverter feeds pulse voltage waveform to PT. As the pulse voltage is produced at resonant frequency matched with resonant frequency of PT internal equivalent circuit, then alternating current is generated at output terminal of PT as higher voltage. The output sinusoidal voltage will have higher magnitude as the internal resonant tank has higher quality factor[6].

As current drawn by load from PT, temperature of PT rises. More current causes temperature of PT close to the maximum limit. The latter condition makes deterioration of internal elements of PT (i.e. polarization, mechanical transfer, and friction), consequently, voltage shape become non sinusoidal and decreases[7]. A cooling system with specified heat transfer material and fans to dissipate the heat had been applied previously [8,9]. However these efforts enlarged the circuit and consumed more energy. To overcome the problem without additional equipments, the heat must be transferred and dissipated from PT to surrounding environment during power injection period of PT and it is expected that the temperature is reduced faster during relaxation period.

In this paper, a pulse dropping technique is proposed to be implemented. In this technique, at first duration of period called power injection period, a power electronic switch is turned on and off in operating frequency for certain length of time to enable sufficient high voltage and power delivered to the load. At second duration called relaxation period, a switch is completely off without any signal triggered on it, and at this duration it is expected that heat will dissipated faster to ambient environment. To implement the technique, a a single high frequency inverter is made from a MOSFET, a pulse witch modulation IC controller is used as control circuit, a combination of parallel conductive electrode, PT and dielectric material is used as a model of resistive-capacitive load. A KW06-559 infra red thermometer was used to detect temperature of PT. The thermometer was no contact thermometer type and it was set up in the rig together with a holder to keep fixed distance between thermometer and piezoelectric in 10 cm.

II. PIEZOELECTRIC TRANSFORMER

A piezoelectric transformer is transformer made from ceramic material and replacing a conventional magnetic transformer. This type of transformer has small size, high efficiency, good insulation capability, its potentially low cost and ability to operate at high frequencies and due to the absence of winding. In their construction, physics, and operation principle piezoelectric transformers are totally different devices from conventional magnetic transformers.

A typical piezoelectric transformer (Rosen type) is made of lead zirconate titanate (PZT) or in chemical formula Pb(Zr-Ti) O_3, and construction is shown in Fig.1.

Fig. 1. Piezoelectric Transformer

The equivalent circuit of piezoelectric transformer is shown in Fig.2.

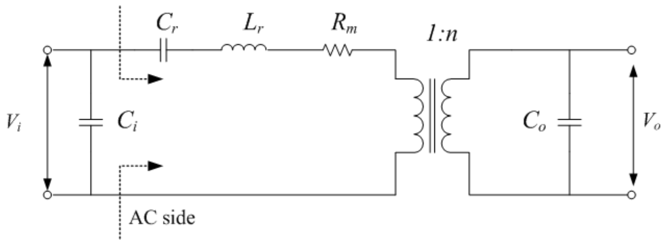

Fig. 2. Equivalent Circuit of Piezoelectric Transformer

Where V_i and V_o are the input and output voltages, C_i and C_o are capacitances of the input and output capacitor, L_r and C_r are series equivalent inductance and capacitance, R_m is equivalent mechanical resistance, and n is the mechanical output transfer ratio.

When the input capacitance C_i is considered as part of inverter, mechanical resistance R_m is considered small, and the secondary elements can be transferred into the primary side, then the simplified circuit is shown in Fig.3.

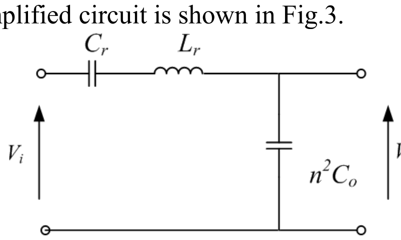

Fig. 3. Simplified Circuit of Piezoelectric Transformer

In this work, the PT used is ELM-610. The parameters values obtained from the manufacture as shown in Table 1.

