Performance Evaluation of a Five-Level Cascaded Multilevel LLC Boost DC–DC Converter Using FuzzyLogic Control

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Abstract**—**A proposed cascaded five-level with LLC resonant boost DC-DC converter controlled by a fuzzy logic controller is designed to accommodate large variations in load and input voltage, achieve high efficiency, and ensure zero voltage switching (ZVS), meeting the rigorous demands of industrial applications. Detailed design considerations highlight the benefits of integrating multilevel and LLC resonant converter (RC) features. The voltage gain is configured to achieve an output voltage five times the input voltage, with an operating frequency range between 67kHz and 135kHz to sustain ZVS and operate close to the resonant frequency for optimal efficiency. Furthermore, a full-bridge LLC resonant converter with analogous assumptions and parameters was simulated using MATLAB/Simulink to provide a clear comparison of resonant behaviour. The study found that the five-level inverter LLC circuit consistently operates at a switching frequency lower than the resonant frequency, regardless of input and load conditions, which differs from the typical behaviour of full-bridge inverters.

Keywords**—**DC-DC resonant converters, fuzzy logic controller, multilevel inverters, voltage stress, zero current switching (ZCS), LLC resonant converter, zero voltage switching (ZVS).

1. INTRODUCTION

Resonant DC-DC converters are becoming more popular for power conversion in high and low voltage applications. These converters offer great benefits and have proven performance compared to traditional converters. They are widely used in smart grids, electric vehicles, and renewable energy systems. The of these converters include smooth waveforms, good isolation, soft switching at high frequencies, low EMI emission, high power density, and high efficiency. One key advantage of DC-DC resonant converters is their ability to minimize switching losses at the output rectifier diodes and inverter switches. This enables them to operate at higher switching frequencies with greater efficiency. Additionally, they reduce the size of components like passive filters and power transformers.

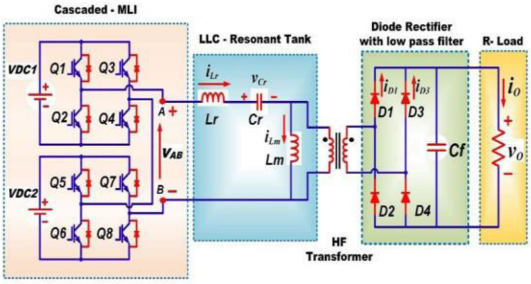

Figure.1 proposed cascaded 5-level LLC converter

Resonant converters can be categorized based on various parameters such as their switching method, mode of operation, and frequency ratio. When the switching frequency exceeds the resonant frequency, zero voltage switching (ZVS) is achieved for all switches. Conversely, a higher resonant frequency than the switching frequency leads to zero current switching (ZCS). One common resonant topology is the LLC resonant converter which excels in regulating output voltage over a wide load and input voltage range with minimal variation in operating frequency. It offers advantages like soft-switching capability, high efficiency, and low EMI emission.

To meet the requirements for high-voltage operation, multi-level resonant DC-DC converters have been suggested. These converters offer various benefits, such as producing high-quality waveforms with minimal harmonic distortion, reducing voltage stress on switching devices, and achieving high power quality and efficiency. They also minimize Electro-Magnetic Interference (EMI) output, reduce switching losses, and can generate multiple voltage levels, which decreases the size of output filters.

Another advantage of multilevel inverters is their ease of interfacing with batteries, renewable energy sources (RES), capacitors, and plug-in electric vehicles. They enable the use of low-voltage rated switches in high-voltage applications, making these devices more cost-effective, accessible, and efficient in switching.

Combining multilevel inverters with resonant DC-DC converters can enhance the performance of both systems. Research has demonstrated that three-level inverters and resonant converters (RCs) can reduce voltage stress to 50% of the input voltage. However, selecting appropriate switches for high power applications can be challenging due to the increased current ratings required as output power levels rise.

A three-phase LLC resonant DC-DC converter has been proposed to maintain the benefits of three-phase converters while achieving soft-switching for all switches. However, these converters have limitations, including a narrow gain range and poor light-load efficiency. The resonant tank parameters in three-phase LLC RCs are not identical for each phase, causing different gain characteristics and exacerbating output current ripples. Correcting these imbalances requires larger output capacitors and the use of three discrete transformers, which increases the converter system’s size and weight. Multilevel LLC resonant DC-DC converters offer a better alternative to existing topologies. By employing multilevel inverters on the input side, these converters can reduce voltage stress between switching devices and enhance the power range of LLC RCs, making them suitable for high power and high voltage applications. Studies have discussed the pairing of multilevel inverters with LLC resonant converters. For example, one study presented a multi-phase multi-level LLC RC with a modular design that achieves Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) for primary switches and rectifier diodes under various load and input voltage conditions, minimizing voltage stress to a fraction of the input voltage.

