

Design of High Voltage Low Power Supply Device

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Abstract The objectives of this paper are to investigate and develop a device that will produce high voltage low power supply. Generation of high voltage low power supply can be determined by using Flyback converter as an optimum method which can improve the design of the device to make it smaller in size, simpler and cost effective. In this paper, the device circuits are simulated using PSPICE software to determine the characteristics of the output voltage of the circuits. Fundamental of Flyback converter, design of the circuit, simulation and construction of the device are conducted. The Flyback converter principle is analyzed to find the suitable design of the device in this paper. The chosen circuit components are simulated and their values are calculated. The device circuit is implemented and its output variables are compared with the simulation result.

Keywords Flyback, High Voltage, Power Supply

1. Introduction

In many application, the used of high voltage with low power supply devices are needed in communication, biomedical equipment, high voltage testing and any other field are in high demand. Depending on the application the converted power ranges from some Watts to values above 100kW while output voltages above 1kV up to a few 100kV are needed.

The aims of this paper is to design a high voltage low power supply device that can produce high voltage up to 10 kV with lowest current and power values. On top of that, the powers supply device is small in size, simple and low cost. Power supply using Flyback converter and high frequency transformer are investigated in this paper.

Generation of high DC voltages is mainly required in research work in the areas of pure and applied physics. Sometimes, high direct voltages are needed in insulation tests on cables and capacitors. Impulse generator charging units also required high DC voltages of about 100 to 200 kV. Normally, for the generation of high voltages DC around 100 kV, the output currents are about 10 mA. Many methods are found to generate high voltage that are stated in section 2,

while Flyback converter method is found to be suitable for implementing small size and low cost device.

2. Literature Review

A. Voltage Doubler

The voltage doubler circuits make use of the positive and the negative half cycles to charge two different capacitors. These are connected in series aiding to obtain double the direct voltage (Figure 1). In this case, transformer has a small rating equals the direct voltage rating with only simple rectification. Furthermore, for the same direct voltage output the peak inverse voltage of the diodes will be halved.

From previous research, entitle a novel organization of switched capacitor charge pump circuits based on voltage doubler structures. Each voltage doubler takes a DC input and then outputs a doubled DC voltage. By cascading n voltage doublers the output voltage increases up to 2^n times [1]. A two-phase voltage doubler and multiphase voltage doubler structures are discussed and design considerations are presented. In order to evaluate the power delivered by a charge pump, a resistive load or an equivalent load is attached to the output of the charge pump and an equivalent capacitance is evaluated.

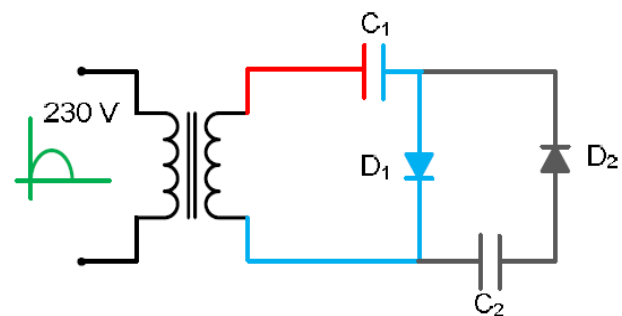


Figure 1. Voltage doubler

B. Cockcroft-Walton's Voltage Multiplier

There are two types of CWVM, half-wave and full-wave CWVM. Figure 2 and 3 show both types of CWVM circuit diagram. The CWVM is basically the same as voltage doubler where it converts AC or pulsing DC electrical power from a low voltage level to a higher DC voltage level. It is

made of a voltage multiplier ladder network of capacitors and diodes to generate high voltages. Each stage consists of couple of diodes and capacitors to increase voltage to one level higher. Such stages function as a complementary extension of a single topology, adding voltage steps to the output value [2].

The main disadvantages of CWVM are the delay between input and output, large output voltage ripple, voltage drop and non-negligible amount of capacitance needed [3].

