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ENHANCING THREE-LEVEL DC-DC CONVERTER PERFORMANCE USING ZVS AND ZCS TECHNIQUES

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Abstract - The ZVZCS three-level DC/DC converter enhances efficiency by addressing the limitations of traditional ZVS converters. While ZVS reduces voltage-related switching losses, it struggles with circulating energy losses, parasitic ringing, and a limited ZVS range. To overcome these issues, the ZVZCS converter incorporates an auxiliary circuit and phase shift control. This allows outer switches to achieve ZVS, minimizing voltage-related losses, while inner switches operate under ZCS, ensuring they turn on and off at zero current, eliminating current-related losses. This approach suppresses parasitic ringing, reduces energy dissipation, and extends the ZVS range across varying loads, improving overall performance. A lamp load is used to evaluate its stability and power delivery. By enhancing power efficiency, stability, and thermal management, the ZVZCS converter is ideal for high-power applications such as renewable energy systems, electric vehicles, and industrial power supplies, ensuring optimal energy conversion with minimal losses and improved system reliability.

Key words — Zero Voltage Switching, Zero Current Switching, Three level DC-DC converter, Circulating energy losses, Parasitic ringing, Phase shift control, High efficiency, Load range, High power DC-DC conversion.

1.INTRODUCTION

Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) are two essential techniques used in power electronics to improve the efficiency of power conversion systems by minimizing switching losses. In conventional switching, when a power switch such as a transistor or a MOSFET turns on or off, there is an overlap between voltage and current. This overlap results in energy dissipation in the form of heat, reducing overall system efficiency and increasing thermal stress on the components. ZVS and ZCS are designed to eliminate or significantly reduce these switching losses by ensuring that the switch transitions occur at specific moments when either voltage or current is zero, thereby preventing unnecessary power dissipation.

Zero Voltage Switching (ZVS) is a technique where the power switch is turned on when the voltage across it reaches zero. This is typically achieved using a resonant circuit consisting of an inductor and a capacitor (L-C circuit). The resonant circuit allows the voltage across the switch to oscillate naturally, and the switch is turned on precisely when the voltage is zero. By doing so, the energy stored in the circuit components is used efficiently, and the power losses that would otherwise occur due to capacitive discharge are minimized. ZVS is particularly useful in high-frequency power conversion applications, such as in soft-switching power supplies, where it helps to reduce electromagnetic interference (EMI) and switching stress on components. The technique is widely used in resonant inverters, induction heating systems, and high-frequency DC-DC converters, where reducing switching losses is critical to improving overall efficiency.

Zero Current Switching (ZCS), on the other hand, focuses on ensuring that the switch transitions occur when the current flowing through it is zero. This technique is particularly beneficial in circuits where high currents are involved, as it prevents the power switch from experiencing high current surges during switching operations. When a switch turns off while current is still flowing, the sudden interruption leads to energy dissipation and can cause voltage spikes due to circuit inductance, which may damage the switch or require additional snubber circuits. ZCS eliminates this issue by ensuring that the switch turns off only when the current has naturally decreased to zero. This reduces the stress on the switch and lowers energy dissipation, improving system reliability and extending the lifespan of power devices. ZCS is commonly used in high-power converters, resonant converters, and circuits where inductive loads are present.

By employing ZVS and ZCS, power electronics designers can achieve significant improvements in system efficiency. Reduced switching losses mean less wasted energy, which directly translates into cost savings and lower operational expenses over the lifetime of a product.

Additionally, minimizing switching losses reduces heat generation, which is a critical factor in power electronic design. Excess heat often necessitates additional cooling mechanisms, such as heatsinks, fans, or liquid cooling systems, which increase both the size and cost of the overall system. With ZVS and ZCS, the need for extensive thermal management is minimized, making power electronic designs more compact, lightweight, and cost-effective. This is particularly beneficial in applications where space and weight are constraints, such as in electric vehicles, solar inverters, and portable electronic devices.

The importance of ZVS and ZCS extends beyond efficiency and cost savings. By reducing switching losses, these techniques also help in lowering electromagnetic interference, which is crucial for ensuring compliance with electromagnetic compatibility (EMC) standards in modern electronic systems. Furthermore, improved efficiency leads to better system reliability, as components experience less thermal and electrical stress.

As power electronics technology continues to evolve, the adoption of ZVS and ZCS is expected to remain a crucial aspect of designing high-performance and energy-efficient power conversion systems. These techniques are widely used in various applications, including renewable energy systems, industrial motor drives, power supplies, and electric vehicle charging infrastructure. With ongoing advancements in semiconductor technology and circuit design, ZVS and ZCS will continue to play a key role in optimizing power conversion efficiency and enhancing the performance of power electronic devices.

