



Recent Advances in Power Electronics Converters for Renewable Energy Applications

Kenjiro Quintanilha

Department of Electrical and Computer Engineering, Kelana Technical and Management College, Malaysia
kenjiro.quintanilha@ktmc-my.net

Peer Review Information	Abstract
<i>Submission: 20 Jan 2015</i> <i>Revision: 09 Feb 2015</i> <i>Acceptance: 26 March 2015</i> Keywords <i>Power electronics, renewable energy, photovoltaic inverter, wind energy converter, multilevel converter</i>	This paper reviews and methodologically compares the principal advances in power-electronic converters used for renewable-energy conversion up to 2015. The study focuses on photovoltaic (PV), wind and storage-coupled interfaces and evaluates the progression from conventional two-stage conversion toward transformerless, multilevel, impedance-source, module-integrated and full-scale converter structures. A structured literature-selection procedure was applied to peer-reviewed studies with traceable DOI records. Converter families were classified by conversion stage, voltage-gain capability, isolation, switch stress, harmonic performance, component count, control complexity, scalability and suitability for maximum-power-point tracking (MPPT) and grid support. The synthesis shows that no single topology dominates all renewable applications. Transformerless PV inverters improve efficiency and power density but demand careful leakage-current control; multilevel converters reduce device stress and output harmonics at medium-to-high power; Z-source concepts combine buck-boost conversion and inversion; full-scale back-to-back converters increase controllability in modern wind turbines; and silicon-carbide devices offer a route to higher switching frequency and reduced losses. The paper concludes that converter selection should be application-specific and jointly optimized for efficiency, reliability, power quality, cost and grid-code compliance.

Introduction

Renewable-energy sources deliver electrical power with characteristics that differ from those required by utility grids and regulated loads. PV arrays produce variable dc voltage, wind generators produce variable-frequency ac power, and energy-storage systems require controlled bidirectional power flow. Power-electronic converters therefore perform essential interface functions including voltage adaptation, dc/ac conversion, frequency decoupling, MPPT, synchronization and power-quality conditioning. Early dispersed-generation studies established power electronics as the controllable link between renewable sources and the grid [3]. By 2015, research had moved

beyond basic conversion toward higher efficiency, modularity, reduced passive-component size, improved reliability and enhanced grid-support capability [1], [4].

The evolution is especially visible in PV systems. Central inverters were supplemented by string, multistring and module-integrated converters, while transformerless single-phase topologies were developed to reduce size and conversion loss [1], [2], [6], [14]. High step-up structures reduce dependence on bulky line-frequency transformers, whereas multilevel and impedance-source families provide alternative methods for voltage boosting and harmonic reduction [7]-[9]. Wind-energy conversion

followed a related but power-dependent trajectory: partially rated converters remained attractive for doubly fed induction-generator systems, while permanent-magnet and direct-drive turbines increasingly used full-scale back-to-back converters because they provide independent generator and grid control [10]-[12].

The design problem is multi-objective. A topology with fewer stages may reduce conduction and switching loss, but may increase semiconductor voltage stress or common-mode leakage. Higher switching frequency can shrink inductors and filters, yet increases switching loss unless improved semiconductor technology is used. Likewise, multilevel converters can achieve lower dv/dt and harmonic distortion, but require additional devices, gate drives and balancing control [9]. Emerging silicon-carbide (SiC) switches were already demonstrating the potential for higher efficiency in large wind-power converters by 2011 [13]. Consequently, converter advances should be evaluated through a common engineering methodology rather than by topology novelty alone.

The objective of this paper is to develop such a methodology and apply it to converter advances reported up to 2015. The analysis addresses four questions: (i) which converter families became most important for PV, wind and storage integration; (ii) which performance benefits motivated their adoption; (iii) what limitations constrain each family; and (iv) how a designer can select an appropriate converter architecture for a given renewable-energy application.

