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# Design and Simulation of a Zero Voltage Switching DC - DC Buck Converter

Hayder Yousif Abed *

*Department of Electrical Engineering, College of Electrical Engineering, University of Technology, Iraq.*

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## Abstract

In this paper, a circuit was designed control circuit of zero voltage switching dc - dc buck converter. The simulation of the Zero Voltage Switching (ZVS) circuit involved the integration of a scope block featuring two ports, each linked to the output of a MOSFET. During simulation execution, the resulting graph exhibited a series of Pulse Width Modulation (PWM) signals corresponding to the switching MOSFETs. Time was represented along the x-axis, segmented according to a simulation time step of 0.03 seconds. The y-axis depicted binary PWM signals, indicating the MOSFETs' operational states: fully on (logic high) or fully off (logic low). The width of the rectangular pulses illustrated the duty cycle of the PWM signals, determining how long the MOSFETs remained on during each switching cycle. By adjusting the phase shift parameter, the relative timing of the PWM signals for both MOSFETs could be manipulated, which was pivotal for achieving ZVS operation and regulating power flow in the converter. Moreover, the frequency parameter, fixed at 50Hz in this setup, influenced the frequency of the PWM signals and the switching frequency of the MOSFETs. Ultimately, the objective of ZVS operation, aimed at reducing switching losses and improving efficiency by ensuring MOSFETs switch when the voltage across them is close to zero, was evidenced by the smooth transitions observed in the plot between the on and off states of the PWM signals.

**Keywords:** Buck converter; Zero Voltage Switching; Pulse Width Modulation; Full-Bridge Converter; Continuous Conduction Mode

## 1. Introduction

DC-DC converters, also known as voltage regulators or voltage converters, play a pivotal role in modern electronics by transforming direct current (DC) power from one voltage level to another. These converters are essential components in electronic devices, facilitating the efficient and precise control of voltage levels required for different components within a system. They form a crucial link in power supply chains, ensuring that electronic circuits receive the appropriate voltage for optimal performance [1].

The primary purpose of DC-DC converters is to address the diverse voltage requirements of electronic components within a system. This is particularly vital in scenarios where the input power source does not match the voltage levels needed by the electronic circuitry. By stepping up or stepping down the voltage, DC-DC converters enable seamless compatibility between various components, contributing to the overall functionality and reliability of electronic devices. Whether in battery-powered gadgets, renewable energy systems, or industrial applications, the versatility and efficiency of DC-DC converters make them indispensable in modern electronics [2,3].

Full-Bridge Converter: The full-bridge converter utilizes a bridge topology for bidirectional power flow. This design is particularly advantageous in applications such as motor drives and renewable energy systems, where the bidirectional power capability allows for efficient energy transfer and control as shown in figure 1. The full-bridge configuration is known for its versatility and effectiveness in various power conversion scenarios [4,5].

* Corresponding author: Hayder Yousif Abed

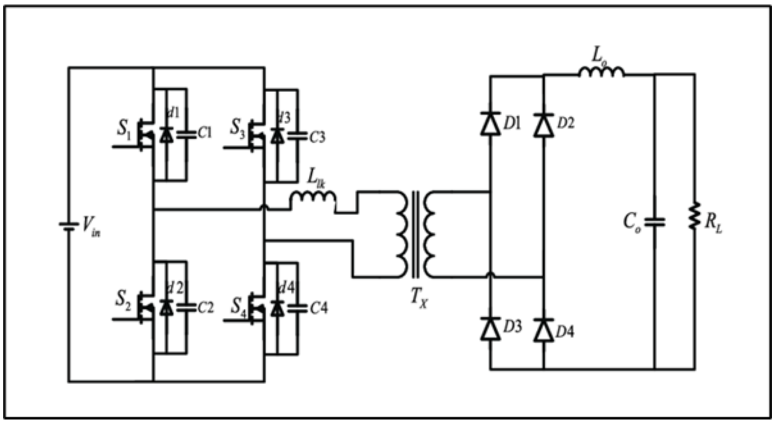


**Figure 1** Full Bridge Converter

A buck converter is a type of DC-DC converter that steps down (reduces) the input voltage to a lower output voltage. It is a switched-mode power supply (SMPS) circuit that efficiently converts a higher DC voltage to a lower one. The basic components of a buck converter include an inductor, a diode, a switch (usually a transistor), and a capacitor [6].

