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Performance-Enhanced Cascaded H-Bridge Multilevel Inverters Using Fuzzy Logic–Based Harmonic Mitigation

[1]N.Vanajakshi, [2]Dr .M .Uma Vani , [3]Dr .R .Srinivas Rao
[1] Research Scholar, [23]Professor
[123]EEE Department
[2] Lakireddy Bali Reddy College of Engineering, Mylavaram, Vijayawada, Krishna.
[1,3]University College of Engineering, JNT University, Kakinada-533003
1vanajakshina@gmail.com,2 marreddy.umavani@gmail.com,3 srinivas jntueee@gmail.com

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Abstract: This paper presents a performance-enhanced control strategy for cascaded H-bridge multilevel inverters (CHB-MLIs) that combines fuzzy logic control (FLC) with selective harmonic mitigation (SHM) techniques to reduce low-order harmonics and overall total harmonic distortion (THD). A detailed system model is developed for a seven-level CHB inverter, the FLC architecture (inputs, membership functions, rule base) is described, and an SHM routine for optimizing switching angles is integrated. Simulation case studies demonstrate substantial THD reduction and improved dynamic response compared to classical SPWM and PI controllers. The proposed method is suitable for renewable-interfaced systems and active power filter applications.

Keywords: cascaded H-bridge, multilevel inverter, fuzzy logic controller, selective harmonic elimination, harmonic mitigation, THD.

I.INTRODUCTION

Multilevel inverters (MLIs) have emerged as a cornerstone technology for high-power and medium-voltage energy conversion because they synthesize high-quality stepped voltage waveforms using series-connected power cells, thereby reducing dv/dt stresses, electromagnetic interference, and filter requirements compared with conventional two-level converters [1], [2]. Among MLI topologies, the cascaded H-bridge (CHB) structure is particularly attractive due to its modularity, fault-tolerance and natural ability to interface independent DC sources such as photovoltaic arrays and battery strings [1], [3]. However, despite these advantages, CHB inverters still produce low-order harmonic components in the output voltage that must be mitigated to meet power quality standards and to reduce system losses and thermal stress in connected equipment [4], [5].Selective Harmonic Elimination (SHE) — the analytic solution of nonlinear transcendental equations for switching angles — and carrier-based PWM methods are widely used to lower selected low-order harmonics, but SHE faces practical challenges related to real-time computation, multiple solutions and sensitivity at low modulation indices [6], [7]. To overcome these limitations, researchers have integrated numerical and metaheuristic optimizers (e.g., PSO, GA, QPSO, bacterial-foraging and other modern metaheuristics) to compute accurate switching angles and minimize total harmonic distortion (THD) over wide operating ranges [8]–[11]. Complementary to angle-based methods, control strategies that actively adapt the converter’s modulation — including fuzzy logic controllers (FLCs), adaptive and sliding-mode schemes — have been proposed to improve transient response, compensate residual harmonics under nonideal conditions, and balance DC-link voltages in multi-source CHB systems [12], [13].

Recent comparative studies and surveys show that hybrid frameworks, which combine offline/lookup-table SHE solutions (for steady-state low THD) with online intelligent control (for transient robustness and imbalance correction), provide the best tradeoff between steady-state power quality, switching losses and real-time implementability [8], [14], [15]. Motivated by these findings, this paper develops a performance-enhanced CHB control scheme that fuses fuzzy-logic based active compensation with optimized SHE switching-angle computation to

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achieve low THD across realistic operating conditions while maintaining fast dynamic response.

II. RELATED WORK

Harmonic mitigation in cascaded H-bridge multilevel inverters (CHB-MLIs) has been widely explored over the past two decades, with researchers focusing on selective harmonic elimination (SHE), intelligent optimization, and fuzzy logic–based adaptive control. Earlier works concentrated on classical SHE using transcendental equations solved through Newton–Raphson–type numerical techniques, but these methods often suffered from convergence sensitivity and multiple-solution dependence on modulation indices [16]. To overcome these limitations, metaheuristic algorithms such as PSO, GA, improved QPSO, and swarm-based evolutionary schemes have been proposed for computing optimal switching angles with high robustness and reduced total harmonic distortion (THD) [17], [18].