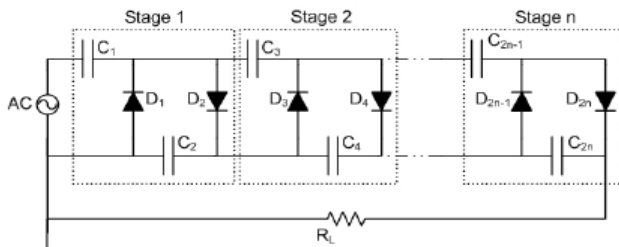


Figure 2. Half-wave CWVM circuit diagram

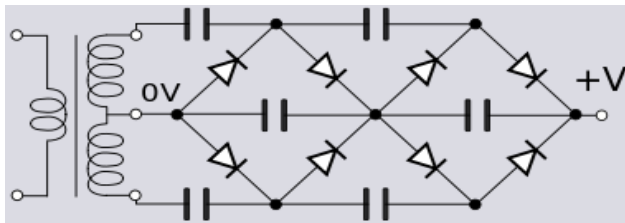


Figure 3. Full-wave CWVM circuit diagram [3]

C. Marx Generator

The purpose of this generator is to generate a high-voltage pulse from a low-voltage DC supply. Marx generators are probably the most common way of generating high voltage impulses for testing when the voltage level required is higher than available charging supply voltages.

The basic principle involved is to charge a set of capacitors in parallel and then discharge them in series. A typical Marx generator consists of an N number of modules. Each module consists of two resistors, a capacitor and a switch in the form of a spark gap a shown in Figure 4. Marx generator for repetitive applications is the same as conventional Marx generator but with only in compact size. The Marx generator has 25 stages. Each of the stage was constructed using 4 door knob ceramic capacitors and a ball spark gap switch. It is designed as compact and repetitive as possible. Inductor charging method is used for higher repetitive operation [4].

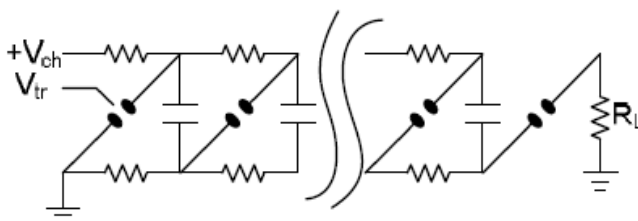


Figure 4. Marx generator circuit diagram

D. Tesla Coil

Nikola Tesla invented the Tesla coil, a type of resonant air core transformer which is used to generate high voltage and high frequency electrical currents [6]. Today, many devices were developed using the concept of Tesla coil even though it is an old invention. Tesla coil has been used to conduct innovative experiments in electrical lighting, x-rays, wireless energy transfer for electrical power transmission, industries and also for educational purposes.

A Tesla coil is an air-cored resonant transformer. Figure 5 shows the typical Tesla coil circuit configuration. It is similar to a standard transformer but the mode of operation is different. The voltage in Tesla coil is gain due to the resonance rather than the turn's ratio. A normal transformer uses an iron core in order to operate at low frequencies, whereas the Tesla coil uses air-cores to operate at high frequencies [5]. Tesla coil designs employed AC power source, high voltage capacitor, inductive coil and a spark gap to excite the primary side of the Tesla coil system with periodic bursts of high frequency current. The primary and secondary coils are designed precisely in order to resonate at the same frequency.