### 1.1. Discontinuous Conduction Mode (DCM) [7]:

*1.1.1. Duty Cycle (D)*

$$D = \frac{V_{out}}{V_{in}}$$

The duty cycle represents the fraction of the switching period during which the switch is on.

*1.1.2. Output Voltage (V out)*

$$V_{out} = \frac{D.V_{in}}{1 - D}$$

The output voltage is the desired voltage level that the buck converter is designed to produce.

*1.1.3. Inductor Current (IL) during ON state*

$$V_{in}.(1 - D).T_s = \frac{\Delta I_L}{2}.\frac{T_s}{L}.(T_s - D.T_s)$$

In the on-state, the inductor current equation ensures continuous current flow through the inductor.

*1.1.4. Inductor Current (IL) during OFF state*

$$V_{in}.(1 - D).T_s = \frac{\Delta I_L}{2}.\frac{T_s}{L}.(D.T_s)$$

In the OFF-state, the inductor current equation shows that the inductor current decrease to zero.

*1.1.5. Output Current (I out)*

$$I_{out} = \frac{V_{out}.D}{E_{SR}}$$

The output current is the average current delivered to the load. ESR is the voltage drop across the series resistance (inductor and switch).

*1.1.6. Output Power (Pout)*

$$P_{out} = V_{out}.I_{out}$$

The output power is the electrical power delivered to the load.

### 1.2. Continuous Conduction Mode (CCM):

*1.2.1. Duty Cycle (D)*

$$D = \frac{V_{out}}{V_{in}}$$

The duty cycle represents the fraction of the switching period during which the switch is on.

*1.2.2. Output Voltage (V out)*

$$V_{out} = \frac{D.V_{in}}{1 - D}$$

The output voltage is the desired voltage level that the buck converter is designed to produce.

*1.2.3. Inductor Current (IL)*

$$V_{in}.(1 - D).T_s = \Delta I_L.\frac{T}{2L}$$

The inductor current equation ensures continuous current flow through the inductor during both the on and off states of the switch.

$I_L$ is the inductor current, $T_s$ is the switching period, $\Delta I_L$ is the peak-to-peak inductor current ripple, and L is the inductance.

*1.2.4. Output Current (I out)*

$$I_{out} = \frac{V_{out}.D}{E_{SR}}$$

The output current is the average current delivered to the load. ESR is the voltage drop across the series resistance (inductor and switch).

*1.2.5. Output Power (Pout)*

$$P_{out} = V_{out}.I_{out}$$

The output power is the electrical power delivered to the load.

## 2. Phase-Shifted Full-Bridge Converter

The Zero-Voltage Switching (ZVS) Phase-Shifted Full-Bridge (PSFB) converter is a power electronics topology that integrates ZVS principles with a full-bridge configuration. It utilizes phase-shifting control to synchronize the switching of the four active switches, minimizing switching losses by turning on the transistors when the voltage across them is near zero. This synchronous operation ensures efficient energy transfer between the primary and secondary sides of the transformer, reducing power dissipation and enhancing overall converter efficiency. The control circuit orchestrates the precise timing of switching events, optimizing ZVS conditions. The transformer facilitates voltage transformation, and the output rectification and filtering stages result in a stable DC output. ZVS PSFB converters find applications in high-power systems, offering advantages such as reduced electromagnetic interference and extended component lifespan, making them suitable for demanding power supply, battery charging, and inverter applications [8].

