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Evolution of Wind Power Electronics and a Converter-Demand Forecast in WECS

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Abstract :
The rapid expansion of wind generation and the increasing scale of individual turbines are shifting power-electronic converters from auxiliary interfaces to the central components of wind energy conversion systems (WECS). This article examines the progression from fixed-speed and partially rated doubly fed induction generator systems to full-scale converter architectures, medium-voltage multilevel converters, modular offshore collection networks, and grid-forming wind plants. The comparative analysis addresses the advantages and limitations of two-level voltage-source converters, three-level neutral-point-clamped and T-type converters, cascaded H-bridge converters, and modular multilevel converters, alongside silicon insulated-gate bipolar transistor and wide-bandgap semiconductor technologies. The review of control strategies encompasses vector control, direct torque and power control, maximum-power-point tracking, model predictive control, sliding-mode control, fuzzy logic, artificial neural networks, fault ride-through, and grid-forming functionalities. A reproducible forecasting framework integrates an exponential numerical model and a compact multilayer-perceptron model, calibrated using the 2024-2030 installation series reported by the Global Wind Energy Council (GWEC). To prevent unconstrained extrapolation, a saturation guard and three post-2030 scenarios are implemented. The base scenario projects annual wind additions of approximately 270 GW in 2035 and 305 GW in 2040. Based on explicit assumptions regarding Type-4 turbine penetration and converter ratings, converter-equivalent demand is projected to increase from 140 GW per year in 2026 to 273 GW per year in 2040, while multilevel converter demand is expected to rise from 56 to 202 GW per year. The analysis identifies reliability, thermal management, grid-code compliance, cybersecurity, converter-dominated system stability, critical material exposure, and model standardization as primary research priorities. The forecast serves as a technology-planning index rather than a commercial market valuation and should be revised as actual installation data and turbine architecture distributions become available.
Keywords: *wind energy conversion system; power electronics; multilevel converter; modular multilevel converter; grid-forming control; wide-bandgap semiconductor; neural network; market forecasting.*

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I. INTRODUCTION

Wind energy has transitioned from a mechanically dominated generation technology to a converter-dominated cyber-physical system. The Global Wind Reports for 2024, 2025, and 2026 document record-setting installations, an expanding offshore project pipeline, and ongoing pressure to accelerate grid connections [1]-[3]. The most recent GWEC outlook projects 969 GW of new capacity additions between 2026 and 2030, averaging 194 GW per year, with offshore installations expected to total 129 GW during the same period [3].

The International Energy Agency (IEA) also forecasts robust growth, although factors such as permitting, network queues, supply-chain constraints, inflation, and project bankability continue to influence the development trajectory [4].

This expansion fundamentally alters the engineering challenges associated with wind energy systems. Increases in rotor diameter and generator ratings elevate requirements for voltage, current, insulation, thermal cycling, and fault energy management. At the plant level, power converters are now required to deliver active and reactive power control, voltage regulation, harmonic compliance, low- and high-voltage ride-through, frequency support, synthetic inertia, oscillation damping, and, in weak networks, grid-forming capabilities.

Communication systems increasingly coordinate turbines, plants, offshore substations, HVDC terminals, storage units, and supervisory controllers. Consequently, latency, interoperability, time synchronization, cybersecurity, and fail-safe local control have become central engineering concerns.

Recent literature has separately reviewed high-power renewable converters [5], multi-megawatt generator-converter configurations [6], multilevel doubly-fed induction generator (DFIG) interfaces [7], wide-bandgap devices [8], wind-conversion topologies [9], wind energy conversion system (WECS) control [10], synchronous-generator systems [11], and cascaded multilevel implementations [12].

This study integrates these research strands and introduces a transparent demand index that connects projected wind capacity additions to the rated power processed by converters and to the anticipated share of multilevel technologies. The main contributions are: (i) a technology evolution map; (ii) a comparative analysis of architectures and control strategies; (iii) a combined numerical and neural forecast through 2040; and (iv) a research agenda linking converter design with grid services and communication requirements.