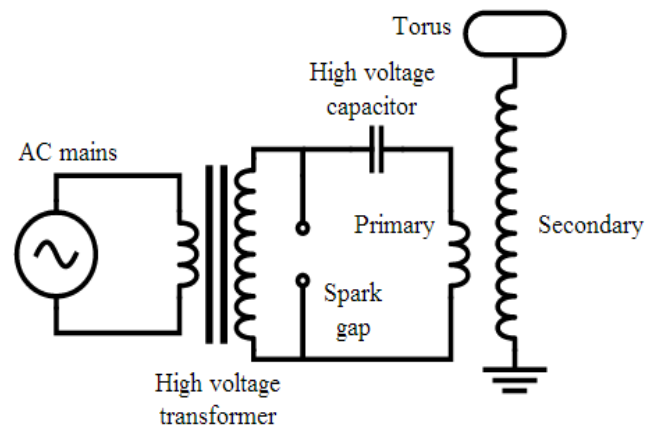


Figure 5. Tesla coil circuit diagram [5]

E. Flyback Converter

Flyback circuit is the most attractive topology because of its relative simplicity and low cost when compared with other topologies used in low power applications. PWM switching technique has been used for its high power capability, fast transient response and in switch-mode power supply used in industry. Using this approach, PWM DC-DC power converter has been used to increase the power density and actual efficiency.

It can provide multiple isolated outputs with a single low side switching transistor and limited number of external components. Both multiple outputs and output isolation may be implemented depending on the DC-DC application. In addition, input to output isolation may be required to meet safety standards or provide impedance matching. Isolated power supplies not only protect users from potentially lethal voltages and currents, but also provide performance benefits.

3. Methodology

The designs of the device is investigated in details and break-up the some of the components in the system to develop the subcomponent separately before combine all the parts together and become a complete working design [8]. From Figure 6, the power supply or voltage source provides the input DC voltage to the driver. The driver which is the 555 timer chip will generate square wave pulse or also known as PWM to increase the frequency until thousands of Hertz. Next, the PWM produced will be amplified and controlled the switching on and off by using transistor [10]. The on and off mechanism will be transfer into input of the Flyback transformer. Flyback transformer will increase the voltage to produce the desired output high voltage value according to the input frequency applied. Figure 7 shows the flow of work for this paper.

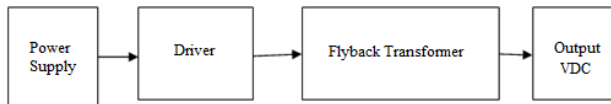


Figure 6. Overall circuit block diagram

A. Design Details

1. Calculation

Table 1 shows the duty cycle and frequency values when the resistor R_1 and R_2 are varied. Calculation is done for each of the resistors used to obtain the value of duty cycle and frequency. From the table, it can be seen that the value of duty cycle is different except when the resistors have the same value. The frequency is changing for all the combination of resistor but the duty cycle is the same when the both of the resistor values are the same.

Table 1. Resistors, Frequencies and Duty Cycles Values from Calculation

Resistor (k Ω)	Frequency (kHz)	Duty Cycle (%)
$R_1 = 10.00$ $R_2 = 4.76$	7.38	75.61
$R_1 = 10.00$ $R_2 = 0.50$	12.73	64.45
$R_1 = 10.00$ $R_2 = 10.00$	4.80	93.67
$R_1 = 4.76$ $R_2 = 4.76$	10.00	66.67
$R_1 = 2.00$ $R_2 = 2.00$	24.00	56.43

1. Simulation

PSPICE software is used in this paper to simulate the circuit design [9]. This software is used to show the results and characteristics of the output waves. Two circuits are simulated by this software; these are PWM from the 555 timer circuit and Flyback converter circuit. The simulation for Flyback converter cannot be done due to limitations of the software.