The traditional phase-shifted (PS) full-bridge (PSFB) converter exhibits benefits in medium-to high-power applications: all primary switches are turned ON under zero-voltage switching (ZVS) without the help of any auxiliary circuits. The switches' voltage stress is clamped to that of the input voltage. Hence, high-frequency MOSFETs are suitable as main switches for the converter, which raise the power density of the converter. However, such a converter has several serious problems: first, the ZVS range of lagging-leg switches is very narrow under load variation. For this reason, its conversion efficiency is severely degraded as the load decreases. Severe voltage overshoot and oscillation across the diode rectifier are generated due to the resonance between the transformer leakage inductance and the parasitic junction capacitance of the rectifier diode. This increases the diode voltage rating and cost, and causes electromagnetic interference (EMI) problems. Especially in applications where the output voltage is high, much higher voltage diodes are required. However, the use of higher voltage diodes increases power loss and voltage overshoot in the diodes because higher voltage diodes have poor recovery characteristics. Finally, if the converter is fit for a relatively wide input voltage range due to the design considerations such as the hold-up time requirement, the steady-state duty cycle becomes small and the freewheeling interval lengthens under normal operating conditions. Then, excessive circulating current appears on the primary side during the freewheeling interval, increasing the primary-side conduction losses and turn-off switching losses of the lagging-lag switches [9].

The basic switching waveform of PS-FB converter is presented in figure 2. showing the gating control signals, the primary and secondary current-voltage waveform. The ZVS is achieved during the turn-on transition via resonance between the FET device output capacitance and the energy stored in the transformer leakage inductance [10].

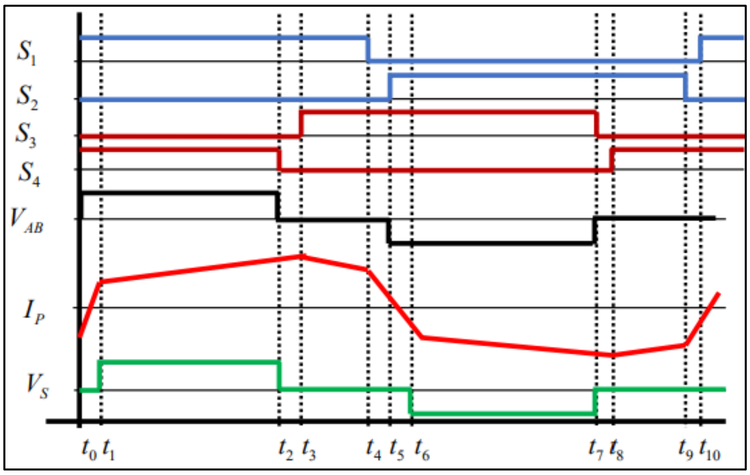


**Figure 2** Phase shifted FB ZVS converter basic waveform

## 3. Operation Principles of ZVS Phase Shifted Full Bridge Converter

The phase shifted full bridge dc-dc converter is as shown in the figure 1. This converter is used to step down high voltages and used in medium to high power applications. The PSFB converter consists of a full bridge inverter, a high frequency transformer, a full bridge diode rectifier, and a low pass filter at the output. The gating signals given to the switches in a phase shifting manner to facilitates ZVS operation for switches.

The full bridge inverter consists of four semiconductor switches such as IGBTs or MOSFETs with their diodes. In phase shifted control, the gate signals of T2 and T3 are phase shifted with respect to T1 and T4. The high frequency transformer is used and the high frequency AC voltage at the secondary is rectified using full wave rectifier and filtered using a low pass filter to obtain smooth DC output voltage. The parasitic capacitance (C1, C2, C3, C4) are connected across the switches in figure 1.

The inductor connected in series with the primary winding of the transformer emphasizes the leakage inductance of the high frequency transformer. If required additional inductor can be connected in series with the transformer primary winding. The two components, the switch output capacitance and transformer leakage inductance decrease the performance of the converter in hard switching but is utilized advantageously in phase shifted converter to achieve ZVS. Hence attaining ZVS condition and elimination of switching losses, the phase shifted full bridge dc-dc converter topology for medium to high power applications.

