A High Voltage Zero Current Switching- Series Resonant Converter Using DSP

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***Abstract* – High voltage DC sources are widely used in power industries. The conventional dc sources have been replaced by solid state DC sources due to its large size and heavy weight. This paper deals with the implementation of high voltage DC source for Marx generator which is used to generate high voltage impulses for various application such as testing of insulation of electrical apparatus, insulators used for supporting power lines etc. The DC sources implemented here achieves zero current switching using series resonant principle so that switching losses can be reduced compared to other DC-DC converters. A complete design of 1 kV (open circuit voltage) zero current switching series resonant DC source is done. A prototype of the converter 410 V, 5 W (open circuit voltage) is implemented using DSP TMS320F28069. Satisfactory results are obtained and presented in the paper. Also effect of increasing the switching frequency of converter on output voltage and output voltage ripple is analyzed.**

Keywords* – *high frequency transformer, series resonance, voltage multiplier circuit, zero current switching.

I. INTRODUCTION

High voltage DC sources are used for various applications such as generation of high voltage impulses for testing power transformers, lighting simulators, microwave generation etc. They are also used as input dc source to the Marx generator. Traditionally, DC sources used for Marx generator consists of linear power circuit, electrostatic generator, voltage multiplier circuit etc [1, 2]. These conventional methods for DC sources have large size and heavy weight. Also, the disadvantage in voltage multiplier circuit is that as number of stages increases its output voltage decreases [2]. By using solid state devices it is possible to have high voltage DC sources with compact size and light weight.

The solid state high voltage DC source using resonant principle is designed and implemented. Resonant converters can be operated in zero current switching or zero voltage switching (ZCS/ZVS) technique. The turning on and turning off of the converter switches in ZCS/ZVS technique is either at the switch current zero or at switch voltage zero respectively [3]. The different types of converter topologies considered for literature survey are - buck-type current-fed push-pull converter giving 5-30 kV output voltage [4], zero current switching-pulse width modulation (ZCS-PWM) converter [5] and fifth order resonant converter for high voltage dc power supplies with 10 kV, 1.1 kW output [6].

Yen Chen et al designed buck-type current-fed push-pull converter giving 5-30 kV output voltage. This kind of configuration has disadvantage of high peak voltage stress upon primary switches during off-state. This voltage is greater than two times the input voltage. Also it doesn't use any soft switching techniques, hence converter losses increases [4]. Chris Iannello et al designed zero current switching pulse width modulation (ZCS-PWM) converter. This has advantages of reducing switching losses but it has no scope for varying the output voltage. If one of the stages of Marx generator fails then the output voltage of its source can be increased to obtain the required output of Marx generator [5]. Navid Shafiei et al designed a 10 kV, 1.1 kW fifth order resonant converter for high voltage DC power supply. This topology uses ZVS technique thereby reducing switching losses. But due to increased complexity of resonant circuit these multi-element resonant converters exhibit complex dynamic behavior [6].

Sze Sing Lee et al designed a 5.6 kV high voltage DC source for X- ray power supply application using zero current switching - series resonant (ZCS-SR) technology [7]. The authors used analog devices for generation of switching pulses whereas in this paper DSP TMS320F28069 is used for generation of switching pulses for application of source to Marx generator. A 410 V (open circuit voltage) ZCS-SR source is designed and analyzed. In section II, working principle of ZCS-SR converter is explained. Section III explains design of power circuit and control circuit. Section IV gives hardware results. Effect of increasing switching frequency of converter on output voltage and output voltage ripple is presented in section V. Conclusion is given in section VI.

II. WORKING OF ZCS-SR CONVERTER

Fig. 1 shows the schematic diagram of a zero current switching- series resonant converter. The converter has two main parts- power circuit and control circuit [7]. Fig. 1 shows the power circuit in detail. Power circuit consists of input voltage V_{CC}, single phase inverter, resonant capacitor C_S, leakage inductance of high frequency transformer L_S, high frequency transformer and voltage doubler circuit. The working of ZCS-SR converter is explained in three different modes.