Multilevel DC-DC converters have been recommended for high-voltage operations as they offer benefits like reducing voltage stress on switching devices and improving power quality. They can interface easily with batteries, renewable energy sources, capacitors, and electric vehicles. Combining multilevel inverters with resonant DC-DC converters has shown promising results in enhancing system capabilities while achieving soft-switching for all switches. Moreover, cascaded five-level LLC resonant DC-DC step-up converters with advanced control techniques have been proposed to address energy production requirements for modern energy systems as shown Figure 1.

These innovative converters ensure isolated power conversion with high efficiency and power density. By utilizing variable frequency control strategies to achieve zero voltage switching (ZVS) and zero current switching (ZCS), they provide effective energy solutions for diverse industrial applications.In conclusion, these advancements in resonant DC-DC converters present a friendly approach to sustainable power conversion solutions for various modern applications.

2. PROPOSED SYSTEM BLOCK DAIGRAM REPRESENDETION

The block diagram outlines a sophisticated power conversion system designed for industrial applications. It begins with a supply voltage input, which serves as the primary power source.

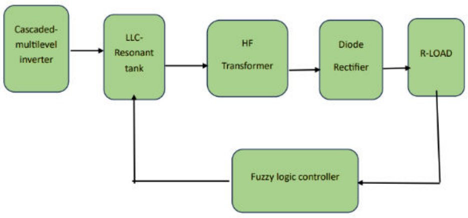

Figure 2. Block diagram for proposed system

This input is initially processed by a cascaded-multilevel inverter, a key component that converts the DC input into a higher voltage AC output using multiple levels of DC voltage sources. The output from the multilevel inverter then passes through an LLC-resonant tank circuit, where it undergoes further conditioning to optimize efficiency and reduce losses. The LLC resonant tank facilitates Zero Voltage Switching (ZVS) for switches, crucial for minimizing switching losses and improving overall converter efficiency. Subsequently, the high-frequency (HF) transformer steps up or steps down the voltage as required before the AC output is rectified by a diode rectifier.

This rectification process converts the AC voltage into a stable DC voltage suitable for powering the load. The load, representing the final stage of the system, utilizes the DC output for its intended industrial applications. Throughout this process, a fuzzy logic controller is intricately involved, dynamically adjusting the operation of the cascaded-multilevel inverter and possibly other components based on varying input conditions and load requirements as shown Figure2. This controller enhances system performance by optimizing control parameters, ensuring efficient and stable operation across a range of operational scenarios.

3. METHODOLOGY USED IN PROPOSED SYSTEM

3.1 Cascaded-multilevel inverter

The “5-level cascaded H-bridge inverter” design involves two H-bridges each comprising four active power switches Q1 to Q8 and operated by two isolated symmetric DC sources. This configuration enables the generation of a 5-level output voltage waveform +Vdc, +2Vdc, -Vdc, -2Vdc, and zero through controlled switching of these eight switches. The switches are paired Q1-Q2, Q3-Q4, Q5-Q6, Q7-Q8 to operate complementarily, ensuring precise voltage level control as shown Figure3. Key to its operation are the duty cycles (Vgs1 = 0.4, Vgs3 = 0.6, Vgs5 = 0.2, Vgs8 = 0.8), which dictate the on-time of each switch pair relative to the total switching period.

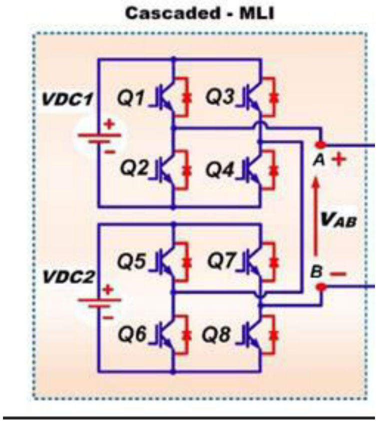

Figure3. Cascaded-multilevel inverter

These duty cycles determine the amplitude and shape of the output waveform, crucial for achieving the intended voltage levels. Practical implementation requires careful consideration of input source isolation and symmetry to maintain inverter efficiency and performance as designed.

The output waveform of a 5-level cascaded H-bridge inverter is characterized by five distinct voltage levels: +Vdc, +2Vdc, 0, -Vdc, and -2Vdc as shown in Figure 4. These levels are achieved by the controlled operation of eight power switches (Q1 to Q8) arranged in two H-bridge configurations. Each H-bridge consists of four switches and is driven by isolated DC sources.

The switches are paired (Q1-Q2, Q3-Q4, Q5-Q6, Q7-Q8) to operate in a complementary manner, allowing the inverter to produce the desired voltage levels. For instance, to generate +Vdc, specific pairs of switches conduct to provide a positive voltage equal to Vdc. Similarly, +2Vdc and -2Vdc are achieved by combinations that double the positive and negative voltage relative to Vdc, respectively. When all switches are off, the output voltage is zero. The transitions between these levels are governed by the switching patterns and duty cycles (such as Vgs1 = 0.4, Vgs3 = 0.6, Vgs5 = 0.2, Vgs8 = 0.8), which determine the on-off timing of each switch pair within the switching cycle. This design flexibility makes the 5-level cascaded H-bridge inverter suitable for applications requiring precise control over multi-level output voltages, such as in renewable energy systems, motor drives, and grid-tied inverters.

