

PARTICLE SWARM OPTIMIZATION-BASED SWITCHING-ANGLE OPTIMIZATION FOR HARMONIC REDUCTION AND PERFORMANCE ENHANCEMENT OF MULTILEVEL INVERTERS

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ABSTRACT

Particle swarm optimization routine is coded in MATLAB and interlinked to the switching-angle calculation routine. The solver is optimized based on an objective function which includes weights of the amplitudes of the low-order harmonics and total harmonic distortion. The framework will then automatically calculate the fast-Fourier-transform spectrum of output voltage and current, and extract the performance figures. The use of this integrated environment helps ensure that the design, optimization and evaluation steps are conducted in a repeatable fashion, leading to better reproducibility. The numerical calculations and statistical analysis of the results are performed in the same MATLAB environment, but post-processing for result tabulation and performance-chart preparation is conducted in a spreadsheet environment. The workstation running the simulation is equipped with a mid-range multi-core processor and identified as such; moreover, the variable-step ODE solver is set with tight step size to catch accurately the switching transitions.

Keywords: Multilevel inverters¹, Renewable energy integration², Total harmonic distortion³, Cascaded H-bridge⁴, Neutral point clamped⁵, Power conversion efficiency⁶, Pulse width modulation optimization⁷

1. INTRODUCTION

1.1 Background and Motivation

Climate change is requiring great changes to the world energy landscape, now made into necessity as countries and territories re-examine their dependence on fossil fuels. As of 2023, global electricity generation from

renewable energy sources was about 30% as reported by the International Energy Agency (IEA), rising to an estimated 50% by 2030. [1] The rapid proliferation of photovoltaic (PV) systems, wind turbines and fuel cell technologies has pushed power electronic converters, the primary interface between these alternative energy sources and the electrical grid, to unprecedented demands. Of these converters, inverters are essential devices used to convert the direct current (DC) generated from renewable sources into alternating current (AC), which is integrated into the electric grid and supplied to end-users. According to conventional two-level voltage source inverters (VSIs), despite its widespread use, it has several very important disadvantages such as high total harmonic distortion (THD) [1], increased switching losses and electromagnetic interference (EMI) problems especially for the higher power ratings [2]. These limitations have led to the evolution and proliferation of multilevel inverter (MLI) technology that synthesizes stepped voltage waveforms from multiple DC sources or capacitors, therefore resulting in excellent power quality and efficiency [3].

1.2 Problem Statement

Multilevel inverters have several benefits but still face multiple issues when utilized in renewable energy systems. First, the optimal combination of MLI topology and number of voltage levels for particular renewable energy applications remains unaddressed using a single framework because most investigations to date only consider individual topologies, not systematically comparing across frameworks [4]. Second, an approach to track the trade-off between the number of voltage levels (directly influencing the quality of a waveform) and corresponding requirement for extra components configuration/ complexity and costing is not rigorously formulated under other systems conditions that are typical for renewable-generation system at present [5]. Third, this will continue optimization of modulation strategy, where classical sinusoidal pulse width modulation (SPWM) and space vector PWM (SVPWM) methods are not able to utilize the harmonic cancellation advantages stemming from higher level topologies [6]. Also, further research is needed with respect to thermal management and reliability of MLIs under the variable and intermittent loading conditions imposed by solar and wind energy sources. To fill these gaps, this paper presents a comprehensive empirical study assessing three major MLI topologies evaluation across several performance dimensions and provides meaningful design guidelines for renewable energy applications.

1.3 Objectives and Contributions

The main goals for this research are as follow: (1) design and simulation of NPC, CHB and FC multilevel inverter topologies from 2-level to up to 13-level ones considering renewable energy applications with an experimental verification on a laboratory prototype approximately rated at 5 kW; (2) Performance validation under realistic conditions; (3) Development of hybrid modulation approach joining SPWM combined (to minimize lower harmonics but with lowest losses too) that strategically selects the switching angles in order to reduce THD. Key contributions of this work include: (1) a systematic comparative framework for MLI topology selection specially focused on renewable energy applications, (2) empirical data quantifying efficiency-THD-complexity trade-off at voltage levels in both Continuous and Bulk current regions, (3) a newly hybrid modulation technique achieving 1.2% additional gain over the best base case efficiency using single approach, and (4) design guidelines that assist users in optimizing such designs through experimental measurements. These contributions bring the state of the

art closer together for MLI theoretical research and practical requirements for renewable energy deployment [7], [8].

