

Design and Implementation of ZVS Half-Bridge DC-DC Converter for High Power Applications

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Abstract—An improved ZVS Half-bridge DC-DC converter for High-Power Applications is discussed in this paper. Operating at higher frequencies with hard switching leads to a rise in switching losses. By using soft switching methods switching losses decrease. With relatively higher band gaps and improved thermal conductivity, new-generation SiC MOSFETs, used in the proposed converter, are predicted to have better conduction losses and higher converter efficiency. The total losses in the switch is analyzed and presented in addition to the design principles and techniques. This work achieves high-efficiency functioning and zero-voltage switching throughout the entire load range. For a 2kW load, the functioning and design factors are discussed. At an operating frequency of 150 kHz, the simulation was successfully tested in LTspice. Implemented hardware is validated by comparison with simulation results. This converter is suitable for high-power applications due to its straightforward topology, great efficiency, and affordable price.

Index Terms—Zero-Voltage-Switching (ZVS), switching losses, Half-bridge DC-DC converter, Capacitors, and Operating frequency..

I. INTRODUCTION

Employing the DC-DC converter in hard switching at higher frequencies results in increased switching losses [1]. Soft switching techniques in Power Electronics aim to reduce stress and losses during switching by reducing the overlap between voltage and current during the process. By ensuring that the switching happens only when there is no voltage or current, it reduces electromagnetic interference (EMI) and increases efficiency [2]. One of the main techniques for soft switching is Zero Voltage Switching (ZVS). In ZVS, the switch turns on and off when there is no voltage across it. Two soft switching methods that are essential for improving power electronic converter dependability and efficiency are ZVS and ZCS. Because of its benefits, which include isolation, low primary voltage, low power losses per switching element, ease of construction, and affordability, the DC-DC Half-bridge converter is the favored type of insulated DC-DC converter circuit. One of the key benefits of the Half-bridge DC-DC converter architecture is the isolation provided by the transformer [4] [5]. The DC-DC Half-bridge converter topology has two rectifying diodes and two power MOSFETs. For isolation and transformation, a high-frequency transformer is used.

The SMPS output is controlled using the PWM method [6]. The converter can operate at a greater switching frequency by reducing switching losses with the use of zero-voltage switching (ZVS) for the primary side during "turn-on time" and zero-current switching (ZCS) for the output rectifier diodes [7]. The soft-switching method ZVS is used in DC-DC converters, which combine series and parallel resonances because it provides a high power conversion efficiency. It also exhibits a good transient response [8]. The SiC MOSFETs operate in the third quadrant when current passes through the internal body diode. Because it affects the power converter's performance, the body diode's reverse recovery behaviour is crucial in this final scenario during the switching transient [9]. The power supply becomes more expensive since high-voltage semiconductor devices such as MOSFETs are required. Designing a high-voltage DC-DC converter that is inexpensive, incredibly dependable, and efficient across the entire load range is a time-consuming process. The power converter system based on silicon carbide MOSFETs functions more efficiently at higher frequencies due to its faster switching and reduced on-state resistance [3] [10]. Because of their greater efficiency and high power density, DC-DC switching power supply circuit topologies are used in isolated DC-DC applications [11]. Using a Half-bridge LLC resonant converter operating under ZVS is advised for the entire load range. Integrated transformers are used to create resonant tank inductances, which minimizes the size of converters [12] [13]. To remove the imbalance in the current between input capacitors, it is also advised to utilize a capacitor current balance control, which switches between the two working modes of the preferred ZVS PWM technique. In [14], a control methodology is proposed that balances the thermal stresses that reduces the switching losses and also noises that results in increased efficiency and dependable DC-DC converter. A short circuit is one of the most dangerous type of issue in a power-supply subsystem. It can cause the system to completely fail to produce power, or it can cause the single-circuit power supply to lose its capacity. Consequently, the short-circuit mode output power of the system should be taken into consideration while designing the operating condition of a power-supply subsystem, and short-circuit protection should be implemented to improve fault tolerance [15] [16]. The design and operation of the ZVS Half-bridge DC-DC converter for a 2kW load, has been successfully verified at 150 kHz operating frequency for the entire load range and simulated in LTspice, to demonstrate and validate the design and operation. The proposed converter is popular for high-power applications due to its simple topology, excellent efficiency, and affordable price. Figure. 1 displays a block diagram of the ZVS Half-bridge DC-DC converter.

