Design and Simulation of High Voltage DC Power Supply using ZVS Full Bridge AC-DC Converter

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Abstract - **The conventional phase-shifted zero voltage switching (ZVS) DC-DC converter is applied to the many power supplies in order to reduce the voltage and current stresses of the main switching devices. The ZVS method needs fairly large leakage inductance in the primary side of the high frequency power transformer to get good ZVS characteristics. During the small dead time between conductions of the two bridge legs, the increased magnetizing current resonates with MOSFET output capacitance, resulting in ZVS operation. Switching losses is quite reducing with the ZVS operation in Full bridge converter so efficiency of converter is increased. A crockroft-Walton voltage multiplier circuit is connected in secondary side of high frequency transformer which increases the output voltage level and rectified it. This study describes the details of high voltage DC power supply whose output voltage is 10kV, 100mA. Simulation is done by using PSIM 6.0 software. Design equations and Simulation results are presented and discussed.**

Index Terms - **DC-DC Converter, DC Power Supply, Voltage Doubler circuit, Voltage Tripler Circuit, Zero Voltage Switching.**

I. INTRODUCTION

DC voltages are mainly used for pure scientific research work and in industry the main application of the DC high voltage is in test on cables with a relatively large capacitance, which takes a very large current if it is tested with AC voltages [1]. High voltages are primarily produced for insulation testing of high voltage equipment under power frequency AC, DC, switching and lightning impulse voltages. For insulation testing equipment, the voltages are increased up to several million volts but currents are decreased to a few mA or maximum 1 ampere both for AC and DC test sets. In the fields of electrical engineering and applied physics, high voltage DC are required for several applications such as electron microscopes and x-ray units require high DC voltages of the order of 100 kV or more, electrostatic precipitators, particle accelerators in nuclear physics and so on [2].

Nowadays PWM DC-DC converters are designed to operate at the high frequency in order to have them smaller and lighter in weight. However, that makes much large switching loss, and high voltage, current stress to switching devices [3]. The conventional phase-shifted ZVS Full Bridge DC-DC converter has much reduced switching losses and no stress to the switching devices even though no snubbers. The conventional ZVS Full Bridge DC-DC converter has large leakage inductance in primary side of the high frequency transformer to achieve adequate ZVS characteristics. The proposed ZVS full bridge DC-DC converter unit of 10 kV, 100mA (1kW), 10kHz for Anode power supply in pre-driver stage of RF amplifier was designed.

In this paper, the main emphasis is laid on the simulation and design of the high voltage DC power supply. At the first stage of this work is to study the zero voltage switching in full bridge converter and voltage multiplier circuits i.e. voltage doubler circuits, voltage tripler circuits and so on and simulate all the circuits. Finally Design and simulation is done on ZVS in full bridge converter with the Cockcroft-Walton(C-W) voltage multiplier circuits of High Voltage DC power supply of 10 kV, 100mA.

Joseph M. Beck [4] has presented his paper the basic operation of voltage multiplier circuits such as half wave voltage doubler and tripler circuits and discussed guidelines for electronic component selection for diode and capacitor. Juichi Tanaka, et al [5], has explained the new idea to develop the high voltage DC power supply. They introduced a high frequency switching converter, as a result its shape becomes smaller. The conventional C-W multiplier circuit ignores the inductance but they have used the inductance as well. They were able to produce 70 kV, 0.15-ampere DC power supply. Yamamoto and his group, [6], have proposed a power factor correction scheme using a voltage doubler rectifier circuit without switching devices. In this method using a voltage doubler rectifier, the input current is divided into two periods, where one period charges the small input capacitor and the other charges the large output capacitor through a filter capacitor. Chao Yan and his group [7] discussed the precise ZVS range calculation method for full bridge converter. Weidong Fan and Goran stojcic [8] in their paper discussed a simple zero voltage switching full bridge DC bus converters and how the inductor current make resonant with capacitor of MOSFET.