Mode 1- In this mode Q_1,Q_2 are ON. The current flows from source V_{CC} to Q_1,C_S ,L_S and back to source V_{cc} through Q_4. Assume that capacitor is initially charged with voltage V_{C0}. When Q_1, Q_4 are turned ON capacitor starts charging in positive direction and inductor current increases. Inductor charges to its maximum value and then starts discharging. Now the capacitor is charged both by source voltage and inductor, hence the capacitor charge further increases. Maximum capacitor voltage reached is two times the source voltage V_{CC}. Also maximum capacitor voltage will occur when inductor current becomes zero as shown in Fig.2 [8]. Fig. 2 is the simulation results of the converter which is carried out using Proteus software. This marks the end of Mode 1.

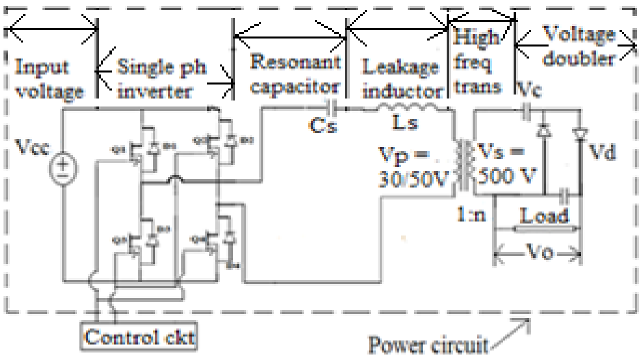

Fig. 1 Schematic diagram of ZCS-SR converter

Mode 2 - In this mode, capacitor starts discharging through anti-parallel diodes D_1, D_4 and inductor L_S. The direction of current reverses through inductor as seen in Fig.2. The capacitor voltage reduces from its maximum value to the initial value V_{C0} which is a positive value.

Dead zone - During this mode all the devices are off. The inductor current is zero while the capacitor voltage remains constant. This time period for dead zone depends on the value of switching frequency and resonant frequency. This same process repeats itself in the next half cycle for Q_2Q_3[3].

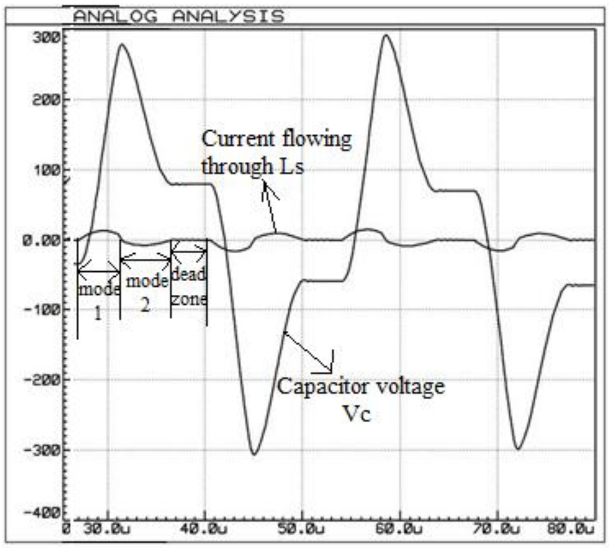

Fig. 2 Graphs for current flowing through Ls and voltage across Cs [8].

Output of the inverter is connected to a high frequency transformer through resonant capacitor C_S . High frequency transformer is used for isolation purpose and also for boosting the voltage. The high frequency transformer output is connected to a voltage doubler circuit. Voltage doubler circuit is utilized to further increase the voltage two times the original voltage and convert the ac voltage to dc voltage.

III. DESIGNING OF POWER CIRCUIT AND CONTROL CIRCUIT

ZCS- SR operates in two modes – continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The circuit in Fig. 1 is operated in discontinuous conduction mode. In DCM, current becomes zero at a particular instant and at this moment switching is done whereas in CCM the current doesn't become zero. Hence DCM is preferred. For discontinuous conduction mode of operation [3]

$$f_S < \frac{1}{2} f_r \qquad (1)$$

where f_S is switching frequency and f_r is resonant frequency. As switching frequency needs to be considered in kHz range, f_S considered for this ZCS-SR dc-dc converter is 37 kHz [7].