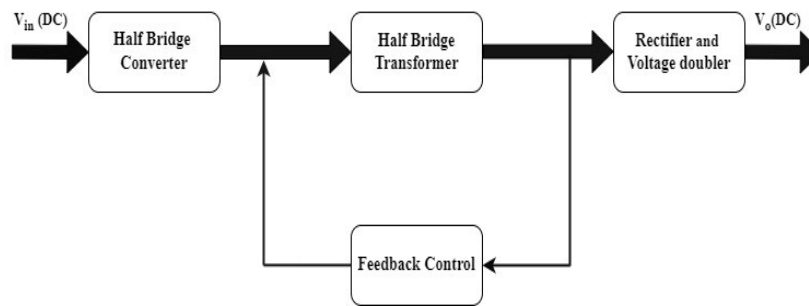


Figure 1: Block Diagram of ZVS Half-bridge DC-DC converter

II. PRINCIPLE OF OPERATION

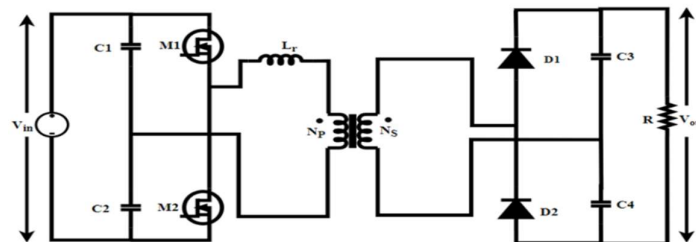


Figure.2: Circuit diagram of ZVS Half-bridge DC-DC converter

The circuit diagram of the ZVS Half-bridge DC-DC converter is displayed in Figure.2. The converter consists of capacitors (C1 and C2) which produce a constant mid-point voltage which is half the input voltage at the primary side of the transformer. The MOSFETs (M1 and M2) are the two switching elements that operate at a switching frequency of 150kHz which is complimentary to each other. The resonant inductor (L_r) and capacitor (C1 and C2) in the circuit form a resonant tank circuit to form a sinusoidal current waveform. This is also important for soft switching techniques, which reduce switching losses and improve efficiency. The transformer provides isolation between input and output. It steps down the voltage depending on the turns ratio. The diodes (D1 and D2) are the rectifier diodes that converts AC to DC. They are unidirectional which allows the current to flow in one direction which rectifies the sinusoidal current into pulsed DC. The Capacitors (C3 and C4) are the voltage doubler which doubles the output voltage as per the design requirements. The resistive load is connected to the output side of the DC-DC converter. This converter is suitable for high-power applications as it has high efficiency, simple topology, and low cost making the proposed converter more attractive.

There are four ways that the converter may operate:

Mode 1: While switch M2 is off and switch M1 is on

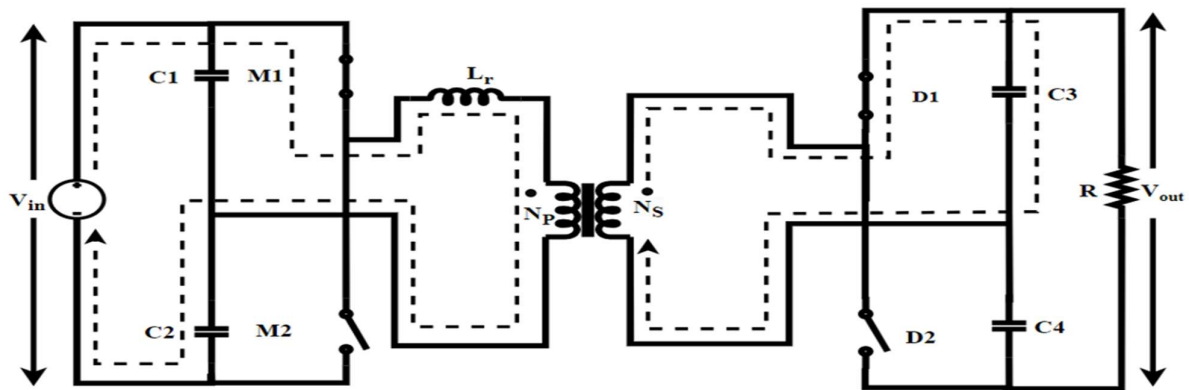


Figure.3: Half-bridge DC-DC converter operating in mode 1

In this condition, D2 gets reverse biased and D1 conducts while M1 is ON and M2 is OFF as shown in Figure.3 . The main voltage, or V_p , is equal to $V_s/2$. When the primary current I_P starts to build, energy is stored in the primary winding. The rectifier diode D1, the voltage doubler capacitor C3, and the load together experience forward energy transfer.

Mode 2: While M1 and M2 switches are both off.

In this condition, D1 and D2 are compelled to conduct the magnetizing current that was produced during mode 1 because M1 and M2 are both OFF.

Mode 3 and 4: While switch M1 is off and switch M2 is on.

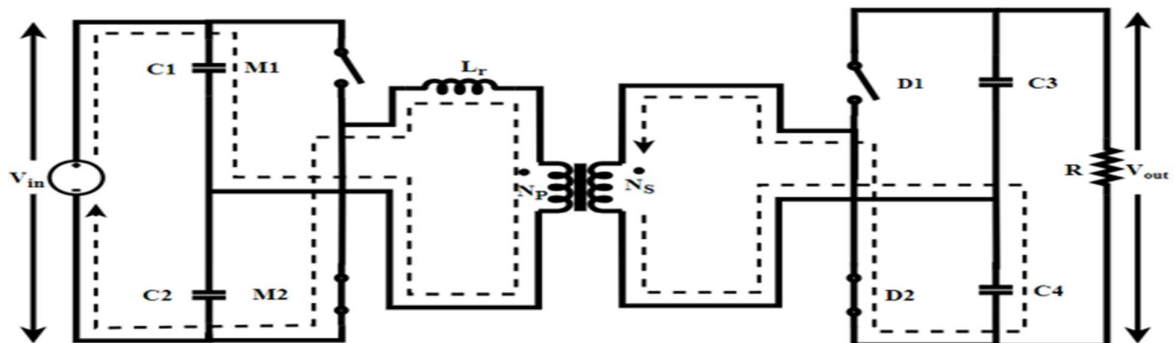


Figure 4: Half-bridge DC-DC converter operating in mode 3

In this condition, while D1 is reverse biased and D2 conducts, M2 is on and M1 is off as shown in Figure.4. The primary voltage V_p is $-V_s/2$. Through the voltage doubler capacitor C4, diode D2, and the load, the energy is delivered to the secondary. The circuit functions in the same manner as in modes 1 and mode 4 which is equivalent to modes 2.

III. TECHNICAL REQUIREMENTS AND DESIGN METHODOLOGY

A. Technical Requirements

Table I shows the ZVS Half-bridge DC-DC converter's technical requirements.

TABLE I. TECHNICAL REQUIREMENTS FOR HALF-BRIDGE DC-DC CONVERTER

Sl. No	Parameter	Value	Unit
1	Input voltage	700-725	V
2	Output voltage	500-525	V
3	Output current	4	A
4	Output Power	2	kW
5	Switching Frequency	150	kHz
6	Duty Cycle	0.48	
7	Ripple voltage	26	V
8	Efficiency	>94%	

B. Design Methodology

In accordance with parameters in Table 1, the Half-bridge DC-DC converter is designed.

Transformer Design

Transformer selection is mostly based on two factors: area product and power handling capabilities. ZP44416TC, a toroid core, has been chosen here.