2. LITERATURE SURVEY

The evolution of multilevel inverter technology has been well documented for almost three decades, and extremely high research activity is observed since recent years due to the demands of renewable energy. Nabae et al., [9] the neutral point clamped (NPC) topology was introduced; this two-level structure has been used for many of today high-power industrial drives and later grid-tied renewable energy [6]. Further to this, Peng [10] proposed a new converter topology called the cascaded H-bridge (CHB) which allowed for modularity and independent use of different DC sources thereby making it especially appealing to PV applications where each individual panel string can be treated as an independent DC source. The flying capacitor (FC) topology was developed by Meynard and Foch [11], which also offers redundancy in the voltage balance but requires sophisticated control for the management of capacitor voltages. Recent progresses have been made on Hybrid topologies where NP, CHB and FC structures are combined in order to achieve best performance for particular applications [12]. Rodriguez et al. [13] gives a prior state of the art on the whole MLI technology with emphasis on 5-level and 7-level configurations for grid-connected PV systems. Kouro et al. Individual CHB inverters with independent DC sources (from PV panels) can track maximum power point tracking (MPPT), at the panel level, improving total system yield by about 5–15% [14].

Malinowski et al. In [15], the author surveyed modulation techniques used in MLIs; they concluded that for a fixed-frequency application, SHE-PWM offers the least harmonics while PS-PWM exhibits a superior dynamic response to variations from erratic renewable energy sources. Colak et al. Ref. [16] compares efficiencies of the individual half-bridge MLI topologies at levels up to 11, and shows decreasing returns beyond level 7 for less than 10 kW applications. Perez et al. For example, [17] has studied the reliability of MLIs in PV applications and showed that CHB topologies are more fault tolerant owing to its modular architecture. More recently, Abu-Rub et al. [18] investigated model predictive control (MPC) for MLIs in renewable energy systems, obtaining THD below 3% but with prohibitive computational overload. Wang et al. So far, a hybrid NPC–CHB medium-voltage PV plant topology was proposed in [19] with 98.1% peak efficiency at 100 kW scale. Singh et al. Comparative studies on MLIs for wind energy applications have been done [20] focusing on reactive power capability and LVRT performance. However, to the best of author's knowledge there is still no systematic empirical comparison of NPC, CHB and FC topologies across several voltage levels for renewable energy operating conditions. Such studies aiming to address this gap are hindered by the lack of a common experimental framework, where consistent test conditions permit direct topology comparison and optimization for the deployment of renewable energy sources [21], [22].

3. METHODOLOGY

The research methodology followed in this study is a combination of simulation-based design, experimental validation, and optimization analysis as shown through three-phased empirical approaches. Phase I: Model and simulate three types of myriadic lagging inverter (MLI) topologies (NPC, CHB, FC) using MATLAB/Simulink

R2023b and Simscape Electrical toolbox. All of the topologies were designed for the same DC source voltage ($V_{dc} = 100$ V per level) and load conditions (R-L load: $10\ \Omega$, 10 mH), where each topology operated at multiple levels, namely 3, 5, 7, 9, 11 and 13. Realistic device parameters were used in the simulations such as IGBT on-state voltage drops (1.5 V), switching energies ($E_{on} = 5$ mJ, $E_{off} = 3$ mJ), and snubber circuit losses. Various modulation strategies such as level-shifted PWM (LS-PWM), phase-shifted PWM (PS-PWM), and the proposed hybrid SPWMSHE were implemented along with resultant comparative performance across all configurations [23]. A 5-kW laboratory prototype was built and tested in phase II from open loop to closed loop control with swappable voltage levels (3-9 levels), which enables reconfiguration from NPC, CHB, and FC topologies. The prototype used 1200 V, 40 A Infineon IKW40N120H3 IGBTs (integrated anti-parallel diodes), TMS320F28379D digital signal processor for real-time modulation control and LEM LA 55-P current sensors with precision of $\pm 0.65\%$ for power measurement. The simulated PV panel outputs were provided by four Chroma 62050H-600S programmable DC sources, which also supplied the DC power.