The benefits of lossless Zero Voltage Transition (ZVT) switching techniques are well known throughout the power supply industry. The parasitic circuit elements are used advantageously to facilitate resonant transitions rather than snubbing dissipatively. The resonant tank functions to put zero voltage across the switching devices prior to turn-on, eliminating power loss due to the simultaneous overlap of switch current and voltage at each transition. High frequency converters operating from high voltage input sources gain significant improvements in efficiency with this technique [9].

II. SYSTEM DESCRIPTION

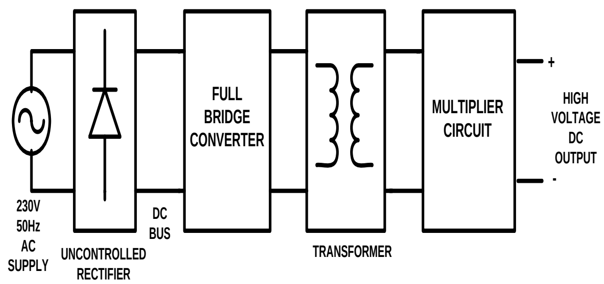


Fig.1 Basic Block diagram of High Voltage DC Power Supply

To achieve zero voltage switching in full bridge converter the leakage inductance of transformer is used and magnetizing current produce the sufficient energy to make the zero voltage switching with the parasitic capacitor of MOSFET and if the leakage inductance of transformer is less than the required inductance than external inductor is connected in series with the primary winding of the High frequency transformer to achieve the ZVS in full bridge converter to reduce the switching losses and so increases the efficiency of full bridge converter. In above fig.1 the output of full bridge converter is given to high frequency step-up transformer and so increase the secondary voltage of the transformer and this voltage is given to Crockroft-Walton multiplier circuit which increase the output voltage and rectified it so high voltage dc output is available.

So, to reduce the switching losses in high frequency converter the zero voltage switching or zero current switching (ZCS) methods are used. ZVS is more commonly used as compared to ZCS because it has following advantages:

Advantages of ZVS over ZCS :

- No power loss due to discharging Coss in ZVS.
- No higher peak currents in zero voltage switching.
- High efficiency with high voltage input at high frequency.
- Can incorporate parasitic circuit and component L and C.
- Reduce gate drive requirements (no miller effect)
- Short circuit tolerant
- ZVS is preferred over ZCS at high frequency, the reason has to do with internal capacitance of switch. When the switched is turned-on a zero current but at finite voltage, the charge on the internal capacitance is dissipated in the switch. This loss does not occur if the switch turn- on at zero voltage.

III. RESONANT CIRCUIT DESIGN

Compute L_R and C_R:
There are several ways to calculate the value of the resonant inductor (L_R=External series inductance + Leakage inductance) and minimum primary current required for any application. Each of these is based upon the following fundamental relationships. The resonant tank period must be at least four times higher than the transition time to fully resonate within the maximum transition time t_{MAX} at light load.

$$T_{RES} = 4t_{MAX}$$

$$f_{RES} = 1/(4t_{MAX})$$

$$\omega r = 2\Pi f_{RES} = 2\Pi/4t_{MAX} = \Pi/2t_{MAX}$$

The resonant radian frequency ωr is related to the resonant components by the equation $\omega r = 1/(L_R C_R)^{1/2}$

So, Resonant Inductor value $L_R = 1/(\omega r^2 C_R)$

The specified MOSFET switch output capacitance Coss will be multiplied by a 4/3 factor per the MOSFET manufactures Application Notes to approximate the correct average capacitance value with a varying drain voltage. During each transition, two switch capacitances are driven in parallel, doubling the total capacitance to (8/3)*Coss. Transformer capacitance C_{XFMR} must also be added as it is not negligible in many high frequency applications, especially at lower power levels where smaller switches are incorporated.
The resonant capacitance $C_R = (8/3)*Coss + C_{XFMR}$