2. EXISTING METHODOLOGY

2.1. INTRODUCTION TO HARDWARE SWITCHING

Hardware switching is a fundamental technique in power electronics that uses semiconductor devices like MOSFETs to regulate electrical power by switching between "on" and "off" states. This method is widely applied in power supplies, motor drives, and renewable energy systems. MOSFETs are favoured due to their fast switching capabilities, allowing efficient power transfer with minimal resistance when turned on and blocking current flow when turned off. However, switching introduces challenges that impact efficiency and reliability.

2.2. SWITCHING LOSSES AND THERMAL MANAGEMENT

One of the key concerns in hardware switching is switching losses, which occur due to the overlap of voltage and current during transitions. Ideally, MOSFETs should switch instantaneously, but in reality, there is always a brief period where both voltage and current exist simultaneously, leading to power dissipation. This results in heat generation, which must be managed to prevent damage and maintain system efficiency. Effective thermal management strategies such as heatsinks, cooling fans, and optimized circuit design help mitigate these effects.

2.3. PARASITIC RINGING AND ELECTROMAGNETIC INTERFERENCE (EMI)

Parasitic ringing arises due to the interaction between stray inductance and capacitance in the circuit, causing oscillations during switching. These oscillations generate high-frequency noise, voltage spikes, and electromagnetic interference (EMI), which can disrupt circuit operation and damage components like rectifier diodes. To counteract these effects, designers implement techniques such as snubber circuits to absorb excess energy, smooth waveforms, and reduce oscillations.

2.4. ZERO VOLTAGE SWITCHING FOR EFFICIENCY IMPROVEMENT

To enhance efficiency and minimize switching losses, power electronics designers use Zero Voltage Switching (ZVS). This technique ensures that the MOSFET switches when the voltage across it is nearly zero, reducing energy dissipation. Achieving ZVS requires the use of resonant circuits consisting of inductors and capacitors, which create favourable conditions for zero-voltage transitions. Proper timing of switching events allows MOSFETs to turn on and off optimally, reducing heat generation and improving overall efficiency.

3. PROPOSED SYSTEM

The proposed methodology significantly enhances power conversion efficiency by incorporating phase shift control and a flying capacitor in the primary side of a DC-DC converter. This innovative approach is designed to minimize switching losses, improve energy transfer, and optimize the overall performance of power electronic systems. By carefully regulating the timing of switch transitions, this method ensures smoother power flow, reducing abrupt changes that could lead to unnecessary power dissipation and excessive stress on circuit components. Additionally, in this proposed methodology, we have incorporated a lamp load as the output, further demonstrating the system's capability to handle practical load conditions effectively.

Phase shift control is a modulation technique that introduces a controlled delay between the switching signals of the primary-side transistors in a power converter. Instead of switching all transistors simultaneously, a phase shift is applied between them, allowing energy transfer to be managed in a controlled and gradual manner. This method minimizes the overlap between voltage and current, which is a major source of switching losses in conventional hard-switching systems. By reducing the simultaneous occurrence of high voltage and current, phase shift control significantly decreases heat generation, leading to improved efficiency and a longer lifespan for power components.

A critical component of this methodology is the flying capacitor, which dynamically balances voltage across various circuit elements. Unlike a conventional capacitor that maintains a fixed voltage level, a flying capacitor shifts its voltage in response to circuit conditions. This ability to float between different voltage levels helps to prevent excessive voltage spikes, which can otherwise degrade system reliability and cause power dissipation. The flying capacitor ensures voltage balance within the circuit, leading to improved power regulation and increased stability.

In addition to maintaining voltage balance, the flying capacitor assists in achieving Zero Voltage Switching (ZVS) for the outer switches in the circuit. ZVS is a technique that allows switches to turn on when the voltage across them is nearly zero, thereby minimizing switching losses. This approach is particularly beneficial in high-frequency power conversion applications, where conventional switching methods often lead to excessive losses and increased thermal dissipation. By utilizing ZVS, the proposed methodology reduces the energy lost during switching transitions, thereby enhancing efficiency and reducing stress on semiconductor devices. The lower stress on components ultimately improves the durability and performance of the power electronics system.