Window Utilization Factor : $K_u = 0.5$

Wave Form Factor : $K_f = K = 0.17$

Current Density : $J = 4 \text{ A/mm}^2$

Flux Density : $B_m = 0.1284 \text{ T}$

Window area : $A_w = 88 \text{ mm}^2$

Value of core : $AL = 5830 \times 10^{-9}$

Cross section area : $A_c = 187 \text{ mm}^2$

The Area Product of the chosen toroid core is:

$$A_p = \left(\frac{P_{out}}{K * B_m * 2 * F_{sw}} \right)^{\frac{4}{3}} * 10^4 \quad (1)$$

$$A_p = 44312.5144 \text{ mm}^4$$

$$A_p = A_c * A_w = 65824 \text{ mm}^4 \quad (2)$$

Primary turns:

$$N_p = \frac{V_p * 10^4}{F_{sw} * A_c * B_m * K} = 13 \text{ turns} \quad (3)$$

Secondary turns:

$$N_s = \frac{N_p * V_{out}}{V_{in}} = 9 \text{ turns} \quad (4)$$

b) Input Capacitor:

$$C_{in(half)} = \frac{T * I_{out}}{4 * N * d * V_{in}} \quad (5)$$

; where,

T represents the total time.

I_{out} represents the output current.

V_{in} represents input voltage.

N represents transformer turns ratio.

d is a coefficient, given by ratio between the ac component amplitude in the voltage across each of the capacitors C1 and C2 and the input voltage (where $d=0.05$ to 0.15) [1][17].

Resonant inductor:

$$L_r = \frac{(t_h)^2}{q^2 * \pi^2 * C_{in(half)}} \quad (6)$$

; where,

t_h is the time interval during which the voltage across the switches M1 and M2 is V_{in} [1][17].

(where $t_h = \frac{T}{2} - 6 * t_{fall}$)

T represents total time period

t_{fall} represents fall time of MOSFET

q is chosen in the range from 1.05 to 1.1 to provide some additional time for the IGBT transition from the load current [1][17].

Output Capacitor:

$$C_{o(hal)} = \frac{I_{out}}{2 * f * V_{ripple}} \quad (7)$$

; where,

f represents switching frequency.

I_{out} represents the output current.

Efficiency:

$$Efficiency = \frac{P_{out}}{P_{in}} * 100 \quad (8)$$

; where,

P_{out} represents output power.

P_{in} represents input power.

IV. SIMULATIONS OUTCOME

A. Open Loop Half-Bridge DC-DC Converter

As seen in Figure.5, a simulation circuit employing LTspice is developed to monitor the functionality of the designed converter. Figure. 6, 7, 8, and 9 display the results of the simulation. They show the input voltage, the output voltage, the output current, and the output power that corresponds to an input of 700V, output of 500V, 4A, and 2kW respectively. The results show that the circuit is operating satisfactorily for the designed values.