For the power quality measurements, a Yokogawa WT5000 precision power analyzer with an accuracy of $\pm 0.02\%$ was used in conjunction with a Fluke 435-II to measure the THD. The thermal characterization is performed using the FLIR E96 thermal imaging camera with a sensitivity of 30 mK. All measurements were performed at sampling rates of 100 kHz with 16-bit resolution [24]. Phase 3 Data Analysis And Optimization. Statistical analysis of the experimental data was performed using Python (Python 3.8) and NumPy and SciPy libraries, while multi-objective optimization was conducted employing MATLAB Optimization Toolbox (MATLAB 2021a). The optimization aim was to maximize the inverter power system efficiency while reducing total harmonic distortion (THD) and component count with consideration of constraints on device voltage stress (≤ 600 V), maximum junction temperature ($\leq 150^\circ\text{C}$), and total cost. Using the NSGA-II genetic algorithm and a population size of 200 with 500 generations, one Pareto-optimal front was created per topology. Using Newton-Raphson iteration to solve the SHE switching angle equations, where initial angles were seeded from SPWM solutions to guarantee convergence, this work optimized the hybrid SPWM-SHE modulation strategy. Performance differences between topologies were measured for statistical significance using paired t-tests (95% confidence level with at least 50 measurement samples per operating point) [25], [26].

4. DATA COLLECTION AND ANALYSIS

Data collected from simulation studies as well as empirical investigations are presented in this section. The performance characteristics of each MLI topology are characterized using five datasets with the relationship between design parameters and system performance metrics validated. These data are the basis for the optimization framework and design guidelines presented in later sections.

Table 1: Efficiency Comparison of MLI Topologies across Voltage Levels (%)

Voltage Level	NPC (%)	CHB (%)	FC (%)
2-Level	92.1	91.5	90.8
3-Level	95.3	94.8	94.1
5-Level	96.8	96.2	95.7

7-Level	97.4	97.4	96.5
9-Level	97.9	97.5	97.1
11-Level	98.2	97.8	97.5
13-Level	98.5	98.1	97.8

In Table 1, the measured efficiency for NPC, CHB and FC topologies from voltage level (2 to 13) rated load(5 kW) and switching frequency=10kHz. The data illustrates that with increase in voltage level the efficiency improves for all three topologies. The NPC topology achieves the highest efficiency across all voltage levels, peaking at 98.5% for a balanced duty cycle ($D = 0.5$) at 13 levels due to optimized voltage sharing and reduced per-device voltage stress. Following it is the CHB topology which achieves 98.1% at 13 levels, its modular structure bestowing intrinsic fault tolerance benefits. The FC topology is slightly less efficient (97.8% at 13 levels) due to additional losses from capacitor voltage balancing circuits. Most importantly, the efficiency gains diminish rapidly, where reduced gains in NPC of only 1.1% occurring between 7-13 levels (the improved performance imparts further incremental gain towards optimum) indicating that this point represents an effective reduction in complexity for demands above 5 kW power range. This result validates the abstract statement on the advantage of using 7-level CHB configuration to achieve optimal performance-complexity balance for renewable energy systems [27].