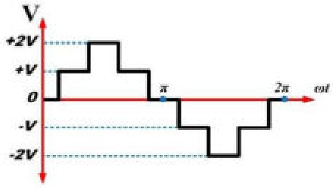

Figure 4. output waveform Cascaded-multilevel inverter

The waveform transitions between these levels depending on the switching states of the H-bridge components, controlled by the assigned duty cycles (Vgs1, Vgs3, Vgs5, Vgs8) that determine how long each switch pair conducts during each switching cycle. This configuration allows the inverter to produce a stepped waveform that can be used in various applications requiring multiple voltage levels, such as in renewable energy systems and motor drives.

3.2 LLC-Resonant tank

Combining the proposed system inverter with the LLC resonant circuit enhances energy efficiency and voltage regulation for power conversion applications. The LLC resonant circuit comprises a component the series resonant capacitor (Cr), series resonant inductance (Lr), and transformer magnetizing inductance (Lm) as shown Figure5. These components form a resonant network that efficiently transfers energy to the load.

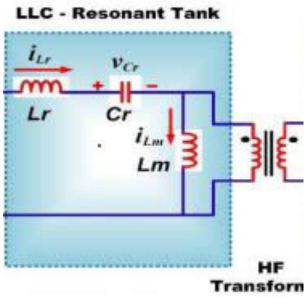

Figure5. LLC-Resonant with transformer

Mathematically, the operation of the LLC resonant circuit can be understood through its resonance frequency fr determined by give belove equation.1.

$$fr = \frac{1}{2\pi\sqrt{Lr.Cr}} (1)$$

where $Lr$is the series resonant inductance and Cr is the series resonant capacitance. This frequency facilitates maximum energy exchange between the inverter and the load, optimizing efficiency.

The transformer magnetizing inductance Lm is crucial for coupling energy from the resonant circuit to the load through a step-up transformer. When driven by a square-wave voltage from the inverter, the LLC circuit ensures that the voltage supplied to the transformer is boosted to the desired output level. This step-up transformation provides both electrical isolation and voltage amplification necessary for various applications, such as in renewable energy systems and high-efficiency power supplies.

In practice, the performance of the combined inverter and LLC resonant circuit relies on precise design parameters and control strategies. These include selecting appropriate values for Lr, Cr, and Lm to achieve optimal resonance characteristics, as well as ensuring that the inverter's square-wave voltage matches the resonance frequency for efficient energy transfer. By integrating these components effectively, the system can deliver stable and regulated output voltages while minimizing losses, making it suitable for demanding industrial and consumer electronics applications.

3.3 Diode Rectifier

A diode rectifier is an essential component used in power electronics to convert alternating current (AC) into direct current (DC). It operates by allowing current to flow in one direction only, which is crucial for converting the AC output from the secondary side of a transformer or converter into a usable DC voltage. The rectification process involves diodes that conduct when they are forward-biased, meaning their anode is at a higher potential than their cathode. This configuration ensures that during each half-cycle of the AC input waveform, current flows through the load in a unidirectional manner, resulting in a pulsating DC output.

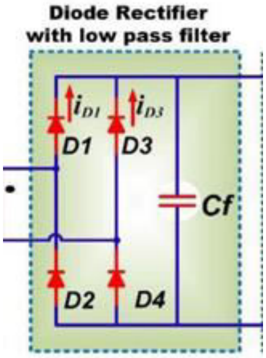

Figure 6. Diode Rectifier

There are different types of diode rectifiers, with the most common being the half-wave and full-wave rectifiers. A half-wave rectifier uses one diode to rectify only one half of the AC waveform, resulting in a DC output with significant ripple as shown Figure 7. In contrast, a full-wave rectifier, such as a bridge rectifier, utilizes four diodes as shown Figure 6. to rectify both halves of the AC waveform, producing a smoother DC output.

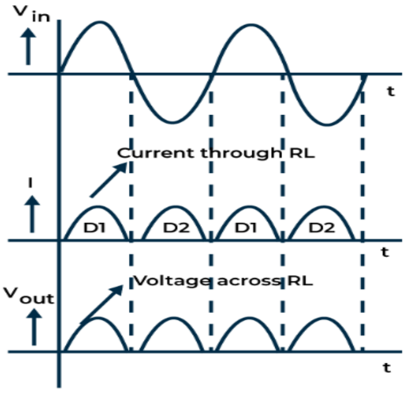

Figure 7. bridge rectifier wave forms

After rectification, a capacitive output filter is often employed to reduce the ripple in the DC output voltage. This filter consists of a capacitor that smooths out the pulsating DC voltage by storing charge during the peaks and supplying current during the troughs of the rectified waveform. This process results in a more stable and constant DC voltage suitable for powering electronic devices and systems. Diode rectifiers are integral to various applications such as power supplies, battery chargers, and DC motor drives, where converting AC to DC is necessary for reliable operation. Proper selection of diodes based on current ratings, voltage ratings, and thermal considerations ensures efficient and dependable rectification in these applications.

