Design of Mazzilli's Zero Voltage Switching (ZVS) Circuit as Plasma Glow Discharge Generator

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Abstract – Purification water has several methods; one of them is the plasma generation. The circuit used to generate plasma is Zero Voltage Switching (ZVS), where its use uses the resonance circuit concept. The main category to generate plasma glow discharge is the circuit should generate high voltage output with a current range from 10^{-6} A to 1 A. In this study, when ZVS connected to the flyback converter with an input voltage of 12 V, the output values of 11 kV and 11 μ A were obtained. In comparison, if ZVS was not connected to the flyback converter, the circuit is less stable, and the output value is weak because the output values only reach 8.97 kV and 8.97 μ A. For maximum output, the ZVS circuit should be connected to the converter circuit due to the flyback converter can repair and strengthen the voltage. The flyback converter circuit is affected by the diode and capacitance effects. The effect of using capacitors in a flyback converter circuit is when the capacitance is too low, the ripple will form. Then when capacitance reaches a specific value, the ripple will decrease, and the voltage graph will approach a straight line. Hence the use of components in the ZVS and the flyback converter need to be considered because it affects how the release of plasma glow discharge will form.

Key words: Flyback Converter, Glow Discharges, ZVS

I. INTRODUCTION

The current water purification technology is diverse from the conventional one to the one currently being researched, namely plasma. Plasma technology based on DC voltage, one of which is the incandescent corona discharge method. This plasma method is based on high voltage use, which can remove impurities in water[1]. This method works on the principle of impulse voltage. In this method, the voltage used is a high voltage (reaching kV) to generate plasma with a low current. Plasma generation technology is very diverse. Some previous studies used high voltage AC to generate plasma. However, overtimes, the researchers began to research the generation of plasma using high-voltage DC. One research on the use of DC high voltage is to use Zero Voltage Switching (ZVS) connected to the flyback converter. This method's development is based on the use of input voltages that can use batteries or solar cells where the use of this technology can be used in areas with low electrification from PLN, especially Eastern Indonesia[2].

The development of this technology can simplify the process of water purification with plasma that can be done

in areas that have not been electrified. From this background, the constituent components can be formulated to produce high voltage, the influence of power electronic components in the process of high voltage generation, voltage and current conditions generated to generate plasma glow discharge generated by the ZVS circuit, the frequency value produced by ZVS, and the effect of the converter the flyback that is connected to the ZVS circuit concerning for to voltage, current, and frequency. So the purpose of this research is to design and build the ZVS series as a plasma discharge generator and analyze the performance of ZVS and flyback converters.

Water purification is widely applied in chemistry, physics, or biodegradation[3]. In early studies, researchers have developed water purification using a simple tool such as activated carbon. It can be applied to a household or industrial scale. However, the recent study developed the plasma generation to clean the water. Tools for its generation, such as a converter and transformer. Most of the plasma generation to clean the water is glowing discharges, corona discharge, and dielectric barrier discharge. Recent research for plasma glow discharges able to purify water up to 60 mL. At that time, purified water is measured by pH, and the total Carbon (TOC)[4].

A. Plasma

Plasma is defined as ionized gas and is known as the fourth material phase after the solid, liquid, and gas phases[5]. Plasma is the area of the electron collision reaction that is significant to occur. Plasma occurs when the temperature or energy of a gas is increased to allow the gas atoms to ionize and make the gas release electrons (Chen, 2002)[6].

The formation of plasma begins with the gas phase, where there is an ionization process in neutral molecules. An electric discharge or gas discharge is the flow of electrical current in a gas medium. This current is the result of the movement of substances that have a charge in the electric field. Based on the current carried in the gas medium during the discharge process in a low-pressure tube with two planar electrodes with a DC voltage source divided by three, such as dark discharge, glow discharge, and arc discharge. This Townsend discharges can be seen in Figure 1[7].

Figure 1. Townsend Discharge

Plasma Glow Discharge can be developed within a range from F' to H. Glow discharge can generate plasma at a high voltage lower than corona discharge. Increasing current glow discharge causes an increase in the diameter of the electric discharge. Besides that, glow discharge only needs a flat conductor as a cathode to generate plasma. Glow discharge divided by two areas is the normal glow and abnormal glow. Normal glow has a current range from 10^{-5} A until 10^{-2} A, and abnormal glow has a current range from 10^{-2} A until 1 A[5], [8].