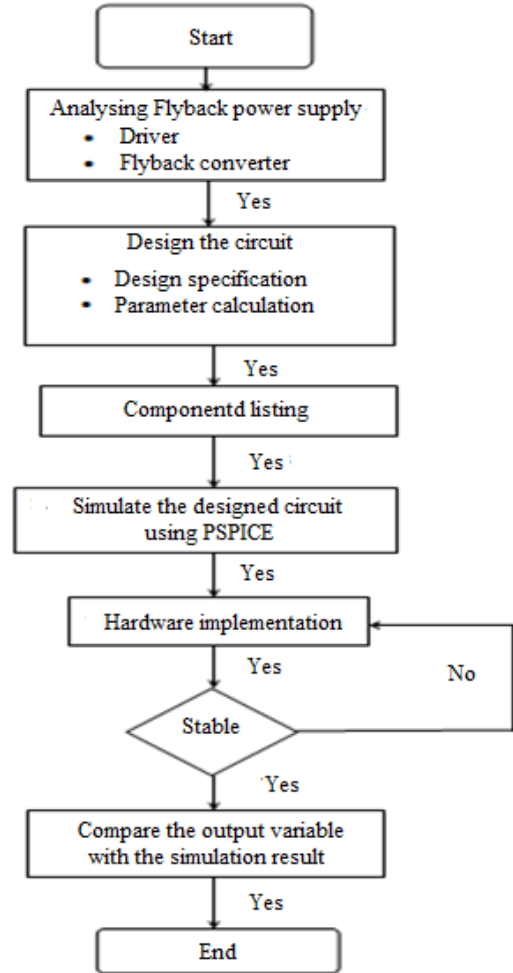


Figure 7. Flow of work

A DC voltage source was used as power supply for the 555 timer. The circuit was simulated using 555D, resistor, R, and capacitor, C. The resistor values are not the optimum value because it can be changed according to the desired frequency. The component value is chosen from the calculation and search in the markets to find if the component value from the calculations exists and can be used to carry the required voltage and current. The timer circuit is simulated to know the characteristics and specification of the output voltage waves. The circuits are shown in Figure 8 and 9.

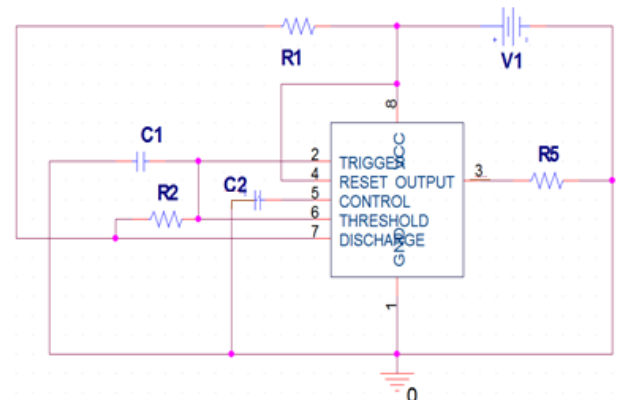


Figure 8. Switching circuit

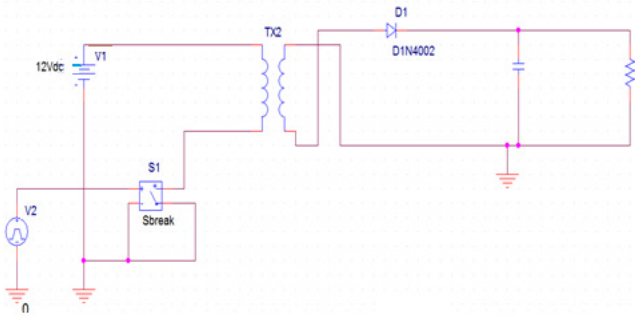


Figure 9. Flyback converter

2. Hardware

The hardware building can be divided into two parts, switching circuit and Flyback converter. TV circuit board was used in this paper for the converter part because it is more stable and mostly all the component can be found inside the circuit board. Only the switching part is implemented. Figure 10 shows the overall circuit diagram for the Flyback power supply.