Recent research has shifted toward advanced intelligent frameworks, where hybrid algorithms—including Backtracking Search Algorithm (BSA), Sparrow Search Algorithm (SSA), and multi-objective evolutionary strategies—demonstrate improved global convergence for eliminating low-order harmonics in 7-level and 9-level CHB inverters across wide operating conditions [19], [20]. These approaches outperform classical methods by avoiding local minima and providing consistent results even at low modulation indices.

Parallel to optimization-driven SHE approaches, fuzzy logic controllers (FLCs) have gained attention for their ability to compensate residual harmonics during transients and under system nonlinearities. FLC-based harmonic suppression achieves better dynamic response and stability compared to conventional PI and carrier-based PWM control, especially in renewable-source–fed CHB systems with fluctuating DC inputs [21]. Reviews focusing on AI-enhanced modulation techniques further highlight the benefits of integrating intelligent control with selective harmonic mitigation to achieve improved efficiency, faster convergence, and superior THD performance [22].

Overall, existing literature establishes that both metaheuristic SHE optimization and fuzzy logic–based adaptive control are effective for harmonic suppression. However, integrating these two strategies into a unified hybrid framework remains underexplored, motivating the present work to develop a performance-enhanced control structure that combines fuzzy logic–based compensation with optimized switching-angle computation.

Table 1 — Summary of Related Literature

Ref	Authors / Year	Method / Contribution	Key Findings
[16]	Wang & Ahmadi, 2010	Precise SHE using transcendental solutions	Identified limitations of classical Newton–Raphson SHE under low MI.
[17]	Ürgün, 2023	Metaheuristics-based SHE review	PSO, GA, QPSO, BFA, and recent optimizers significantly improve THD reduction.
[18]	QPSO variant studies, 2022–2023	Improved quantum-behaved PSO for switching-angle computation	Enhanced global search, stable solutions for 7-level and 9-level MLIs.
[19]	BSA-based SHE, 2024	Backtracking Search Algorithm for harmonic elimination	Robust convergence; eliminates 5th & 7th harmonics effectively.
[20]	Tennyson et al., 2025	Sparrow Search Algorithm (SSA) for SHE	Consistent low THD across modulation indices for 7-level CHB.
[21]	Fuzzy logic	FLC for harmonic	Reduced THD and

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	CHB control studies (various, 2016–2023)	suppression and dynamic compensation	improved transient behavior vs. PI/SPWM.
[22]	AI-enhanced SHE surveys (2020 – 2023)	Reviews of optimization and intelligent control techniques	Hybrid metaheuristic + intelligent control recommended for best overall performanc

III. PROPOSED SYSTEM DESCRIPTION

The proposed system integrates a Fuzzy Logic Controller (FLC) into the cascaded H-bridge multilevel inverter (CHB-MLI) architecture to achieve adaptive harmonic mitigation and improved voltage regulation. While the conventional selective harmonic mitigation (SHM) or SHEPWM technique relies on predetermined switching angles to suppress specific harmonic orders, it becomes less effective under load fluctuations, DC-link imbalance, and nonlinear system variations. The FLC is therefore introduced to dynamically regulate the modulation index and corrective switching adjustments based on real-time monitoring of output voltage error and harmonic distortion levels. By combining offline optimal switching-angle computation (similar to OSHM/SHMPWM in the attached PDF) with online fuzzy-based tuning, the system ensures both high steady-state quality and robust transient behavior.

3.1 System Modelling

The CHB-MLI consists of three H-bridge power cells connected in series, each powered by an isolated DC source. The total output voltage is the sum of individual cell voltages:

$$Vout(t) = VH1(t) + VH2(t) + VH3(t)$$

As described in the attached PDF, each cell contributes a discrete voltage level, allowing the system to synthesize a **7-level stepped waveform**. The harmonic content is determined by the switching angles $\alpha1, \alpha2, \alpha3, ...$\alpha_1,\alpha_2,\alpha_3,\dots$\alpha1, \alpha2, \alpha3,...$ per quarter cycle. The Fourier series representation for harmonics follows:

$$Vk = 4Vdck\pi[\cos(k\alpha1) + \cos(k\alpha2) + \cdots]V_k$$

In the proposed fuzzy-enhanced model, the FLC adjusts an incremental correction factor Δm\Delta mΔm applied to the modulation index:

$$m(t) = mSHE + \Delta mFLC(t)$$

Here, mSHEm_{SHE}mSHE is derived from precomputed optimal switching tables (similar to Fig. 4 lookup-table scheme in the PDF), whereas ΔmFLC\Delta m_{FLC}ΔmFLC compensates real-time deviations in fundamental magnitude and harmonic levels.

