

Performance Monitoring of High Voltage Power Supply using Flyback Converter with Extra High Tension

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Abstract—In this study the design and implementation of the high voltage power supply using flyback converter with Extra High Tension and their result are discussed. Flyback converter is used as DC-DC converter is designed to work with maximum wattage 100W and 38V output voltage is connected to extra high tension circuit. This arrangement is results constant DC output voltage between 100V to 40KV with current rating between 0.4mA to 0.7 mA. At high frequency the flyback converter output becomes highly unstable at 5kV to 20kV, in order to produce stable DC output for high voltage application the arrangement extra high tension with the back to back connection of two silicon controlled rectifier is used. The complete hardware design setup is discussed with their result are presented.

Index Terms— High voltage power supply(HVPS), Electrospinning, Flyback, Extra High Tension (EHT).

I. INTRODUCTION

The High voltage power supply is one of the basic requirements of several application systems like communication system, biomedical equipments; high voltage testing etc. Our major concentration was based on the design of electrospinning system. It is the mechanism to fabricate very fine fiber which is used in cotton, biomedical, filter, electronics devices, solar cell and medical application; it uses very high electric field to produce fine fibers [1]. The system is composed of high voltage direct current (DC) power supply; electronics syringe pump and a rotating or stationary collector drum / plate. The objective of the paper is to highlight the design steps for high voltage source needed for electrospinning system which may varies depends on synthesis condition, usually from 5kV to about 30kV.

The studies of the researchers highlight various ways to obtain the high voltage using voltage doublers, Cockcroft-Walton's Voltage Multiplier, Marx Generator, Tesla Coil and Flyback Converter [2,12]. The 32-stage voltage multiplier generate 12KV DC power supply using Cockcroft-Walton technique [3], the output voltage linearly increases and reaches to this range. Some high voltage power supply generates analog square wave output which is necessary in the field of electronics and electrical engineering and applied physics, such as X-rays, electrostatic precipitators, defibrillator in a medical lab, defense shield, electron microscopes, dielectric testing, particle accelerator in nuclear physics, stunt gun [4]. The Cockcroft-Walton voltage multiplier circuit shows the ratio of output voltage to input voltage for one stage. As the number of stages increases it will generate high voltages in order of several KV. The Cockcroft-Walton voltage multiplier is isolated from the main line which results in the mitigation of switching surge voltages [5].

The research paper highlight Cockroft-Walton and Van Der Graff circuits are simplest and easiest voltage multiplier circuit is an electrical circuit that converts AC electrical power from a low voltage to a high DC voltage, typically by means of a network like voltage doubler, tripler, quadrupler and n-plexer they are constructed using capacitors and diodes [6,11] similarly the required amount of high voltage can be taken out through tapings [7-9], but they have low efficiency and they are reasonably expensive and it occupy large space. Considering these weak points, many researchers turn towards switching circuit based on MOSFET, IGBT, Power Transistor etc, it will be best alternative in future industry product in the field of power electronics. It does not require any kind of maintenance and occupy very much less space[16-17]. The next section of the paper discusses the flyback converter basic and its design steps, practical implementation approach of flyback Converter with extra high tension circuit constructed using two back to back connections of silicon controlled rectifier (SCR) / metal–oxide–semiconductor field-effect transistor (MOSFET) to reach out the expected controlled high voltage output and finally the results are discussed to validate the system.

II. FLYBACK CONVERTER BASIC

The flyback converter is a buck-boost converter with the coupled or split inductor to form a transformer, used when power requirement is lower than 100W and the isolation between input and output is required. The flyback transformer hold the energy in the coil as the current flows through the circuit it releases the energy as soon as power is removed. [10,13-15] discuss flyback is referred to as the on and off action of the control switch. Figure 1. shows little number of components is required to construct the flyback circuit as compared to other high voltage power supply constructed by researchers.