3.4 Proposed cascaded five-level LLC resonant boost DC-DC converter

The design and operation of an LLC resonant circuit are critical for achieving efficient power conversion with stable output characteristics across varying input and load conditions. The LLC resonant circuit as shown in Figure 8. of the equivalent circuit derived through the FHA approach, is designed to maintain optimal performance by carefully selecting gain curves. These curves ensure that the resonant tank operates within a narrow frequency variation range around its resonant frequency, minimizing magnetization current and enabling Zero Voltage Switching

(ZVS) for enhanced efficiency throughout its operating range.

The LLC topology adjusts its operational frequency dynamically to maintain a consistent output voltage under changing input voltages and load conditions. At its resonant frequency, the LLC circuit achieves maximum efficiency and stable voltage gain, decoupling the output voltage from load variations. However, in practical scenarios, variations in the coupling between the primary and secondary windings of the power transformer can affect operation. Changes in the output load requirements necessitate adjustments in the resonant frequency to maintain effective input and output regulation.

Therefore, while the LLC circuit ideally operates most efficiently at its resonant frequency, achieving stable operation requires adaptation to real-world conditions where load changes can impact the resonant characteristics. Effective design involves balancing these factors to ensure reliable performance across a range of operating conditions, thereby optimizing the efficiency and effectiveness of the LLC resonant circuit in practical applications.

To properly design an LLC resonant circuit, it is crucial to set its operating frequency within a specific range cantered around its resonance point. According to the analysis provided in references such as the following formulas can be employed to define the circuit parameters:

The LLC RC ''has two resonant frequencies, Fr1 and Fr2, which are defined'' thus give in equation 2. and 3.

$$Fr1 = \frac{1}{2\pi\sqrt{Lr \times Cr}} \quad (2)$$

$$Fr2 = \frac{1}{2\pi\sqrt{(Lr + Lm) \times Cr}} \quad (3)$$

where ''Lr is the resonant inductance, Cr is the resonant capacitor, and $Lm$is magnetizing inductance.'' The calculation of the AC equivalent load resistance, Rac, can be done as follows equation 4.

$$Rac = \frac{8n^2}{\pi^2} \times R_L \quad (4)$$

where RL is the actual resistance of load, and n is the transformer turns ratio.

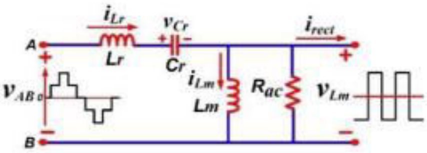

Figure 8. LLC resonant equivalent circuit

The ''expression of the DC voltage gain of the LLC RC as a function of the switching frequency, fs, inductance ratio Ln, and load quality factor Q, may be written'' as equation 5.

$$M_{gain}(F_N, L_N, Q) = \frac{F_n^2 \times (L_1 - 1)}{\sqrt{(L_n \times F_n^2 - 1) + F_n^2 \times (F_n^2 - 1)^2 \times (L_n - 1)^2 \times Q^2}} \quad (5)$$

Where F_N, L_N, Q given belove

$$L_n = \frac{L_m}{L_r}$$

$$F_n = \frac{f_{Sw}}{f_{r1}}$$

$$Q = \frac{\sqrt{L_r/C_r}}{R_{AC}}$$

where Fn and fSw are the normalized and switching frequencies respectively, while Ln is the inductance ratio between Lm and Lr.

CALCULATE THE TRANSFORMER TURNS RATIO (n):

The first step is to select the turn ratio of the power transformer using the relation give belove equation 6.

$$n = \frac{V_{In_{min}}}{V_o} \times M_{nom} (6)$$

where M_{nom} is the required Gain of LLC circuit at nominal output power at rated input and output voltage; $M_{nom}$is usually selected a bit higher or near unity to ensure high efficiency

CALCULATE THE MINIMUM AND MAXIMUM VOLTAGE GAINS OF THE RESONANT TANK:

With the obtained n value, the minimum gains and maximum gain are calculated thus in equations7&8.

$$M_{min} = \frac{n\times(V_O+2VF)}{\left(V_{In_{mAX}}\right)} (7)$$

$$M_{max} = \frac{n\times(V_O+2VF)}{\left(V_{In_{min}}\right)} (8)$$

CALCULATE OF THE EQUIVALENT LOAD RESISTANCE (Rac):