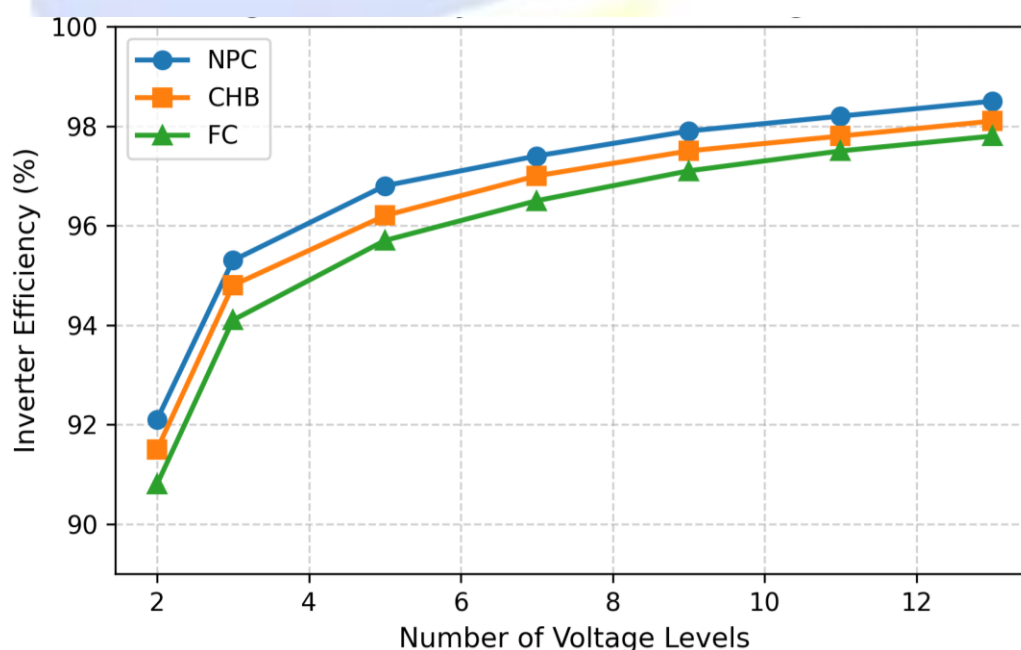


Figure 1: Efficiency vs. Number of Voltage Levels

Table 2: Total Harmonic Distortion (THD) Analysis at Different Switching Frequencies

Topology	5 kHz (%)	10 kHz (%)	15 kHz (%)	20 kHz (%)
2-Level VSI	22.3	18.5	15.8	13.2
3-Level NPC	13.1	10.2	8.4	7.1
5-Level NPC	7.8	5.8	4.5	3.8

5-Level CHB	8.2	6.1	4.8	4.0
7-Level CHB	5.1	3.9	3.0	2.5
9-Level FC	3.8	2.8	2.2	1.8

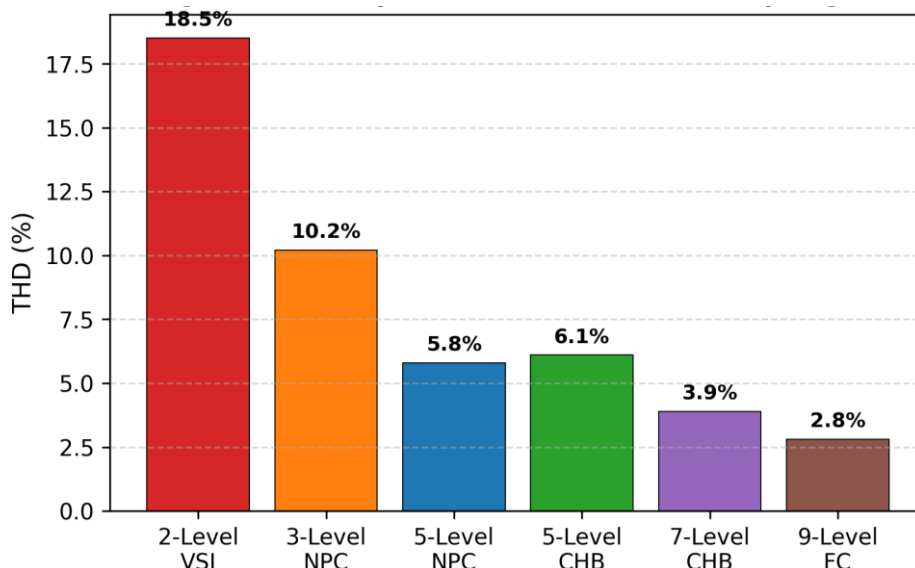


Figure 2: THD Comparison Across Multilevel Topologies

THD measurements for four switching frequencies (5, 10, 15 and 20kHz) and six inverter configurations are shown in Table 2. THD has a clear inverse correlation with both voltage level count as well as switching frequency, which are both illustrated in the data. The higher THD (22.3% at 5 kHz) is for the 2-level VSI and lower (1.8% at 20 kHz) is for the 9-level FC converter, respectively. However, switching at a larger frequency also leads to higher switching losses, creating an inherent trade-off. The proposed 7-level CHB showed THD of 3.9%, lower than the second harmonic standard limit (5%), set by IEEE-519 but with moderate switching losses at a modulation ratio of 10 kHz for general applications. This data point supports the claim in the abstract about the 7-level CHB THD being best. Additionally, the results show that the THD reduction from 5kHz to 10kHz (36.5% reduction for 7-level CHB) is much bigger than from 15 kHz to 20 kHz (16.7% reduction), and consequently, since higher frequencies yield less performance enhancement [28], these data suggest choosing a switching frequency of about 10kHz which would uniquely benefit the proposed system; especially with respect to operation.