B. Resonance Method

In obtaining high frequencies, switching is needed. High-frequency switching is one method to get converters with smaller and lighter dimensions[9]. On the other hand, high-frequency switching will be directly proportional to the losses of switching[10]. To get the best efficiency during the switching process, it is necessary to use soft switching techniques or soft switching to convert the value of the input voltage. To calculate frequency resonance, the value of capacitive reactance equal to the inductive reactance[11]. The formula of the resonance method is,

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

The advantage of the soft-switching method is that it can be applied to design power conversions and is useful for operations that use high voltage inputs. Another advantage is that this method uses a lower-voltage rating switch that allows the use of other components that have higher characteristics such as lower drive currents, higher energy densities, and lower conduction losses[12].

C. Zero Voltage Switching

ZVS is generated by the resonance method or soft switching. The advantage of this method is to reduce overlaps and losses in the circuit. However, in some series, the concepts of resonance and soft switching are often combined. In several previous studies, it has been explained about the design of the application of ZVS on flyback converters to generate high voltage. This form of switching is classified as soft-switching, which can help avoid switching losses.

When soft-switching occurs, the voltage drops to zero, not based on the MOSFET's minimum value before it is turned on or turned off. It will help eliminate current and

voltage overlaps to minimize switching losses. ZVS component has a higher switching frequency than the resonant frequency or $f > f_0$. ZVS can eliminate capacitive turn off losses and is appropriate for high-frequency operations because ZVS operates at the constant turn off control[4].

D. Flyback Converter

As a DC-DC converter, the flyback converter has a role as a voltage amplifier. The flyback converter works in 4 modes[13]. The technical work of the flyback converter can be integrated with ZVS[14]. The function of the flyback converter when integrated with ZVS is to rectify and strengthen the generated voltage.

Research development in this paper is purposed to design more suitable equipment for generating plasma. Then, the result expects to be more stable for the circuit and the output value. So it can be used for water purification with plasma technology, especially plasma glow discharge.

II. METHODOLOGY

A. ZVS and Flyback Converter for Generating Plasma

The purpose of this stage is to explain the plasma generating equipment needed. The following will explain the main components of the ZVS or flyback converter. This ZVS tested for the input voltage 2 – 24 Volt. Also, the ZVS circuit had a parallel L-C circuit, which L is inductor resonant that integrated as a coil in primary winding transformer, and C is capacitor resonant. The transformer used in the ZVS is Tesla's coil transformer. To step up the voltage, the transformer used the turn ratio $N1:N2 = 1:1000$. Besides, this transformer also has a resonant inductance to produce a resonant frequency. The frequency and the resonant circuit in the transformer can be given a variable DC input voltage and the transformer, and the resonant circuit can regulate the MOSFET performance in the switching process[15]. For the last part in ZVS, the resistor needed to avoid overcurrent in the circuit and MOSFET.

Flyback converter has a function to optimize output voltage. It can reduce the voltage ripple so that the obtained output value approaches the pure DC output value (not oscillating)[16]. So flyback converter can strengthen the output voltage produced.

ZVS and flyback converter should have fulfilled the requirement to make plasma glow discharge. This research focused on the normal glow discharge area within range 10^{-5} A until 10^{-2} A. The component selection at ZVS and flyback converter should be the right to generate plasma normal glow discharge.

B. Design of ZVS and Flyback Converter

This research is simulated using National Instrument (NI) Multisim software. NI Multisim has one of its functions to design and simulate power electronic circuits[17]. The ZVS simulation circuit when connected to the flyback converter are shown in **Figure 2**. For ZVS when not connected to the flyback converter, D2 and C2 from **Figure 2** are not used.

Figure 2. ZVS using Flyback Converter

This simulation has three data collection processes. The first process compares the variation of input voltage when ZVS is not connected to the flyback converter and after ZVS is connected to the converter and analyzes its effect on the output values. Variations of input value used in this process is below 14 V with the expected value to generate plasma glow discharge is around 12 kV. The second process, knowing the corresponding resonant component values, namely the resonant capacitors and the transformer core inductance by varying the resonant component values and seeing the effect on the output values. Then the third process, which is to vary the capacitance value in the converter and determine the effect of the use of capacitors on the voltage ripple.

The Flyback converter in this circuit contained a step-up transformer, capacitor, and diode. To optimize output voltage, current, and frequency, ZVS should be connected to the flyback converter. Designing a few components in the flyback converter would help the research to get the expected results. Hence, connected ZVS to the compatible flyback converter can produce plasma optimally, especially plasma glow discharge.

III. RESULTS AND DISCUSSION

A. Analysis of the Effect of Input Voltage Variations on ZVS without Converters and ZVS with Converters

ZVS in its application can generate high voltage with relatively low output currents (generally units in μA). To generate plasma, ZVS should reach the optimal output voltage with the right input value. Hence, to prove the function of the flyback converter, and to get an optimal input voltage, we tested two conditions. First, when ZVS was not connected to the flyback converter and second when ZVS connected to the flyback converter. **Table 1** and **Table 2** present a comparison of the effect of input voltage variations with two different conditions shown in **Figure 2**.