As seen in Fig. 1 the main components of power circuit are input voltage V_{CC}, single phase inverter, resonant capacitor C_S, leakage inductance of high frequency transformer L_S, high frequency transformer and voltage doubler circuit. For designing of 1 kV (open circuit) output voltage, the input voltage to primary side of high frequency transformer is 30 V. With 1:17 turns ratio of transformer, the output voltage obtained from secondary side of transformer is 500 V. Voltage doubler circuit is connected to secondary side of high frequency transformer. This circuit doubles the input voltage and gives 1 kV output voltage (open circuit).

A. *Single Phase Inverter*

The input voltage V_{CC} is given to the single phase inverter. The maximum inverter input voltage is 50 V. The switch in inverter shown in Fig. 1 is IKW40T20 infineon

(IGBT) having maximum collector current I_C= 40 A and maximum collector to emitter voltage V_{CE} = 1200 V.

B. Resonant Capacitor And Leakage Inductane Of High Frequency Transformer

The output of inverter is connected to primary winding of a high frequency transformer through a resonant capacitor C_S. The value of leakage inductance L_S depends on the designing of high frequency transformer. The equation for current flowing through leakage inductance of high frequency transformer is given by equation 2 [3].

$$i_L(t) = \frac{V_{CC} - V_{c0}}{Z_0} \sin w_0(t - t_0) \quad (2)$$

Where,

V_{CC} = Input voltage

V_{c0} = Initial capacitor voltage

Z_0 = Characteristic impedance

w_0 = Resonant frequency

t_0 = Start time

The equation for voltage across resonant capacitor is given by equation 3 [3].

$$v_C(t) = V_{CC} - (V_{CC} - V_{c0}) \cos w_0(t - t_0) \quad (3)$$

The leakage inductance L_S of high frequency transformer measured by LCR meter is 3.3µH and the primary side resistance of high frequency transformer is 0.241 Ω respectively. As $f_r > 2f_S$, the resonant frequency f_r chosen is 128 kHz taking into consideration the zero current crossing and DCM [3]. After substituting all values in equation 4, the value of C_S obtained is 0.47 µF. The resonant capacitor shown in Fig. 4 is polypropylene type AC capacitor of 0.47 µF and 630 V.

$$w_r = \sqrt{\frac{1}{L_S C_S} - \frac{R^2}{4{L_S}^2}} \quad (4)$$

C. High Frequency Transformer

The high frequency transformer is the main component in power circuit. High frequency transformer operates in kHz range and hence the size of such transformers is greatly reduced. This type of transformers are mostly used in DC-DC converter application. They are designed in such a way to obtain minimum values of leakage inductance and leakage capacitance. In this application, high frequency transformer is used to step up voltage [7]. The specifications for high frequency transformer are mentioned in table 1.

Secondary side voltage and current of high frequency transformer are V_2 = 500 V, I_2 = 10 mA respectively. The output power at secondary side is given by equation 5.

Open circuit voltage V_0 (kV)	Output voltage Ripple V_{rippl}	Switching Frequency f_s (kHz)	Max Input Voltage V_{CCmax} (V)	Min Input voltage V_{ccmin} (V)
1	1% of V_0	37	50	30

Power at secondary side = $P_{02} = I_2 V_2$ = 5W (5)

The efficiency of high frequency transformer is assumed to be 80%. The power handling capacity of core is related to its area product. Area product is product of window area A_W and core area A_C.

$$\text{Area product} = A_p = \frac{P_{02}[\sqrt{2} + \frac{1}{\eta}]}{4 K_W J B_m f_s} \quad (6)$$

$$A_p = 0.03460 \text{ X } 10^4 \, mm^4$$

Where K_W= window utilization factor is 0.2 [9]

B_m= Flux density value is taken as 0.3 T [9]

J = Current density = 3 A/mm^2 [9]

The core size for given area product A_p is E 25/13/7.

Area product = A_p= 4780 mm^4

Window area = A_W = 87 mm^2

Core area = A_C = 55 mm^2

The number of turns in primary side of transformer can be calculated by equation 7.