TABEL 1. Parameters of PT

Parameter of PT	Value
$P_{out\ max}$	4 Watt
C_r	8.0 nF
L_r	1.14 mH
transfer ratio (n)	50
$C'_o = n^2 C_o$	280 nF

To get operating frequency of PT and the load, a frequency sweep program using PSpice was carried out for various values of input voltage to the PT. The output voltage and the phase angle of current are shown in Fig. 4. Based on simulation results, the highest voltage was obtained at 53.3 kHz as the input voltage is 24 Volt.

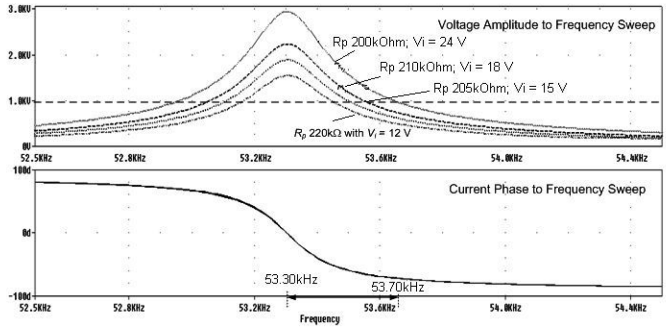

Fig. 4. Simulation Result of Frequency Sweep Program for PT

III. DESIGN OF PULSE DROPPING TECHNIQUE AND INVERTER

In many applications, the use of piezoelectric transformer with full bridge and half bridge inverters to generate high voltage in tube lamps, ozone, and plasma applications, but only few record for the use of single switch resonant converter with PT. Most of inverter switching mechanism causes a heating in PT.

The basic configuration of single switch inverter for PT is shown in Fig. 5. The piezoelectric transformer used in this work specifies a maximum input voltage is 26 volt. At this input, voltage stress and 60% duty cycle the voltage stress on the MOSFET is 117volt. IRF 640 MOSFET with $V_{DS\ max}$ = 200V is chosen as switching device due to the reason above.

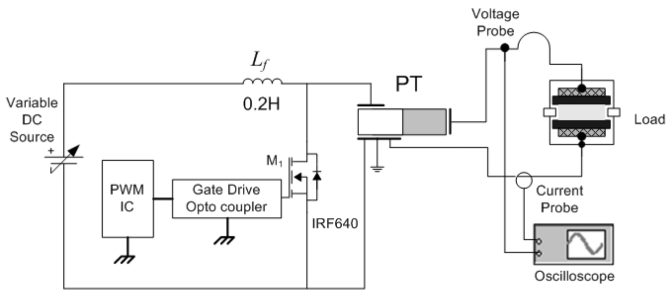

Fig. 5. The Complete Experimental Set up

As the experimental set up in Fig.5 was carried out, the output voltage successfully achieved 2.45 kV_{pp}. The current leads the output voltage due to dominant capacitive characteristics at load side as it is shown in Fig. 6. V_{DS} is voltage between drain and source terminal of MOSFET. The gate voltage from circuit controller to trigger MOSFET is symbolized as V_G. It is also found that MOSFET is turn on and off exactly at zero voltage. Switching at zero voltage reduce the losses of the circuit at inverter side.

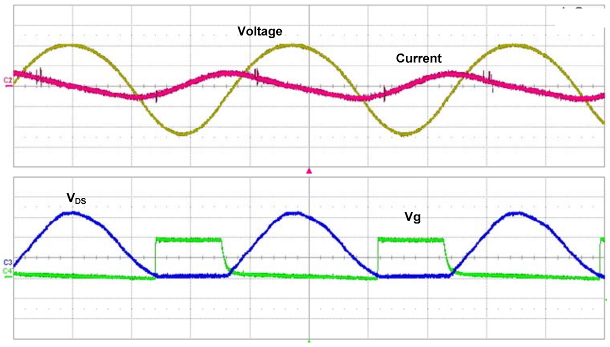

Fig.6. Waveform of Experimental Results
Voltage (500V/div), Current (50mA/div), V_{DS} (20V/div), V_g (10 Volt/div), Horizontal (5µs/div)

As the PT was continuously injected then drop voltage was occurred as more current and power was drawn by load. This power demand made a rising temperature of PT. The maximum temperature of PT is 70ºC, and this temperature rise has limited the capacity of PT to deliver more power to the chamber. The different of normal output voltage before temperature rise and when the PT is close to overheated limit are shown in Lissajous pattern in Fig. 7.a. and Fig.7.b. The horizontal axis represents voltage and the vertical axis represents current. Before temperature rise the horizontal axis is wider then after temperature rise.