Additionally, this methodology incorporates Zero Current Switching (ZCS) to optimize turn-off transitions. ZCS ensures that switches turn off when the current flowing through them is zero, eliminating the energy dissipation typically associated with turn-off events in traditional switching techniques. This is particularly useful in reducing conduction losses and preventing unwanted oscillations or voltage spikes, which could lead to electromagnetic interference (EMI). The combined implementation of ZVS and ZCS enables an efficient soft-switching environment, where voltage and current-related switching losses are significantly minimized.

By integrating phase shift control, flying capacitor balancing, and advanced soft-switching techniques, this methodology effectively addresses key challenges in modern power electronics. The proposed approach leads to significant improvements in power conversion efficiency, enhances system reliability, and reduces thermal stress. As a result, it is highly suitable for high-performance applications such as renewable energy systems, electric vehicles, and next-generation power supplies. This innovative technique ensures better energy management while maintaining operational stability, making it a practical and efficient power conversion strategy for future power electronics advancements. Furthermore, the inclusion of a lamp load as the output validates the system's ability to drive real-world loads, making it a robust and adaptable solution for various power conversion applications.

4. WORKING PRINCIPLE

The proposed methodology aims to enhance the power conversion efficiency and reduce switching losses in DC-DC converters by integrating phase shift control with a flying capacitor. This approach addresses the inherent challenges in power electronic systems, such as energy dissipation, voltage fluctuations, and switching losses, which can degrade overall system performance and reliability. By employing a combination of phase shift control and a flying capacitor, the methodology optimizes energy transfer, minimizes stress on circuit components, and improves operational efficiency.

Phase shift control plays a critical role in refining the timing of switching transitions within the converter. Instead of conventional hard-switching techniques, which lead to abrupt voltage and current changes, phase shift control introduces a deliberate phase shift between the switching signals of primary-side switches. This controlled timing facilitates smooth transitions between switching states, reducing power dissipation and component stress. As a result, the converter operates with lower electromagnetic interference (EMI) and improved thermal performance, leading to enhanced longevity and reliability of the circuit. A key component in the proposed design is the flying capacitor, which dynamically balances voltage across different circuit elements. In high-frequency power conversion systems, sudden voltage spikes can compromise the integrity of semiconductor devices and passive components. The flying capacitor effectively mitigates these voltage spikes by redistributing charge within the circuit, preventing excessive voltage differentials that could otherwise lead to component failure. This voltage regulation function is crucial in maintaining steady and efficient power conversion.

Another significant advantage of integrating a flying capacitor is its role in achieving Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS). ZVS ensures that outer switches in the converter turn on at nearly zero voltage, significantly reducing turn-on losses. This technique is particularly effective in soft-switching topologies, where it minimizes energy dissipation during switching transitions. Meanwhile, ZCS enables switches to transition at zero current, reducing turn-off losses by preventing abrupt current interruptions that can cause voltage spikes and energy dissipation. Together, ZVS and ZCS enhance the efficiency of the power conversion process, contributing to reduced thermal stress and improved overall performance.

To ensure real-time monitoring and adaptive control of the converter's performance, an Arduino microcontroller is integrated into the system. The Arduino processes data from an ACS712 current sensor module and a voltage divider circuit to continuously measure current and voltage values. The ACS712 module provides precise current sensing by leveraging the Hall effect principle, while the voltage divider circuit allows safe measurement of voltage levels by scaling down higher voltages to a readable range for the microcontroller. The collected data is displayed on an OLED screen, providing real-time feedback on voltage and current values. This real-time visualization aids in monitoring the converter's operational parameters, ensuring it functions within defined performance limits. The feedback mechanism allows for quick adjustments to optimize efficiency, prevent overloading, and enhance overall system reliability. In the integration of phase shift control with a flying capacitor presents a robust solution for improving DC-DC converter performance. By optimizing switching transitions, reducing voltage spikes, and implementing real-time monitoring, this methodology enhances efficiency, minimizes power losses, and ensures reliable operation of the power conversion system.