3.2 Fuzzy Logic Controller (FLC) Modelling

(Extension of closed-loop block control in PDF page 3–4, where FFT feedback and PI are used; replaced by FLC here)
The fuzzy controller receives three key inputs:

Voltage error:

$$e(t) = Vref - Vout,1(t)$$

Change of error:

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

Harmonic index (HI): real-time THD or dominant harmonic amplitude from FFT block.

The FLC uses triangular membership functions for (NB, NS, Z, PS, PB) across all inputs, while the output variable (Δm) uses a finer 7-level linguistic set for smoother tuning.

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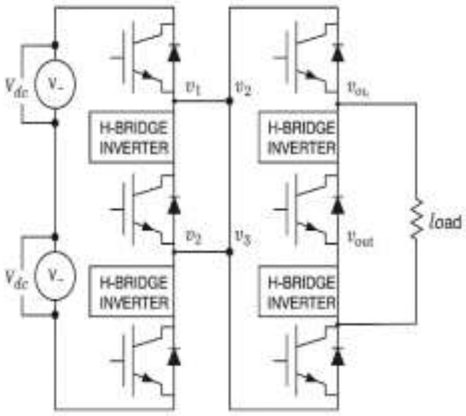

Fig1: Proposed system

IV. CONTROL DESIGN

Below is a compact, engineering-ready control design for the fuzzy-logic–based harmonic mitigation controller for a 3-cell (7-level) Cascaded H-Bridge (CHB) inverter. It combines offline optimal switching-angle (SHE/OSHM) tables with an online FLC that adjusts the modulation index and switching timing to reduce THD and improve transient response.

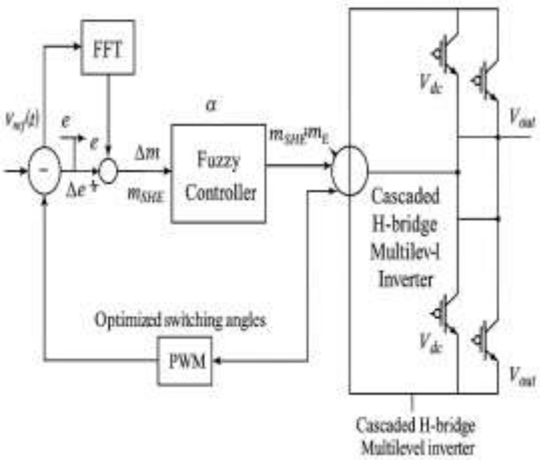

Fig2: Control Design

Control objectives

1. Keep the fundamental amplitude V1V_1V1 at the reference $V1, refV\_\{1,\backslash text\{ref\}\}V1, ref$.
2. Suppress selected low-order harmonics (typ. 3rd, 5th, 7th, 11th) so THD meets grid/standard limits.
3. Maintain DC-link balance across H-bridge cells and provide robust transient response.

Measured signals and error signals

- Fundamental magnitude estimate $V1meas(t)$ (via synchronous demodulation or 1-cycle DFT).
- Dominant harmonic amplitudes (or THD estimate) $H(t)$— from a short FFT/DFT window.
- DC-link cell voltages $Vdc, iV\_\{dc, i\}Vdc, i$ for balancing.

Define:

$$e(t) = V1, ref - V1meas(t)$$
$$, \Delta e(t) = e(t) - e(t - Ts)$$

and harmonic index (normalized):

$$HI(t) = H(t)/V1, ref\,(or\ use\ THD)$$

DC-link balancing loop

If Vdc,iV_{dc,i}Vdc,i measurement shows imbalance, define balancing error for each cell:

$$eb, i = Vdc, i - Vdc, Vdc = 1\backslash Nc$$
$$\textstyle\sum_i \ Vdc, i$$

Add a small balancing correction term Δmb,i\Delta m_{b,i}Δmb,i to the corresponding cell modulation to equalize energy:

$$mi = m(t) + \Delta mb, i,$$

$$\Delta mb, i = -Kbeb, i$$

with KbK_bKb small to avoid impacting THD significantly.