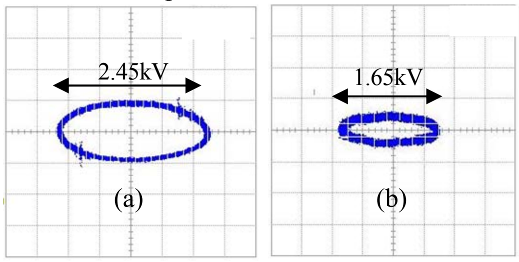

Fig.7 (a) before temperature rise (b) after temperature rise

To overcome the problem, the heat must be transferred and dissipated from PT to surrounding environment during power injection period of PT and it is expected that the temperature is reduced faster during relaxation period. This solution is possible to conduct by proposing pulse drop mechanism.

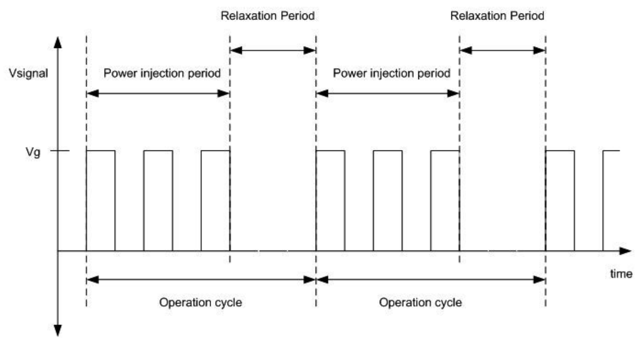

Fig.8. Illustration of pulse drop signal

In pulse drop mechanism, at first duration of period called power injection period, MOSFET was turned on and off in operating frequency for certain length of time to enable sufficient high voltage and power delivered to the chamber and initiate discharge. At second duration called relaxation period, MOSFET was completely off without any signal triggered on it, and at this duration it is expected that heat will dissipated faster to ambient environment. The mechanism above was called pulse dropping technique. The illustration of pulse drop signal was shown in Fig.8.

To execute this pulse drop operation a micro controller PIC 16F628 combined with PWM IC TL 494was designed as shown in Fig.9.

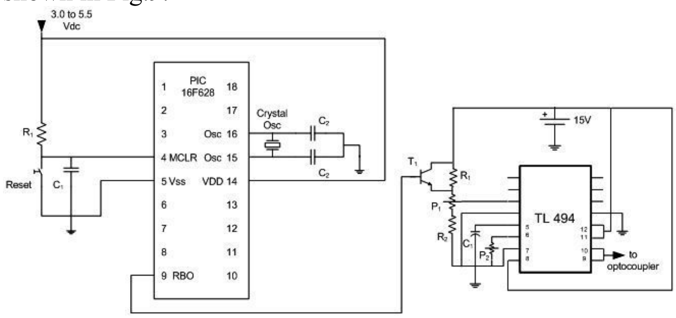

Fig.9. Illustration of pulse drop signal

When there is microcontroller deliver low signal, then transistor T_1 will be off and PWM IC operate normally to deliver pulses at operating frequency for several duration of time to driver circuit. When microcontroller generate high signal, then transistor T1 will be on and make PWM IC has zero reference voltage and stop deliver pulse for several duration of time to driver circuit.

Due to no available specification data provided by manufacture of piezoelectric transformer to determine duration of the relaxation period to dissipate the heat rapidly, several trail experiment was carried out. It was found that this type of PT was able to generate the output voltage high to maintain micro discharge when the maximum power injection period was 18 ms and the minimum relaxation period was 200 ms as they are shown in Fig.10.

