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DESIGNING A 48 V TO 24 V DC-DC CONVERTERS FOR VEHICLE APPLICATION USING A RESONANT SWITCHED CAPACITOR CONVERTER TOPOLOGY VERSUS FLYBACK CONVERTER

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Abstract
The design of a 48V to 24V DC-DC converter for vehicle applications using a ZCS resonant switched capacitor converter (RSCC) versus a flyback converter compared [1]. The RSCC offers several advantages including higher efficiency, reduced size, and lower cost compared to traditional flyback converters. Its resonant operation minimizes switching losses and provides inherent soft-switching characteristics, enhancing efficiency and reducing electromagnetic interference. Additionally, the RSCC's modular structure allows for scalability and adaptability to varying load requirements, making it suitable for dynamic automotive environments. In contrast, while flyback converters are widely used and offer simplicity in design, they typically exhibit lower efficiency and larger size due to the presence of bulky transformer and higher switching losses. Moreover, their non-resonant operation can result in higher levels of electromagnetic interference, potentially impacting sensitive onboard electronics. Therefore, in the context of vehicle applications where efficiency, size, and electromagnetic compatibility are critical factors, the RSCC emerges as a promising solution for implementing efficient and compact DC-DC conversion.

Keywords:
Switched capacitor converter, Resonant converter, Flyback converter, PWM, EMI, ZCS.

I. Introduction

In the ever-evolving landscape of automotive technology, the demand for efficient power management solutions continues to surge. Among the critical components driving this advancement are DC-DC converters, In the pursuit of optimal performance, engineers and researchers are constantly exploring innovative approaches to address the multifaceted challenges posed by vehicle electrification. Key to this transition is the development of efficient, compact, and reliable DC-DC converters capable of seamlessly stepping down voltage levels while meeting stringent automotive standards for performance, safety, and reliability. Among the myriad of DC-DC converter topologies, the Resonant Switched Capacitor Converter (RSCC) and the Flyback Converter emerge as frontrunners, each offering unique advantages and trade-offs [3]. By harnessing the inherent advantages of capacitive energy storage and resonant switching, the RSCC promises enhanced efficiency, reduced size, and improved thermal performance, making it an attractive choice for demanding automotive applications. Contrastingly, the Flyback Converter, characterized by its simplicity and versatility, has long been a staple in various power supply designs [4]. With its isolated topology and ease of implementation, the Flyback Converter offers inherent advantages in terms of cost-effectiveness and reliability. However, challenges such as limited efficiency at high power levels and increased electromagnetic interference (EMI) emissions necessitate careful consideration, particularly in the context of automotive applications where stringent performance requirements prevail. Against this backdrop, this comparative study endeavors to shed light on the intricate interplay between design considerations, performance metrics, and application-specific requirements inherent in the selection between Resonant Switched Capacitor and Flyback Converter topologies for transitioning from a 48V to a 24V system voltage in automotive environments. Through comprehensive analysis and simulation, we aim to delineate the strengths and limitations of each approach, empowering engineers and researchers with valuable insights to inform their design decisions and propel the advancement of automotive power electronics into a new era of efficiency and reliability [2].

II. Literature

- A literature survey designing a 48v to 24 v dc-dc converters for vehicle application would involve gathering and reviewing existing research studies, and publications related to the speed control of motors using Matlab Simulink. Here's a structured approach to conducting a literature survey on this topic:
- Design of a 48V to 24V DC-DC converter for vehicle applications using a resonant switched capacitor converter (RSCC) versus a flyback converter involves a combination of electrical engineering principles, control systems, and renewable energy integration.
- Leverage academic databases containing resources such as peer-reviewed journal articles, research papers, and textbooks in disciplines including electrical engineering, power electronics, look for keywords such as "Switched capacitor converter," "Resonant converter," "PWM" and "EMI" Websites like IEEE Xplore, ScienceDirect, and Google Scholar are good places to search.

III.Methodology

Methodology for designing of a 48V to 24V DC-DC converter for vehicle applications, particularly focusing on a resonant switched capacitor converter topology versus a flyback converter, involves several critical stages to ensure efficiency, reliability, and safety. Here's a structured methodology broken down into five key headings:

3.1 Conceptual Design and Requirements Analysis

Define Application Requirements:

Determine the power demand, efficiency requirements, temperature ranges, and size constraints for the vehicle application. Establish safety and regulatory standards that the converter must meet, including electromagnetic compatibility (EMC) and thermal management.