So, resonant inductor is given by

$$L_R = 1/[(\Pi/2t_{MAX})^2 * ((8/3)*Coss + C_{XFMR})]$$

Stored Energy Requirements :
The energy stored in the resonant inductor must be greater than the capacitive energy required for the transition to occur within the allocated transition time. So,

$$½ * L_R I_{PRI(MIN)}^2 > ½ * C_R * V_{IN(MAX)}^2$$

Since C_R and V_{IN} are known, so L_R can be calculated

Minimum (critical) Primary Current :
The minimum primary current required for the phase shifted application can now be determined by reorganizing the previous equation. Operating below this critical current level will result in lossy transitions.

$$I_{PRI(MIN)} = [(C_R * V_{IN}^2)/L_R]^{½}$$

This value can be supported by calculating the average current required to slew the resonant capacitor to the full rail voltage. Although this figure will be lower than $I_{P(MIN)}$, it can be used to confirm the calculations.

$$I_{R(AVG)} = C_R\, V_{IN}/T_{MAX}$$

Obtaining the necessary amount of primary current can be done in several ways. The most direct approach is simply to limit the minimum load current to the appropriate level. One alternative, however, is to design the transformer magnetizing inductance accordingly. Also assisting the magnetizing current is the reflected secondary inductor current contribution which is modeled in parallel.

IV. SIMULATION OF THE SYSTEM

Simulation is carried out by Using PSIM Software

As shown in Fig.2 an inductor is connected in series with the primary winding of high frequency transformer to achieve the zero voltage switching and Five Stage Crockroft-Walton Voltage Multiplier Circuit is connected in the secondary side of the transformer which gives 10 kV output voltage. Fig.3 gives the Gate pulse to the MOSFET's which gives the phase shifted pulses.

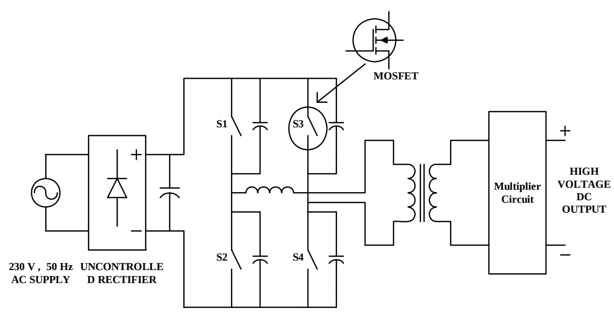


Fig.2 Open loop simulation diagram of High Voltage DC Power Supply

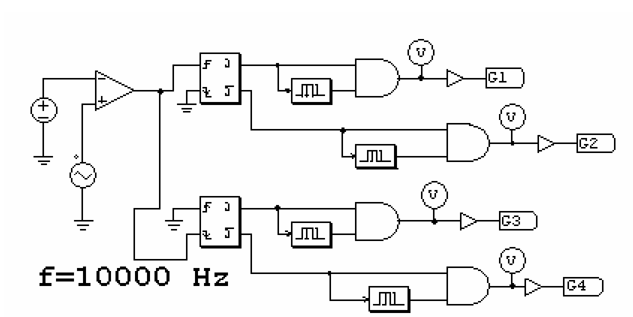


Fig.3 Gate Pulse Generation Circuit

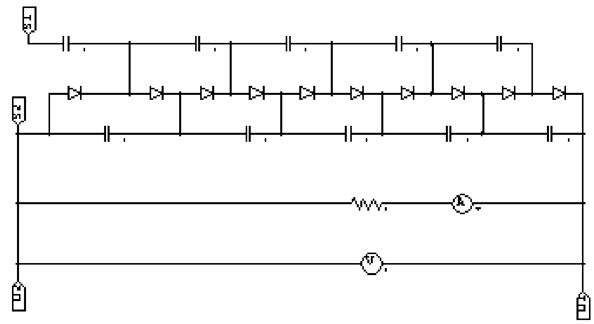


Fig.4 Five Stage Crockroft-Walton Multiplier Circuit

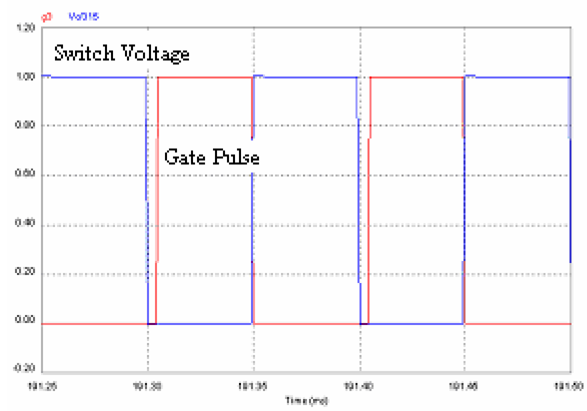


Fig.5 Zero Voltage across the switch before the gate pulse is ON with open loop operation