Having obtained the transformer turns ratio in Step 1, the Rac can be determined as equation 9.

$$R_{ac} = \frac{8n^2}{\pi^2} \times R_L (9)$$

CALCULATE OF THE RESONANT TANK COMPONENTS (Lr, Cr, AND Lm):

After determining the proper values for Ln and Q and getting Rac, the resonant tank's parameters can be calculated as follows equations

The calculation of the Cr can be done thus equation 10.

$$C_r = \frac{1}{2\pi\times f_r\times Q\times R_{ac}} (10)$$

Then, Lr can be obtained as equation 11

$$L_r = \frac{1}{(2\pi\times f_{r1})^2\times C_r} (11)$$

By using (3), the magnetizing inductor Lm can be found as equation 12.

$$L_m = L_n \times L_n (12)$$

4.FUZZY LOGIC CONTROL STRATEGY USE IN PROPOSED SYSTEM

In the design of a proposed cascaded five-level LLC resonant boost DC-DC converter, the fuzzy logic controller plays a crucial role in ensuring optimal performance under varying operating conditions. The primary function of the fuzzy logic controller is to adaptively regulate the converter's output in response to changes in load and input voltage, ensuring high efficiency and zero voltage switching (ZVS). Unlike traditional controllers that rely on precise mathematical models, a fuzzy logic controller uses a rule-based approach, which makes it highly effective in handling the nonlinearities and uncertainties associated with complex power electronics systems.

The fuzzy logic controller continuously monitors key parameters such as input voltage, output voltage, and load current. Based on these inputs, it applies a set of predefined rules to adjust the converter's switching frequency and duty cycle. This dynamic adjustment helps maintain the desired output voltage and improves the converter's efficiency by minimizing losses. Additionally, by ensuring ZVS, the controller reduces the switching losses and electromagnetic interference, which are critical for industrial applications.

Overall, the fuzzy logic controller enhances the robustness and reliability of the LLC resonant boost DC-DC converter, making it well-suited to accommodate large variations in load and input voltage while achieving high efficiency and maintaining stable operation in demanding industrial environments.

5. SIMULATION OF PROPOSED SYSTEM

Modelling and simulating a cascaded five-level LLC resonant boost DC-DC converter controlled by a fuzzy logic controller involves developing a comprehensive understanding of a complex power conversion system as shown Figure9. This converter configuration combines the benefits of a cascaded five-level topology with an LLC resonant circuit Parameters Values as shown Table 1. and fuzzy logic control for enhanced performance. The cascaded structure uses multiple voltage levels to distribute the voltage conversion across stages, reducing stress on individual components and improving overall efficiency. The LLC resonant topology further minimizes switching losses by achieving ZVS (Zero Voltage Switching), enhancing efficiency and reducing electromagnetic interference. The fuzzy logic controller optimizes the converter's operation by adjusting switching frequencies and duty cycles based on input variables like voltage and current. Modelling and simulation, typically performed using tools like MATLAB/Simulink, enable engineers to analyse the converter's dynamic behavior, validate control strategies, and optimize performance parameters such as efficiency, voltage regulation, and transient response. This approach ensures robust and reliable operation of the converter across various load conditions, making it suitable for applications in renewable energy systems, electric vehicles, and industrial power supplies where high efficiency and precise control are critical.

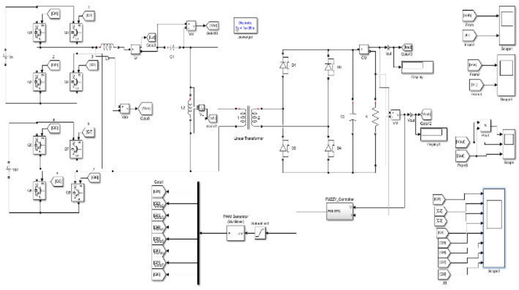

Figure9. simulation of cascaded five-level resonant boost DC-DC converter

The cascaded five-level resonant boost DC-DC converter is a sophisticated power conversion system designed to efficiently increase DC voltage while minimizing losses. The key elements of this system include.

This type of converter utilizes multiple voltage levels that typically five to achieve higher efficiency and lower voltage stress on components. The cascaded configuration means that the converter stages are connected in series, allowing each stage to handle a portion of the voltage boost. This multi-level approach reduces the harmonic distortion and enhances the overall performance of the converter.

S.NO	Parameter	Value
1	Resonant Capacitor (Cr)	450nF
2	Resonant Inductor (Lr)	$9\mu H$
3	Magnetizing Inductor (Lm)	$29\mu H$
4	Transformer turns ratio (n)	0.25
5	Switching Frequency Range	67kHz - 135kHz

Table .1

A fuzzy logic controller is employed to manage the complex dynamics of the resonant boost converter as shown Figure 10. Unlike traditional controllers that require precise mathematical models, FLC uses a set of heuristic rules based on expert knowledge. It processes inputs such as output voltage and inductor current and applies fuzzy logic to determine the control actions. This approach is particularly effective in dealing with non-linearities and uncertainties within the system, providing robust performance under varying load conditions.

