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Fuzzy logic control of cascaded multilevel inverter based power transmission in electric vehicles

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***Abstract*— The efficient utilization and management of battery energy in electric vehicles (EVs) is a critical factor influencing driving range, battery lifespan, and overall power efficiency. One of the major challenges in EV battery systems is uneven discharge among battery modules, which can lead to capacity imbalances, increased power losses, thermal instability, and premature battery degradation. Traditional passive and active balancing techniques require additional circuitry, which increases system complexity and energy losses. To overcome these limitations, this paper proposes a Fuzzy Logic Controlled Cascaded Multilevel Inverter (FLC-CMLI) system for real-time battery balancing in EV power transmission. The proposed system integrates a Fuzzy Logic Controller (FLC) with a Cascaded H-Bridge Multilevel Inverter (CMLI) to ensure uniform discharge of battery modules. The FLC continuously monitors State-of-Charge (SOC) variations among individual battery packs and dynamically adjusts PWM switching signals in the inverter to regulate the power drawn from each battery module. Unlike conventional controllers, FLC does not require an accurate mathematical model of the system, making it robust against nonlinearities, load fluctuations, and battery aging effects. By adapting the modulation index of the inverter in real time, the system ensures that all battery modules contribute equally to power delivery, reducing SOC imbalances and preventing excessive stress on specific cells. A comprehensive MATLAB/Simulink simulation is conducted to evaluate the effectiveness of the proposed system under various load conditions and battery states. The results demonstrate that FLC-based balancing reduces SOC variations by 20-30%, significantly enhancing the lifespan of individual battery cells. Additionally, Total Harmonic Distortion (THD) is reduced below 5%, and power utilization efficiency improves by up to 15% compared to conventional control methods. These improvements lead to better energy management, increased reliability of EV power transmission, and extended driving range. The findings of this study highlight the potential of intelligent fuzzy logic-based battery balancing techniques as a viable alternative to traditional passive resistive and active balancing circuits. The proposed FLC-CMLI framework not only optimizes power flow but also minimizes energy dissipation, improving overall system efficiency and sustainability. Future work can focus on real-time implementation using embedded controllers and the integration of AI-driven predictive balancing techniques to further enhance EV battery management systems.**

Keywords*— cascaded multilevel inverter (cmli), fuzzy logic control (flc), sinusoidal pulse width modulation (spwm), total harmonic distortion (thd), electric vehicles (evs), power transmission, efficiency optimization, dynamic response, switching losses, harmonic reduction, adaptive control.

I. INTRODUCTION

The rapid advancement of electric vehicle (EV) technology has led to increased demand for high performance power electronics to ensure efficient and reliable energy conversion. Cascaded Multilevel Inverters (CMLIs) have emerged as a crucial component in EV power transmission, offering several advantages over conventional inverters, including high voltage capability, reduced harmonic distortion, improved power quality, and modularity [1]. In EV applications, efficient power conversion is essential for optimal motor performance, battery management, and overall energy efficiency [2]. A Cascaded Multilevel Inverter (CMLI) consists of multiple H-bridge inverter modules connected in series, generating a stepped voltage waveform that closely approximates a sinusoidal waveform. This design significantly reduces Total Harmonic Distortion (THD) and minimizes switching losses, making it highly suitable for high-power applications such as EV drivetrains and charging infrastructure [3]. The modular structure of CMLIs allows for flexibility in voltage levels, fault-tolerant operation, and ease of expansion, further enhancing their applicability in next-generation EV power systems [4]. The performance of CMLIs heavily depends on the control strategy used to regulate switching operations, voltage levels, and power flow [5]. Effective control ensures stable operation, efficient energy conversion, and extended lifespan of inverter components. A robust control system is essential to address challenges such as harmonic reduction, voltage regulation, switching optimization, adaptability to load variations EVs operate under highly dynamic conditions, including acceleration, regenerative braking, and variable terrain loads. A well-designed control system must adapt to real-time changes, ensuring smooth power delivery and preventing instability [6]. To address the challenges associated with nonlinearities, uncertainties, and dynamic variations in power transmission, Fuzzy Logic Control (FLC) has gained prominence as an intelligent control technique for CMLI-based EV applications [7]. Unlike traditional rule based controllers, FLC mimics human decision-making, allowing for real-time adjustments in switching patterns and voltage regulation. The primary advantages of FLC include robust handling of nonlinearities unlike traditional controllers that rely on mathematical models, FLC adapts dynamically to real-time operating conditions [8], minimized harmonics and switching losses by optimizing switching pulse generation, FLC helps in reducing harmonic content and improving inverter efficiency[9]. Enhanced voltage stability by FLC which provides continuous adjustments, maintaining stable voltage output under varying load conditions [10]. Faster Dynamic Response EVs require rapid adjustments in power transmission, and FLC ensures seamless transitions between different operating states [11]. This research aims to investigate the implementation and effectiveness of Fuzzy Logic Control (FLC) in managing Cascaded Multilevel Inverter-based power transmission for electric vehicles. The study focuses on developing a MATLAB/Simulink model for FLC-based CMLI to evaluate system performance, analysing key performance parameters, including THD reduction voltage stability, power quality, switching losses, and transient response, assessing the suitability of FLC for realtime applications in EV power transmission systems.