Table 1 High frequency transformer specifications

Primary turns = $N_1 = \frac{V_{ccmax}}{4 A_C B_m f_s} \approx$ 20 turns (7)

The turns ratio and number of turns on secondary side of transformer is calculated by taking 10% compensation on secondary side. Hence, V_2 = 550 V.

$$n = \frac{N_2}{N_1} = \frac{V_2}{V_1} = 18.333 = 18 \text{ approx.}$$

$$N_2 = nN_1 \approx 367 \text{ turns}$$

N_1= 20 turns, N_2 = 367 turns

The wire gauge for primary and secondary side windings are calculated from the current rating. Therefore, SWG 31 with area 0.06818 mm^2 is selected for primary side and SWG 45 with area 0.003973 mm^2 for secondary side from [9].

Leakage inductance L_S and magnetizing inductance L_m of the designed high frequency transformer measured by LCR meter is 3.3 µH and 300 µH respectively. Leakage inductance of high frequency transformer produces voltage spikes due to the stored energy in it. Also parasitic capacitances of high frequency transformer will be charged and discharged in every half-cycle. The transformer leakage inductance and parasitic capacitance have inverse relationship. If leakage inductance decreases, parasitic capacitance increases and vice-versa. There is trade-off between leakage inductance value and parasitic capacitance value for designing best transformer for a particular application.

D. Voltage Doubler Circuit

The secondary ac voltage of high frequency transformer is rectified and boosted with voltage doubler circuit. Voltage doubler circuit is designed for maximum output voltage of 1 kV (open circuit). A voltage doubler circuit has R2000F high voltage diode having maximum peak reverse voltage of 2000 V and maximum average forward rectified current of 200 mA. Also, the capacitor used in voltage multiplier circuit is a high voltage KT 22 polyester capacitor of 0.1 µF and 1000 V DC [2].

The control circuit is basically the pulse generating circuit. The pulses for this hardware are generated from DSP TMS320F28069. A program was written in code composer studio version 4 (CCSv4) to generate these pulses. The 3.3 V pulses generated from DSP are given as input to driver circuit which increases the voltage level of pulses to 15V. Hence pulses suitable for switching IGBT are generated.

The gate driver circuit converts logic level signals into appropriate voltage and current required for switching the IGBT. Also it provides isolation so that the logic signals are not connected to the high voltage side of the power circuit. Driver circuit should be able to withstand against high voltage and high current in power circuit. The driver circuit used for the topology is shown in Fig. 3.

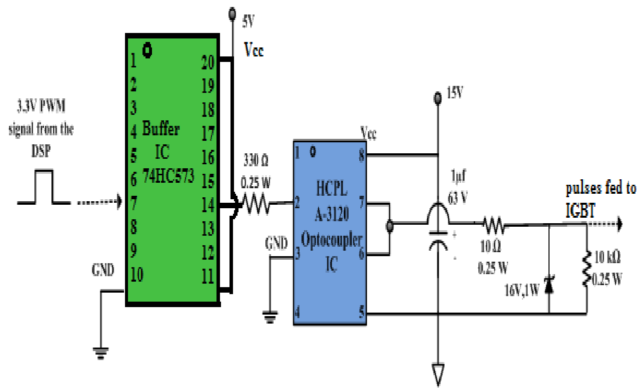

Fig. 3 Driver circuit for IGBT switching

IV. HARDWARE RESULT

A 410 V, 5 W prototype of the ZCS-SR system was implemented. Fig.4 shows the hardware implementation of power circuit.

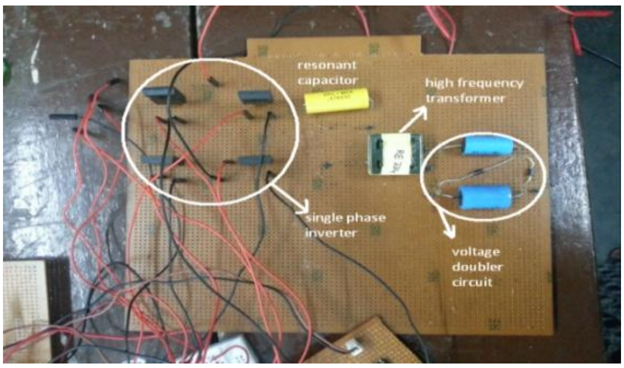

Fig. 4 ZCS-SR DC-DC resonant converter

Control circuit consists of one buffer IC 74HC573 and four IGBT gate drive opto-coupler IC HCPL3120. The output of driver circuit is shown in Fig. 5.