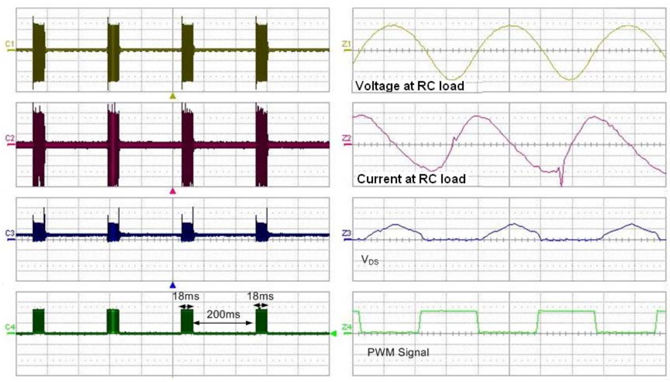

Fig. 10 Waveform Experimental Result of Pulse Drop Operation
(a) normal view, Voltage (500V/div), Current (50mA/div),
(b) zoom view VDS (20V/div), Vg (10 Volt/div), Horizontal (5µs/div)

MOSFET was turn ON and OFF in 53.5 kHz of switching frequency by PWM IC for 18 ms, and during this period, PT was capable to maintain high voltage at 2.45 kV peak to peak and average delivered power about 4 watt without PT got excessive heat. The average working temperature was 35-40ºC which was detected by KW06-559 infra red thermometer. This working temperature is safe for PT normal operation.

In practical, the RC load can be representative of ozone chamber. Ozone chamber is a box where ozone is generated. This chamber can be constructed by using dielectric barrier discharge chamber[10]. Based on dielectric barrier discharge mechanism, oxygen molecules injected into the chamber can be broken and recombine with other oxygen molecules to form ozone[11]. The ozone production with and without pulse drop technique is shown in Fig.11. Without pulse drop operation, ozone production was constant and higher, but PT easily reached its maximum temperature limit. The fluctuated ozone production was unavoidable due to pulse dropping mode. At power injection period, electrical discharge and ozone formation were initiated, but ozone production decreased when no power injected during relaxation period. Single atomics oxygen remained inside chamber and kept making collision with oxygen molecules although no power delivered into the chamber. This continued chemical reaction maintained ozone production at relaxation periods. The ozone production was 46.99 ppm or 100.56 mg/m^3 by using the proposed method.

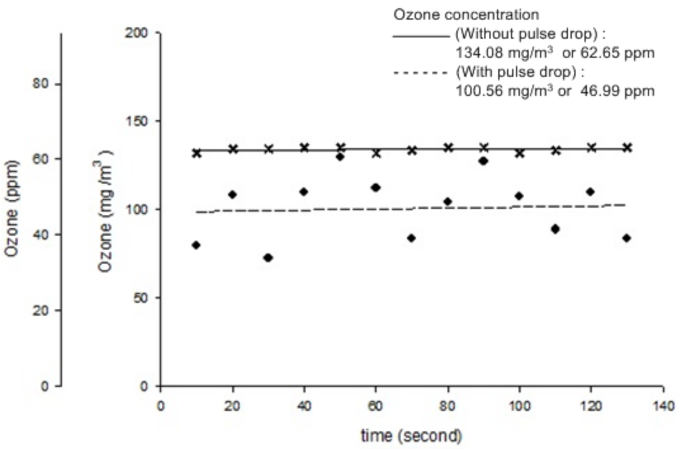

Fig.11. Ozone concentration at 2.45 kVpp

CONCLUSION

Based on the experimental result produced by the proposed pulse dropping technique, several conclusions can be summarized as follow:

1. The proposed pulse drop technique was successfully carried out to produce high voltage at 2.45 kV peak to peak for power injection period and maintain normal average working temperature at 35-40ºC as the relaxation period was introduced consecutively.
2. It is found in the experiment that the maximum power injection period was 18 ms and the minimum relaxation period was 200 ms. No crack was found at PT structure as the PT was operated at 35-40ºC
4. The use of pulse drop technique was successfully applied for ozone generation by replacing the load side with an ozone chamber to produce 46.99 ppm or 100.56 mg/m^3 of ozone.

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