II. THEORETICAL BACKGROUND

2.1 Aerodynamic and electromechanical conversion

The captured aerodynamic power is:

$$P_t = 0.5\rho A C_p(\lambda, \beta) v^3 \qquad (1)$$

$$\lambda = \frac{\omega_t R}{v} \qquad (2)$$

where ρ is air density, A is swept area, C_p is the power coefficient, λ is tip-speed ratio, β is pitch angle, v is wind speed, ω_t is turbine speed, and R is blade radius. Below rated wind speed, the controller seeks $\lambda \approx \lambda_{opt}$ and maximum C_p; above rated speed, pitch and torque regulation limit mechanical and electrical loading. The cubic wind-speed relation explains both the value of fast maximum-power-point tracking (MPPT) and the high stochastic stress imposed on the drive train and dc link.

2.2 WECS generations and converter rating

Type-1 and Type-2 turbines connect induction generators almost directly to the grid, providing only limited variable-speed operation. Type-3 turbines employ a doubly-fed induction generator (DFIG) with a rotor-side converter rated for slip power, typically a fraction of the machine's total rating. This configuration reduces converter cost and losses but retains the use of brushes and slip rings, resulting in stator-side vulnerability to grid disturbances. Type-4 turbines decouple the generator from the grid using a full-scale converter, which enables a wide speed range, robust fault control, and increased generator flexibility, although it requires processing all generated power. Large offshore wind turbines are increasingly adopting permanent-magnet synchronous generators and full-scale conversion, as enhanced controllability and reduced drivetrain maintenance can justify the higher converter cost [6], [11].

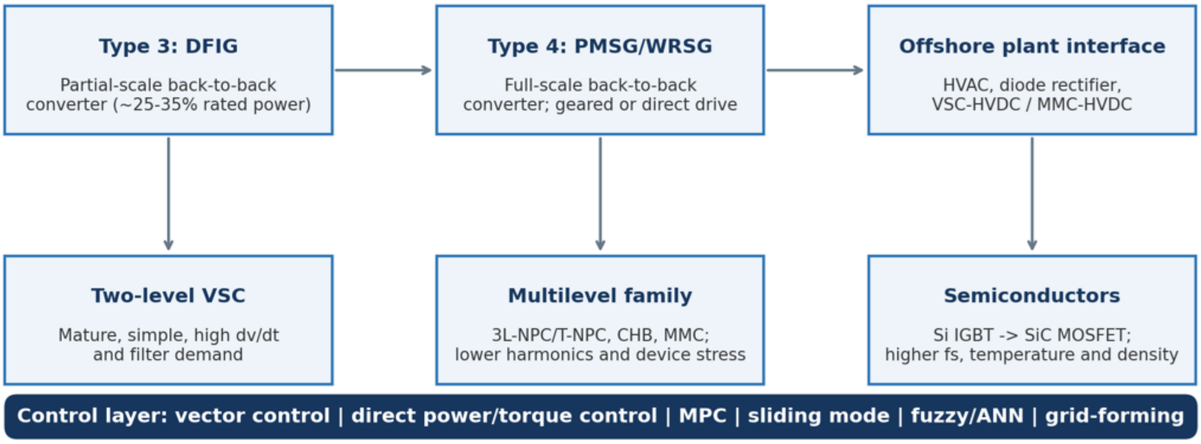

Fig. 1. Technology families linking turbine architecture, converter topology, semiconductor platform, and control layer

2.3 Converter and semiconductor families

The two-level back-to-back voltage-source converter is widely regarded as the reference architecture due to its maturity, compactness, and controllability. For multi-megawatt applications, however, challenges such as high device voltage stress, common-mode voltage, switching losses, dv/dt, and filter requirements drive the adoption of multilevel converter solutions. Three-level neutral-point-clamped (3L-NPC), active-NPC, and T-type converters distribute blocking voltage and enhance waveform quality, although issues related to neutral-point balancing and unequal loss distribution must be addressed. Cascaded H-bridge (CHB) converters provide modularity and a high number of voltage levels but necessitate isolated sources or multiphase machines.