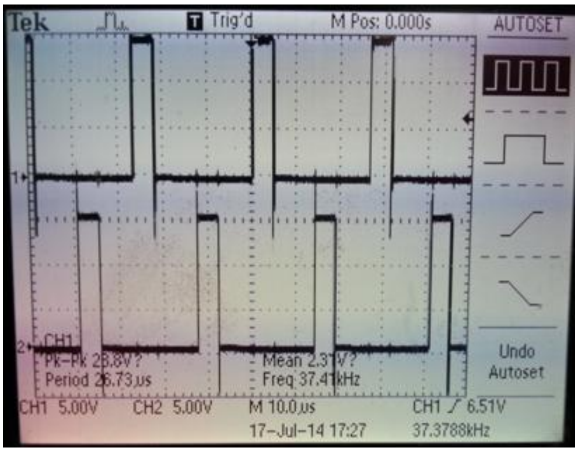

Fig. 5 15V output pulses from driver circuit

The prototype was tested for an input voltage of 8V, due to the limitations of measuring instruments. By giving 8 V input voltage, the open circuit voltage obtained is 410 V. By connecting 1.5 k Ω, 5 W resistor as load, the output voltage is reduced to 18 V.

Fig. 6 shows the current flowing through leakage inductance of high frequency transformer. The converter is designed for discontinuous conduction mode (DCM), hence it is seen that the current waveform obtained for leakage inductance of high frequency transformer is discontinuous.

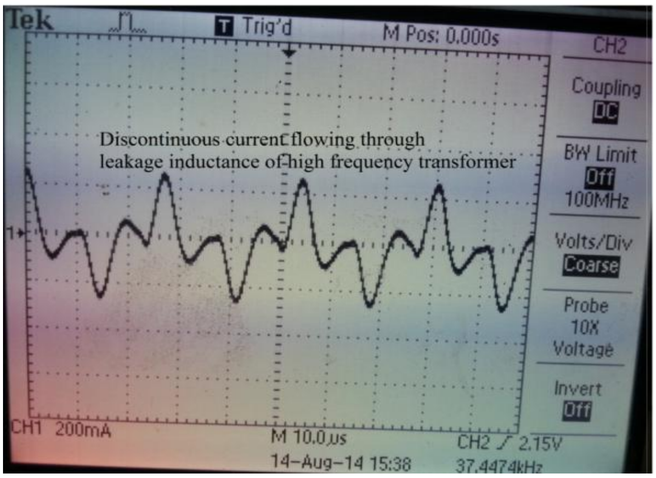

Fig. 6 Graph obtained for current flowing through leakage inductance of high frequency transformer

From Fig. 6 it is seen that the peak value of the resonant current passing through leakage inductance of high frequency transformer is 280 mA. For an input voltage V_{in} of 8 V, the initial capacitor voltage V_{c0} from Fig.7 is 7.21 V. The characteristics impedance Z_0 is

$$Z_0 = \sqrt{\frac{L_r}{C_r}} = \sqrt{\frac{3.3\mu}{0.47\mu}} = 2.6497\ \Omega$$

And from equation 2, I_{max} or $I_{peak} = \frac{V_{in}-V_{c0}}{Z_0} = \frac{8-7.21}{2.6497} =$ 298.15 mA. It is observed that the value obtained by calculation and the hardware differ by only 18.15 mA.