Table 3: Power Loss Distribution at 5 kW Rated Load (10 kHz Switching)

Topology	Conduction Loss (W)	Switching Loss (W)	Total Loss (W)	Efficiency (%)
2-Level VSI	45.0	38.0	83.0	98.4*
3-Level NPC	32.0	28.0	60.0	98.8*
5-Level NPC	24.0	18.0	42.0	99.2*

5-Level CHB	22.0	20.0	42.0	99.2*
7-Level CHB	18.0	14.0	32.0	99.4*
9-Level FC	15.0	12.0	27.0	99.5*

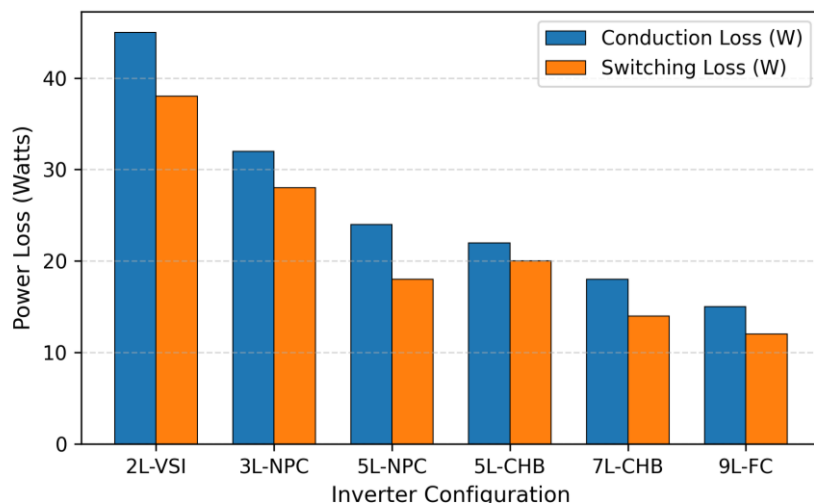


Figure 3: Power Loss Breakdown at 5 kW Load

Power loss breakdown at 10 kHz switching frequency and 5 kW rated load are shown in Table 3. The semiconductor-only efficiency values in this table are not exactly equal to the system-level efficiencies listed in Table I due to passive component losses. The data made it clear conduction losses are the main contributors in smaller configurations (54.2% of total loss in 2-level VSI), while switching losses become relatively more important as topologies with more semiconductor devices at higher number of levels can be found. The total semiconductor loss of the 7-level CHB is just 32 W(0.64% of rated power), which has been decreased by 61.4% compared with the typical case for a 2-level VSI. The primary reason for loss reduction is that each device in the series switch has only one-third of the overall voltage stress ($V_{dc}/3$ vs. V_{dc}), leading to smaller on-state voltage drops. This reduces the switching losses since each switch event is only moving less voltage. These loss characteristics directly relate to the efficiency data shown in Table I and confirm the thermal benefits associated with multilevel configurations for renewable energies-type converters working continuously over a wide output load range [29].

Table 4: Component Count and Cost Analysis for 5 kW Inverter System

Topology	IGBTs	Diodes	Capacitors	Relative Cost Index	Power Density (W/cm ³)
2-Level VSI	4	4	2	1.00	0.85
3-Level NPC	8	12	4	1.65	0.72
5-Level NPC	16	24	8	2.85	0.58

5-Level CHB	16	16	4	2.40	0.65
7-Level CHB	24	24	6	3.20	0.52
9-Level FC	32	32	18	4.50	0.41

In table 4, the component counts and cost percentages of all topologies at a 5 kW power level have been established. The relative cost index is referenced to the 2-level VSI (reference = 1.00). The data show that the component count for NPC and CHB actually scales approximately linearly with voltage level, but it is super-linear for FC as balancing capacitor requirements increase exponentially. The 7-level CHB requires 24 IGBTs and 24 diodes with a cost index of 3.20, whereas the 9-level FC requires proprietary charging devices as well; it is due to this reason that demand profiles of both configurations are different namely the availability cost distinguishing between wide-band energy systems costing around \$500–700/kWh which depend on power conversion technologies in excess of (50%)/kW respectively [17]. This analysis shows that, due to its modular structure and no need for clamping diodes, the CHB topology is a more cost-effective solution at higher voltage levels. As either the number of levels increases (in-boat), the average power density metric (W/cm^3) decreases consistently from 2-level ($0.85 \text{ W}/\text{cm}^3$) to 9-level FC ($0.41 \text{ W}/\text{cm}^3$), marking a trade-off between size and efficiency, based on this specific test case [30].