Literature Review

Kjaer, Pedersen and Blaabjerg [14] provided an early systematic classification of single-phase grid-connected PV inverters and showed how central, string and module-integrated architectures influence conversion stages, efficiency and component requirements. The central-inverter structure benefits from high power rating and low converter count, but partial shading or mismatch can reduce array-level energy capture. String and multistring arrangements distribute MPPT across smaller groups of modules, improving energy harvesting and fault localization at the expense of more converter hardware. Module-integrated conversion pushes this concept further by assigning conversion and MPPT to individual modules.

Li and Wolfs [6] compared module-integrated converter arrangements with different dc-link configurations, emphasizing the trade-off

between energy decoupling, voltage transformation and stage count. Kouro et al. [1] later documented the rapid diversification of grid-connected PV structures and identified emerging alternatives to the conventional boost-converter-plus-inverter chain. The literature therefore shows a transition from one high-power interface toward distributed power processing where converter granularity is selected according to mismatch, reliability, installation flexibility and maintenance requirements.

Transformerless conversion became a major PV research direction because eliminating the line-frequency transformer can increase efficiency and reduce mass and cost. Meneses et al. [7] reviewed step-up transformerless topologies for PV ac-module applications and showed how voltage boosting can be incorporated into the conversion structure. Islam, Mekhilef and Hasan [2] examined single-phase transformerless grid-tied topologies and emphasized common-mode voltage behavior and leakage-current suppression. By 2015, transformerless design had therefore evolved from simple transformer removal into a coordinated problem involving circuit topology, modulation, parasitic capacitance and safety constraints.

Multilevel conversion matured as a practical solution for higher-voltage and higher-power applications. Colak, Kabalci and Bayindir [9] reviewed neutral-point-clamped, flying-capacitor and cascaded H-bridge structures together with their modulation methods. The principal attraction is that individual semiconductor devices block only a fraction of the total dc-link voltage while the stepped waveform reduces dv/dt and harmonic content. This characteristic is valuable when large renewable plants must meet stringent grid-current requirements without excessive switching frequency or filter volume.

The advantages of multilevel conversion are accompanied by design challenges. Neutral-point-clamped converters require neutral-point voltage management; flying-capacitor converters need capacitor-voltage balancing; and cascaded H-bridge systems need multiple isolated dc sources or front-end stages. The number of switches and gate drivers grows with level count. Consequently, multilevel topologies are strongest when voltage rating and power quality justify their additional control and hardware burden, rather than as a universal replacement for two-level conversion [9].

Impedance-source conversion introduced a different concept. Peng's Z-source inverter [8]

used an impedance network and shoot-through states to provide buck-boost capability in a single inverter stage. This is especially relevant to renewable sources whose dc voltage varies widely with irradiance, temperature or operating speed. The same shoot-through state that would damage a conventional voltage-source inverter becomes an intentional control state in a Z-source structure. The cost is added inductive/capacitive energy storage, nontraditional modulation and a need to manage impedance-network stress and resonance.

In wind energy, Chen, Guerrero and Blaabjerg [10] reviewed the transition from fixed-speed systems to variable-speed turbines with power-electronic interfaces. Variable-speed operation improves energy capture and reduces mechanical stress, but it requires an electrical interface capable of controlling generator torque and grid current across a broad speed range. Doubly fed induction-generator systems process only a fraction of rated power through the converter, which is economically attractive, whereas full-scale converter systems process the entire generator output and provide greater electrical decoupling.

Blaabjerg, Liserre and Ma [11] analyzed converter structures and semiconductor technologies for modern wind turbines, and Blaabjerg and Ma [12] identified full-scale converters, multilevel structures, reliability improvement and higher-voltage semiconductor technology as important development directions. The literature shows that converter selection in wind turbines is closely linked to generator type and turbine rating. As ratings increase, device thermal cycling, dc-link capacitor stress, fault ride-through capability and maintenance become as important as nominal efficiency.

