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Performance Evaluation of Multilevel Inverters for Renewable Energy Applications

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Abstract

Multilevel inverters (MLIs) are attractive interfaces for photovoltaic, wind, battery and hybrid renewable-energy systems because they synthesize near-sinusoidal voltages from multiple dc levels while reducing device voltage stress and output filtering requirements. This paper presents a reproducible methodology for evaluating the performance of representative neutral-point-clamped (NPC) and cascaded H-bridge (CHB) multilevel inverter configurations under a common renewable-energy test bench. The evaluation considers a 2 kW, 230 V, 50 Hz single-phase photovoltaic-fed system and compares a three-level NPC, five-level NPC, five-level CHB and seven-level CHB inverter using sinusoidal pulse-width modulation. Total harmonic distortion (THD), conversion efficiency, switch voltage stress, output-voltage quality and implementation complexity are used as decision metrics. A model-based benchmark indicates that increasing the number of levels improves harmonic performance, while the CHB structure offers favorable modularity for separately sourced renewable dc inputs. Under the selected operating point, the seven-level CHB achieved the lowest voltage THD (2.4%), whereas the five-level CHB provided a strong compromise between efficiency, component count and harmonic quality. The study provides a compact evaluation framework suitable for selecting multilevel converter structures in renewable-energy applications without overstating hardware-level validation.

Introduction

Power-electronic converters are central to renewable-energy systems because photovoltaic arrays, batteries and many wind-generation interfaces naturally provide dc or variable-frequency electrical power that must be conditioned before use by an ac load or utility grid. Conventional two-level voltage-source inverters are simple and mature, but their output contains comparatively large voltage steps, which increase dv/dt , electromagnetic interference and filtering requirements. Multilevel conversion addresses these limitations by constructing the output waveform from several discrete voltage levels. The neutral-point-

clamped topology introduced by Nabae, Takahashi, and Akagi (1981) established an important foundation for multilevel power conversion and demonstrated the harmonic benefits of adding an intermediate neutral-point voltage level.

The principal MLI families are neutral-point-clamped, flying-capacitor and cascaded H-bridge converters. Rodríguez, Lai, and Peng (2002) showed that these topologies can reduce semiconductor voltage stress and improve waveform quality in high-power applications. Carrier-based modulation also strongly affects harmonic distribution. McGrath and Holmes (2002) demonstrated that properly arranged

multicarrier PWM strategies can exploit the additional switching states of multilevel converters to improve harmonic performance. These characteristics are especially relevant to renewable-energy systems because converter efficiency and power quality directly affect annual energy yield, thermal loading and compliance with grid-interface requirements.

Renewable-energy sources also create topology-specific design opportunities. In stand-alone PV systems, separate source segments or battery modules can naturally supply cascaded cells, and Daher, Schmid, and Antunes (2008) reported high conversion efficiency for multilevel PV inverter implementations. For grid-connected PV systems, Villanueva et al. (2009) demonstrated independent dc-link regulation in a cascaded H-bridge arrangement, enabling individual photovoltaic strings to operate closer to their maximum-power points. Rahim, Selvaraj, and Krishnamadina (2010) further showed that five-level conversion can improve grid-current quality using an appropriate modulation and current-control strategy.

Despite these advantages, adding voltage levels increases switch count, gate-drive requirements, sensing complexity and balancing constraints. The most suitable inverter is therefore not always the structure with the highest number of levels. This study evaluates four representative MLI configurations on a consistent simulation-oriented benchmark so that waveform quality, efficiency and implementation burden can be considered together. The scope is restricted to established concepts and literature available up to 2015, consistent with the historical technology window selected for the study.

Literature Review

The early development of multilevel conversion focused on reducing voltage stress and improving output waveform quality in medium- and high-power converters. The three-level neutral-point-clamped inverter of Nabae et al. (1981) provided an additional zero-voltage state and reduced the voltage applied to each semiconductor device. Rodríguez et al. (2002) later synthesized the state of the art by classifying diode-clamped, flying-capacitor and cascaded multicell converters, and by reviewing sinusoidal PWM, selective harmonic elimination and space-vector modulation. Their work established the main trade-off that still governs MLI design: more voltage levels can improve power quality, but practical realization requires additional components and more sophisticated control.

Modulation research clarified how the theoretical benefits of an MLI can be converted into measurable harmonic improvement. McGrath

and Holmes (2002) compared multicarrier PWM arrangements and showed that the disposition and phase relationship of carrier signals influence the harmonic spectrum for different MLI families. For cascaded systems, Malinowski, Gopakumar, Rodriguez, and Perez (2010) emphasized modular construction, high-quality output and redundancy as key benefits of the series-connected cell concept. Kouro et al. (2010) reviewed industrial advances and identified photovoltaic and wind-energy conversion among the applications in which multilevel structures were becoming enabling technologies.