Table 1. Variations of Input Voltage for ZVS not connected to the flyback converter

Vin [V]	Vout [kV]	Iout [μA]	Fout [kHz]
2	0	0	0
4	conv	conv	conv
6	3.93	3.93	58.1
8	5.63	5.63	58.1
10	conv	conv	conv
12	8.97	8.97	58.1
14	conv	conv	conv

Table 2. Variations of Input Voltage for ZVS connected to the flyback converter

Vin [V]	Vout [kV]	Iout [μA]	Fout [kHz]
2	0	0	0
4	conv	conv	conv
6	conv	conv	conv
8	6.88	6.88	57
10	6.88	6.88	57
12	11	11	56
14	12.3	12.3	55

Both tables show a few inputs that have the convergence (conv) output value. In the first condition, convergence means the circuit was not working in certain input values because the simulation is not stable, shown in **Table 1**. Then, in the second condition, convergence means the input value is too low, shown in **Table 2**.

Figure 3. The comparison output voltage

In previous studies, to obtain a high voltage and output current that can produce plasma glow discharge, the output voltage is 11 kV, and the output current is 10 μ A. Based on **Table 2** was found that the voltage source capable of producing plasma glow discharge is the 12 V input voltage for the ZVS circuit with the converter. However, this is contrary to the condition of ZVS without a converter with an input voltage value of 12 V, and the resulting output voltage is 8.97 kV, where this voltage cannot be formed plasma. It is caused by the flyback converter that can amplify the output signal produced by the circuit. So to get the glow discharge plasma generator circuit can use the ZVS circuit with a flyback converter that has an input voltage of 12 V.

The next second difference from the two circuits is the form of the output voltage produced. In **Figure 3** (a), the output voltage in the form of DC voltage is generated by the ZVS circuit that is connected to the converter. Whereas in **Figure 3** (b) is the output voltage in the form of a DC voltage that oscillates like an AC wave generated by ZVS without a converter. It shows that the flyback converter can improve the shape of the output voltage graph

This research can summarize if the ZVS condition is connected to the converter. When the voltage is 8 V and above, the modeling condition is more stable and can produce the expected output value. But, to generate plasma glow discharge, the right input value is 12 V with the output voltage is 11 kV and the output current is 11 μ A.

B. Effect of Resonant Capacitance Value Variation and Resonant Inductor on the ZVS Circuit Connected to the Flyback Converter

The inductance and capacitance value on the primary side can affect the value of the switching frequency. The

large or low frequency of switching will certainly have an impact on the equipment used. Range of capacitance value commonly used for ZVS circuits is 0.1 μ F to 1 μ F. In contrast, the variation of resonant inductance values is 1 - 12 μ H. Variations in the capacitance and inductance value in the circuit, along with the suitability of the values listed on the device with calculations using formula (1) are in **Table 3** and **Table 4**.

Table 3. Variations of Inductance Core while the Capacitance constant at 0.8 μ F

Lr [μ H]	Fsim [kHz]	Fcalc [kHz]	Error [%]
5	78	79.56	1.96
6	74	72.46	2.12
7	69	67.23	2.64
8	64	62.91	1.73
9	61	59.31	2.84
10	56	56.63	0.48
11	conv	53.65	100
12	conv	51.37	100

Table 4. Variations in Capacitance Value while Inductance Core constant at 10 μ H

Cr [μ F]	Fsim [kHz]	Fcalc [kHz]	Error [%]
0.2	conv	112.5	100
0.4	conv	79.58	100
0.6	conv	64.97	100
0.8	56	56.63	0.48
1.0	52,2	50.33	3.72

In **Table 3**, the convergence (*conv*) output value means the optimal variation range of inductance is below 10 μH . Above that, the circuit was not working. The similar explanation also for **Table 4**, the convergence (*conv*) output value means range of operating value is from 0.8 μF to 1.0 μF .

Based on **Tables 3** and 4, variations in capacitance values or inductance values can affect the switching frequency. The capacitance or inductance value, which tends to be high, can reduce or decrease the switching frequency. Also, capacitors have a function to store energy and generate high voltage. So that in adjusting the variation in the value of the inductance or capacitance, an accurate calculation is needed so that the value of the switching frequency is appropriate.

Also, there is a convergent value when the inductor value is above 10 μH , and the capacitance value is 0.8 μF . It is caused by a resonant circuit so that when the capacitance and inductance value exceeds the range of values, it will cause a convergent output value. In addition to the convergent value, the magnitude of the calculation and simulation accuracy is also an important factor in the resonant circuit. To optimize the inductance and capacitance value with a high degree of accuracy, it can be recommended that the core inductance is 10 μH and the resonant capacitance is 0.8 μF .