Modular multilevel converters (MMCs) are prevalent in VSC-HVDC applications due to their scalability, low harmonic distortion, redundancy, and distributed energy storage. Nevertheless, challenges such as submodule count, circulating currents, capacitor energy control, and protection complexity remain significant [5], [7], [12].
Silicon IGBTs are currently the dominant technology in high-power wind energy conversion. Silicon-carbide MOSFETs offer advantages such as reduced switching losses, higher junction temperature and frequency operation, smaller filter requirements, and improved power density. However, factors including cost, short-circuit withstand time, gate-drive sensitivity, insulation stress, and packaging reliability limit their immediate adoption. Hybrid silicon/silicon-carbide approaches and selective implementation in auxiliary converters or high-frequency stages represent feasible transitional strategies [8].

Table 1. Converter and semiconductor families. Advantages and limitations

Family	Principal advantages	Principal limitations	Best-fit wind role
2L-VSC	Maturity; simple control; established supply chain	High dv/dt; larger filters; device stress	Low/medium voltage Type-3 and Type-4
3L-NPC / ANPC	Lower THD and device stress; medium-voltage suitability	Neutral-point balance; unequal losses; more parts	Multi-MW full-scale converter
T-type	High efficiency at moderate switching frequency	Device-voltage asymmetry; protection complexity	High-efficiency medium-voltage interface
CHB	Modular; many levels; fault bypass potential	Isolated dc sources or multiphase generator	Medium-voltage generator-side conversion
MMC	Scalable voltage; excellent waveform; redundancy	Capacitor energy, circulating current, protection	Offshore HVDC and future integrated collection grids

III. DEVELOPMENT: ARCHITECTURES, CONTROL, AND FORECASTING METHOD

3.1 Architecture evolution

Current architectural trends are shifting from minimum converter ratings toward enhanced controllability. Onshore fleets continue to rely heavily on doubly-fed induction generator (DFIG) systems, as partial-scale conversion provides favorable capital costs and efficiency. However, new large turbines, especially those deployed offshore, increasingly employ full-scale conversion. The forthcoming development is not characterized by a single dominant circuit, but rather by a suite of modular medium-voltage solutions. These include multilevel machine-side converters, direct current (DC) collection options, offshore diode rectifier units for cost-effective transmission, and modular multilevel converter high-voltage direct current (MMC-HVDC) terminals capable of forming offshore alternating current (AC) networks. Co-located energy storage can be integrated at turbine DC links, array hubs, or the onshore point of common coupling. The choice of storage location significantly affects semiconductor utilization, protection boundaries, and communication requirements.

3.2 Control hierarchy and algorithms

Conventional cascaded vector control continues to serve as the industrial benchmark. Fast inner current loops regulate direct-quadrature (dq) currents, while outer loops control dc voltage, active and reactive power, generator speed, or terminal voltage. Direct torque control and direct power control reduce the number of transformation and modulation layers; however, these methods may increase current or torque ripple unless predictive or multilevel switching strategies are implemented. Maximum power point tracking (MPPT) typically utilizes optimal torque, tip-speed-ratio, perturb-and-observe, power-signal feedback, or intelligent estimator techniques.

Model predictive control (MPC) explicitly manages multivariable constraints and discrete switching states, which makes it suitable for multilevel converters and doubly-fed induction generators (DFIGs) [13], [14]. However, MPC is limited by computational complexity, sensitivity to model accuracy, weighting-factor selection, and variable switching frequency in finite-control-set implementations. Sliding-mode control provides robustness to parameter variations but requires effective chattering mitigation strategies [15]. Fuzzy and neural controllers can model nonlinear relationships and accommodate uncertain wind conditions. Nevertheless, issues such as stability certification, training-domain coverage, sensor faults, dataset shift, interpretability, and real-time execution must be resolved prior to safety-critical deployment. Neural direct-power control demonstrates the performance potential of data-driven control approaches [18].