The back-to-back voltage-source converter became a dominant reference architecture because it separates machine-side and grid-side control through a dc link. The machine-side converter can regulate torque and speed for maximum energy extraction while the grid-side converter controls dc-link voltage, active/reactive power and current quality. This functional decoupling is technically powerful, although it increases component count and causes the entire generated power to pass through semiconductor switches in full-scale systems [10]-[12].

A parallel development concerned modularity and multifunctional interfaces. Kramer and Chakraborty [5] argued that standardized modular power-electronic interfaces could reduce engineering cost while adding functions such as voltage/VAR support, power-quality conditioning and compatibility with multiple distributed-energy sources. Chakraborty [4] described the convergence of power converters, electrical drives and digital control as renewable penetration increased. These studies shifted the design target from a single conversion function toward a reusable electronic interface capable of energy management and grid support.

At the device level, Zhang and Tolbert [13] examined the efficiency impact of SiC technology in a full-scale wind-turbine frequency converter. The importance of this advance is broader than the specific wind application. Lower switching loss and higher permissible switching frequency can reduce filter and heat-sink requirements, changing the optimal relationship between semiconductor loss, passive-component size and converter power density. By 2015 SiC remained an emerging technology relative to silicon IGBTs, but the literature already showed its potential to alter converter architecture rather than merely replace an individual switch.

Table 1. Comparative characteristics of major converter families

Converter family	Main strength	Main limitation	Typical renewable use	Relative complexity
Conventional two-stage	Independent MPPT and dc-link control	Extra conversion stage and losses	PV strings, storage-fed inverters	Medium
Transformerless / integrated	High efficiency and power density	Leakage current and common-mode control	Residential and module-level PV	Medium-High
Multilevel	Low device stress, low dv/dt and harmonics	More devices and balancing requirements	Medium/high-power PV and wind	High
Z-/quasi-Z-source	Single-stage buck-boost inversion	Impedance-network design and control	Wide-input PV/wind interfaces	High

Back-to-back VSC	Full generator/grid decoupling	Two active bridges and dc-link components	Variable-speed wind systems	High
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Methodology

This work uses a structured comparative-review methodology rather than an experimental prototype. The review boundary was fixed at December 2015. Publications were retained when they (a) addressed power-electronic interfaces for PV, wind or renewable-energy integration; (b) described a converter topology, converter family, modulation/control method or semiconductor technology; (c) were peer-reviewed or issued by a recognized technical publisher; and (d) had a verifiable DOI. The final core set contains fourteen publications from 2003-2015, ensuring that every reference cited in the paper satisfies the required time limit.

Step 1 - Search and Screening Strategy

The search process was organized around the terms power electronics, renewable energy converter, photovoltaic inverter, transformerless inverter, multilevel inverter, Z-source inverter, wind turbine converter, module-integrated converter and silicon carbide. Titles and abstracts were first screened for direct relevance to renewable-energy power processing. Papers dealing only with semiconductor fabrication, motor drives unrelated to renewable generation, or grid studies without converter analysis were excluded. Duplicate review concepts were retained only when they contributed a distinct design dimension, such as PV leakage-current behavior, wind converter rating or wide-bandgap efficiency.

Step 2 - Converter Classification

Each study was mapped into one or more converter classes: dc-dc conversion, voltage-source/grid inverter, transformerless or module-integrated PV interface, multilevel converter,

impedance-source converter, back-to-back wind converter and advanced-semiconductor implementation. Classification was based on the dominant power-processing function rather than the renewable source alone. This avoids treating identical converter principles as unrelated merely because they appear in different applications.

Step 3 - Performance Criteria

Seven engineering criteria were used: conversion efficiency, voltage-gain capability, output power quality, semiconductor voltage/current stress, passive-component and switch count, control complexity, and scalability/reliability. Where a study reported quantitative measurements, standard definitions were retained: efficiency $\eta = (P_{out}/P_{in}) \times 100\%$; voltage gain $G = V_{out}/V_{in}$; and harmonic distortion $THD = [\sum (n \geq 2) V_n^2]^{1/2} / V_1$. For qualitative studies, the criteria were recorded as low, medium or high relative to conventional two-level two-stage conversion.