In the first stage of building Flyback power supply, old TV circuit board needed to be finding with schematic diagram of the circuit board to locate the component that are used. Moreover, the schematic diagram helps to know the connection of each component. Next, the circuit for switching circuit is build using 555 timer IC. The timer will

act like an oscillator which will give a signal to the transistor. After building the switching circuit, the output of the signal from pin 3 is connected to the H_{out} inside the TV circuit board. H_{out} is actually the pin inside the circuit board that gives signal to the transistor Q_1 . Instead of using the TV signal, the signal from the 555 timer will be transmitted to the transistor Q_1 by connecting them together. Q_1 will send the signal to transistor Q_2 via a step-down transformer. The transformer is designed to match the high output impedance of Q_1 into the low impedance base circuit of Q_2 . The connections of T_1 are so arranged that the ‘turning-on’ of Q_1 causes Q_2 to ‘turn-off’ and conversely. The signal is then transmitted to the Flyback transformer from pin 10.

Q_1 and Q_2 are driver and output transistors respectively. The output transistor operated as an electronic switch. When forward bias, it saturates to close and on reverse biasing cuts-off to cause an open circuit. When in saturated mode, it to deliver large burst of power to the secondary coil of Flyback transformer. Therefore, it is of great importance that the controlling voltage waveform fed to the base of Q_2 shall always be large enough to turn it on and sufficiently negative to reverse bias when it required to cut-off. The Q_1 is also operated as an electronic switch and triggered into conduction by positive pulse applied to the base. This Q_2 can withstand base current (I_B) up to 3.5 A, while the collector current (I_C) resist until 4 A. Q_1 can withstand I_B up to 70 mA.