5. HARDWARE IMPLEMENTATION

The three-level DC-DC converter operates in three key stages:

1. DC to AC Conversion and Switching Optimization
2. AC Processing and DC Output Stabilization
3. Real-Time Monitoring and Performance Optimization

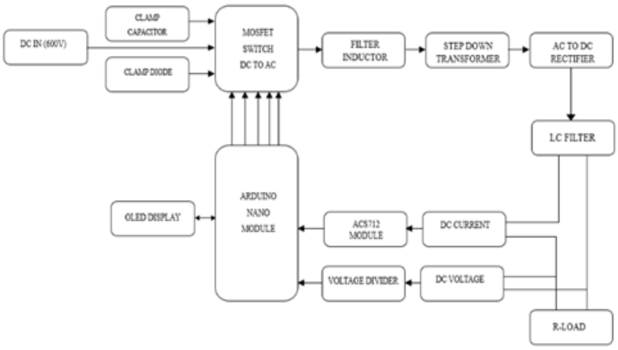

Figure.1 Block Diagram

5.1. DC to AC Conversion and Switching Optimization:

The three-level DC-DC converter begins its operation with a high-voltage DC input, typically around 600V, which serves as the primary power source. This high voltage ensures efficient power transfer and is essential for applications requiring substantial energy conversion, such as industrial power supplies, electric vehicles, and renewable energy systems. However, working with such high voltages introduces challenges like excessive stress on switching components, potential voltage spikes, and significant power dissipation. To mitigate these issues, a clamp capacitor and a clamp diode are incorporated into the system. The clamp capacitor plays a crucial role in voltage balancing by distributing the voltage evenly across the MOSFET switches, while the clamp diode helps in suppressing transient voltage spikes that occur during switching operations. Without these components, MOSFETs would experience uneven voltage stress, leading to reduced reliability and potential failure over time.

The primary function of the MOSFETs in this converter is to perform high-frequency switching, converting the DC input into an AC signal. This alternating signal is necessary for further processing, as it allows efficient voltage transformation and conditioning before being converted back into a regulated DC output. Traditional power converters suffer from substantial switching losses due to abrupt changes in voltage and current during transitions. These losses generate excess heat, reducing overall efficiency and increasing cooling requirements. To address this, the system employs Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) techniques, which significantly optimize the switching process. ZVS ensures that switching occurs when the voltage across the MOSFETs is zero, effectively eliminating capacitive discharge losses. This is achieved by carefully timing the switching events so that the voltage naturally reaches zero before the switch turns on or off. By doing so, the system prevents energy stored in parasitic capacitances from being dissipated as heat. On the other hand, ZCS ensures that switching takes place when the current through the MOSFETs is zero, minimizing energy losses caused by inductor currents. This is particularly important in circuits with high inductance, where switching at non-zero current levels can lead to excessive energy dissipation. The combination of ZVS and ZCS greatly enhances efficiency by reducing both voltage and current-related switching losses. This not only improves power conversion efficiency but also lowers heat generation, reducing the need for additional cooling mechanisms. Furthermore, by minimizing stress on the switching components, the lifespan of MOSFETs and other semiconductor devices is extended, reducing maintenance costs and enhancing overall system reliability.

5.2. AC PROCESSING AND DC OUTPUT STABILIZATION:

Once the high-voltage DC input has been successfully converted into an alternating signal, it must undergo further processing to ensure a stable and well-regulated output. The first stage in this process is passing the AC signal through a filter inductor. This inductor plays a critical role in eliminating high-frequency noise and unwanted distortions that may arise due to rapid switching transitions. If left unfiltered, these high-frequency components can cause electromagnetic interference (EMI) and affect the performance of other electronic devices. By smoothing out the AC waveform, the filter inductor ensures cleaner power transmission. After filtering, the AC signal is fed into a step-down transformer, which adjusts the voltage level based on the specific requirements of the connected load. The transformer operates on the principle of electromagnetic induction, where the primary winding receives the alternating signal, inducing a corresponding voltage in the secondary winding. The turns ratio of the transformer determines how much the voltage is reduced, ensuring that the output is suitable for further rectification and use.

This step is particularly important in applications where the initial high-voltage DC must be converted into a lower voltage for safe operation, such as in battery charging or electronic device power supplies. Since the final output of the system needs to be DC, the stepped-down AC signal undergoes rectification using an AC to DC rectifier.

The rectifier consists of diodes or active switching components that allow current to flow in only one direction, converting the bidirectional AC waveform into a unidirectional DC signal. However, even after rectification, some AC ripple remains in the output, which can affect the performance of sensitive electronic circuits. To further refine the output, an LC filter is employed. The LC filter, composed of an inductor and a capacitor, is designed to smooth out any remaining voltage fluctuations, ensuring a clean and stable DC output. The inductor in the LC filter prevents sudden current changes, while the capacitor absorbs high-frequency variations, providing a continuous DC supply to the connected load. This filtering process is crucial for maintaining power quality, as excessive voltage fluctuations can lead to unstable performance or even damage to electronic components. Once the filtering is complete, the final DC output is delivered to the resistive load (R-Load), representing the application where the converted power is utilized.