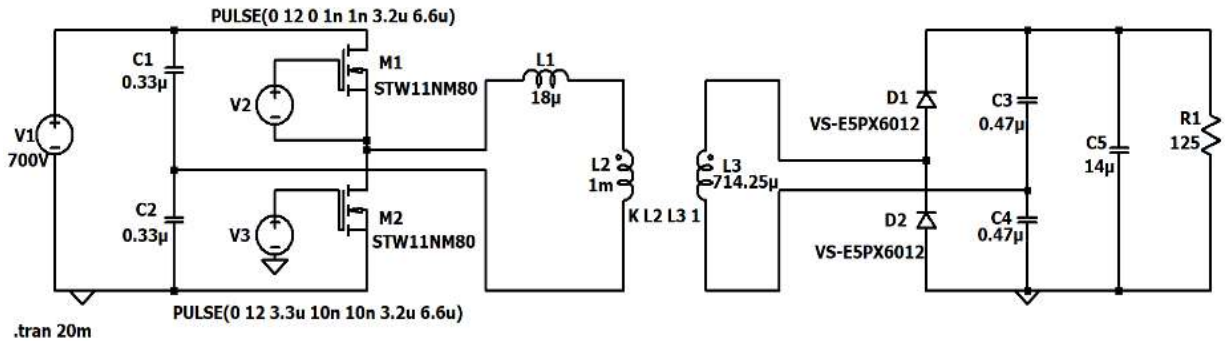


Figure.5: Open-loop simulation circuit

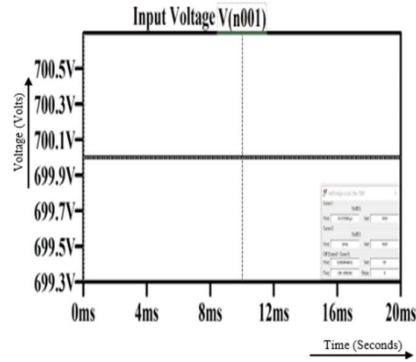


Figure 6: Input Voltage

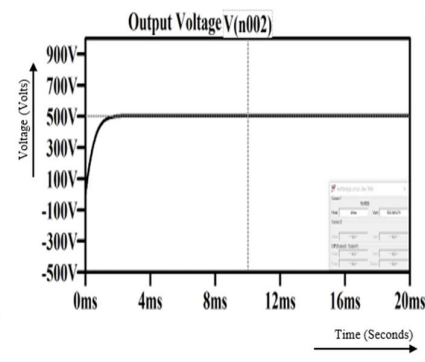


Figure 7: Output Voltage

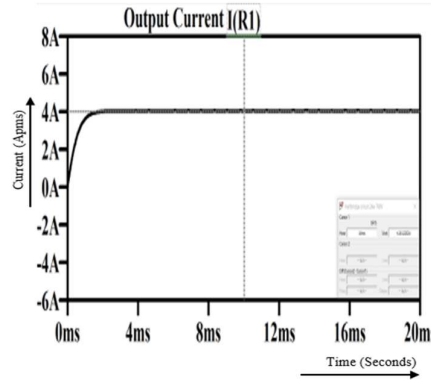


Figure 8: Output Current

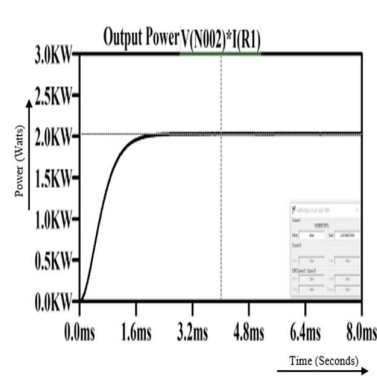
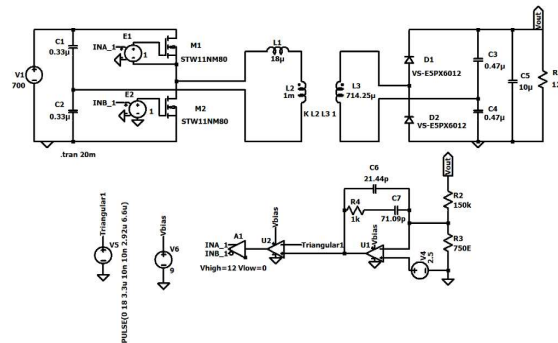


Figure 9: Output Power

B. Closed-Loop Half-Bridge DC-DC Converter

ZVS Half-bridge DC-DC converter must maintain voltage at the output that is constant regardless of variation in the load during operation. The voltage at the output in an open loop Half-bridge DC-DC converter fluctuates in response to changes in load and resonant inductor. To overcome this issue, the closed loop has been implemented to achieve a constant output voltage irrespective of any load variations. To reduce overshoot voltage, undershoot voltage, damping, and stabilization, Type-2 compensation is implemented across the error amplifier.

The closed-loop simulation circuit using LTspice is displayed in Figure.10. The proposed design values are used to examine implementation and outcomes. Figure.11 indicates the input voltage is 700V, Figure.12 indicates the output voltage is 500V, Figure.13 indicates the output current is 4A and Figure.14 indicates the output power is 2kW as specified in the design.