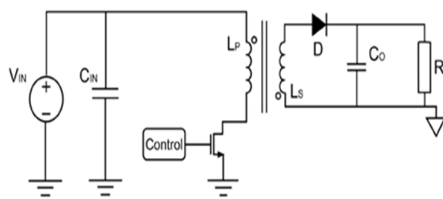


Figure 1. Flyback converter [3-5]

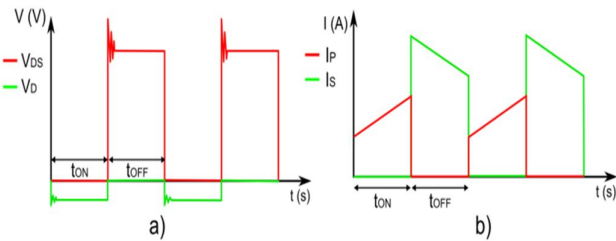


Figure 2. a) VDS across MOSFET and VD across Diode b) Current in Primary and Secondary of transformer [3-5]

III. FLYBACK CONVERTER DESIGN STRATEGY

A. Flyback Converter Design

In this section the flyback converter and flyback transformer design strategy is discussed. The coupled inductor shows power conversion strategy and provides isolation between the input and output. It has two operation strategies based on MOSFET's switching t_{ON} and t_{OFF} . Figure 2.b shows during t_{ON} state, as MOSFET is turned on the drain to source current I_{DS} flows through the primary of transformer and no voltage drop across switch, it shows linearly charging of the coupled inductor and produces a magnetic field around it. The series connected diode in the secondary of the transformer is reverse-biased, it disconnect the transformer from the output shown in Figure 2.a.

The voltage across the primary winding is same as the DC source V_{IN} and the current I_{pri} is flowing through the primary winding.

$$I_{pri} = \frac{1}{L_{pri}} \int V_{IN} dt \quad (1)$$

Where L_{pri} is the primary inductor.

As the current I_{pri} is flows from the primary of the inductor coil, flux is induced, it results voltage V_{sc} is induced in the secondary coil.

$$V_{sec} = \frac{N_1}{N_2} V_{IN} \quad (2)$$

Where N_1 is the primary winding turns and N_2 is the secondary winding turns. Many researchers select the duty

cycle arbitrarily at 50%, but it is important to understand how to optimize this relation: maximum duty cycle, transformer turn ratio, peak current and voltage rating. In our design it is observed that if duty cycle is greater than 50%. The increase of maximum duty cycle reduces the peak current on the primary of the transformer, resulting in better copper transformer utilization on the primary and lower ripple on the input source. At the same time the increase of the maximum duty cycle increases the maximum stress voltage between drain to source of the main switching MOSFET, and increases the peak current on the secondary side. Assume the output voltage $V_o = 38V$, Output current $I_o = 0.416 A$, ripple factor $R_f = 1$, DC source $V_{IN} = 24V$, efficiency $\eta = 80\%$ and switching frequency $F_s = 100KHZ$ is represented by

$$V_o = \left(\frac{N_1}{N_2} \right) \left(\frac{D}{1-D} \right) \cdot V_{IN} \quad (3)$$

Similarly, when $N_1 = N_2$

$$D = \left(\frac{V_o}{V_o + V_{IN}} \right) = \left(\frac{38}{38 + 24} \right) = 0.612 \quad (4)$$

Some industry designers adds diode drop of 0.3V in duty cycle equation. To calculate the primary inductance value of coil (L) is represented by

$$L_p = \frac{\eta \times D^2 \times V_{IN}^2}{2 \times f_s \times R_f \times P} = \frac{0.8 \times 0.612^2 \times 24^2}{2 \times 100 \times 10^3 \times 1 \times 38 \times 0.416} = 54.58 \mu H \quad (5)$$

Similarly to selection of the switching devices like power transistor, MOSFET, IGBT etc in various application the following set of calculation provided they are based on the maximum drain to source current and voltage that the switch can withstand. Consider the minimum voltage and maximum voltage range for the input voltage is 12V to 24V.

$$V_{DS_{MAX}} = V_{IN_{MAX}} + \frac{D \times V_{IN_{MIN}}}{1-D} = 24 + \frac{0.612 \times 12}{1-0.612} = 42.92V + 20\% = 51.50V \quad (6)$$