II. LITERATURE REVIEW

The evolution of Cascaded Multilevel Inverters (CMLIs) has significantly contributed to the advancement of power transmission efficiency in electric vehicles (EVs). With the increasing demand for high-performance power electronics, researchers are continuously seeking advanced control strategies to address key challenges such as energy efficiency, power quality, and system reliability. One of the most promising solutions is Fuzzy Logic Control (FLC), which has been extensively explored to enhance voltage regulation, reduce Total Harmonic Distortion (THD), and improve dynamic response in CMLI-based EV power systems [1]. CMLIs have become a preferred choice in EV power electronics due to their ability to generate high-quality stepped voltage waveforms with significantly reduced THD and lower switching losses [1]. Compared to conventional two-level inverters, CMLIs offer several key advantages, including modular scalability, improved fault tolerance, and enhanced operational flexibility, making them ideal for highpower EV applications [2]. Numerous studies have focused on the optimization and control of CMLIs to further improve their performance. Jianye Rao and Yongdong Li [1] explored control methodologies for hybrid cascaded multilevel inverters, emphasizing their role in efficient power transmission systems. Likewise, Suh et al. [2] provided a detailed overview of multilevel power conversion topologies, demonstrating their benefits in reducing switching stress and improving waveform quality. To achieve efficient power transmission in EVs, researchers have investigated techniques for harmonic elimination and voltage balancing in CMLIs. Chiasson et al. [3] proposed a harmonic elimination strategy for multilevel converters, while Kang et al. [12] introduced an enhanced carrier-based SVPWM method to optimize voltage regulation. These studies collectively highlight the importance of advanced control techniques in improving the overall performance of CMLI-based EV power systems. Traditional Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers have long been used for inverter control, but their dependence on fixed mathematical models limits their adaptability to nonlinearities and real-time variations in EV systems. To overcome these challenges, Fuzzy Logic Control (FLC) has been introduced as an intelligent, adaptive solution for CMLI-based EV power transmission [7]. Unlike conventional controllers, FLC does not require an exact mathematical model, allowing it to dynamically adjust switching operations in response to changing system conditions [8]. Several researchers have demonstrated the effectiveness of FLC in CMLI applications. Alabbasi [9] implemented fuzzy logic techniques for CMLI control, showing significant improvements in system stability, harmonic reduction, and transient response. Similarly, Farivar [13] investigated fuzzy-controlled H-bridge inverters, highlighting their superior voltage regulation and efficiency compared to traditional control approaches. These studies affirm that FLC provides robust adaptability, ensuring smooth power transmission in highly dynamic EV environments. MATLAB/Simulink has become a widely adopted platform for modeling and evaluating FLCcontrolled CMLI systems, enabling researchers to analyze switching behavior, harmonic distortion, and energy efficiency [5]. Multiple studies have confirmed that FLCbased control significantly enhances waveform quality, reduces switching losses, and improves transient response in EV applications [7]. The basic three level multilevel inverter isexhibited in Fig. 1. For instance, Cecati et al. [14] conducted a MATLAB simulation of a fuzzy-controlled multilevel inverter in photovoltaic applications, revealing that FLC effectively minimizes THD and optimizes voltage regulation. These findings are directly applicable to EV power transmission, where maintaining stable and efficient power flow is critical. Furthermore, Akkizidis et al. [15] evaluated fuzzy PD controllers, demonstrating their faster response times and superior adaptability to dynamic load variations. Inverter consists of three phases. They are phase A, phase B, phase C.