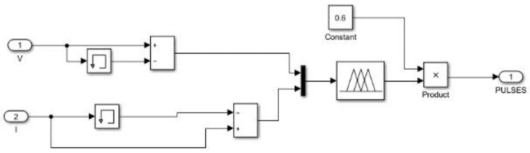

Figure 10. fuzzy logic controller

This type of converter is suitable for applications requiring high-efficiency DC power conversion, such as renewable energy systems (e.g., solar power), electric vehicles, and industrial power supplies.

the cascaded five-level resonant boost DC-DC converter with fuzzy logic control represents an advanced approach to power conversion, combining high efficiency, reduced component stress, and robust control to meet the demands of modern power electronics applications.

6. SIMULATION RESULTS

In the prosed simulation model, the DC input supplied to the cascaded five-level converter is set at 250V, as illustrated in Figure 5.1. This voltage waveform serves as the primary input to the converter system, representing the steady DC voltage provided by an external dc source such as an input supply. The waveform depicted in Figure 10. visually shows the constant 250V level over time, which is crucial for simulating and analysing the converter's performance under stable operating conditions.

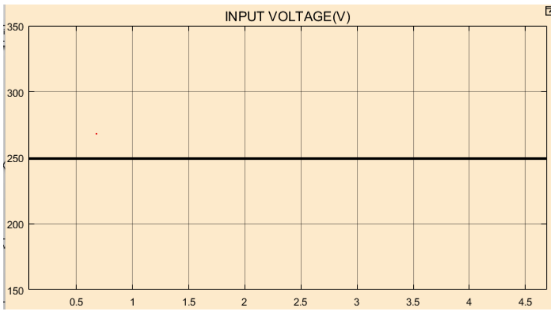

Figure 10 DC input voltage

The cascaded five-level converter, supplied with a 250V DC source, can generate stepped output voltages through its multi-level topology. This converter structure typically consists of 2-stages connected in series, each contributing to the overall voltage conversion process. The advantage of this configuration lies in its ability to generate several discrete output voltage levels, which are fractions or multiples of the input voltage.

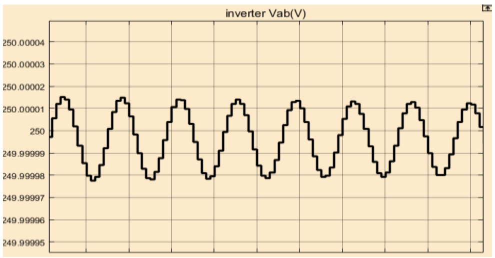

Figure 11. cascaded five-level inverter output

A 250V input DC supply, a cascaded five-level converter can produce output voltages as 250V shown in Figure 11, this is specific design and nominal switching patterns of the converter stages. These stepped output voltages are achieved by fuzzy controlling the switching of semiconductor devices MOSFET in each stage of the converter.

Once the stepped output voltages are generated, they pass through the LLC resonant tank. The LLC resonant tank, typically comprising inductors (L), capacitors (C), and sometimes additional components like resistors (R), is designed to operate at a resonant frequency. This resonance allows the converter to achieve zero voltage switching (ZVS) or zero current switching (ZCS) conditions during switching transitions, thereby minimizing switching losses and improving overall efficiency.

In a cascaded five-level LLC resonant boost DC-DC converter controlled by a fuzzy logic controller, after the output from the LLC resonant tank, the voltage is typically increased further using a high-frequency transformer. This transformer steps up the voltage to a level and given to the diode rectifier which convert that controller AC supply from the transformer DC supply it will passing through capacitor filter. The output DC voltage is getting 900V as shown in Fig.12

This transformer steps up the voltage to a level and given to the diode rectifier which convert that controller AC supply from the transformer DC supply it will passing through capacitor filter. The output DC current is getting 0.9A as shown in Figure.12

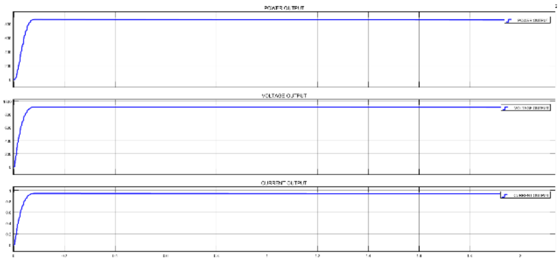

Figure.12 Power(P), Voltage(V) and Current(I) Output wave forms

This transformer steps up the voltage to a level and given to the diode rectifier which convert that controller AC supply from the transformer DC supply it will passing through capacitor filter. The output DC power is getting 854W as shown in Figure.12

7.CONCLUSION

The cascaded five-level LLC resonant boost DC-DC converter, integrated with a fuzzy logic controller, represents an advanced solution tailored for demanding industrial applications. With an input DC voltage of 250V, the converter efficiently delivers an output voltage of 950V, current of 0.9A, and power output of 860W. This design is meticulously engineered to accommodate significant variations in both load and input voltage, ensuring stable and reliable operation across diverse industrial environments.