5.3. REAL-TIME MONITORING AND PERFORMANCE OPTIMIZATION:

To ensure optimal efficiency, stability, and safety, the three- level DC-DC converter is equipped with an Arduino Nano microcontroller, which acts as the control and monitoring unit. The primary function of the Arduino is to manage the MOSFET switching sequences, ensuring that ZVS and ZCS techniques are implemented correctly for maximum efficiency. In addition to controlling switching operations, the Arduino continuously collects real-time data from various sensors to monitor the system's performance and adjust parameters as needed. One of the key sensors integrated into the system is the ACS712 current sensor module, which provides continuous measurements of the DC current flowing through the circuit. This data is crucial for detecting overcurrent conditions, which could indicate excessive load demand or faults within the system. If an overcurrent situation is detected, the Arduino can trigger protective mechanisms such as shutting down the circuit or adjusting switching patterns to prevent damage.

To ensure accurate voltage monitoring, a voltage divider circuit is used to step down high-voltage signals to a safe range that the Arduino can process. Since the microcontroller operates at lower voltage levels, direct measurement of high- voltage signals is not possible. The voltage divider reduces these signals proportionally, allowing the Arduino to process and analyze voltage fluctuations in real-time. Once the Arduino processes the collected data, it displays key system parameters on an OLED screen. This real-time display provides essential information such as voltage levels, current flow, and switching states, allowing users to monitor performance and make necessary adjustments for improved operation. The ability to visualize real-time data enhances troubleshooting capabilities, making it easier to identify and resolve potential issues before they impact system performance. By integrating real-time monitoring and control, the system ensures high efficiency, reduced energy losses, and enhanced reliability. In renewable energy applications, such as solar and wind power systems, the converter plays a crucial role in stepping down and regulating power from high-voltage sources to usable levels. In electric vehicles, it is used for efficient battery charging and energy distribution. Similarly, industrial automation and telecommunications rely on such converters to provide stable DC power for critical equipment. The aerospace sector benefits from the system's high efficiency and reliability, making it suitable for mission-critical power management applications.

Overall, the three-level DC-DC converter with ZVS and ZCS techniques represents a highly efficient, reliable, and intelligent power conversion solution. By combining optimized switching methods, advanced voltage balancing, effective filtering, and real-time monitoring, this system achieves superior performance with minimal energy losses.

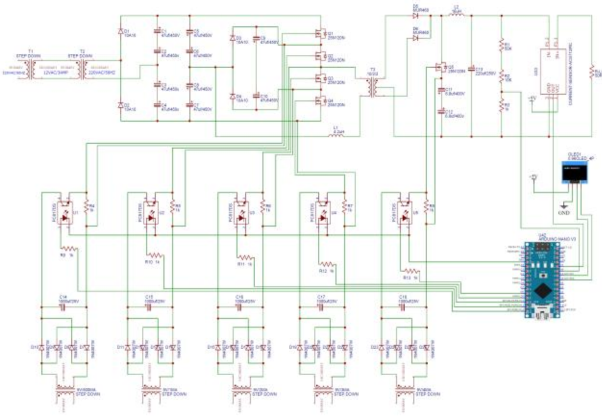

Figure.2 Circuit Diagram of the proposed system

The integration of an Arduino-based control mechanism further enhances its adaptability, ensuring stable operation across various applications. As power electronics continue to evolve, such advanced converters will play a crucial role in developing next-generation energy-efficient systems.