This 20% safe margin is added for safe operation of converter, the maximum current is given by

$$I_{P_{PK}} = \frac{P_{IN}}{D \times V_{IN_{MIN}}} + \frac{D \times V_{IN_{MIN}}}{2 \times f_s \times L_{p_{MAX}}} = \frac{12 \times \frac{1}{0.8}}{0.612 \times 12} + \frac{0.612 \times 12}{2 \times 100 \times 10^3 \times 54.58 \times 10^{-6}} = 2.71A \quad (7)$$

From this calculation one can select the MOSFET of the rating approximately 80V / 3A.

Similarly during the turn off state t_{OFF} , the drain to source voltage is reversed and gate trigger pulse is absent which result MOSFET is off and the charged coupled transformer/ inductor start to demagnetize through the series connected diode. The output capacitor starts charging through the inductor and supplies power to the load. The required turn ratio (n) calculated using,

$$n = \frac{N_p}{N_s} \quad \text{or} \quad n = \frac{V_R}{V_{OUT} + V_D} \quad \text{or} \quad n = \frac{V_{IN_{MAX}} \times D}{(1-D) \times (V_{OUT} + V_D)} \approx 1 \quad (8)$$

Where N_p is the primary turns, and N_s is the secondary number of turns, V_{out} signifies the output voltage, and V_D tells us regarding the voltage drop across the secondary diode.

$$V_D = V_{OUT} \frac{V_{IN_{MAX}}}{n} = 38 + \frac{24}{1} = 62 V \quad (9)$$

Practically to protect the external section add 30-40% voltage as safe margin, the peak inverse voltage of the diode can carries the maximum reverse voltage is $62 + 40\% = 86.8V$.

B. Flyback Transformer Design

The flyback transformer design is a complex procedure that involves several steps: determining the core size, proper selection of core material and geometry, determining the maximum peak magnetic flux density, defining the primary and secondary windings (turns number and wire gauge) as well as calculating the air-gap necessary to achieve the desired inductance. Moreover, additional considerations concerning the assembly are needed for meeting safety requirements, maximizing magnetic coupling and minimizing parasitic high frequency effects,

not to mention the constraints imposed by the specific application.

To find the area of the transformer A_P and it is the product of the winding window area A_E and the area of the core cross-section A_W .

$$A_P = A_E \times A_W \text{ mm}^2 \quad (10)$$

The following area calculations are provided for a rough initial estimation of the core size in various applications.

$$A_P = \left(\frac{L_P \times I_{P_{\max}} \times I_{P_{\text{RMS}}}}{B_{\text{MAX}} \times 0.0085} \right)^{3/4} \times 10000 = \left(\frac{54.58 \mu\text{H} \times 2.71 \times 0.77 \text{ A}_{\text{RMS}}}{0.2 \times 0.0085} \right)^{3/4} \times 10000 \approx 168 \text{ mm}^2 \quad (11)$$

The operating flux density (B_{MAX}) is 0.2 to 0.4T.

To construct the transformer at laboratory level it is necessary to select the number of primary and secondary turns around the bobbin. The number of primary turn revolution around the bobbin is calculated as follows

$$N_P = \left(\frac{L_P \times I_{P_{\max}} \times 10^6}{B_{\text{MAX}} \times A_E} \right) N_P = \left(\frac{54.58 \mu\text{H} \times 2.71 \times 10^6}{0.2 \times 20.1 \text{ mm}^2} \right) \approx 59.40 \quad (12)$$

Similarly to estimate the secondary turn number

$$N_S = \frac{N_P}{n} = \frac{60}{1} = 60 \quad (13)$$

The above design parameters are used to implement the flyback converter circuit prototype is shown in Figure 3. The fast switching speed controls the ON and OFF action of the power transistor, IGFET or, MOSFET. The flyback converter is designed in boost mode to convert electrical energy from one voltage to a higher one. The boost converter topology is connected with switching transistor it results a direct current path between VIN and VOUT through the transformer coil and diode D.