Step 4 - Application Matching

The converter classes were matched to application constraints. Low-power rooftop PV prioritizes efficiency, leakage-current control, compactness and independent MPPT. Utility PV emphasizes modularity, grid support, thermal management and medium-voltage scaling. Variable-speed wind systems require wide operating range, generator-side torque control and grid-side current control, while storage coupling requires bidirectional energy flow. A topology was considered favorable only when its technical advantages directly addressed the dominant constraints of the target application.

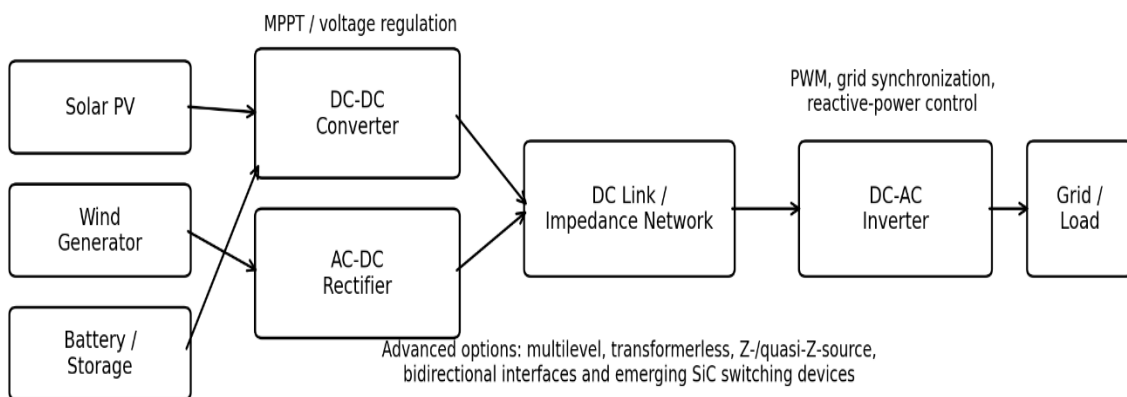


Figure 1. Generalized converter chain used for the comparative methodology.

Step 5 - Comparative Scoring

For transparent synthesis, each converter family was assigned an ordinal score from 1 (least favorable) to 5 (most favorable) for efficiency potential, power quality, voltage-range capability, component economy, controllability and scalability. The scores summarize recurring engineering tendencies reported in the literature and are not substitutes for prototype measurements. Equal weighting was used so that no single criterion, such as peak efficiency, could dominate the interpretation. The score matrix was then compared against the application-specific conclusions of the source studies [1], [2], [7], [9], [11]-[13].

Step 6 - Validity and Limitations

Three checks were used to limit bias. First, both broad review papers and topology-specific papers were included so that mature and emerging converter families were represented. Second, conclusions were based on repeated trends across multiple sources rather than on a single reported efficiency value. Third, the analysis distinguishes measured performance from qualitative design potential. The method does not perform a meta-analysis because test voltages, powers, switching frequencies, thermal conditions and grid standards differ substantially across the selected publications.

Results

The review indicates that the strongest advance up to 2015 was not a single new converter but the shift from generic conversion stages to application-optimized interfaces. In PV systems, string and module-level conversion increased localized MPPT, while transformerless and integrated step-up converters reduced magnetic components and conversion stages [1], [2], [6], [7], [14]. Their principal engineering challenge is common-mode behavior: removing the transformer eliminates galvanic isolation, so topology and modulation must prevent excessive leakage current while preserving grid-current quality.