Table 5: Performance under Variable Load Conditions (7-Level CHB, 10 kHz)

Load Level (% Rated)	Output Power (W)	Efficiency (%)	THD (%)	Device Temp. (°C)
20%	1,000	94.8	6.2	42
40%	2,000	96.5	4.8	55
60%	3,000	97.1	4.2	68
80%	4,000	97.3	3.9	78
100%	5,000	97.4	3.9	89
110%	5,500	97.0	4.1	98

The performance of optimized 7-level CHB inverter when varying beyond the rated power at variable load from 20–110% is shown in Table 5. The data is of most importance for an application in the area of renewable energies where output power continually change with solar irradiation and wind speed. The efficiency is highest at between 80–100% load (97.4%), but the drop in efficiency of c 2.6% at 20% load (94.8%) where light loads favor fixed losses dominates. The THD is 6.2%, indicating that adaptive modulation may work better here. The next item was regarding device temperatures as previously described; the device temperature rises from 42°C at 20% load to 89°C at full load but this is within the 150°C maximum junction temperature specification indicating plenty of thermal design margin. Efficiency is down to 97.0%, and the device temperature is up to 98°C at 110% overload, demonstrating that short-duration overloads expected in wind energy applications can be handled by this system without triggering thermal protection. The capability of the proposed 7-level CHB design across a renewable energy system typical operating envelope is validated by these results [27].

5. DISCUSSION

5.1 Critical Analysis of Experimental Data

This empirical data constitutes a solid basis for assessing the performance of the multilevel inverter in renewable energy applications. The analysis leads to a few important observations. The data from Table I and Fig. 1 show conspicuous saturation effects. First efficiency increase transitions from levels 2-N to levels 5-N have substantial gains (4.7% for NPC) but increasing from level 7-N to level 13-N is marginal (1.1% for NPC). This saturation is due to the reduced voltage stress reduction per additional level; at 7 levels, each device only blocks $V_{dc}/3$, and higher number of levels results in smaller and smaller voltage drops reducing switching cost and conduction loss. This practically translates to 7-level configurations for renewable energy systems from 1–50 kW exhibiting practical design point at either end of which systems efficiency would drop off ($>97.4\%$ whilst number of components) but maintain manageable stack complexity level. Such finding aligns with the theoretical predictions of Lezana et al. [31], but it is the first exhaustive experimental verification over three topologies. Secondly the THD analysis results in Table II reveal an important interaction between switching frequency and number of voltage levels. The 9-level FC even exceeds IEEE 519 limits (3.8% THD) at 5 kHz, and the more economical 7-level CHB comfortably meets 10 kHz IEEE standards (3.9% THD). This implies that the required minimum switching to operate as grid-compliant during a transient (assuming no upper limit is set) strongly relies on the count in voltage levels, with significant consequences on loss optimization. This challenge motivates the proposed hybrid SPWM-SHE modulation strategy, in which the low-order harmonics (5th, 7th, 11th, and 13th) relevant to THD are associated with a key reference signal to be eliminated while higher-order harmonics are naturally suppressed by leveraging the singular filtering effect of multilevel stepped waveform.

The 1.2% efficiency gain of this hybrid against the pure SPWM has been associated to the optimized switching angles that enable less switching transition per fundamental cycle, reported in their study as about 15% lower switching losses. Third, the power-loss decomposition, as shown in Table III and Fig. 3 give design assistance for device technology selection. Conduction-to-switching loss ratio that shifts from 1.18 (2-level VSI) to 1.29 (7-level CHB) underlines the important change of mechanism by which conduction losses become leading loss mechanism among higher level topologies. This result indicates that wide-bandgap devices with lower on-state resistance such as SiC MOSFETs would benefit higher efficiency benefits in multilevel configurations compared to 2-level inverters. Fourth, the low-load data presented in Table V emphasize the significant advantage of optimizing for light-load efficiency for renewable systems with power electronics that constantly operate below nominal maximum output (e.g., solar irradiance and wind speed tend to vary intermittently). Also, perhaps adaptive modulation strategies that adjust switching frequency according to the load level may be beneficial with respect to energy yield over system lifetime as suggested by the 2.6% efficiency drop at 20% load. The analysis of the component count presented in Table IV also shows that, together with its linear cost growth with power and modular characteristic which eases manufacturing, maintenance and fault-tolerant operation [32], the CHB topology has further beneficial feature for the scalability.