By varying the duty cycle (D) of a boost converter, the output voltage can be controlled and with $D < 1$, the DC output from the boost converter is greater than input voltage VIN as a consequence of the inductors self-induced voltage.



Figure 3. Prototype Flyback converter



Figure 4. Prototype EHT and control circuit

The high voltage output is produced using the Extra-high-tension (EHT) based power supply it is capable to deliver variable DC voltage from about 100 V to 50 kV with load current up to 500 mA. The back to back connection of SCRs is used to maintain alternating current supply input voltage at the primary of the power transformer which is capable to produce high DC voltage with lower range of load current. The SCR controlled EHT based high voltage power supply is shown in Figure 4.

C. Control Circuit Design

The flyback control circuit is shown in Figure 5. The control circuit is able to limit the throughput power of an overloaded flyback converter independently of its switching frequency. It consists of PWM comparator, latch, driver circuit, error amplifier and voltage and current protection circuit. The power delivered by converter increases considerably with the switching frequency, despite current mode control provides inherent current limitation. The 60kHz to 140kHz switching frequency is tested for high voltage but as frequency rises the ripple

in output causes unstable output this problem is eliminated by extra high tension circuit. Extra- high tension power supply capable of delivering variable DC voltage from about 100 V to 40 kV with load current up to 0.7mA. To control the ripple input voltage to the primary of a power transformer using high- power SCRs connected back to back. The same principle is used in designing this power supply. The most important design aspect of this circuit is the generation of SCR triggering pulses synchronised with the ripple input sine wave. This ensures that the SCRs used for controlling the positive and negative halves of the sine wave can be switched on at the same angle determined by the intersection of a synchronised sawtooth wave and DC control voltage.

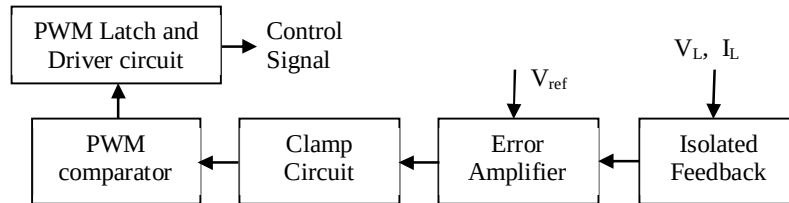


Figure 5. Control circuit

IV. RESULT AND DISCUSSION

To validate the prototype of flyback converter based EHT with control circuit is implemented in the present study. Figure 6 show the flyback converter and EHT with control circuit. The rectified signal from the rectifier is applied to channel 3(purple line) as input voltage $V_{in}=10V$ to flyback converter circuit operating at 150 kHz. The DC-DC flyback converter output voltage obtained between 5V and 40V it depend on the applied control signal, which are considered for adapter applications of smart phone, notebook, personal computer etc. further it is connected to EHT through control circuit to obtain extra high voltage for electrospinning application. The flyback boost converter is tested with the applied input Figure 6 shows the channel 4 (green line) output voltage $V_{out}=100V$ with channel 1(yellow line) Drain to source voltage $V_{DS}=10V$.



Figure 6. Input voltage V_{in} , output voltage V_{out} , Drain to source voltage V_{DS}



Figure 7. Drain to source voltage V_{DS} , voltage across diode V_D



Figure 8. Drain to source voltage V_{DS} , drain to source current I_{DS} @24W and R_L is 6 Ω

Figure 7 shows when the MOSFET is in the on state, the drain to source voltage $V_{DS} = 0V$ shown at channel 1 (yellow line) and the drain current is flows through the primary winding of the transformer. Due to which the magnetic field is induced and energy is stored in the primary side of the transformer. This current is rising linearly with time. On the secondary side of the transformer the series connected diode D is reversed biased due to which zero current flowing through the secondary of the transformer shown in Figure 7. In this situation the output capacitor will start discharging, it release the stored energy which causes current flows through the load I_L and V_{out} is present. When the gate trigger pulse turn off the MOSFET, the transformer start releasing the energy stored from the primary due to which the series connected diode conducts shown at channel 1 (green line) and the output capacitor gets charging.