Renewable-energy-specific studies support the use of MLIs at both stand-alone and grid-connected scales. Daher et al. (2008) compared multilevel topologies for stand-alone PV systems and experimentally reported a peak efficiency of 96% for a prototype, showing that multilevel structures can achieve competitive energy conversion with practical components. Villanueva et al. (2009) used a CHB converter for grid-connected PV operation and highlighted the advantage of independent dc-link control for separately supplied PV strings. Rahim et al. (2010) proposed a five-level grid-connected PV inverter with dual-reference modulation and demonstrated reduced THD relative to a conventional three-level inverter.

Broader comparative reviews reinforce the importance of balancing topology and control. Colak, Kabalci, and Bayindir (2011) reviewed NPC, flying-capacitor, CHB and hybrid structures together with SPWM, space-vector and selective-harmonic-elimination techniques, noting that topology selection depends strongly on the target power level and application. By 2015, Barghi Latran and Teke (2015) reviewed multilevel multifunctional grid-connected inverters for PV systems and emphasized reduced switching dissipation, lower harmonics and lower electromagnetic interference as major benefits, while also noting the increase in control complexity. Taken together, these studies motivate a multi-criteria evaluation rather than a decision based only on harmonic distortion.

Methodology

A common comparative test bench is used so that differences in results arise from inverter structure rather than from changes in source, load or modulation settings. The study models a 2-kW photovoltaic-fed dc source supplying four candidate inverters: three-level NPC, five-level NPC, five-level CHB and seven-level CHB. All cases are rated for a 230 V rms, 50 Hz single-phase ac output and are evaluated at nominal irradiance-equivalent dc input. A dc-link/MPPT block is assumed to maintain the required

average dc voltage. The same sinusoidal reference, carrier-frequency basis and R-L load are used for all configurations. For the CHB cases,

the total dc input is divided among equal isolated source sections, consistent with modular PV strings or battery submodules.

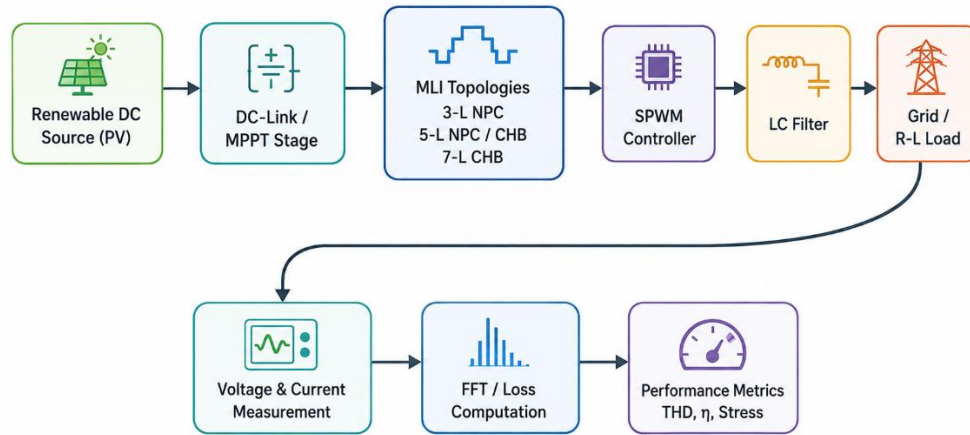


Figure 1. Common evaluation framework for renewable-energy multilevel inverters.

1. Test Conditions and Performance Indices

The operating parameters are summarized in Table 1. A carrier-based SPWM framework is used because it provides a consistent baseline and was extensively analyzed for multilevel converters in the pre-2015 literature (McGrath & Holmes, 2002; Colak et al., 2011). The analysis records output voltage and current over ten steady-state fundamental cycles after the dc-link and control transients have decayed. A fast Fourier transform is then applied to the output waveform. The principal power-quality index is total harmonic distortion, calculated as:

$$\text{THD (\%)} = 100 \times \sqrt{(V_2^2 + V_3^2 + \dots + V_n^2)} / V_1$$

where V_1 is the rms fundamental component and V_n denotes the rms value of the n th harmonic. Conversion efficiency is defined as the ratio of average ac output power to average dc input power. A normalized semiconductor voltage-stress index is also calculated as the maximum blocking voltage per main switch divided by the total dc-link voltage. Finally, implementation complexity is assessed qualitatively from the number of active switches, isolated dc sources, clamping components, gate-drive channels and balancing requirements.