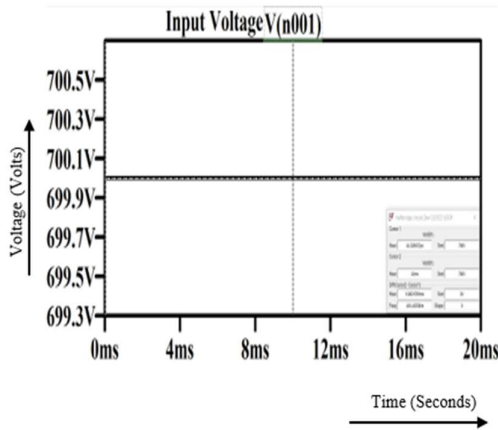


Figure.11: Input Voltage

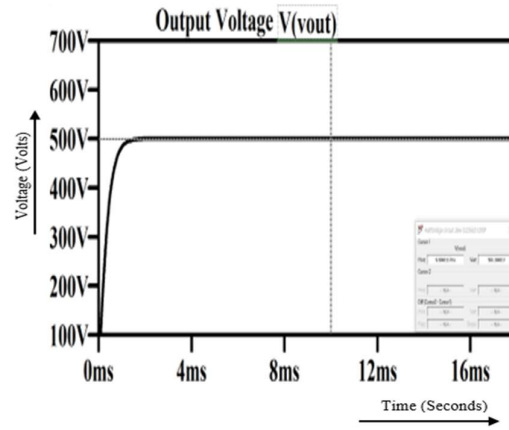


Figure.12: Output Voltage

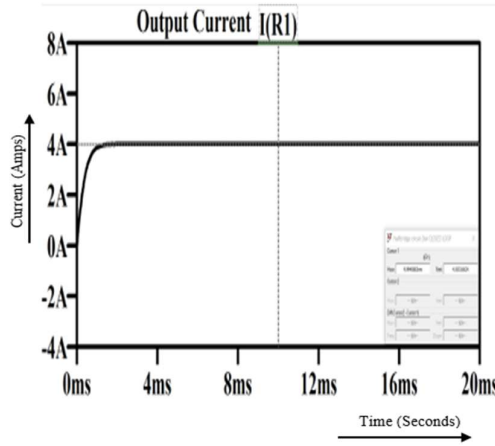


Figure.13: Output Current

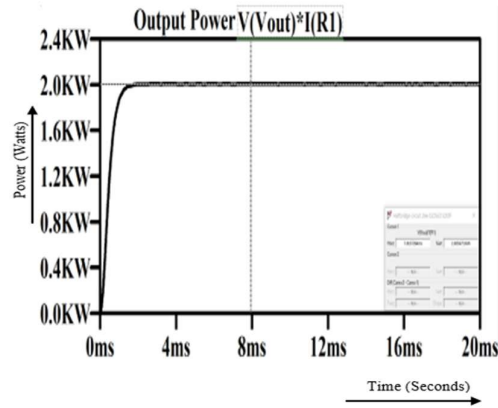


Figure.14: Output Power

The load variations are shown in Table II to demonstrate how the designed closed-loop controller operates. Load resistance of 125Ω equates to full load current and power, which is expressed as 100%. It is discovered that the output voltage remains constant at 500 V even during the load variation from 10% to 100%. It is observed from the result that the designed closed-loop controller is working satisfactorily.

TABLE II. RESISTIVE LOAD VARIATION IN A CLOSED-LOOP HALF-BRIDGE DC-DC CONVERTER

Sl.No	R load (ohms)	Vin (Volts)	Vout (Volts)	Iout (Amps)	Pout (Watts)
1	1250 (10%)	700	500	0.4	204
2	250 (50%)	700	500	2	1000
3	125 (100%)	700	500	4	2000

V. HARDWARE IMPLEMENTATION

A. Hardware Experimental Test Setup

The hardware implementation of a ZVS Half-bridge DC-DC converter focuses on achieving high efficiency and reduced electromagnetic interference (EMI) in power conversion applications. The ZVS technique is leveraged to minimize switching losses by ensuring that the switching transitions occur when there is no voltage across the switching devices. The hardware prototype of the designed converter as seen in Figure .15 has been implemented in the laboratory.