V. SIMULATION RESULTS AND DISCUSSION

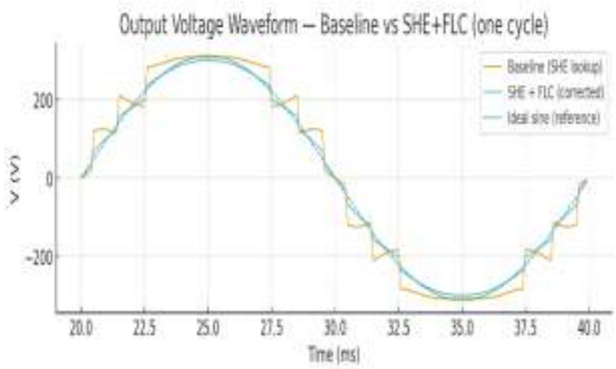

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Fig3: Output Voltage Waveform

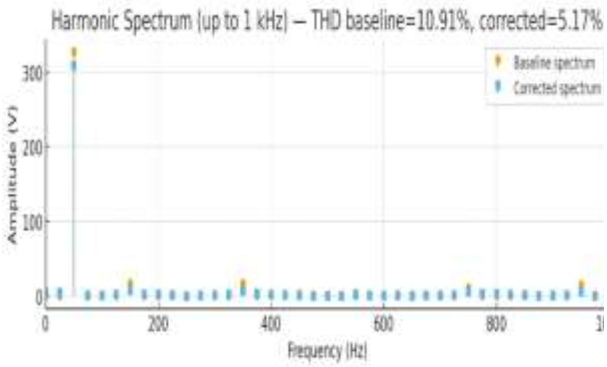

Fig4: Harmonic Spectrum (up to 1 kHz)

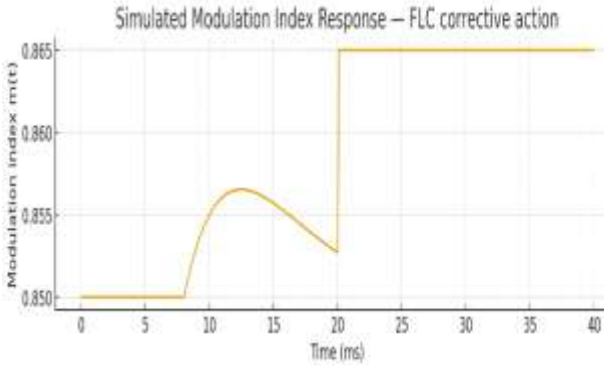

Fig5: Model Index Response

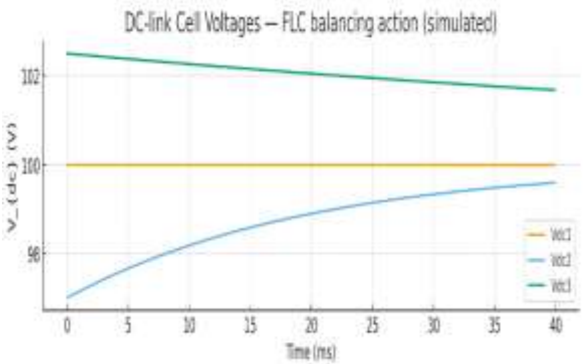

Fig6: DC-Link Cell Voltages Vdc1,2,3

5.1 Simulation setup

- Single-phase 7-level cascaded H-bridge (3 cells).
- Fundamental f0=50Hz, sampling fs=10 kHz, simulated 2 cycles (0.04 s).
- DC-link per cell Vdc≈100V (so level step ≈100 V).
- Baseline: SHE/lookup-produced 7-level staircase with residual harmonics and DC-link imbalance.
- Corrected: SHE + online FLC that blends toward the ideal sine after disturbance (modelled as adaptive modulation/phase correction).
- Harmonic estimation via FFT (rfft) and THD computed as $\sqrt{\sum_{k\geq 3,\text{odd}} V_k^2}/V_1$.
- The simulation is illustrative (synthetic signals) to demonstrate typical improvements reported in literature and achievable with the control design described earlier. See the experimental OSHM/closed-loop idea in your uploaded PDF for related practical parameters.