Initially the transformer secondary current is starts at a high peak value and start decreasing linearly. As soon as the transformer secondary current drops to zero before this instant the MOSFET is again turned on shown in Figure 8. Similarly if the transformer secondary current does not fall to zero. Channel 1 (yellow line) shows during turn on state of the MOSFET, the transformer holds energy which is affected by the leakage current shown by channel 4 (green line) and it is absorbed by snubber circuit, its purpose is to protect the semiconductor

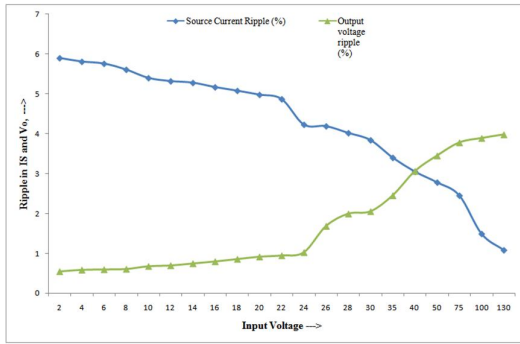


Figure 9: Input Voltage Vs ripple in output voltage, input current

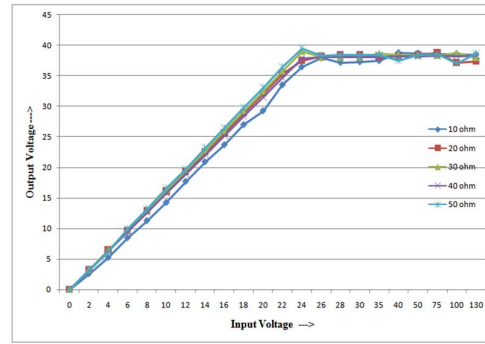


Figure 10: Input voltage vs output voltage with load 10 Ω , 20 Ω , 30 Ω , 40 Ω , 50 Ω

switch from highly inductive voltage. This type of power is dissipated only during the switching transition is carried between the ON and OFF states.

Figure 9. Shows input signal with ripples in output voltage and input current of flyback converter is shown. The operation of flyback converter depends on the switching frequency of switch, as the frequency increases the ripple in the output voltage increases. At high voltage application as the switching frequency increases the output has many ripple and flyback converter output becomes unstable.

The flyback converter design is tested with different load condition Figure 10. shows the variation of output voltage with load.

V. DESIGN AND RESULT COMPARATIVE ANALYSIS

In this section the design and their result are compared with the different literature of the researcher's

Table I. Comparative Analysis

Sr. No.	Comparative Parameters	Electrospinning System from different Researcher's [1-7]	Designed Prototype of Electrospinning System
1	Process Control Mechanism	Automatic (Cost above \$15000) [1-3]	Semi Automatic / Manual
2	Rating of High Voltage DC power supply	20KV to 25KV using only Power converter [3,4,7]	100V to 40KV using Power Converter and EHT
3	Rating of High Voltage DC power supply using EHT	100V to 5kV https://klingereducational.com/product/5324-high-voltage-power-supply-5kv-eht/	100V to 40KV using Power Converter and EHT
4	System is environment friendly	No, Separate Protective devices and Electrically Insulated cabinet is required	Yes

VI. CONCLUSION

In this paper the design of high voltage power supply is discussed the flyback converter is connected to the back to back connected two SCR with extra high tension circuit. It is found that the flyback converter output becomes unstable at high frequency it causes high ripple at high voltage, to obtain stable high voltage with required current the extra high tension circuit is connected. The back to back connection of SCR with extra high tension circuit is controlled for 100V to 40KV with the current rating between 0.4 mA to 0.7 mA. The design circuit eliminates the drawback of bulky transformer, high value component and large heat sink of component, it does not require routine maintenance; provide low ripple with various loads. In future the extra high tension circuit may have provision to control to obtain output voltage at 1000V step as well as variable output voltage.

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