Figure 15: Half-bridge DC-DC converter experimental hardware model

B. Experimental Results of Gate-Source-Voltage (V_{gs}), Drain-Source-Voltage (V_{ds}), and Resonant Current of the Transformer at 2kW Load.

At 2kW load and 150kHz switching frequency, the observations show that the ZVS Half-bridge DC-DC converter output waveform presents good performance features, such as low ripple voltage and steady output voltage in addition to attaining 94% efficiency as per the design requirement. The advantages of applying ZVS techniques in high-power and high-frequency power conversion applications are shown by these results. The results indicate that the converter is appropriate for demanding industrial and commercial applications since it can effectively manage large loads while preserving excellent output quality. The gate-source-voltage (V_{gs}), drain-source-voltage (V_{ds}), and transformer's resonant current at a 2kW load obtained experimentally is presented in Figure .16.



Figure.16: Experimental results of gate-source- voltage (V_{gs}), Drain-source-voltage (V_{ds}), and transformer's resonant current at 2kw load.

Figure.17 shows the ZVS across the MOSFET transitions from on to off as obtained from the experimental setup. It is observed from the results that, the switching transition is very fast and the transformer's primary current reaches the required value without any transient current.

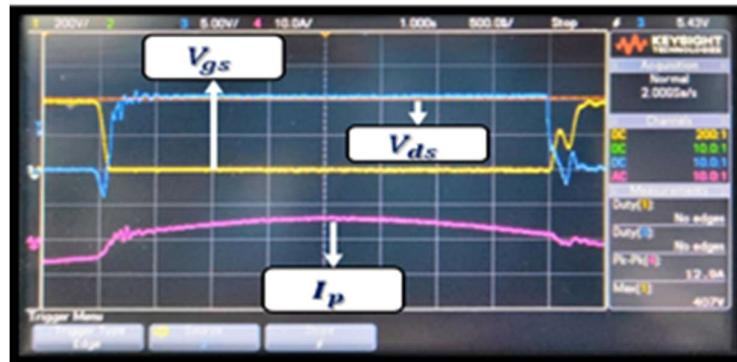


Figure.17: Experimental results of Zero-Voltage-Switching transitions at gate-source voltage (V_{gs}), Drain source voltage (V_{ds})

TABLE III. EXPERIMENTAL READINGS OF ZVS HALF-BRIDGE DC-DC CONVERTER

Sl.No	Vin (volts)	Iin (Amps)	Pin (Watts)	Vout (Volts)	Iout (Amps)	Pout (Watts)	Efficiency	Temperature
1	700	2.457	1720.4	487	3.23	1570.75	91.30	47.8
2	700	2.846	1992.4	487	3.741	1824.14	91.37	44.6
3	700	3.312	2318.8	487	4.393	2142.07	91.52	57.4
4	700	3.774	2641.8	487	4.5	2197.24	93.16	65.5

The output voltage is maintained constant for 487 V, according to the results shown in Table III. A 2kW load is achieved by connecting the 200W and 250V bulbs in a series-parallel configuration. The simulation results are validated with the hardware results.

VI. CONCLUSIONS

An enhanced ZVS Half-bridge DC-DC converter for high-power applications has been developed during this work. Both the design process and the operational philosophy are explained. Using LTspice, for 2kW load, the circuit has been tested effectively at an operating frequency of 150kHz. At full load, the achieved efficiency is 94%. A prototype for 2kW output power converter with an input voltage of 700V has been designed and tested in the laboratory. For MOSFETs M1 and M2, ZVS transitions are seen at V_{gs} and V_{ds} , and the transformer's primary resonant current is seen for entire load range. The simulated and theoretical conclusions closely match the experimental findings. The proposed converter's low cost, excellent efficiency, and straightforward topology make it appealing for high-power applications.

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