## 4. Design of ZVS using MATLAB Simulation

The converter consists of a full-bridge topology, which includes four switches (transistors or MOSFETs) arranged in a bridge configuration. Two switches are on the primary side, and the other two are on the secondary side of a transformer. Phase-Shift Control: The term "Phase-Shift" refers to intentionally introducing a phase difference between the switching of the two sets of switches in the full-bridge. By controlling the phase shift between the primary and secondary side switches, the converter can achieve ZVS for certain operating conditions. Zero Voltage Switching (ZVS): ZVS occurs when the voltage across a switch is close to zero at the moment of switching (turning on or off). During ZVS, the switching device experiences minimal voltage stress, leading to reduced switching losses and improved efficiency. Operation: The ZVS Phase-Shift Full-Bridge Converter typically operates by controlling the phase shift between the primary and secondary side switches. This phase shift causes the voltage across the switches to approach zero during switching, allowing ZVS to be achieved. The proposed method has been tested using electric circuit as shown in figure 1. and further specification of electric circuit is mentioned in Table (1):

**Table 1** Circuit parameters

| Parameter | Value |
|---|---|
| Input voltage | 100 Volt |
| Output voltage | 10 Volt |
| Inductance | 10 mH |
| Load resistance | 5 Ohm |
| Switching frequency | 100 KHz |

The whole ZVS design in MATLAB simulation is shown in figure 3. The components of design are described in details. Source Voltage: The input voltage to the ZVS full-bridge converter, typically derived from a DC power source. Full-Bridge MOSFETs: Four MOSFETs configured in a full-bridge topology, used to switch the input voltage across the transformer primary. Linear Transformer: A transformer with primary and secondary windings, used to step up or step down the input voltage based on the turn's ratio. Full-Bridge Diodes: Diodes connected in a full-bridge configuration across the transformer secondary to rectify the stepped-down voltage. RLC for Buck Converter: An RLC (Resistor-Inductor-Capacitor) circuit used as a buck converter to regulate the output voltage. PID Controller: Proportional-Integral-Derivative (PID) controller used for closed-loop control of the output voltage. The PID controller adjusts the duty cycle of the PWM signals to maintain the desired output voltage.

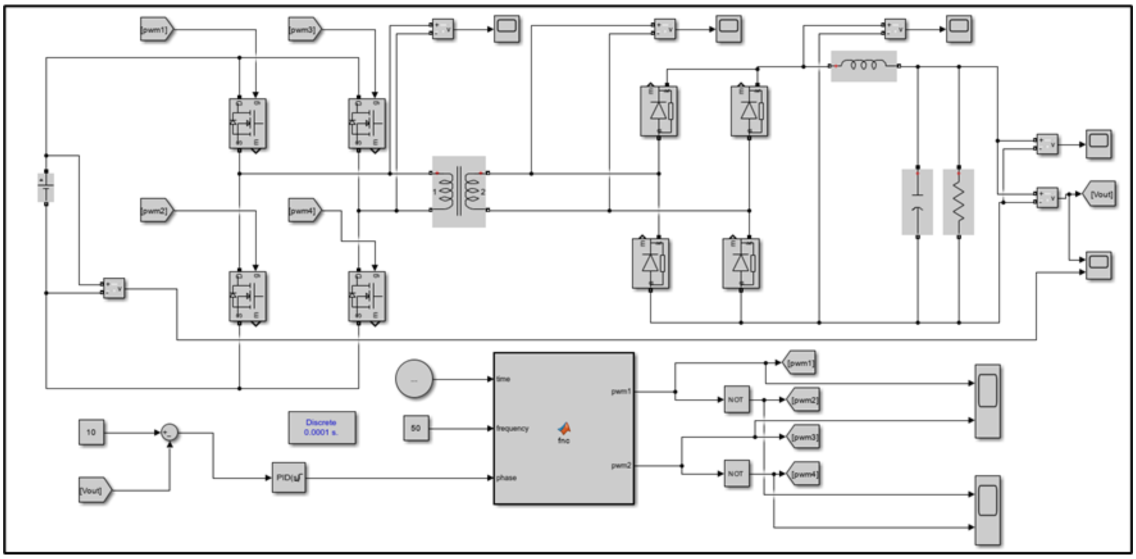


**Figure 3** Design ZVS with full bridge

In simulation design of ZVS circuit, a scope block has been added with two ports, each of port connected to the output of MOSFET. After run the simulation, figure 4 below showing the sequence of PWM of switching MOSFETS. The description of operation within figure above discussed below: Time Axis: The x-axis of the plot represents time, which is typically divided into discrete intervals determined by the simulation time step which is the y-axis represents the PWM signals generated for the two MOSFETs in the full bridge configuration. Each PWM signal is binary, meaning it has two states: either fully on (logic high) or fully off (logic low). Pulse Width Modulation (PWM) Pattern: The plot will display a sequence of rectangular pulses for each PWM signal. The width (duration) of these pulses corresponds to the duty cycle of the PWM signal, which determines how long the MOSFET remains on during each switching cycle. Phase