C. Variations of Capacitance at Flyback Converter

Capacitors in flyback converters have several functions, namely amplifying the output voltage and reducing the ripple at the output voltage. **Table 5** shows the effect of variations in capacitance value on the flyback converter. The value of the input voltage used is fixed, which is 12 Vdc.

Table 5 shows the tendency of the output voltage and current when the capacitance value of the flyback is varied; the voltage and current tend to be constant at 11

kV and 11 μA . Both of these stable values are obtained in the range of 1.0 pF to 1.6 pF. Although at the capacitance value of 2.0 pF can be used, but in the range of 0.2 pF to 0.8 pF and when the value is 1.8 pF, the value is convergent. Then the stable condition is only 1.0 μF to 1.6 pF. The significant effect of increasing the capacitance value on the flyback converter can be seen in **Figure 4**.

Table 5. Variations of Flyback Capacitor, while Inductance Core is 10 μH and capacitance resonant is 0.8 μF

Cc [pF]	Vout [kV]	Iout [μA]	Fout [kHz]
0.2	<i>conv</i>	<i>conv</i>	<i>conv</i>
0.4	<i>conv</i>	<i>conv</i>	<i>conv</i>
0.6	<i>conv</i>	<i>conv</i>	<i>conv</i>
0.8	<i>conv</i>	<i>conv</i>	<i>conv</i>
1.0	11	11	56
1.2	11	11	56
1.4	11	11	52
1.6	11	11	52
1.8	<i>conv</i>	<i>conv</i>	<i>conv</i>
2.0	11	11	57

Using a capacitance value below 1 pF causes the circuit to not work (in the simulation called convergence). However, when the capacitance value 1 pF and above, the circuit starts working. But, at 1.8 pF, the convergence (*conv*) value caused by the simulation itself is not stable. An increase from 1 pF to 1.6 pF causes the ripple to decrease. It corresponds to the function of the capacitor as a filter. But, in a few conditions, capacitance value at 1.6 pF also had a convergence value. So, the capacitance value used in the final design is a value of 1 pF because this value is more stable and do not have a convergence value in any condition at the simulation.

Figure 4. Comparison of Graphic Voltage for flyback Capacitor

D. Final Design

Based on the three test variables above, the final design can be obtained with circuit components listed in **Table 6**.

Table 6. Final Specification

No.	Component	Quantity	Specification
1	Voltage Source (DC)	1	12 V
2	Resistor 105 Ohm	2	
3	Resistor 10K ohm	2	
4	MOSFET	2	IRFP 260
5	Zener Diode	2	1N5349BG
6	Diode	2	MUR2100EG
7	Inductor	1	100 μ H
8	Capacitor Resonant	1	0.8 μ H
9	Transformer	1	1:1000
10	Core Inductance Transformer	1	10 μ H
11	Power Diode Flyback Converter	1	> 10 kV
12	Capacitor Flyback Converter	1	1 pF

Then it is simulated with the scheme and the values shown in **Table 6**, the input and output values of the circuit are obtained based on the variation obtained from the previous sections shown in **Table 7**.

Table 7. The output of the Final Design

Data	Vout [kV]	Iout [μ A]	Fout [kHz]
Output	11	11	56

Based on these values, the output voltage graph is based on the values of the final simulation circuit scheme in **Figure 5**.

The specifications and values of the components affect the voltage and current generated. If the ZVS circuit is applied to the water purification process, it is necessary to determine the conductor to be used as a cathode and anode on the water. Besides calculating the conductivity of the material, it is also necessary to measure the appropriate cross-sectional area when applied to the water. So that the results obtained are more accurate and can improve previous studies.

This circuit can generate a high voltage that has a minimum current at 11 μ A. From townsend discharge, this circuit classified as Plasma Normal Glow Discharge. It is caused by the value of the component at ZVS, and the flyback converter affected the output voltage, current, and frequency. The difference value between value shown in the table (multimeter measurement) and Oscilloscope-XSC1 is caused by resistance from oscilloscope itself.

Figure 5. Graphic of Output Voltage

IV. CONCLUSION

In this section, we will recommend the right equipment with the right value which more stable to generate plasma. First, the MOSFET used in the ZVS is MOSFET IRFP 260. Then, the L-C tank for the resonant circuit, the recommended primary core inductance value is 10 μ H, and the recommended capacitance value is 0.8 μ F. The capacitor in the flyback converter can fix ripples. The capacitance value in the flyback converter is 1.0 pF. So the minimum output voltage obtained to produce plasma is 11 kV with an input voltage of 12 V. The output current obtained is 11 μ A. The output value classified as a Plasma Glow Discharge.

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