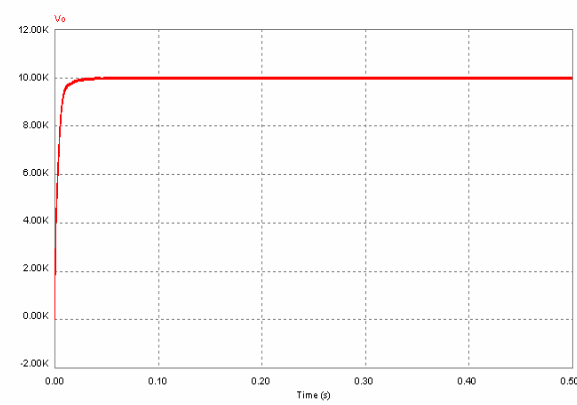


Fig.6 Output Voltage of proposed High Voltage DC Power Supply with open loop operation

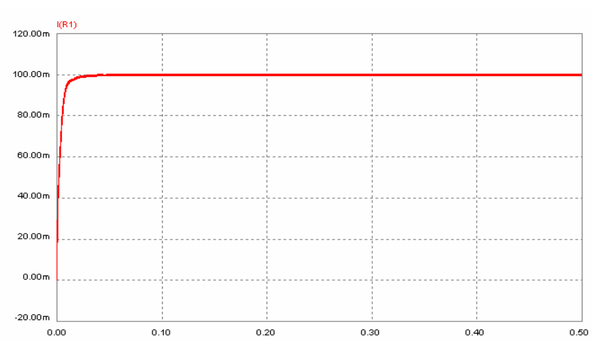
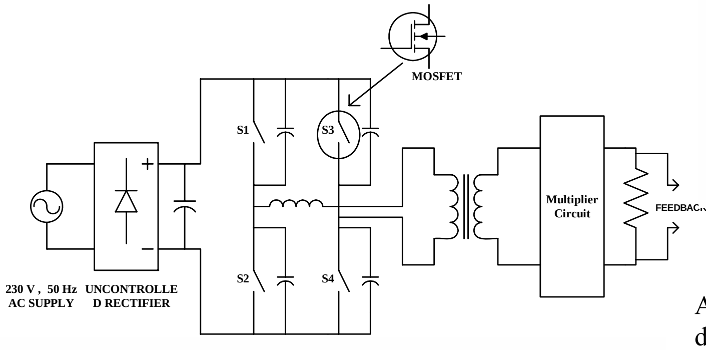


Fig.7 Output Current of proposed High Voltage DC Power Supply with open loop operation

Fig.4 shows the five-stage Crockroft-Walton Multiplier Circuit. Fig.5 shows the zero voltage switching is achieved and Fig.6 and Fig.7 shows the output voltage 10 kV and output current 100 mA of high voltage dc power supply.