Shift: The phase shift parameter in the function affects the timing of the PWM signals relative to each other. By adjusting the phase shift, can control the relative timing of the PWM signals for the two MOSFETs. This adjustment is essential for achieving ZVS operation and controlling the power flow in the converter. Frequency: The frequency parameter determines the frequency of the PWM signals and, consequently, the switching frequency of the MOSFETs in the ZVS converter. Higher frequencies result in shorter switching periods and faster transitions between the on and off states. In our design, the frequency has been set as 50Hz. ZVS Operation: In a ZVS converter, the goal is to achieve zero-voltage switching, meaning the MOSFETs switch on and off when the voltage across them is close to zero. The plot should reflect this by showing smooth transitions between the on and off states of the PWM signals, minimizing switching losses and improving efficiency.

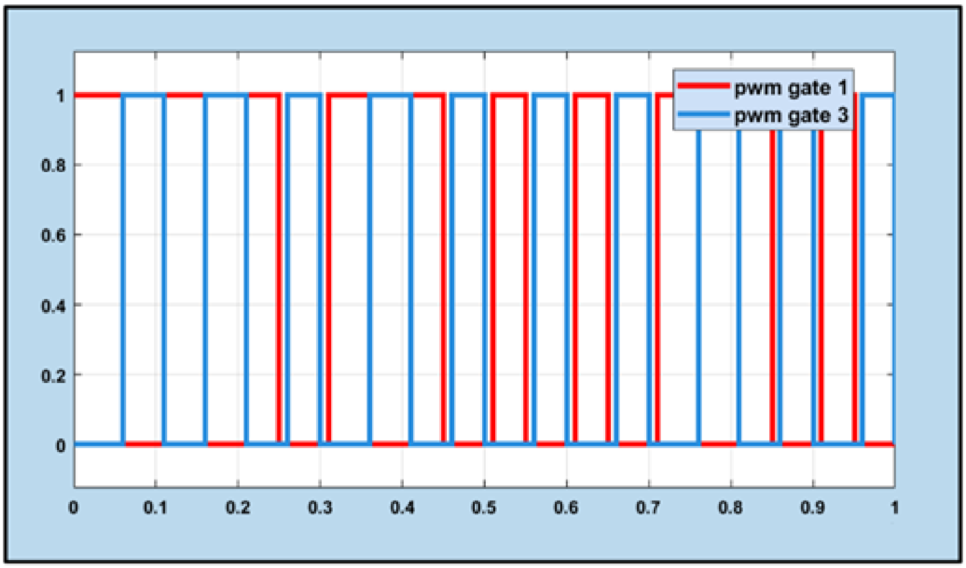


**Figure 4** Sequences of PWM of ZVS

The shape of the alternating voltage waveforms of the power source used in the circuit under study is illustrated in the figure 5 and figure 6. The waveforms of the main power source voltage to be stepped down, the obtained voltage, and the load current waveform using the Zero Voltage Switching method are also illustrated in the figure 7 and figure 8.