Grid-forming control represents a strategically significant transition in converter operation. Instead of tracking a measured grid angle via a phase-locked loop, a grid-forming converter establishes voltage magnitude and frequency based on droop control, virtual synchronous machine principles, matching control, dispatchable virtual oscillator control, or related methodologies. Demonstrations with Type-4 turbines indicate that converter and dc-link dynamics, current limiting, turbine energy buffers, and fault ride-through capabilities must be co-designed for optimal performance [16], [17]. Recent reviews published in 2025 synthesize the rapidly expanding set of grid-forming control strategies [19].

Table 2. Control families. Strengths and main chalenges

Control family	Strength	Main challenge	Recommended use
Vector PI/PR	Mature, fixed-frequency, certifiable	Gain scheduling; weak-grid interaction	Baseline inner loops and grid-following operation
DTC/DPC	Fast torque/power response	Ripple and variable switching	Fast generator or grid power control
MPC	Constraints and multilevel states handled directly	Computation and model mismatch	High-performance multilevel conversion
Sliding mode	Strong robustness	Chattering; noise sensitivity	Fault/disturbance rejection
Fuzzy / ANN	Nonlinear mapping and adaptation	Certification, data shift, explainability	Supervisory MPPT, estimation, tuning
Grid-forming	Voltage/frequency establishment and black-start potential	Current limiting and large-signal stability	Weak grids, islands, offshore hubs

3.3 Forecast definition and assumptions

The response variable y_t is annual global wind capacity added (GW/year). The calibration vector is {117.0, 164.6, 178.0, 186.5, 193.3, 199.9, 211.8} for 2024-2030. The first value is reported for 2024, the second is the 2025 value presented in the 2026 report, and 2026-2030 are GWEC outlook values [2], [3]. The dataset therefore mixes one historical observation, a subsequently reported value, and policy-based projections; this is appropriate for a planning index but insufficient for causal inference. Model A is exponential growth and it is estimated by nonlinear least squares and indicated in Eq. (3). Model B is a compact multilayer perceptron (MLP) with two hidden layers (6 and 3 tanh neurons), standardized time input, L2 regularization α = 0.02, deterministic seed 17, and L-BFGS optimization. The ensemble is given by Eq. (4):

$$\hat{y}_{exp}(t) = ae^{bt} \qquad (3)$$

$$\hat{y}_{ens}(t) = 0.65\hat{y}e^{t} + 0.35\hat{y}_{MLP}(t) \qquad (4)$$

Because unconstrained exponential and neural extrapolations can become physically implausible, the post-2030 base path applies a smooth saturation guard approaching 360 GW/year. Low and high scenarios use 2.5% and 6.0% annual growth after 2030. These bounds are not probabilistic confidence intervals; they represent technology-planning scenarios. Converter-equivalent demand DPE is derived from annual additions W, the share s4 of Type-4 turbines, and the partial converter rating r3 = 0.33 for Type-3 turbines:

$$DPE(t) = W(t)\left[s_4(t) + 0.33\left(1 - s_4(t)\right)\right] \qquad (5)$$

The Type-4 share rises from 0.68 in 2026 to 0.84 in 2040. Multilevel-equivalent demand is given by Eq. (6), with sML increasing from 0.40 to 0.74. These shares are transparent engineering assumptions motivated by larger turbine ratings, medium-voltage conversion, and offshore growth—not observed vendor market shares. A sensitivity analysis should replace them when proprietary shipment data become available.

$$DML(t) = DPE(t)sML(t) \qquad (6)$$

IV. RESULTS

The in-sample ensemble fit produces RMSE = 15.88 GW and MAPE = 7.59%. These values describe agreement with a seven-point mixed actual/outlook series; they do not constitute independent predictive validation. The exponential parameters are a = 143.16 and b = 0.0708 year^{-1}.