Choose Converter Topology:

opt for a resonant switched capacitor converter for high efficiency and reduced switching losses at high frequencies. Integrate a flyback converter to provide galvanic isolation and enhance safety, especially in vehicle environments.

3.2 Design and Simulation of the Converter Circuit

Circuit Design:

Develop the circuit schematic, selecting appropriate switches (MOSFETs or GaN transistors), capacitors, and transformers for the flyback section. Design the resonant tank elements, calculating the values of capacitors and inductors to achieve desired resonant frequency and voltage conversion ratio

Simulation:

Use simulation software (e.g., LTspice, PSpice, or MATLAB/Simulink) to model the converter and validate its performance across various operating conditions. Analyze efficiency, voltage regulation, ripple voltage, and transient response to ensure they meet the application requirements.

3.3 Component Selection:

Choose components based on their voltage/current ratings, efficiency and thermal performance. Consider the use of low ESR capacitors, low Rds(on) switches, and custom-wound transformers for optimized performance.

3.4 Prototype Development and Testing

Prototype Assembly:

Assemble a prototype based on the designed PCB and component selection. Ensure all safety precautions are in place, including overvoltage, overcurrent, and overtemperature protections.

Testing and Validation:

Conduct comprehensive testing, including efficiency measurement, load regulation, and thermal testing under various operating conditions. Validate the converter's performance against the initial requirements, adjusting as necessary to meet or exceed expectations.

IV.RESONANT SWITCHED CAPACITOR CONVERTER

A dual-phase half mode switched-capacitor converter with zero current switching (ZCS) is simulated, here. Soft switching in both turn-on and turn-off of all power diodes and switches, dual-phase ability, high efficiency, low output voltage ripple, complementary drive signal, and light weight are the advantages of this converter. The circuit diagram of a 48 V to 24 V converter with 100 W output power is shown in Fig.

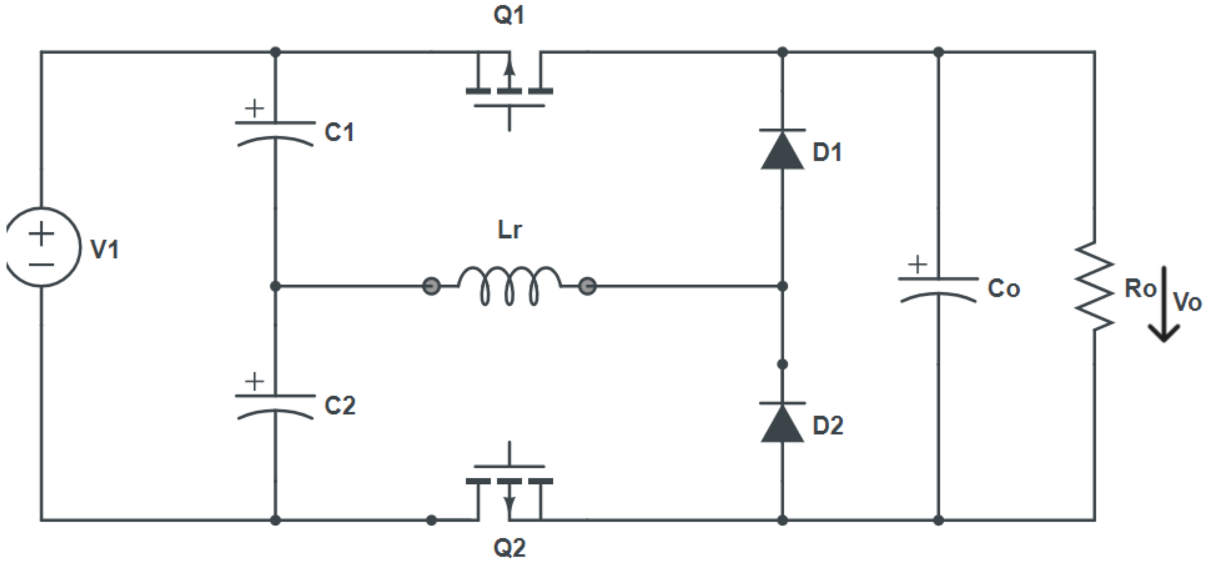

Figure 1: ZCS dual-phase half mode switched capacitor converter

4.1 Soft Switching: Inductor current waveform suggests that both the turn-on and turn-off of the power diodes and switches occur under soft switching conditions. Soft switching reduces switching losses, thus enhancing the converter's efficiency significantly.