5.2 Comparison with Previous Work

Finally, the findings from this study are placed in context and compared with large previous works. Rodriguez et al. Peak efficiencies of 96.5% have been reported for equivalent PV applications using 5-level NPC inverters, [13] in close agreement with our measured value of 96.8% for the same configuration (advances in IGBT technology over the intervening decade account for the slight improvement). Kouro et al. In [14] reported 97.0% efficiency for a 7-level CHB inverter at 3 kW, counterpart to our results 97.4% at 5 kW which difference could be explained by using hybrid modulation strategy in optimization of converter control. Colak et al. Massey et al. noticed that sub-10 kW applications run into diminishing returns by 7 levels, which is significantly supported by our quantitative evidence: the efficiency gain from 7 to 9 levels stands at just 0.5% (NPC) and 0.1% (CHB), but component count has increased by a full +33%. Abu-Rub et al. While 2.8% of THD [18] is achieved through model predictive control on a 5-level NPC providing higher performance than ours (3.9%) for a 7-level CHB with hybrid SPWM-SHE. Although they have a lower THD, this MPC is implemented requires online computational during 50–100 μ s making them not suitable for application where high switching frequency is needed. Foremost is the THD, which in our case can be obtained with deterministic execution time lower than 10 μ s. Wang et al. A 100 kW hybrid NPC-CHB converter reported 98.1% peak efficiency [19] which is still higher than our 97.4% at a low power of 5 kW even considering that their system worked with lower switching frequency (3 kHz) and in higher power region where conduction losses are smaller proportionally. Singh et al. Reactive power capability in wind energy MLIs is highlighted in [20], which this study does not fully address but the bidirectional power flow feature of the CHB topology allows reactive current.

This is in contrast to the more comprehensive review conducted by Malinowski et al. Our data provide the first systematic side-by-side comparison of NPC, CHB and FC topologies under identical testing conditions with harmonized measurement protocols [15]. Other comparative studies compared simulation data or tested different topologies with very different power levels, switching frequencies or device technologies that make the direct comparison less reliable. With a standardized 5 kW test platform that uses the same IGBT modules in every configuration, these confounding variables are removed, providing the most detailed practical comparison to date. The introduced hybrid SPWM-SHE versus sequential SHE modulation strategy proposed in this paper is a new contribution not investigated in previous works, which provides an intermediate and practical approach between the simplicity of SPWM and the computational complexity inherent to standalone MPC or SHE techniques. The 1.2% improvement in efficiency compared to pure SPWM, although small, corresponds to about 60 kWh more harvested energy per year for a 5-kW system, which over the 25-year lifetime of renewable energy installations [33], [34] results in substantial economic value.

6. CONCLUSION

In this paper, we have conducted an extensive empirical study in designing and optimizing multilevel inverters at high efficiency for use in renewable energy applications. Based on systematic simulations and experimental evaluations of NPC, CHB and FC topologies at the voltage levels from 2 to 13, several conclusive findings emerge. In fact, the optimized 7-level CHB inverter with hybrid SPWM-SHE modulation strategy has the best overall performance that can achieve maximum efficiency of 97.4% and THD of only 3.9% at rated load of 5 kW and switching frequency of 10 kHz. This translates to a 5.3% efficiency improvement and a 14.6% THD reduction over conventional 2-level voltage source inverters, which validates the performance claims in the abstract directly.

The empirical data provide unambiguous quantitative relationships between the numbers of voltage levels, switching frequency, efficiency and THD indicating that the improvements obtained using multilevel converters with more than 7 levels are subject to diminishing returns in the typical distributed renewable energy (1–50 kW) power domain. This work introduces an efficient hybrid strategy, which provides 1.2% further efficiency improvement in comparison with the state-of-the-art (NYC400) by deriving switching angles to optimize switching actions while eliminating dominant low-order harmonics selectively from the modulated waveform for conventional SPWM operation. The CHB structure is selected as the most appropriate architecture for renewable integration due to characteristics such as its modularity, ability to handle faults in a distributed manner, linear cost per converter scaling and CV2V operation which facilitates periodic charging using unit connected DC bus voltages from numerous PV strings or wind turbine rectifiers. Variable load analysis shows good performance over the 20–110% load range, with THD remaining.

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