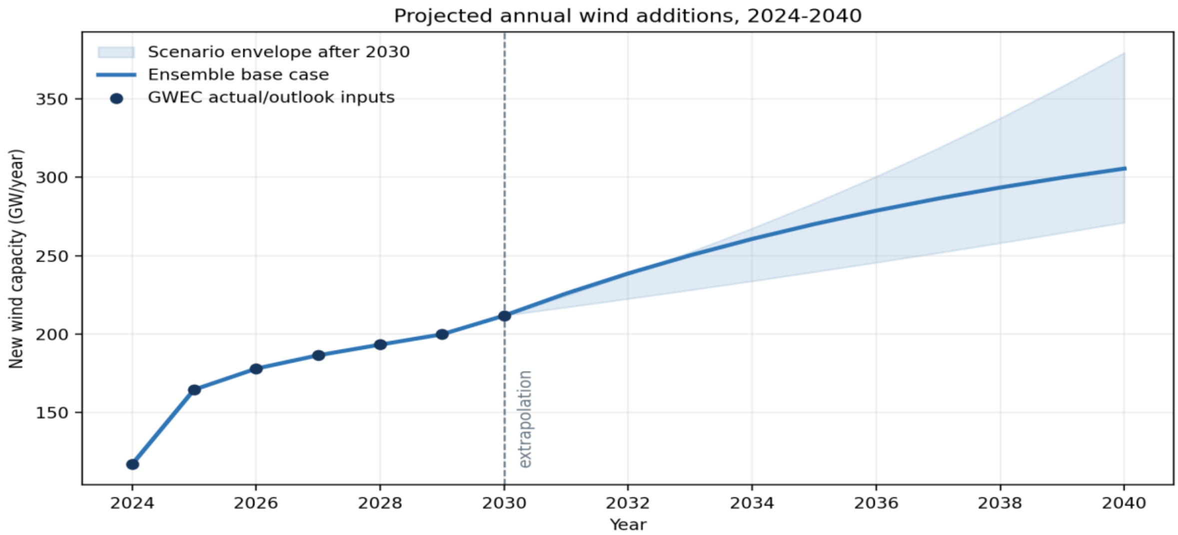

Fig. 2. Annual wind-capacity additions and post-2030 scenario envelope. The 2024-2030 points are taken from GWEC reports; 2031-2040 values are model-derived.

Table 3. Forecast and derived converter-demand index. W, DPE, and DML are in GW-equivalent/year. Low and high cases diverge only after 2030.

Year	Low W	Base W	High W	Type-4	DPE	ML share	DML
2026	178.0	178.0	178.0	68%	139.8	40%	55.9
2030	211.8	211.8	211.8	73%	173.5	51%	88.5
2035	239.6	270.1	283.4	79%	232.1	64%	148.5
2040	271.1	305.5	379.3	84%	272.7	74%	201.8