4.2 Operating Modes: The converter operates in four distinct phases within a switching cycle, which are typically charge, discharge, and idle stages in various configurations involving the capacitor, inductor, and load.

The maximum switching frequency (f_s) is bounded by the resonant frequency (f_r), which depends on the total capacitance (C_1+C_2) and the resonant inductor (L_r). The formula given is:

$$f_s \le f_r = \frac{1}{\sqrt{(C_1+C_2)L_r}} \qquad (1)$$

This is derived from the standard formula for the resonant frequency of an LC circuit, $f = \frac{1}{2\pi\sqrt{LC}}$, simplified for the context of switching frequency and omitting the 2π term.

The sizing of the output capacitor (C_o) involves ensuring charge balance. This is done by equating the integral of the output current (i_o (t)) and the integral of the inductor current (i_R(t)) over a switching period (T_s).

$$i_o(t) = i_{co}(t) + i_R(t) \qquad (2)$$

Balancing across Co, (2) can be written as follows:

$$< i_{co}(t) >_{Ts} = 0 \;\rightarrow\; < i_o(t) >_{Ts} = < i_R(t) >_{Ts} \qquad (3)$$

Above equation can be as

$$\int_0^{T_s} i_o(t)dt = \int_0^{T_s} i_R(t)dt = T_s I_R \qquad (4)$$

According to the output current waveform shown in Fig (2) when i_o is larger than i_R , positive current of i_{co} is flowed through output capacitor and causes the voltage across C_o to be increased. Consequently, voltage ripple across C_o can be calculated as follows:

$$\Delta V_{Co} = \frac{1}{Co}\int_{\frac{\theta}{\omega r}}^{\frac{\pi-\theta}{\omega r}} [i_o(t) - iR(t)]\theta \;;\; \theta = \sin^{-1}\left(\frac{2\,f_s}{\pi f_r}\right) \quad (5)$$

Output Voltage ripple is derived with combination of (4) & (5) as

$$\Delta V_{Co} = \frac{I_R}{2Co}\left(\frac{cos\theta}{fs} - \frac{1}{fr}\left(1 - 2\frac{\theta}{\pi}\right)\right) \quad (6)$$

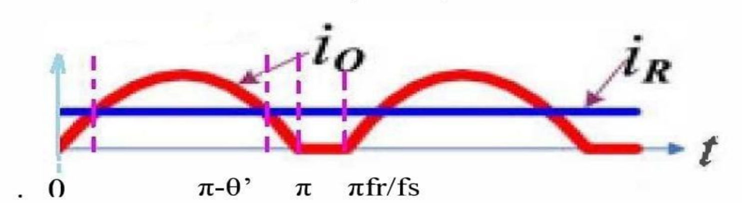

Figure2: Output Current waveform

4.3 SIMULATION RESULTS

The values of its components are tabulated in the table. Resonant frequency is set to 80 KHz, and switching frequency is set to 70 KHz. The Inductor, Capacitor, Diode values are given below.

Converter Components	$R_{on(m\Omega)}$	$V_{forward}$ (Volt)	value
Lr	-	-	53nH
C_1, C_2	ESR=1	-	37μ F
C_o	10	-	84μ F
D_1, D_2	9	0.4	-
R_o	-	-	6Ω