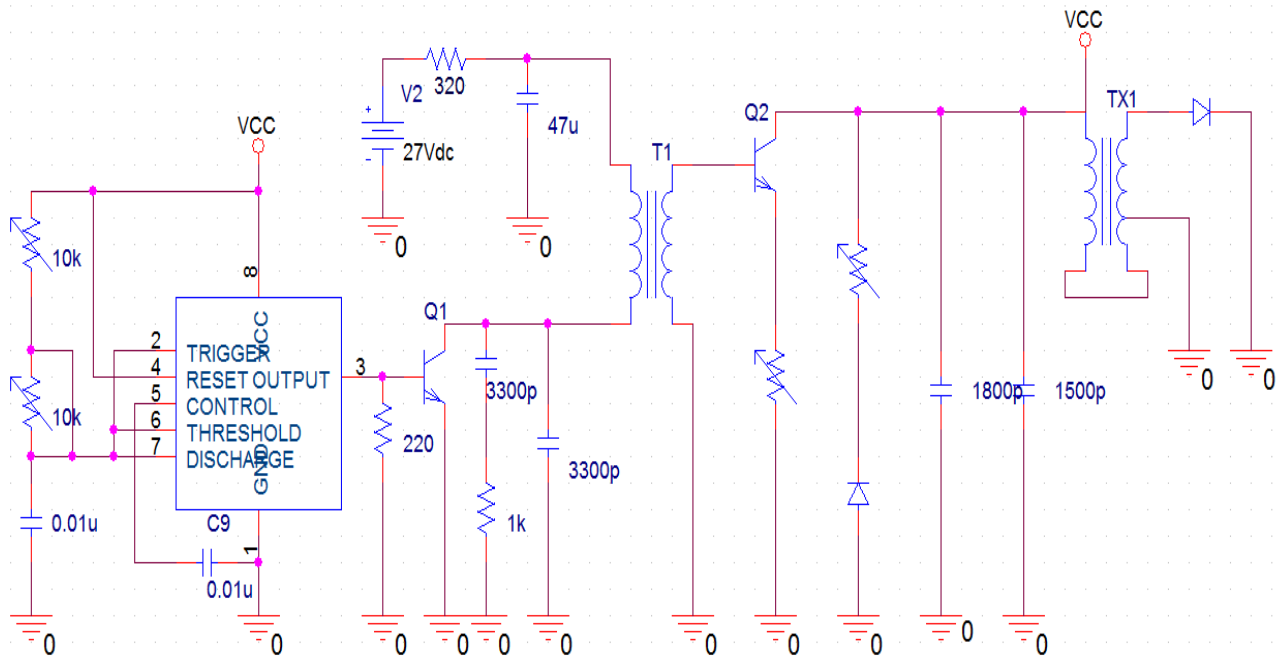


Figure 10. Flyback power supply circuit diagram

When Q_1 is saturated its collector is nearly earthed and when turned-off, the collector voltage rises to about the same value as the supply voltage (V_s). Hence, the waveform appearing at the collector of Q_1 takes the form of a series of square wave pulses nearly equal to V_s . Thus the waveform appearing at the collector of Q_1 takes the form of a series of square wave of amplitude almost equal to V_s . Basically the amplifier is operating like a switch, operating at a frequency from 1 kHz to several kHz. It operates either saturation or cut-off mode. The duty cycle can be driven from 0% to 90%. Figure 11 shows the overall hardware of this device.

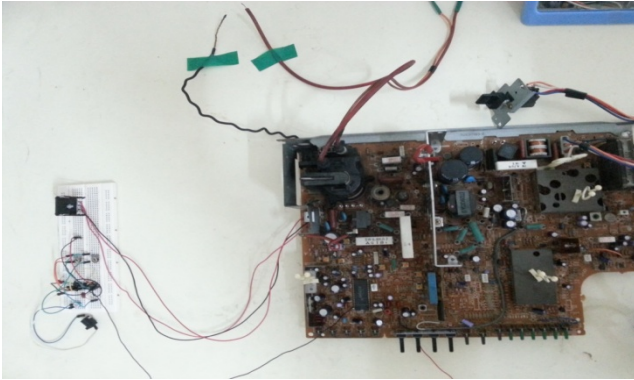


Figure 11. Flyback power supply circuit

4. Result & Discussion

A. Simulation Result

All the waveform of simulation for different values of R_1 and R_2 are discussed and the frequency for both the simulated and calculated results are almost the same. Thus, it is proven that the switching circuit is operating accordingly with the calculation

B. Oscilloscope Result

Table 2. Resistors, Frequencies and Duty Cycles Values from Calculation

R_1 (k Ω)	R_2 (k Ω)	f_{calc} (kHz)	f_{meas} (kHz)	D_{calc} (%)	D_{meas} (%)
10.00	4.76	7.38	10.62	75.61	73.34
10.00	10.00	4.8	5.2	93.67	89.88
4.76	4.76	10	11.45	66.67	65.55
2.00	2.00	24	25	56.43	54.67

The waveform for all the switching circuit is tested using oscilloscope to determine the frequency of the circuit. As can be seen, the waveforms are almost similar to the simulation waveforms. The duty cycle is changing depending on the value of resistor used. Using digital oscilloscope, the frequency can also be obtained. All the measured and calculated frequencies are shown in Table 2. The frequencies calculated and measured have been compared and the

frequencies of both of them are slightly different but not that so far apart. This can be happened due to the noise problem of the oscilloscope and probe used.

C. Measurement and Instrumentation

In Figure 12, a high voltage probe was used to measure the output voltage of the Flyback power supply. This probe will withstand high voltage up to 40 kV DC or peak AC of 28 kV rms. The voltage being measured is 1000 times greater than the voltmeter reading. However if the two conductors are separated by a small gap of air, it is possible to make the electric current jump across the gap. If the arc gap becomes too long, the applied voltage could be insufficient to maintain the arc and it will breaks off. Due to some difficulties, the reading cannot be taken. A simple calculation can be done to determine the voltage of the device by the length of the spark gap. From the theory of electric breakdown in air, 1 MV/m is the ratio for the voltage to breakdown in the air. Which means 1cm will produce 10 kV. From the experiment, the maximum length was measured to obtain the maximum voltage of 30 kV is approximately 3 cm



Figure 12. High voltage probe [2]

D. Discussion

Flyback transformers cannot be connected to the mains directly. They start working at a frequency of about 1 kHz to several kHz. The intermediate frequency has many advantages, such as smaller and lighter cores. The frequency of the square wave is varied from 1 kHz to 93 kHz with a variable duty cycle from 50% to 95%. Figure 13 shows the arc produced from the Flyback power supply. When the frequency of the oscillator is increased then the diameter of the arc at the output becomes thinner with hissing sound which indicated a decrease in high voltage. This is because when the frequency increased, voltage amplitude decreased. If the frequency of the oscillator is reduced, the diameter of the arc becomes thicker with a quieter sound which indicated an increased in voltage. The same principle happens here, when frequency decreased, voltage amplitude increased.