Key design considerations include achieving a voltage gain that scales the output to approximately five times the input voltage, demonstrating robust voltage regulation capabilities essential for industrial applications requiring precise power delivery. Operating within a frequency range of 67kHz to 135kHz optimizes efficiency by enabling zero voltage switching (ZVS) and maintaining proximity to the resonant frequency of the LLC circuit. This strategic frequency control minimizes switching losses and maximizes power transfer efficiency, essential for reducing operational costs and enhancing overall system reliability.

Moreover, the integration of a fuzzy logic controller enhances adaptability and responsiveness in dynamic operating conditions. By continuously optimizing switching frequencies and duty cycles based on real-time input variables, the controller ensures efficient performance under varying loads and input voltage fluctuations.

Comparative simulations with a full-bridge LLC resonant converter underscore the unique operational advantages of the cascaded five-level design. Unlike traditional full-bridge configurations, the five-level converter consistently operates at a lower switching frequency than the resonant frequency, highlighting its ability to achieve stable operation with reduced electromagnetic interference (EMI) and improved harmonic performance.

REFERENCES

[1] A. Bughneda, M. Salem, M. A. Nazari, D. Ishak, M. Kamarol, and S. Alatai, ''Resonant power converters for renewable energy applications: A comprehensive review,'' Frontiers Energy Res., vol. 10, Mar. 2022, Art. no. 846067.

[2] S. D. Gore, A. Iqbal, S. Islam, I. Khan, M. Marzband, S. Rahman, and A. M. A. B. Al-Wahedi, ''Review on classification of resonant converters for electric vehicle application,'' Energy Rep., vol. 8, pp. 1091–1113, Nov. 2022.

[3] F. C. Lee, Q. Li, and A. Nabih, ''High frequency resonant converters: An overview on the magnetic design and control methods,'' IEEE J. Emerg. Sel. Topics Power Electron., vol. 9, no. 1, pp. 11–23, Feb. 2021.

[4] M. T. Outeiro, G. Buja, and D. Czarkowski, ''Resonant power converters: An overview with multiple elements in the resonant tank network,'' IEEE Ind. Electron. Mag., vol. 10, no. 2, pp. 21–45, Jun. 2016.

[5] M. Salem, A. Jusoh, N. R. N. Idris, H. S. Das, and I. Alhamrouni, ''Resonant power converters with respect to passive storage (LC) elements and control techniques—An overview,'' Renew. Sustain. Energy Rev., vol. 91, pp. 504–520, Aug. 2018.

[6] C.-Y. Tang, H.-J. Wu, C.-Y. Liao, and H.-H. Wu, ''An optimal frequencymodulated hybrid MPPT algorithm for the LLC resonant converter in PV power applications,'' IEEE Trans. Power Electron., vol. 37, no. 1, pp. 944–954, Jan. 2022.

[7] L. A. D. Ta, N. D. Dao, and D.-C. Lee, ''High-efficiency hybrid LLC resonant converter for on-board chargers of plug-in electric vehicles,'' IEEE Trans. Power Electron., vol. 35, no. 8, pp. 8324–8334, Aug. 2020.

[8] Mohsen M. Mohaidat, "Control of Variable Speed Drive (VSD) based on Diode Clamped Multilevel Inverter Using Direct Torque Control and Fuzzy Logic", Master's Thesis, Yarmouk University, Jordan, 2013.

[9] Laith Quraan, "Control of Variable Speed Drive (VSD) Based on Diode Clamped Multilevel Inverter Using Field Oriented Control", Master's Thesis, Yarmouk University, Jordan, 2012.

[10] Amin Alqudah, Ibrahim Altawil, Laith Quraan, "Control of Variable Speed Drive based on Diode Clamped Multilevel Inverter Using Field Oriented Control", Jordanian International Electrical and Electronics Engineering Conference (Jordanian IEEE Conference) - Symposium on Power, Machines and Control, pp: 195-200. April, 2013.

[11] K. Jin and X. Ruan, ''Hybrid full-bridge three-level LLC resonant converter—A novel DC–DC converter suitable for fuel-cell power system,'' IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1492–1503, Oct. 2006.

[12] H. Dang, S. Du, Y. Zhang, and J. Liu, ''A novel LLC resonant converter with configurable capacitors in output stage for wide output voltage range operation,'' IEEE Trans. Power Electron., vol. 37, no. 6, pp. 6233–6236, Jun. 2022.

[13] Y. Zhou, S. Liu, J. Ren, Q. Wu, F. Hong, A. Shen, and W. Xu, ''Design methodology of LLC

resonant converters for single-stage power factor correction application,'' J. Electr. Eng. Technol., vol. 16, no. 5, pp. 2573–2584, Sep. 2021.