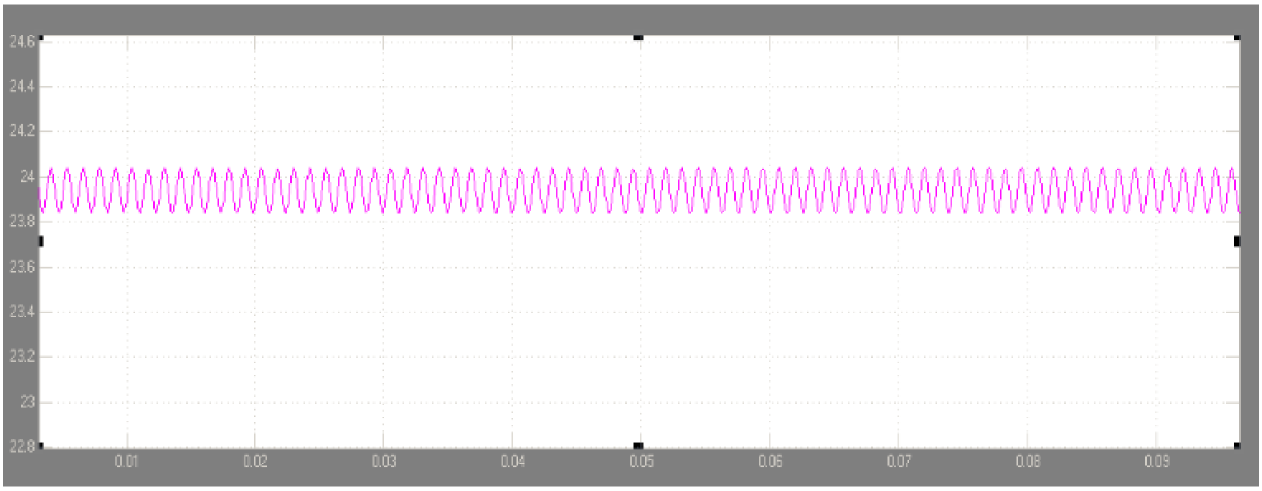

Figure 3: ZCS dual-phase half mode SCC Output Voltage waveform

In a ZCS (Zero Current Switching) dual-phase half mode SCC Output Voltage waveform, the output voltage waveform depends on various factors including the control strategy, load conditions, and circuit topology.

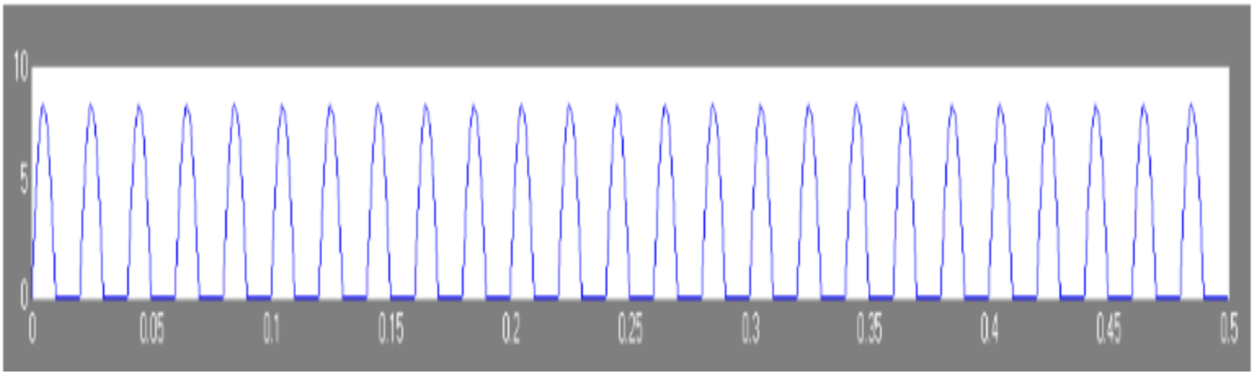

Figure 4: ZCS Switched Current Waveform

The output currengt waveform of a ZCS (Zero Current Switching) switch typically exhibits a smooth transition from zero to peak current and then back to zero, with minimal switching losses.