Multilevel converters achieved the best qualitative balance for medium- and high-power

systems where low harmonic distortion and reduced device voltage stress are primary requirements. Their stepped voltage waveform allows smaller filters or lower switching frequency compared with two-level converters, but the advantage is exchanged for more semiconductor devices, isolated drivers and balancing states [9]. The method therefore rates multilevel structures high in power quality and scalability but lower in component economy and simplicity.

Z-source conversion scores highly in voltage-range capability because shoot-through states enable buck-boost operation without a separate conventional boost stage [8]. This is attractive for sources whose dc voltage changes substantially with irradiance, temperature or operating speed. Nevertheless, its impedance network and nontraditional modulation increase design complexity. For many mainstream PV products up to 2015, transformerless two-stage or integrated step-up arrangements had a stronger practical literature base [1], [2], [7].

For wind systems, the full-scale back-to-back voltage-source converter provides the highest controllability because the generator is electrically decoupled from the grid. This enables wide-speed operation, independent active/reactive power regulation and compliance with grid requirements [10]-[12]. The cost is that the entire generated power passes through the converter. The literature trend therefore suggests that higher-rated wind turbines increasingly benefit from improved converter packaging, thermal design and multilevel arrangements rather than from minimizing converter rating alone.

The device-level result is equally important. The SiC study of Zhang and Tolbert [13] showed that wide-bandgap switching devices can reduce losses in a full-scale wind converter, supporting higher switching frequency and smaller passive components. Up to 2015 this represented an emerging rather than universally adopted solution, but it changed the converter-design trade space: higher frequency could be pursued without the same switching-loss penalty associated with conventional silicon devices.

Table 2. Literature-based comparative score (1 = low, 5 = high)

Family	Efficiency	Power quality	Voltage range	Economy	Control	Scalability
Two-stage	4	3	4	3	5	4
Transformerless	5	4	3	4	4	3
Multilevel	4	5	4	2	3	5
Z-source	4	3	5	3	3	3

Back-to-back VSC	4	5	4	2	5	5
SiC-enabled*	5	4	4	3	4	4

Overall, conventional two-stage converters rank highest for design maturity and control separation; transformerless/integrated converters rank highest for compact PV efficiency; multilevel converters rank highest for power quality and voltage scaling; impedance-source converters rank highest for single-stage voltage-range capability; and back-to-back converters rank highest for wind-system controllability. No family ranks highest across all criteria. This supports a multi-criteria topology-selection process rather than selection based on peak efficiency alone.

Conclusion and Discussion

Power-electronic converter development up to 2015 transformed renewable-energy systems from passive energy sources into controllable grid-interfaced resources. The literature shows a clear movement toward fewer conversion stages, higher voltage gain, transformerless operation, multilevel waveforms, impedance-source energy processing, modular interfaces and advanced semiconductor devices. PV research emphasized compact transformerless and module-level conversion [1], [2], [6], [7], whereas wind research emphasized full-scale controllability, multilevel scaling and converter reliability [10]-[13]. The Z-source concept [8] broadened the available single-stage buck-boost alternatives, while modular-interface research [5] highlighted the importance of standardized, multifunctional power-electronic building blocks.

Design Implications

A practical selection sequence follows directly from the results. The designer should first determine source voltage range and isolation requirements, then establish the required power level and grid voltage, and only then select conversion stage count and semiconductor rating. For low-power PV, transformerless or module-integrated architectures are attractive when leakage-current limits can be satisfied. For higher-voltage renewable plants, multilevel structures become favorable when reduced dv/dt and semiconductor stress justify the extra hardware. For sources with unusually wide input-voltage range, impedance-source or high-step-up conversion can reduce the need for separate boosting stages. In wind systems, full-scale back-to-back conversion is justified when generator decoupling, reactive-power control and grid-code compliance dominate converter cost.

Converter optimization should also consider the interaction between switching frequency and passive components. Increasing frequency usually reduces inductor and filter size, but conventional silicon devices may incur higher switching losses. The SiC evidence available before the review boundary [13] indicates that advanced semiconductors can shift this trade-off toward higher power density. Therefore, topology and semiconductor selection should not be performed independently; the optimal circuit may change when switching-loss characteristics, thermal limits and packaging technology change.