If the duty cycle of the square wave is increased the arc of the output voltage becomes thinner. In contrast, the arc of the output voltage will become thicker when duty cycle of the

square wave is decreased.

In addition to higher voltage requirements, some applications need more current and also some degree of stabilization. The current requirement is met by using larger currents in the primary of the coupling transformer so that the amount of power that is switched through Q_2 is substantially higher. Output transistor may have collector voltage as low as 26 V but the current draw up to 1 A or more. Therefore, transformer windings, rectifier and necessary power supplies need to have higher current ratings.

If the frequency of the oscillator is increased, current at the output of the oscillator will increase approximately from 6.5 mA to 12.5 mA during operation.

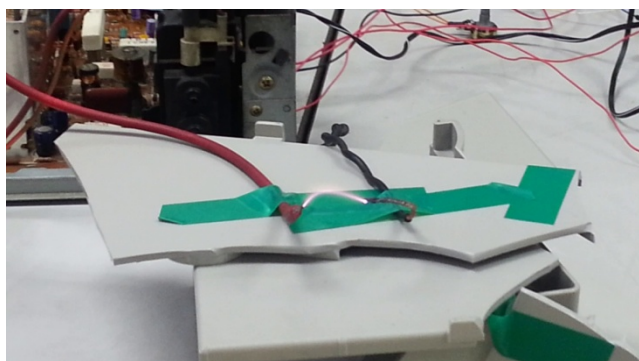


Figure 13. Arching at spark gap

The theory of dielectric breakdown strength of gases can be used to calculate the output voltage of this device the term dielectric strength is the maximum electric field that a pure material can withstand under ideal conditions without breaking down. Dielectric breakdown strength of air transpires when a charge accumulation surpasses the electrical boundary or dielectric strength of a material. The negatively charged electrons are pulled in one direction and the positively charged ions in the other. When electrons are removed from a nucleus, it becomes positively charged and when air molecules become ionized in a very high electric field, the air changes from an insulator to a conductor. From the electrical breakdown strength of air, air will break down at about 1MV/m [7].

5. Conclusions

A. Summary

In this paper, different topologies of implementing high voltage have been reviewed. There were five different ways to build the circuit designs which are Voltage Doubler and Cockcroft-Walton's Voltage Multiplier, Marx generator, Tesla coil and Flyback power supply. The most suitable topology is Flyback power supply was chosen to be used for this design. Design and calculations in these studies were done according to literature reviews. The first step was to analyze the operation and characteristics of the driver or switching circuit and Flyback converter. Component

selections were analyzed to identify the suitable materials. Then, calculations were done to determine the most suitable component value, parameters and efficiency for implementing the high voltage low power supply device. The device circuit was simulated using PSPICE software to determine the characteristics of the output voltage. The simulation for Flyback converter cannot be done due to limitation of the software but the simulation for the switching circuit is developed. The results show that voltage, frequency and duty cycle are controlled by the two resistance of the switching circuit, and the output voltage proportionally changes by changing the electrode distance.

B. Recommendation

Although this device can produce a very high voltage, the output voltage will be keeping increasing to a much higher value of voltage. The design of the Flyback power supply can be added with voltage multipliers at the output of the transformer to obtain additional voltage. Adding voltage multipliers minimizes the insulation requirements of the transformer. Different type of transformer can be used instead of Flyback to minimize the size of the device. This device circuit can be implemented by taking off all the components inside the TV circuit board to make one complete device.

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