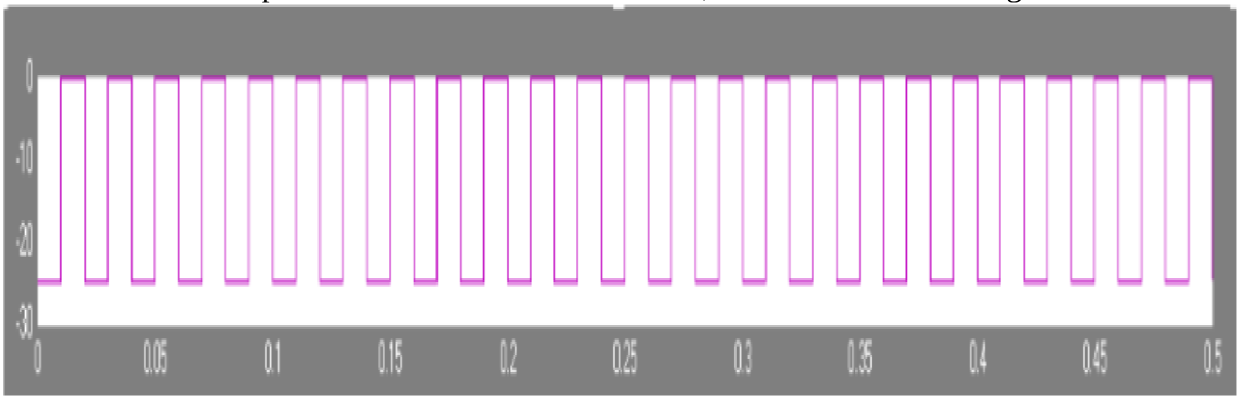

Figure 5: ZCS Switched Voltage Waveform

In a Zero Current Switching (ZCS) circuit, the output voltage waveform depends on various factors such as the topology of the circuit (e.g., buck, boost, or flyback converter), the switching frequency, the load characteristics, and the control strategy employed.

V.FLYBACK CONVERTER

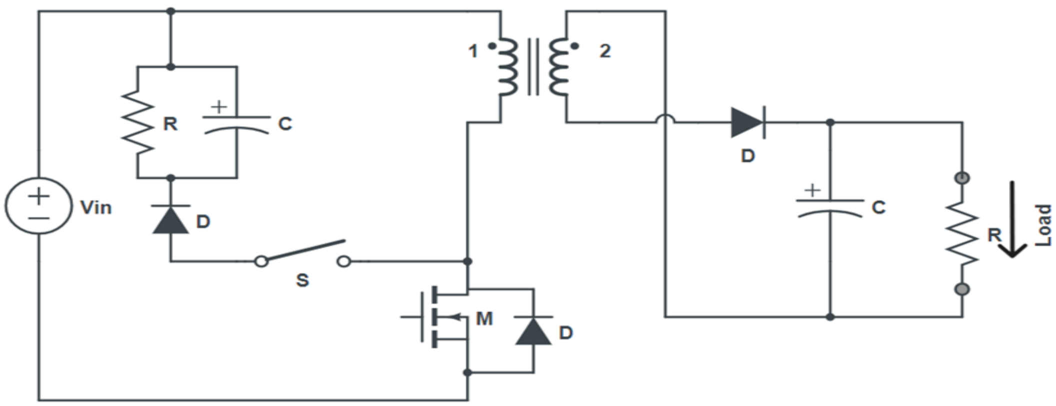

Figure 6: Flyback converter

The circuit diagram of a flyback converter with transformer leakage inductance, along with the associated waveforms and mathematical equations for its operation. Here's an explanation of the circuit operation and the mathematical equations:

5.1 CIRCUIT OPERATION:

MOSFET Switching: The MOSFET is the active switching element controlled by a pulse generator. It alternately connects and disconnects the primary winding of the transformer from the input voltage (V_{in}).

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Energy Storage: When the MOSFET is on, energy is stored in the transformer's magnetic field. During this phase, the diode (D1) is reverse-biased, and no current flows to the load.

Energy Transfer: When the MOSFET is turned off, the transformer's magnetic field collapses, transferring energy to the secondary winding and forward biasing the diode (D_1), which allows current to flow to the load.

Snubber: The snubber circuit is designed to dampen voltage spikes caused by the switching of the MOSFET and the leakage inductance of the transformer.

Transformer Leakage: The schematic symbol with a gap represents transformer leakage inductance, which is the non-ideal behavior of the transformer where some magnetic flux does not couple perfectly between the primary and secondary windings.

Output: The output consists of a capacitor (C) to filter the pulsed current from the transformer into a smoother DC current and a load resistor (Load) that represents the actual device powered by the converter [5] .

5.2 Mathematical Equations

Output Voltage (V_o): The output voltage is a function of the input voltage (V_{in}), the duty cycle (D), and the turns ratio of the transformer (n = N2/N1), which is the ratio of the number of turns in the secondary winding (N2) to the number of turns in the primary winding (N1).