6. CONCLUSION:

The three-level DC-DC converter with Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) techniques represents a pinnacle in efficient power conversion technology. This sophisticated converter system is designed to handle high-voltage DC inputs, typically around 600V, and efficiently transform them into regulated DC outputs with minimal energy loss and heat generation. This makes it highly suitable for applications that require substantial energy conversion, such as industrial power supplies, electric vehicles, and renewable energy systems. One of the key challenges in high-voltage power conversion is managing the excessive stress on switching components, potential voltage spikes, and significant power dissipation. To address these issues, the converter incorporates a clamp capacitor and a clamp diode. The clamp capacitor plays a crucial role in voltage balancing by distributing the voltage evenly across the MOSFET switches. This ensures that no single MOSFET experiences undue stress, which could otherwise lead to reduced reliability and potential failure over time. The clamp diode helps suppress transient voltage spikes that occur during switching operations, protecting the MOSFETs from damage and enhancing the overall durability and efficiency of the system. The primary function of the MOSFETs in this converter is to perform high-frequency switching, converting the DC input into an AC signal. This alternating signal is necessary for further processing, allowing efficient voltage transformation and conditioning before being converted back into a regulated DC output. Traditional power converters often suffer from substantial switching losses due to abrupt changes in voltage and current during transitions, generating excess heat and reducing overall efficiency. To optimize the switching process, the converter employs ZVS and ZCS techniques. ZVS ensures that switching occurs when the voltage across the MOSFETs is zero, effectively eliminating capacitive discharge losses. This is achieved by timing the switching events so that the voltage naturally reaches zero before the switch turns on or off. By doing so, the system prevents energy stored in parasitic capacitances from being dissipated as heat. ZCS, on the other hand, ensures that switching takes place when the current through the MOSFETs is zero, minimizing energy losses caused by inductor currents. This is particularly important in circuits with high inductance, where switching at non-zero current levels can lead to excessive energy dissipation. The combination of ZVS and ZCS greatly enhances efficiency by reducing both voltage and current-related switching losses. This not only improves power conversion efficiency but also lowers heat generation, reducing the need for additional cooling mechanisms. Furthermore, by minimizing stress on the switching components, the lifespan of MOSFETs and other semiconductor devices is extended, reducing maintenance costs and enhancing overall system reliability. The AC processing stage of the converter involves filtering, step-down transformation, and rectification to ensure a stable and ripple-free DC output. The LC filter plays a crucial role in smoothing voltage fluctuations, making the system suitable for applications requiring precise power regulation. Real-time monitoring and control, facilitated by an Arduino Nano microcontroller, significantly enhance the system's adaptability. Continuous voltage and current measurements, combined with OLED-based visual feedback, allow for dynamic adjustments, ensuring optimal performance under varying load conditions. The integration of protective features, such as overcurrent detection, further improves system safety and longevity. This converter's ability to deliver high efficiency, real-time adaptability, and reliable operation makes it ideal for modern power applications. As industries continue to demand energy-efficient solutions, this technology will play a vital role in shaping the future of power electronics, ensuring sustainable and optimized energy utilization across various sectors, including aerospace, telecommunications, and industrial automation. Through the effective management of high voltages and the implementation of advanced switching techniques, the three-level DC-DC converter achieves superior performance with minimal energy losses, positioning it as a cornerstone of next-generation power electronics.

7. SUSTAINABLE DEVELOPMENT GOALS

SDG Goal 7: Affordable and Clean Energy by promoting efficient energy use and advancing sustainable power electronics.

SDG Goal 8: Decent Work and Economic Growth by fostering innovation in power electronics, reducing energy costs, and promoting sustainable industrial productivity.

SDG Goal 9: Industry, Innovation, and Infrastructure by supporting sustainable industrial growth, improving energy efficiency, and fostering innovation in power electronics.

8. REFERENCES

[1] Zhiliang Zhang, Xinbo Ruan, "Full-bridge Three-Level Converter with the Flying Capacitor and Two Clamping Diodes, in: 2005" IEEE 36th power electronics specialists conference, 2005, pp. 425–430.

[2] Guo, Z.; Sun, K.; Sha, D. Improved ZVS three-level DC–DC converter with reduced circulating loss. IEEE Trans. Power Electron.2016.

[3] M. Pahlevani and P. K. Jain, ''Soft-switching power electronics technology for electric vehicles: A technology review,'' IEEE J. Emerg. Sel. Topics Ind. Electron., vol. 1, no. 1, pp. 80–90, Jul. 2020.

[4] R. Faraji and H. Farzanehfard, ''Fully soft switched multi-port DC-DC converter with high integration,'' IEEE Trans. Power Electron., vol. 36, no. 2, pp. 1901–1908, Feb. 2020.

[5] R. Faraji, H. Farzanehfard, M. Esteki, and S. Ali Khajehoddin, ''A lossless passive snubber circuit for three-port DC–DC converter,'' IEEE J. Emerg. Sel. Topics Power Electron., vol. 9, no. 2, pp. 1905–1914, Apr. 2021.

[6] S. S. Dobakhshari, S. H. Fathi, and J. Milimonfared, ''A new soft-switched three-port DC/DC converter with high voltage gain and reduced number of semiconductors for hybrid energy applications,'' IEEE Trans. Power Electron., vol. 35, no. 4, pp. 3590–3600, Apr. 2020.

[7] Shi, Y.; Yang, X. Wide-range soft-switching PWM three-level combined DC–DC converter without added primary clamping devices. IEEE Trans. Power Electron. 2014.