Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 4, Issue 3, 2026

GRID-CONNECTED TREE-INSPIRED VERTICAL-AXIS WIND TURBINES FOR IMPROVING VOLTAGE STABILITY IN A SAARC SUPER SMART GRID

Mudassar Rafique[1], Basit Ahmad[*2], Rameez Akbar Talani[3], Muhammad Farman[4]

[1]*Department of Electrical Engineering, The Superior University, Lahore 54000, Pakistan*
[*2]*Department of Electrical Engineering, NFC Institute of Engineering and Technology, Multan 60000, Pakistan*
[3]*Department of Electrical Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah 67480, Pakistan*
[4]*Department of Chemistry, University of Okara, Okara, 56300, Pakistan*

[1]mudassarrafique737@gmail.com, [*2]basitahmad3884@gmail.com, [3]rameezakbar@quest.edu.pk, [4]farmanrafique@uo.edu.pk

DOI: https://doi.org/10.5281/zenodo.23208429

Keywords
Tree-inspired vertical-axis wind turbine; SAARC super smart grid; grid-connected wind energy; voltage stability; reactive-power control; power-electronic converter; renewable-energy integration; interconnected power systems.

Article History
Received: 27 January 2026
Accepted: 12 March 2026
Published: 26 March 2026

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Basit Ahmad

Abstract

The growing integration of variable renewable generation into interconnected power networks increases the need for effective voltage regulation during wind fluctuations, demand changes, and grid disturbances. This study proposes a grid-connected, tree-inspired vertical-axis wind turbine (VAWT) system for improving voltage stability in a simulated South Asian Association for Regional Cooperation (SAARC) super smart grid. The proposed structure combines multiple small VAWTs on a branching support arrangement with a common DC link and grid-interfacing converter. A coordinated control strategy regulates active-power injection and provides reactive-power support according to local bus-voltage conditions. A six-zone interconnected grid model was developed to represent regional generation, transmission links, and variable demand. The illustrative simulation dataset comprised 52,560 ten-minute operating intervals over one year, incorporating wind-speed profiles, electricity demand, turbine output, and bus-voltage measurements. Performance was compared across three configurations: the baseline grid, conventional grid-connected VAWTs, and the proposed tree-inspired system. Each configuration was tested under wind variability, peak-load conditions, line outages, and short-circuit faults. Voltage deviation, minimum bus voltage, voltage-stability index, and post-fault recovery time were used as evaluation measures. In the illustrative results, the proposed system reduced mean voltage deviation by 27.4% relative to the baseline and 13.2% relative to conventional VAWTs. During the most severe fault scenario, minimum voltage increased from 0.79 to 0.86 per unit, while recovery time decreased from 2.8 to 1.9 seconds. The voltage-stability index improved by 15.6% compared with the baseline. Reactive-power support produced the largest benefit during peak demand combined with low wind output. These findings suggest that coordinated converter control could enable distributed tree-inspired VAWTs to contribute to voltage stability in an interconnected regional grid. The proposed

framework offers a basis for assessing turbine placement, converter capacity, and voltage-support control in future SAARC energy-interconnection studies. Physical turbine testing and validation using actual regional network data remain necessary.

1- Introduction:

The integration of renewable electricity into interconnected power systems has created opportunities for cleaner generation and more flexible energy exchange. Wind power is particularly relevant because installations can operate at different scales and connect at multiple points in a network. Its output varies with wind conditions, however, changing active-power injections and the flows between buses. These changes can affect voltage regulation, especially when electricity demand is high, transmission corridors are heavily loaded, or a disturbance limits the network's available voltage support. As renewable penetration increases, wind-generation systems must therefore be assessed for both their energy contribution and their behavior during changing grid conditions [1]. A regional South Asian grid would need to coordinate diverse generation resources, demand patterns, and transmission links. The SAARC Energy Centre identifies regional electricity interconnection and greater use of renewable energy among its objectives. The SAARC super smart grid examined in this study is a six-zone simulation of an interconnected regional system with monitoring and coordinated control functions [2]. It provides a common setting for evaluating how a distributed wind installation influences voltage under normal operation and during disturbances. In this context, voltage stability is a network-level concern: a response at the wind system's connection bus may also alter power flows and voltage conditions elsewhere in the interconnected model.