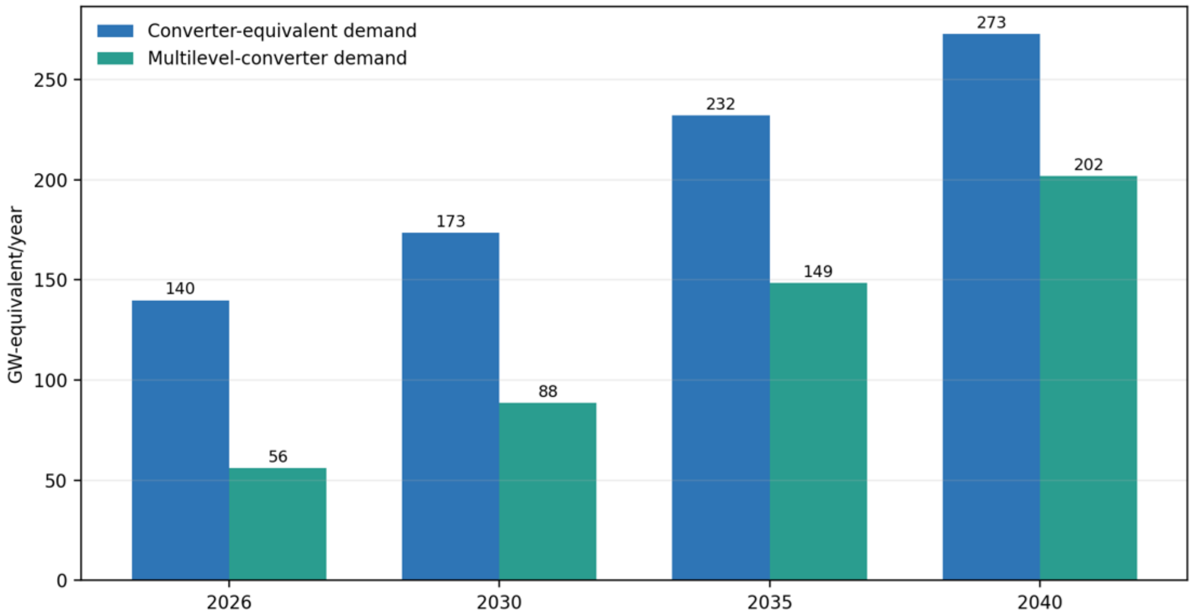

Fig. 3. Derived converter-equivalent and multilevel-converter demand under the base scenario.

The base scenario projects approximately 270 GW per year of wind capacity additions by 2035 and 305 GW per year by 2040. Under the specified architecture assumptions, the proportion of new turbine ratings processed by power converters increases from 78.6% in 2026 to 89.3% in 2040. As a result, converter-equivalent demand grows at a faster rate than wind capacity additions alone. The multilevel index increases more significantly due to simultaneous expansion in both the wind market and the assumed multilevel share.

V. FINDINGS AND COMMENTS

5.1 Interpretation of the technology trajectory

The forecast serves as an indicator of engineering workload. Each additional gigawatt necessitates semiconductor dies and modules, gate drivers, laminated busbars, capacitors, cooling hardware, sensors, controllers, filters, protection systems, software, qualification tests, and maintenance resources. The transition to full-scale and multilevel conversion suggests that demand for these subsystems may increase even if the annual rate of turbine installations slows. Offshore projects further intensify this effect by requiring medium-voltage turbine converters, array-grid compensation, offshore substations, and HVDC terminals.

No single converter topology is expected to dominate across all power ratings. Two-level converters maintain cost and service advantages at lower voltages. Three-level NPC/ANPC and T-type systems represent credible near-term solutions for multi-megawatt turbines. CHB architectures are advantageous when generator winding segmentation provides isolated cells. MMCs are particularly relevant where conversion and transmission functions are integrated; however, adoption of MMCs at the turbine level depends on factors such as component count, stored energy, protection, and maintenance economics. Consequently, fault-tolerant modulation, cell bypass, health monitoring, and remaining-useful-life estimation have become central research topics. Recent studies review the available fault-tolerance strategies [20].

5.2 Control and communications implications

Future wind plants are expected to integrate fast local control loops with slower distributed optimization processes. Protection and current control functions must remain local and deterministic. Plant-level optimization of voltage, frequency, congestion, wake effects, storage, and market participation can be achieved through networked coordination, provided that systems are designed to degrade gracefully in the event of packet loss or latency. IEC 61850-based substation communication, time-sensitive networking, synchronized measurement, digital twins, and secure over-the-air software management warrant joint investigation alongside converter control. Cybersecurity measures must encompass authentication, least privilege, signed firmware, anomaly detection, and a physically safe fallback, rather than relying solely on encrypted communications.

Artificial intelligence is most effective when it augments, rather than replaces, certified control systems. Near-term applications include wind and torque estimation, adaptive maximum power point tracking (MPPT) references, semiconductor-junction temperature estimation, predictive maintenance, gain scheduling, fault classification, and surrogate modeling within model predictive control (MPC). Safety assessments should quantify training coverage, uncertainty, out-of-distribution detection, deterministic execution time, and the stability of the surrounding closed loop. A neural controller that enhances nominal tracking but does not exhibit bounded behavior during faults is not suitable for deployment.