Discussion of Reliability and Grid Integration

Reliability emerges as a cross-cutting issue because renewable converters are exposed to variable mission profiles. PV inverters experience daily temperature cycling and irradiance-dependent loading, while wind converters experience power fluctuations and mechanical-electrical transients. A topology with excellent laboratory efficiency may be less attractive if it increases the number of thermally stressed semiconductor junctions or electrolytic capacitors. Similarly, a converter that minimizes hardware may require a more aggressive switching pattern or higher common-mode voltage. The comparative method therefore treats reliability and controllability as design criteria equal in importance to efficiency.

Grid integration also changes the role of the converter. The grid-side stage is not merely an inverter that transfers real power; it may regulate reactive power, support voltage, synchronize under disturbed conditions and limit harmonic injection. Full-scale wind converters and advanced PV inverters therefore act as controllable grid interfaces. This trend explains why modular control, digital modulation and multifunctionality appear repeatedly in the literature [1], [5], [10]-[12].

Limitations and Future Research

The study is intentionally limited to publications available up to 2015 and therefore does not evaluate later commercial penetration of wide-bandgap devices, grid-forming control, modular multilevel converters at very high ratings, or modern multiport energy-storage interfaces. In addition, direct numerical comparison is restricted because the reviewed papers use different power levels, dc-link voltages, switching frequencies, cooling conditions and test standards. The ordinal scoring should

therefore be interpreted as a design aid rather than a universal ranking.

Within the stated period, the most defensible design principle is application-specific co-optimization of topology, semiconductor technology, modulation, thermal management and control. Future investigations extending beyond 2015 should use common mission profiles and standardized loss models so that converter efficiency, lifetime, power density and cost can be compared on a consistent basis.

Step-by-Step Converter Selection Procedure

Step 1 - Define the renewable source and electrical range. Record the minimum and maximum source voltage, current, rated power and expected variability. PV systems require irradiance- and temperature-dependent dc-voltage limits; wind systems require generator speed and frequency ranges; storage systems additionally require charge and discharge operation.

Step 2 - Decide whether galvanic isolation is mandatory. If safety, grounding, or installation rules require isolation, an isolated dc-dc stage or transformer-based interface should be retained. If isolation is not mandatory, transformerless PV structures can reduce losses, cost and mass, provided leakage-current and common-mode constraints are satisfied [2], [7].

Step 3 - Select the required voltage-conversion capability. A narrow dc range can be handled by a conventional boost stage followed by an inverter. A wide input range may justify high-step-up or impedance-source conversion. When simultaneous buck and boost operation is required, the Z-source principle is a candidate because shoot-through states create the required voltage-boost function [8].

Step 4 - Match topology to power level and grid voltage. Two-level structures remain attractive at low and moderate voltage because of their maturity and simple control. As voltage and power increase, multilevel converters become more attractive because device blocking stress, dv/dt and harmonic content can be reduced [9].

Step 5 - Evaluate control and grid-support requirements. Applications requiring independent generator control, dc-link regulation, reactive-power control and strong grid-code support favor back-to-back voltage-source conversion. This is particularly important in variable-speed wind systems, where machine-side and grid-side functions must be decoupled [10]-[12].

Step 6 - Select semiconductor technology and switching frequency together. The switching device should not be chosen after the topology is fixed. SiC devices can reduce switching and conduction losses and may permit higher frequency, which can lower passive-component volume [13]. The final choice must still include thermal design, gate-drive requirements and cost.

Step 7 - Compare whole-system trade-offs before final selection. The final decision should use efficiency, harmonic quality, component count, voltage stress, reliability, controllability, cooling burden and maintenance as simultaneous criteria. A converter should be selected because it best satisfies the application mission profile, not because it produces the highest value for one isolated metric.

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