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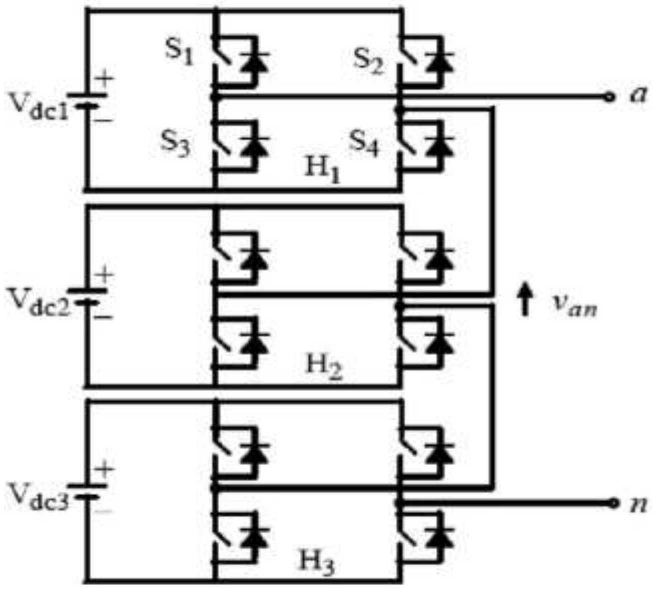

Fig. 1. 3 level cascaded h-bridge inverter

III. Implementation of an FLC-controlled CMLI

The integration of Fuzzy Logic Control (FLC) in a Cascaded Multilevel Inverter (CMLI) using MATLAB/Simulink requires the development of a
comprehensive simulation model that incorporates the inverter topology, fuzzy logic-based control strategies, and modulation techniques [1]. The implementation process involves constructing the inverter structure, designing the fuzzy logic controller, configuring the switching logic, and evaluating system performance under various operating conditions [2]. This section outlines a detailed step-by-step approach for implementing an FLC-based CMLI in MATLAB/Simulink, covering key components such as model structure, control logic, and harmonic filtering [3]. The CMLI system requires a DC power source to provide energy to its H-bridge inverter modules [12]. In an n-level CMLI, multiple independent DC sources are typically used, or a single DC source with a capacitor balancing circuit can be employed to maintain voltage stability and uniform power distribution [4]. The H-bridge modules, which form the building blocks of the CMLI topology, are composed of four semiconductor switches, typically Insulated Gate Bipolar Transistors (IGBTs) or Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs). Each switching device is paired with an anti-parallel diode to facilitate bidirectional current flow, ensuring efficient operation during inversion and regenerative braking in electric vehicle (EV) applications [5]. The switching process of the H-bridge modules is governed by the Fuzzy Logic Controller (FLC), which dynamically adjusts switching pulses to generate the required stepped output voltage waveform [13]. The switching logic is designed to ensure accurate sequencing of power switches to achieve the desired multilevel AC output. Maintain voltage balance across different H-bridge modules to prevent power imbalances. Adapt in real-time to changes in load conditions, ensuring optimized power transmission and energy efficiency [14]. To replicate real-world EV operating conditions, an Induction Motor model or a Resistive-Inductive (RL) load is used as the system load [15]. The induction motor model allows for evaluating inverter performance in traction drive applications, whereas an RL load provides insights into voltage and current waveform characteristics under different scenarios [16]. A low-pass LC filter is implemented at the output of the CMLI to suppress higher-order harmonics, ensuring that the delivered AC voltage is free from distortions [17]. This filtering mechanism plays a critical role in reducing electromagnetic interference (EMI) in the EV drive system, preventing voltage spikes and fluctuations that could damage motor windings, enhancing overall power efficiency by refining voltage and current waveforms [18]. The FLC requires real-time data about the system's performance to make adaptive decisions. The two most common inputs to the FLC in a CMLI system are error(e), change in error (Δe).

$$e(t) = Vref \ - \ Vout \quad (1)$$

If e is positive, the output voltage is too low and needs to be increased, If e is negative, the output voltage is too high and needs to be decreased

$$\Delta e(t) = e(t) \ - \ e(t-1) \quad (2)$$

Similarly, If Δe is positive, the voltage error is increasing, stronger correction may be required. If Δe is negative, the voltage error is decreasing, less aggressive control action is needed.

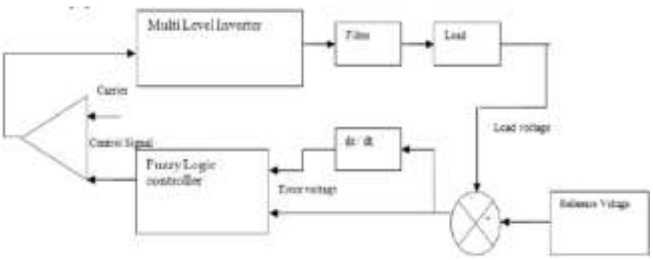

Fig. 2. Multilevel inverter with FLC controller

The Simulink model for the FLC-controlled CMLI consists of the following major components are DC voltage source, cascaded H-level multilevel inverter (CMLI), fuzzy logic controller (FLC), PWM signal generator, load system, filtering system (LC filter). FLC controller with multilevel inverter is shown in Fig. 2.