[14] J. Zeng, G. Zhang, S. S. Yu, B. Zhang, and Y. Zhang, ``LLC resonant converter topologies and industrial applications—A review,'' Chin. J. Electr. Eng., vol. 6, no. 3, pp. 73–84, Sep. 2020.

[15] J. Luo, J. Wang, Z. Fang, J. Shao, and J. Li, ``Optimal design of a high efficiency LLC resonant converter with a narrow frequency range for voltage regulation,'' Energies, vol. 11, no. 5, p. 1124, May 2018.

[16] Y. Wei, Q. Luo, and H. A. Mantooth, ``An LLC converter with multiple operation modes for wide voltage gain range application,'' IEEE Trans. Ind. Electron., vol. 68, no. 11, pp. 11111–11124, Nov. 2021.

[17] N. A. Samsudin and D. Ishak, ``Full-bridge LLC resonant high-voltage DC–DC converter with hybrid symmetrical voltage multiplier,'' IETE J. Res., vol. 67, no. 5, pp. 687–698, Sep. 2021.

[18] H.-P. Park, M. Kim, and J.-H. Jung, ``A comprehensive overview in control algorithms for high switching-frequency LLC resonant converter,'' Energies, vol. 13, no. 17, p. 4455, Aug. 2020.

[19] C.-Y. Lim, Y. Jeong, M.-S. Lee, K.-H. Yi, and G.-W. Moon, ``Halfbridge integrated phase-shifted full-bridge converter with high efficiency using center-tapped clamp circuit for battery charging systems in electric vehicles,'' IEEE Trans. Power Electron., vol. 35, no. 5, pp. 4934–4945, May 2020.

[20] V. R. K. Kanamarlapudi, B. Wang, N. K. Kandasamy, and P. L. So, ``A new ZVS full-bridge DC–DC converter for battery charging with reduced losses over full-load range,'' IEEE Trans. Ind. Appl., vol. 54, no. 1, pp. 571–579, Jan./Feb. 2018.

[21] Y. Shen, W. Zhao, Z. Chen, and C. Cai, ``Full-bridge LLC resonant converter with series-parallel connected transformers for electric vehicle on-board charger,'' IEEE Access, vol. 6, pp. 13490–13500, 2018.

[22] Y. Wei, Q. Luo, Z. Wang, and A. Mantooth, ``Wide voltage gain range application for full-bridge LLC resonant converter with narrow switching frequency range,'' IET Power Electron., vol. 13, no. 15, pp. 3283–3293, Nov. 2020.

[23] P. Rehlaender, F. Schafmeister, and J. Böcker, ``Interleaved single-stage LLC converter design utilizing half- and full-bridge configurations for wide voltage transfer ratio applications,'' IEEE Trans. Power Electron., vol. 36, no. 9, pp. 10065–10080, Sep. 2021.

[24] I.-O. Lee and G.-W. Moon, ``Analysis and design of a three-level LLC series resonant converter for high- and wide-input-voltage applications,'' IEEE Trans. Power Electron., vol. 27, no. 6, pp. 2966–2979, Jun. 2012.

[25] S. Choudhury, M. Bajaj, T. Dash, S. Kamel, and F. Jurado, ``Multilevel inverter: A survey on classical and advanced topologies, control schemes, applications to power system and future prospects,'' Energies, vol. 14, no. 18, p. 5773, Sep. 2021.

[26] M. Vijeh, M. Rezanejad, E. Samadaei, and K. Bertilsson, ``A general review of multilevel inverters based on main submodules: Structural point of view,'' IEEE Trans. Power Electron., vol. 34, no. 10, pp. 9479–9502, Oct. 2019.

[27] A. Bughneda, M. Salem, A. Richelli, D. Ishak, and S. Alatai, ``Review of multilevel inverters for PV energy system applications,'' Energies, vol. 14, no. 6, p. 1585, Mar. 2021.

[28] M. Salem, A. Richelli, K. Yahya, M. N. Hamidi, T.-Z. Ang, and I. Alhamrouni, ``A comprehensive review on multilevel inverters for gridtied system applications,'' Energies, vol. 15, no. 17, p. 6315, Aug. 2022.

[29] S. Alatai, M. Salem, D. Ishak, H. S. Das, M. A. Nazari, A. Bughneda, and M. Kamarol, ``A review on state-of-the-art power converters: Bidirectional, resonant, multilevel converters and their derivatives,'' Appl. Sci., vol. 11, no. 21, p. 10172, Oct. 2021.

[30] Y. Gu, Z. Lu, L. Hang, Z. Qian, and G. Huang, ``Three-level LLC series resonant DC/DC converter,'' IEEE Trans. Power Electron., vol. 20, no. 4, pp. 781–789, Jul. 2005.