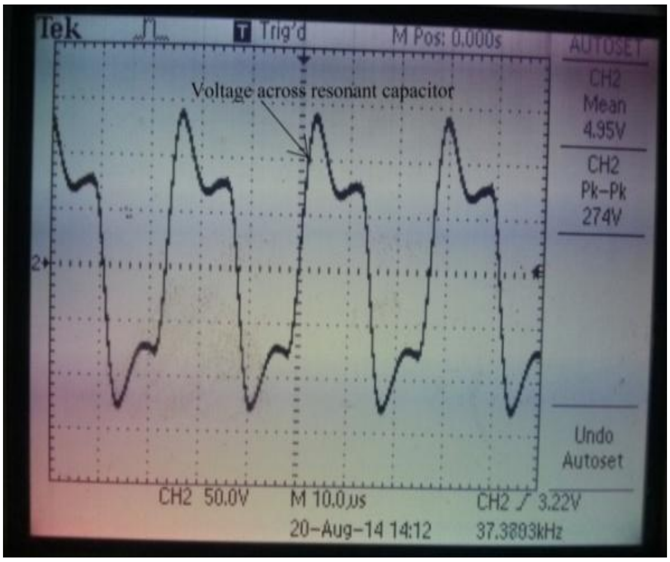

Fig. 7 Graph obtained for voltage across resonant capacitor

Resonant capacitor voltage in Fig.7 shows the peak voltage attained by the resonant capacitor is 14 V. As explained in *Mode-1*, the peak voltage value of resonant capacitor should be twice that of input voltage i.e. 2 X V_{in} = 2 X 8 = 16 V. Hence the values obtained for resonant capacitor voltage from hardware and calculation has a difference of 2 V.

V. EFFECT OF VARIATION OF SWITCHING FREQUENCY

In discontinuous conduction mode (DCM) switching frequency of converter is varied from 15 – 45 kHz and the output voltage and output voltage ripple is measured. Table 2 and table 3 gives the variation of output voltage with change in switching frequency and variation of output voltage ripple with change in switching frequency respectively.

It is observed that as the switching frequency increases, the rms output voltage increases as shown in fig. 8 whereas the percentage output voltage ripple decreases as seen in fig. 9 [7]. Switching frequency can be increased up to 45 kHz only. Beyond this value the resonance condition is not satisfied.

Table 2 Variation of output voltage with change in switching frequency

Switching frequency f_s (kHz)	Output voltage V_0 (rms value in volt)
15	10.2
25	13.7
30	13.1
33	16.8
37	18.4
45	19.5

Table 3 Variation of output voltage ripple with change in switching frequency

Switching frequency f_s (kHz)	Percentage output voltage ripple (%V)
15	12.8
25	7
30	9
33	9.8
37	10.8
45	9.6

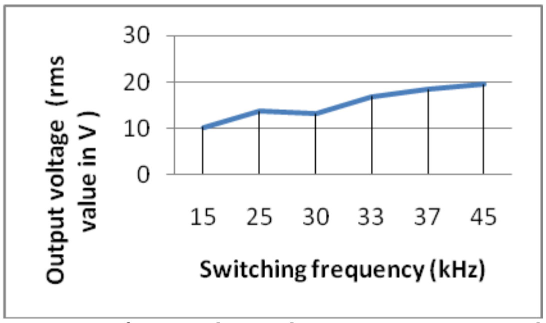

Fig. 8 Variation of output voltage with respect to increase in switching frequency

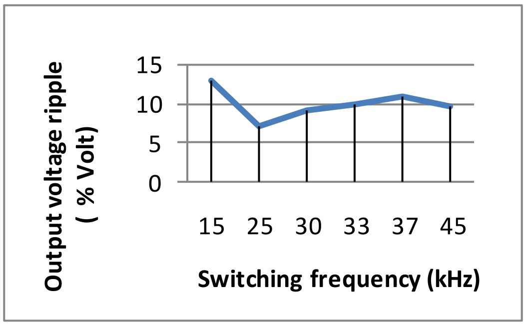

Fig. 9 Variation of output voltage ripple with respect to increase in switching frequency

VI. CONCLUSION

This paper presents the design and implementation of a 410 V, 5 W ZCS-SR DC-DC converter. The ZCS-SR technique is successfully implemented with the calculated and experimental values coming out to be approximately same. The source is tested for an input dc voltage of 8 V which gives an output voltage of 410 V in open circuit condition whereas the output voltage decreases to 18 V when it is connected to a resistive load of 1.5 kΩ , 5 W. Also it is observed that output voltage ripple decreases with increase in switching frequency and the output voltage increases as the switching frequency increases.

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