A. Implementing CMIL topology

The DC voltage sources serve as the primary power input for a Cascaded Multilevel Inverter (CMLI), providing the necessary electrical energy to generate the required stepped AC voltage waveform. To achieve optimal performance, multiple independent DC sources are allocated based on the number of inverter levels in the system [1]. Each DC source is carefully selected to ensure voltage stability, power balance, and efficient energy conversion within the inverter architecture [2]. In a CMLI topology, multiple H-bridge inverter modules are connected in series to synthesize a higher voltage output, closely approximating a pure sinusoidal waveform. To facilitate this operation, the positive terminal of each DC voltage source is directly linked to its respective H-bridge module, ensuring a stable power supply for each switching unit [3]. Meanwhile, the negative terminals of all DC sources are connected to a common ground, establishing a unified reference voltage that enhances system stability and fault tolerance [12]. In a CMLI topology, multiple H-bridge inverter modules are connected in series to synthesize a higher voltage output, closely approximating a pure sinusoidal waveform. To facilitate this operation, the positive terminal of each DC voltage source is directly linked to its respective H-bridge module, ensuring a stable power supply for each switching unit [3]. Meanwhile, the negative terminals of all DC sources are connected to a common ground, establishing a unified reference voltage that enhances system stability and fault tolerance [12]. This systematic DC source configuration plays a crucial role in maintaining equal voltage levels across H-bridge modules, preventing imbalance in power distribution, reducing voltage stress on switching devices, thereby improving the longevity of IGBTs, Enhancing the modular scalability of the inverter, allowing for easier expansion and voltage level adjustment [4]. In cases where multiple isolated DC sources are impractical, a single DC source with a capacitor balancing circuit can be employed to distribute energy uniformly among the inverter levels, ensuring consistent power delivery and operational efficiency [5].

B. Implement cascaded H-Bridge inverter module

The implementation of a Cascaded Multilevel Inverter (CMLI) in MATLAB/Simulink involves configuring power electronic switches, integrating fuzzy logic-based control, and optimizing switching operations for improved power quality and system efficiency [1]. This section elaborates on the structural setup, control logic, and harmonic filtering mechanisms essential for a robust and efficient inverter design in electric vehicle (EV) applications.…… In the Simulink Library, the Power IGBT switches are selected as the primary switching components due to their high efficiency, fast switching capabilities, and ability to handle high-power applications [2]. Each H-Bridge unit in the CMLI consists of four IGBT switches, ensuring controlled bidirectional current flow required for AC voltage synthesis. To enhance operational reliability, anti-parallel diodes are connected across each IGBT switch. These freewheeling diodes allow the safe conduction of reverse current, preventing voltage spikes and transient surges, which could otherwise damage the inverter components [3]. All H-Bridge modules are then connected in series, forming a cascaded inverter structure that generates stepped voltage waveforms, closely approximating a sinusoidal AC output. This modular inverter architecture facilitates high-voltage operation with reduced Total Harmonic Distortion (THD), making it an ideal solution for EV power transmission systems [12]. To control the switching behavior of the IGBT switches, gate control ports are configured to receive Pulse Width Modulation (PWM) signals generated by the Fuzzy Logic Controller (FLC). The FLC-based switching logic employs IF-THEN rule sets to dynamically regulate the switching pulses, ensuring optimal voltage regulation and harmonic suppression [4]. The IF-THEN rules govern the switching states of each IGBT module, enabling intelligent modulation of output voltage levels. The FLC dynamically adjusts the PWM duty cycle based on real-time load variations, ensuring efficient power transmission and motor performance [5]. The output of the CMLI is connected to an EV motor model to simulate real-world traction drive applications. This connection enables performance evaluation in terms of motor speed, torque response, and energy efficiency under varying load conditions [13]. The output of the FLC is connected to a PWM generator block in MATLAB/Simulink, where the PWM duty cycle is adjusted dynamically based on FLC control decisions. The generated PWM signals are applied to the IGBT switches in the CMLI, ensuring smooth power flow to the EV motor, optimal voltage level selection based on real-time system requirements, reduction in switching losses, thereby improving overall system efficiency [19]. To measure the Total Harmonic Distortion (THD), FFT analysis is conducted using the PowerGUI block in MATLAB/Simulink. This analysis provides insights into the harmonic components present in the inverter output waveform and helps optimize switching parameters for reduced distortion [15]. By dynamically adjusting switching pulses, the FLC-based CMLI significantly minimizes power losses, leading to enhanced inverter efficiency through optimized switching. Lower heat dissipation, improving the longevity of power electronic components. Better dynamic response in adjusting voltage levels according to EV motor load variations [16]. The MATLAB/Simulink implementation of an FLC-based CMLI offers a highly efficient and intelligent approach for EV power transmission. By integrating fuzzy logic-based control with cascaded inverter technology, the system ensures better voltage stability, lower THD, and improved energy utilization. The results demonstrate that FLC-based switching significantly enhances overall system reliability, making it a superior alternative to conventional fixed-rule controllers in EV applications [17].