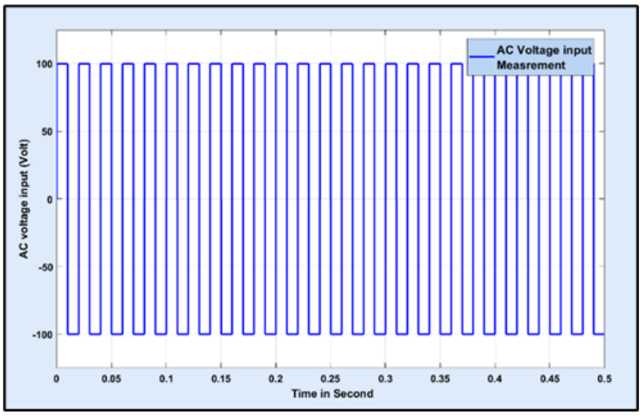


**Figure 5** AC Voltage primary in (Volt)

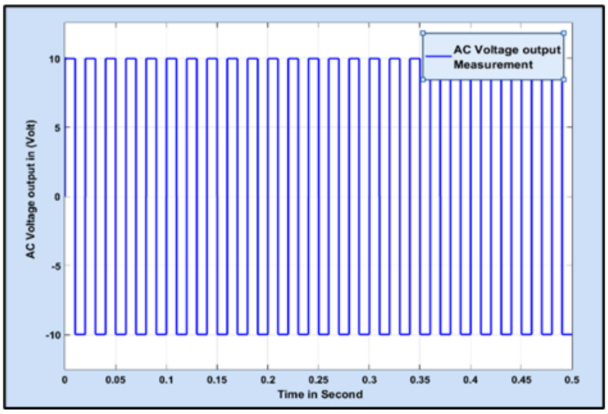


**Figure 6** AC Voltage Secondary in (Volt)

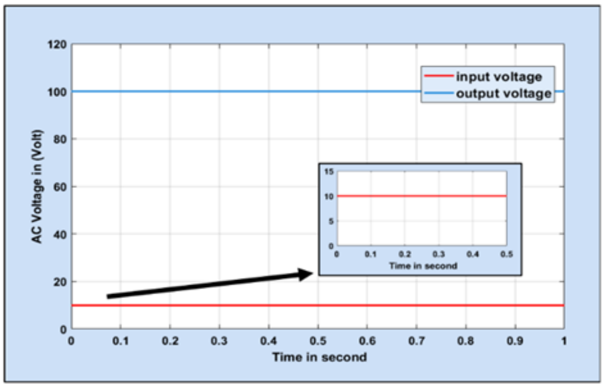


**Figure 7** DC Voltage waveform in (volt)

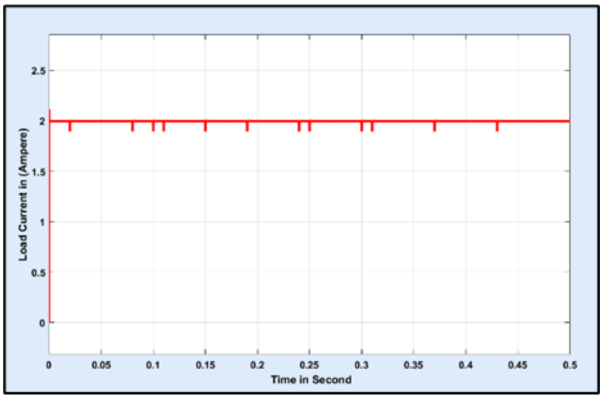


**Figure 8** Load Current in (Ampere)

## 5. Conclusion

The simulation design of the Zero Voltage Switching (ZVS) circuit incorporated a scope block with two ports, each connected to the output of a MOSFET. Upon running the simulation, the generated figure displayed a sequence of Pulse Width Modulation (PWM) signals for the switching MOSFETs. The x-axis represented time, discretized according to the simulation time step of 0.05 seconds. On the y-axis, binary PWM signals were depicted, indicating whether the MOSFETs were fully on (logic high) or fully off (logic low). The width of the rectangular pulses in the plot corresponded to the duty cycle of the PWM signals, determining the duration for which the MOSFETs remained on during each switching cycle. By adjusting the phase shift parameter, the relative timing of the PWM signals for the two MOSFETs could be controlled, crucial for achieving ZVS operation and managing power flow in the converter. Additionally, the frequency parameter, set at 50Hz in this design, influenced the PWM signals' frequency and the MOSFETs' switching frequency. Ultimately, the goal of ZVS operation, to minimize switching losses and enhance efficiency by ensuring MOSFETs switch when the voltage across them is near zero, was reflected in the smooth transitions observed in the plot between the on and off states of the PWM signals.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

The author has declared that no competing interest exists

### *Author Contributions*

The first draft of the manuscript was written by Pham Dang Quyet, author read and approved the final manuscript.

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