5.3 Advantages and challenges

The primary physical failure mechanisms include power cycling, thermal cycling, humidity and salt contamination, vibration, cosmic-ray-induced failures at high blocking voltage, partial discharge, capacitor degradation, and cooling-system faults. Consequently, converter designs should prioritize optimizing lifetime energy yield rather than focusing solely on rated-point efficiency. Implementing mission-profile-based reliability, active thermal control, modular replacement, and standardized field data collection can significantly enhance system availability.

Table 4. Advantages and challenges

Dimension	Advantages enabled by advanced power electronics	Persistent or emerging challenges
Energy capture	Variable speed, MPPT, reduced mechanical stress	Sensor/model error; turbulence; wake interaction
Grid support	Reactive power, FRT, synthetic inertia, grid forming	Weak-grid stability; current limiting; interoperability
Power quality	Lower THD, controllable switching, multilevel waveforms	Common-mode voltage; EMI; filter resonance
Reliability	Redundancy, condition monitoring, fault bypass	Thermal cycling; capacitor aging; offshore access
Economics	Higher turbine rating and reduced balance-of-plant cost	Semiconductor/material cost; supply-chain concentration
Digital operation	Remote optimization, digital twins, predictive maintenance	Cybersecurity; latency; data governance; certification

5.4 Limitations of the Forecast and Validation Plan

The forecast is subject to four principal limitations. First, the use of seven annual data points does not allow for the identification of structural breaks, regional heterogeneity, turbine repowering, or policy cycles. Second, five of these points represent outlook values rather than actual observations. Third, Type-4 and multilevel shares are based on assumptions due to the limited availability of public shipment data by topology. Fourth, the demand index reflects GW-equivalent processed power rather than unit shipments, semiconductor area, revenue, or installed cost. For example, a 20-MW offshore converter and multiple smaller onshore converters may process the same power rating but generate different component demand.

Annual updates to the model using rolling-origin validation are recommended. Each newly realized year should replace the corresponding forecast point, enabling direct comparison of exponential, Gompertz, grey GM(1,1), gradient-boosting, and recurrent models under consistent validation folds. Incorporating regional features such as auction awards, grid-connection queues, turbine ratings, offshore share, interest rates, commodity prices, and policy indicators would facilitate causal or panel-data extensions. Access to vendor or customs shipment data would enable conversion from GW-equivalent processed power to modules, wafers, passive components, and revenue.

VI. CONCLUSION

Power electronics serves as the critical layer influencing wind energy capture, turbine fault tolerance, and the ability of converter-dominated grids to maintain voltage and frequency. The field is advancing from partial-scale doubly-fed induction generator (DFIG) interfaces to full-scale conversion, medium-voltage multilevel architectures, wide-bandgap (WBG) enhanced switching, modular offshore networks, and grid-forming control. While conventional vector control remains significant, predictive, robust, and data-assisted control methods are expected to play a growing role around certified inner control loops.

The numerical-neural planning model forecasts an annual addition of approximately 270 GW of new wind capacity by 2035 and 305 GW by 2040. Under explicit assumptions regarding Type-4 and multilevel converter architectures, converter-equivalent demand is projected to reach about 273 GW per year, while multilevel-equivalent demand is estimated at 202 GW per year by 2040. These figures represent conditional scenarios rather than sales forecasts. The primary contribution of this analysis is the transparent equation that links deployment rates, architecture shares, and processed converter power.

Future research priorities include lifetime-oriented converter design, direct current (DC) fault protection, grid-forming fault ride-through, stability in mixed grid-following and grid-forming systems, interoperable plant controls, cyber-resilient communications, wide-bandgap (WBG) device packaging, modular maintenance strategies, and the development of open reliability datasets. An effective research program should address the turbine converter, communications network, offshore transmission interface, and power-system service as components of a single integrated system.

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