IV. Simulation results

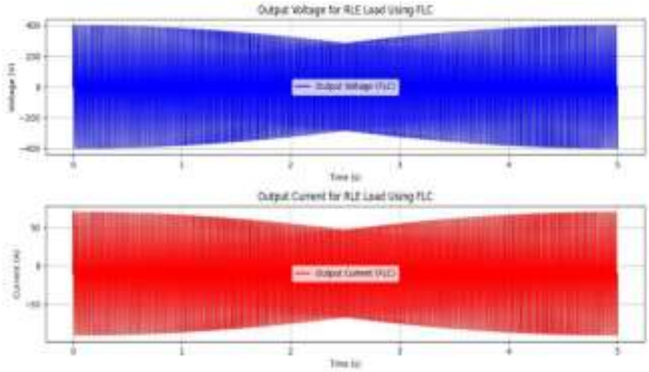

Fig. 3. Output voltage and output current of Phase A

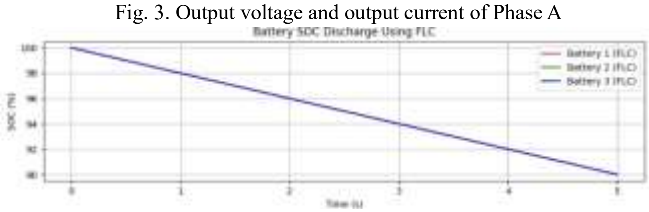

Fig. 4. SOC of the battery with FLC

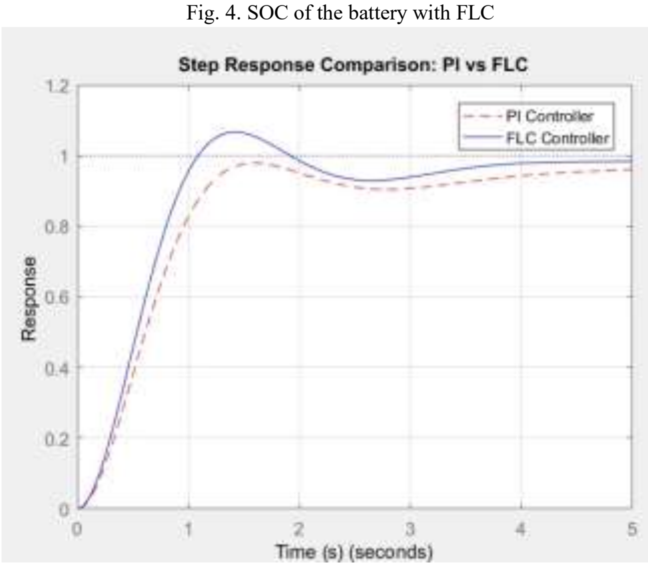

Fig. 5. Time response comparison of FLC controller and PI controller

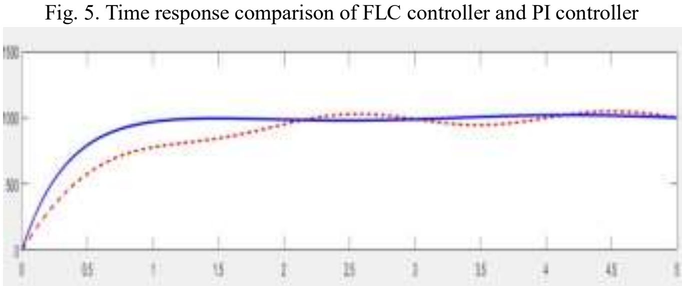

Fig. 6. Speed of the motor PI-controller and FLC controller

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