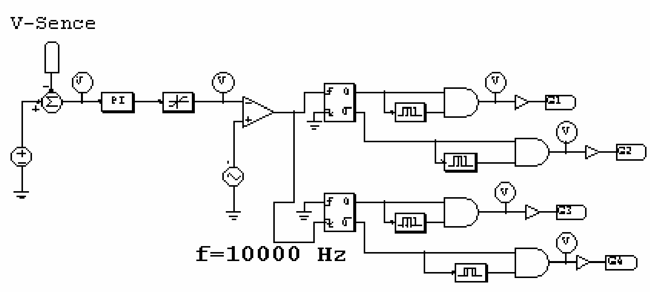


Fig.8 Close loop simulation diagram of High Voltage DC Power Supply

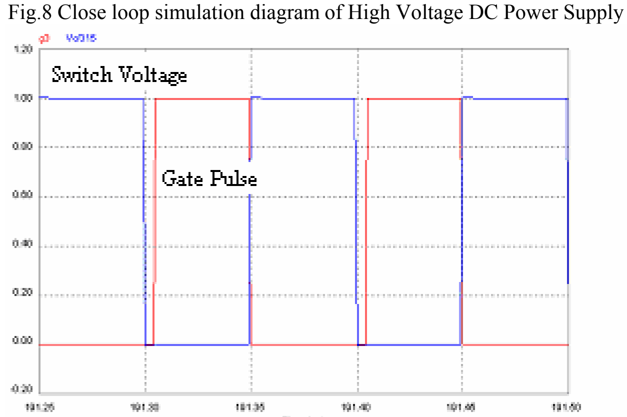


Fig.9 Zero Voltage across the switch before the gate pulse is ON with close loop operation

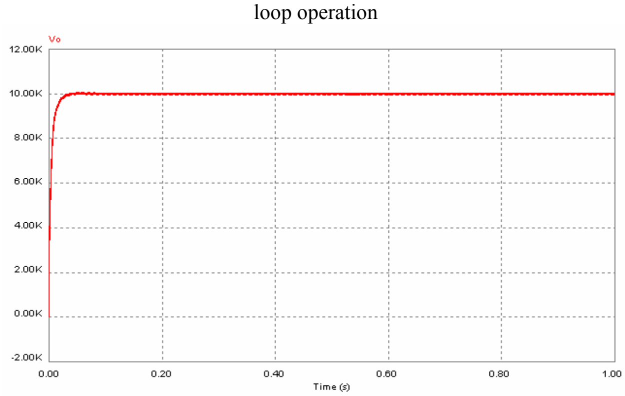


Fig.10 Output Voltage of proposed High Voltage DC Power Supply with close loop operation

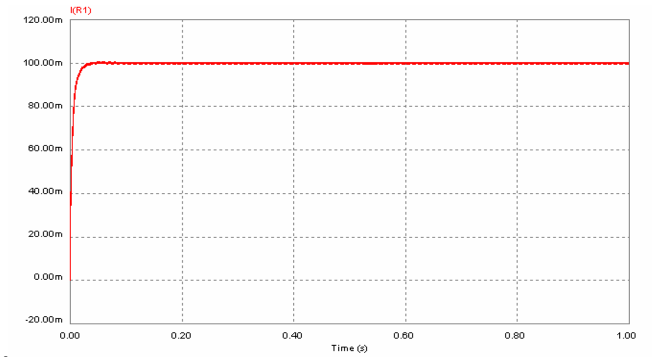


Fig.11 Output Current of proposed High Voltage DC Power Supply with close loop operation

As shown in Fig. 8 which is the closed loop simulation diagram of high voltage dc power supply with ZVS and Fig.9 shows the zero voltage switching is achieved before the gate pulse is ON. Fig.10 and Fig.11 which gives the 10 kV output voltage and 100 mA current of power supply with close loop operation.

The following parameters are taken for the Design and Simulation as shown in Table I:

TABLE I
DESIGN PARAMETER TAKEN FOR SIMULATION

Supply Voltage	230 AC
MOSFET output Capacitance	100 pF
Series Inductor	10 uH
Capacitor of Multiplier circuit	2 uF
Transformer ratio	1: 3.45
Switching Frequency	10 kHz

V. CONCLUSION

The proposed topology shows that the size of high voltage dc power supply can be reduced by increasing the switching frequency. However the switching losses will be more. But if we use resonant technique, switching losses are reduced and therefore the efficiency is increased.

To achieve Zero Voltage Switching with phase shifted PWM, the leakage inductance of transformer should be taken high and give a sufficient dead band between the two lag switches but at the same time duty cycle decreases which is the demerit of ZVS with phase shifted PWM full bridge converter.

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