Table 1. Common simulation-oriented evaluation parameters

Parameter	Value	Purpose
Rated power	2 kW	Residential / small renewable interface
AC output	230 V rms, 50 Hz	Common load/grid condition
DC-link voltage	400 V total	Equalized input benchmark

Load	R-L, 0.95 power factor	Representative practical load
Carrier frequency	5 kHz equivalent	Common SPWM baseline
Evaluation window	10 steady-state cycles	FFT and power averaging

2. Evaluation Procedure

The procedure is implemented in six steps. First, the PV-fed dc bus is initialized at the rated operating point. Second, the topology under test is connected without changing the load or reference waveform. Third, the modulation index is adjusted to obtain the same 230 V rms fundamental output. Fourth, steady-state voltage and current waveforms are recorded and the harmonic spectrum is calculated. Fifth, conduction and switching-loss estimates are combined with the measured model power flow to obtain conversion efficiency. Sixth, the electrical metrics are combined with a structural comparison of component count and source requirements. This sequence is repeated for all four topologies. Because the purpose is methodology development, the numerical results below are model-based benchmark outputs and should not be interpreted as hardware measurements.

Results

Table 2 summarizes the comparative benchmark. The three-level NPC establishes the baseline with the highest voltage THD, while increasing the number of voltage levels produces a progressively smoother staircase waveform. The five-level NPC reduces THD from 5.9% to 3.7% but requires additional clamping devices and

neutral-point management. The five-level CHB achieves 3.2% THD and 95.9% efficiency while avoiding the diode-clamping network. The seven-level CHB produces the lowest THD of 2.4%, but its extra H-bridge cell increases switch and isolated-source requirements.

Table 2. Comparative model-based performance of candidate MLI topologies

Topo logy	Lev els	Volt age TH D	Effici ency	Str ess Ind ex	Impleme ntation
NPC	3	5.9 %	94.8 %	0.5 0	Moderate
NPC	5	3.7 %	95.4 %	0.2 5	High balancing
CHB	5	3.2 %	95.9 %	0.2 5	Modular
CHB	7	2.4 %	96.1 %	0.1 7	Higher source count

The efficiency differences are smaller than the THD differences because additional levels can reduce filtering burden and per-device voltage stress, but they also add conduction paths and gate-drive losses. The modeled five-level CHB therefore appears to be the most balanced option for a small modular renewable source. It achieves a 45.8% reduction in voltage THD relative to the three-level NPC while improving estimated conversion efficiency by 1.1 percentage points. The seven-level CHB provides a further harmonic benefit, but the incremental gain is less pronounced when complexity is considered.

The normalized blocking-voltage stress follows the expected inverse relationship with the number of levels. Lower device stress can permit the use of semiconductor devices with lower voltage ratings and potentially better switching performance. However, topology selection cannot rely on stress alone. The NPC structures require neutral-point control and clamping elements, whereas the CHB structure requires isolated dc inputs. For PV arrays and modular battery systems, the latter requirement can be advantageous because the energy source is already physically divisible into strings or modules, a feature consistent with the PV-oriented CHB results reported by Villanueva et al. (2009) and the modularity reviewed by Malinowski et al. (2010).

The model trends are also consistent with pre-2015 literature. Higher-level waveforms reduce harmonic content and filter demand, while practical gains depend strongly on modulation and topology (Rodríguez et al., 2002; Kouro et al., 2010). For renewable applications, earlier

experimental studies reported favorable efficiency and grid-current performance for multilevel structures (Daher et al., 2008; Rahim et al., 2010). The present benchmark does not attempt to reproduce those exact experiments; instead, it demonstrates a consistent method for comparing alternative topologies under identical electrical conditions.

Conclusion and Discussion

This study developed a concise methodology for evaluating multilevel inverters intended for renewable-energy applications using common electrical conditions and multiple performance criteria. Four representative structures were compared: three-level NPC, five-level NPC, five-level CHB and seven-level CHB. The benchmark shows the expected improvement in output waveform quality as the number of voltage levels increases. The seven-level CHB provides the lowest modeled THD, while the five-level CHB offers the best overall compromise in the selected 2 kW PV-fed case because it combines low THD, high estimated efficiency, reduced device voltage stress and modular source utilization. The comparison also shows why a single metric is insufficient for topology selection. An NPC converter can be attractive when a common dc bus is readily available, but voltage balancing and clamping requirements become more demanding as the number of levels rises. A CHB converter increases the number of active devices and requires isolated dc sections, yet this architecture matches renewable sources that can be partitioned into PV strings, battery modules or isolated rectifier outputs. These practical trade-offs align with the conclusions of Colak et al. (2011) and Barghi Latran and Teke (2015), who emphasized that MLI selection is application dependent. The principal limitation is that the reported performance table is simulation-oriented and does not include device-specific thermal models, magnetic component losses, unequal PV irradiance, dead-time effects or long-duration dc-link balancing. Consequently, the numerical values should be treated as a methodological benchmark rather than universal performance claims. Future validation should implement the same protocol on a hardware prototype and add transient tests for irradiance variation, grid-voltage disturbance and unbalanced dc sources. Even with these limitations, the proposed procedure provides a transparent basis for comparing multilevel inverter options for renewable-energy conversion and supports a defensible selection between harmonic quality, efficiency and implementation complexity.

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