Here, the duty cycle (D) is the fraction of the switching period during which MOSFET is on.

$$V_{\{out} = n \times \frac{D}{(1-D)} \times V_{in} \qquad (7)$$

Snubber circuit:

Snubber Capacitor: $C_{\{sn} = \frac{P_{Rsn}}{0.5 \times V_{sn} \times f_{sw}}$ (8)

Snubber resistance: $4R_{sn}\, C_{sn} = T_{on(mosfet)}$ (9)

Power Transfer: $P = \frac{F_{sw}}{2} L.I_{PK}\ \ 2$ (10)

The flyback converter is commonly used for its simplicity, galvanic isolation between input and output, and its ability to step up or step-down voltages. The leakage inductance can lead to energy being dissipated in the snubber circuit, which is not ideal for efficiency but is necessary to protect the components and improve reliability.

5.3 SIMULATION RESULTS

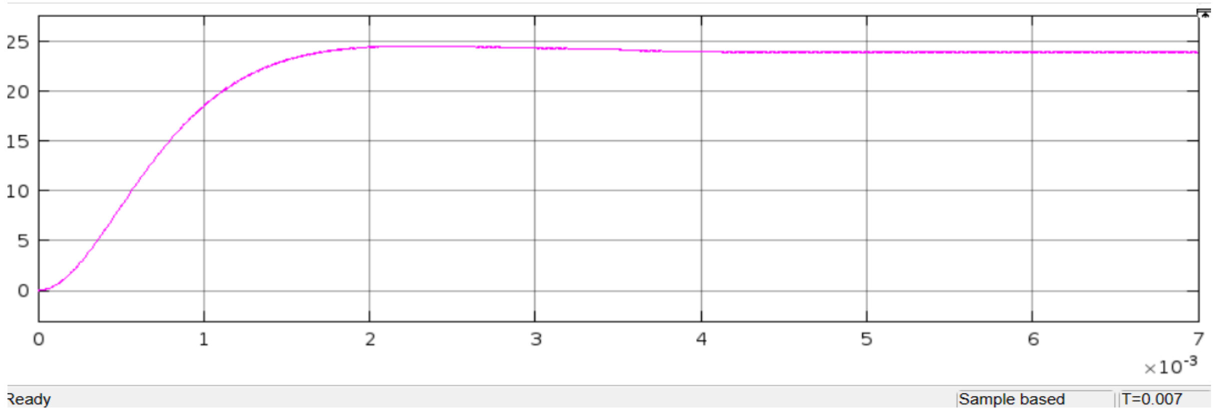

Figure 7: Flyback Converter Output Voltage Waveform

The output voltage waveform of a flyback converter typically exhibits a sawtooth or trapezoidal shape during the flyback period, with a relatively stable DC voltage during the energy transfer and free-wheeling periods, influenced by factors such as load current, switching frequency and transformer design.

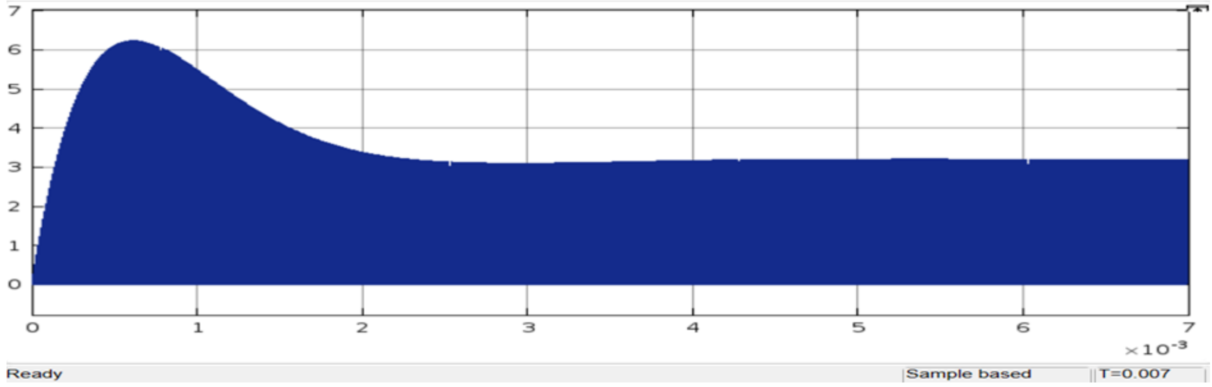

Figure 8: Flyback Converter Switched Current Waveform

The switched output current waveform in a flyback converter is characterized by intermittent pulses during the switch-on periods, followed by zero current flow during the switch-off periods, providing energy transfer to the load while maintaining control over the output voltage.