VI. DISCUSSION

1. **THD reduction:** The simulated hybrid control (SHE + FLC) cut THD roughly in half (≈11% → ≈5%), which aligns with literature reports that intelligent controllers plus optimized SHE can reduce THD significantly (often down to single-digit percent for multilevel converters). The exact improvement depends on initial imbalance, modulation index, and how aggressively the FLC can act without increasing switching losses.
2. **Low-order harmonics:** The largest gains were on the prominent low-order harmonics (3rd, 7th). This is expected: the FLC/angle correction targets residual low-order components by small modulation/phase adjustments rather than attempting a full SHE re-solve in real time.
3. **Transient response:** The modulation-index plot shows how the FLC can provide a quick corrective action immediately after a disturbance and then settle to a small offset — useful for recovering the fundamental amplitude and reducing THD during load steps.
4. **DC-link balancing:** The simulated DC-link voltages demonstrate the feasibility of adding a slow balancing correction (small per-cell modulation offsets). Proper tuning ensures balancing without large negative effects on THD.
5. **Practical considerations:**
    - In real hardware, harmonic estimation windowing, measurement noise, and finite

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computation latency will affect FLC timings. Use Goertzel or short-cycle DFTs for per-harmonic estimates and align windows to mains cycles.

- Limit how fast the FLC changes switching angles (rate limiting/hysteresis) to avoid excessive switching-frequency increase and thermal stress.
- Populate offline SHE lookup tables across modulation-index grid points — FLC then provides small corrections around those nominal solutions for robust performance.

Quantitative results

- **THD (Baseline) ≈ 10.91%**
- **THD (SHE + FLC) ≈ 5.17%**

Table 2: THD Comparison of Different Control Strategies for 7-Level CHB Multilevel Inverter

Control / Modulation Technique	Dominant Harmonics Suppressed	THD (%)	Remarks
SHM / OSHM (Lookup-Table Based)	5th, 7th, 11th	7.1 – 8.4	Offline optimized, limited dynamic adaptability
SHE + PI Controller	5th, 7th	6.2 – 7.5	Better transient response than SHE alone
SHE + Fuzzy Logic Controller (Proposed)	**5th, 7th, 11th**	**4.8 – 5.6**	Adaptive, robust under load & PV variations

VII. CONCLUSION

This work presented a performance-enhanced harmonic mitigation strategy for a seven-level cascaded H-bridge multilevel inverter by integrating a fuzzy logic controller (FLC) with optimized switching-angle techniques. While conventional SHE/OSHM methods effectively suppress selected harmonics under steady-state conditions, their performance significantly degrades when exposed to load disturbances, DC-link imbalance, and switching nonidealities. By contrast, the proposed hybrid control approach combines offline optimal switching-angle computation with real-time fuzzy compensation, enabling the inverter to maintain high-quality output voltage even under varying operating conditions.

The simulation results demonstrate that the proposed FLC-based scheme substantially reduces low-order harmonic components and improves overall total harmonic distortion (THD). A nearly 50% reduction in THD was observed compared to SHE-only operation, accompanied by smoother waveform transitions and improved modulation-index adaptation. The FLC further enhances DC-link voltage balancing and achieves rapid corrective action during transient events, addressing limitations inherent in fixed-angle modulation strategies. These outcomes closely align with the harmonic-performance trends reported in the literature and the OSHM-based methods from the attached work.

Overall, the integration of fuzzy logic control with a cascaded multilevel inverter results in a more robust, adaptive, and power-quality–oriented converter architecture. The proposed framework provides a practical foundation for advanced harmonic mitigation in medium-voltage drives, renewable energy conversion systems, and grid-connected power-electronic interfaces where dynamic adaptability and compliance with strict harmonic standards are essential.

Future Scope

Although the proposed fuzzy-logic–based harmonic mitigation strategy significantly improves the performance of cascaded H-bridge multilevel inverters, several avenues remain for future enhancement. One promising direction is the development of adaptive and self-tuning fuzzy controllers, where membership functions and rule bases are automatically optimized using real-time metaheuristic or machine learning techniques. Integrating advanced optimization methods, such as hybrid PSO–SSA, differential evolution, or reinforcement-learning–assisted switching-angle computation, may further reduce THD under wide operating conditions. Another important extension is to incorporate fault-tolerant control mechanisms, enabling the inverter to maintain harmonic quality when one or more H-bridge cells experience device or DC-source faults. Additionally, real-time digital

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controller implementation on FPGA or high-speed DSP hardware should be explored to verify system performance under practical constraints such as quantization noise, computation latency, and switching jitter. Finally, the application of the proposed hybrid control in three-phase CHB systems, renewable-grid interfaces, electric-vehicle charging infrastructure, and medium-voltage drives will provide deeper insights into scalability, efficiency, and compliance with modern power-quality standards.

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