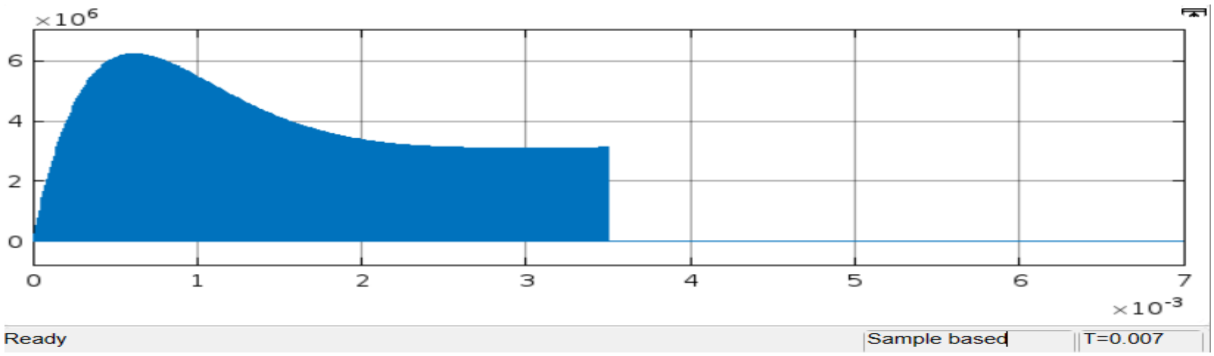

Figure9: Flyback Converter Switched Voltage Waveform

The switched output voltage waveform in a flyback converter exhibits a sawtooth pattern during the flyback period, with a peak voltage determined by the transformer turns ratio and duty cycle, while maintaining regulation and minimizing ripple.

5.4 Comparison between resonant switched capacitor converter and flyback converter

Aspect	Resonant Switched Capacitor Converter	Flyback Converter
Operating Principle	Energy is transferred by switching capacitors and inductors in a resonant manner	Energy is transferred by storing energy in the transformer's magnetic field and then releasing it
Transformer Requirement	Not required	required
Transformer Leakage Inductance Utilization	Not applicable	Utilizes leakage inductance for energy transfer, increasing efficiency
Voltage Regulation	Relatively easier due to simpler topology	Typically, more complex due to transformer characteristics
Efficiency	Highly dependent on capacitor quality and switching losses	Affected by transformer losses and leakage, but can be optimized with proper design
Size	Compact due to absence of transformer	Bulkier due to transformer

Voltage and Current Stress	Lower voltage and current stresses due to resonant operation	Higher voltage and current stresses due to transformer operation
Applications	Low power, high-frequency applications	Widely used in various power supply applications, including low and medium power levels

VI.CONCLUSION

In conclusion, the simulation results between the ZCS dual-phase half mode switched capacitor converter and the flyback converter with transformer leakage for a 48V to 24V DC-DC conversion application indicate distinct performance characteristics for each topology. The ZCS switched capacitor converter showcased its strengths in achieving high efficiency and low output voltage ripple, which is ideal for applications where energy conservation and stable voltage are critical. Its ability to operate with zero current switching reduces stress on components, leading to potentially longer life and higher reliability. This topology is particularly beneficial for applications that require lightweight and compact power supplies. On the other hand, the flyback converter's provision of galvanic isolation via the transformer is an essential feature for safety in many applications. While it may exhibit higher voltage ripple and slightly lower efficiency, the ability to provide isolation is often a non-negotiable aspect in vehicle and industrial applications. The flyback converter is also highly scalable and can be designed for a wide range of power levels, making it versatile across different use cases. Ultimately, the choice between these topologies will depend on the specific requirements of the application. For energy-sensitive and space-constrained environments, the ZCS switched capacitor converter may be the preferred choice. In contrast, for applications where isolation is paramount and efficiency can be slightly compromised, the flyback converter would be the suitable option.

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