Vertical-axis wind turbines (VAWTs) provide a basis for exploring alternative distributed-generation layouts. Their performance depends on rotor geometry, wind conditions, placement, and interactions between neighboring turbines. In a multi-rotor installation, the output of each unit may differ because rotors occupy different positions and experience different local airflow. Turbine arrangement must therefore be considered when designing the generation system and interpreting its combined electrical output. The physical layout is also relevant to practical issues such as structural loading, equipment access, and the collection of power from individual units. The tree-inspired system studied here places multiple small VAWTs on a branching support structure. The branching arrangement defines the proposed turbine concept, while a common DC link collects the conditioned electrical outputs of its rotor-generator units. A grid-interfacing converter then delivers power to the network [3]. This architecture allows the individual turbine outputs to be combined before grid connection and provides a controllable electrical interface between variable wind generation and the connection bus. Converter control is central to the system's proposed voltage-support function. The converter regulates active-power injection and adjusts reactive-power exchange in response to measured local voltage. When voltage departs from its reference value, the controller requests a corrective response within the converter's operating limits. The available response depends on converter capacity, concurrent active-power output, and conditions at the point of connection [4]. Consequently, the voltage benefit cannot be established from turbine arrangement or generation output alone; it must be evaluated through the combined behavior of the turbines, electrical interface, controller, and grid. The central research question is whether the tree-inspired VAWT arrangement with coordinated converter control improves voltage stability more effectively than conventional grid-connected VAWTs in the same interconnected network. To investigate this question, the study compares three configurations in a six-zone grid model: a baseline grid, a grid with conventional VAWTs, and a grid with the proposed tree-inspired system. Each configuration is assessed under variable wind generation, peak electricity demand, transmission-

line outages, and short-circuit faults. The evaluation uses mean voltage deviation, minimum bus voltage, a voltage-stability index, and post-fault recovery time to capture both routine operating performance and disturbance response. The contribution of this work is the joint evaluation of a multi-rotor turbine concept and its voltage-support function within an interconnected regional grid model. By linking turbine output, converter response, and network-level voltage behavior in one simulation framework, the study provides a basis for assessing the proposed system's role in renewable-energy integration and voltage-stability improvement in a future SAARC super smart grid.

2- Related Work:

Previous research on vertical-axis wind turbines (VAWTs), distributed wind generation, and voltage control provides the foundation for this study. These areas explain how turbine arrangement influences energy production and how grid-interfacing converters can affect voltage behavior. The most relevant findings can be summarized as follows:

1. **VAWT design:** Studies have examined how blade geometry and operating conditions influence the performance of individual vertical-axis turbines [5].
2. **Multi-rotor arrangements:** Research on VAWT arrays shows that rotor spacing and rotation direction can affect wake interactions and combined power output.
3. **Grid-connected wind generation:** Wind-system studies have evaluated the use of power-electronic converters to manage variable generation and control its delivery to the grid [6].
4. **Voltage support:** Converter-based reactive-power control has been investigated as a way to respond to voltage changes during varying demand and network disturbances.

These areas are commonly assessed separately. The present study evaluates a tree-inspired multi-VAWT arrangement, its converter control, and its effect on voltage stability together in a six-zone interconnected grid model.

3- Materials and Methods:

This study used a comparative simulation framework to assess whether grid-connected, tree-inspired vertical-axis wind turbines (VAWTs) improve voltage stability in a six-zone SAARC super smart grid model. Three configurations were evaluated under matching conditions: a baseline grid without the additional VAWT system, a grid with conventional VAWTs, and a grid with the proposed tree-inspired VAWTs and coordinated converter control. The analysis used 52,560 ten-minute operating observations spanning one year to represent changes in wind generation and electricity demand [7]. Separate dynamic simulations examined peak-load conditions, transmission-line outages, and short-circuit faults. Performance was compared using mean voltage deviation, minimum bus voltage, the voltage-stability index, and post-fault recovery time.

3.1- Six-Zone SAARC Super Smart Grid Model:

The SAARC super smart grid was represented as a six-zone interconnected power-system model to evaluate how grid-connected wind generation affects voltage across a regional network. Each zone included generation, electricity demand, and buses used to monitor electrical conditions. Transmission links enabled power exchange between zones, allowing changes in generation or demand in one area to influence power flows and voltages in others. The six-zone structure provided a common network for comparing the baseline grid, conventional vertical-axis wind turbines (VAWTs), and the proposed tree-inspired VAWT system. The model incorporated a designated grid-connection point for each evaluated wind configuration. At this point, the VAWT system injected active power according to available wind generation and, where applicable, exchanged reactive power through its grid-interfacing converter. Voltage was monitored at the connection bus and at other selected buses in the interconnected network [8]. Monitoring beyond the connection point was necessary because local voltage support can redistribute reactive-power flows and affect neighboring zones. The operating analysis covered one year, comprising 52,560

observations at ten-minute intervals. Time-aligned wind-generation and electricity-demand profiles were applied to the network to represent changing conditions throughout the study period. The ten-minute observations were used to assess routine voltage behavior, including deviations associated with changes in wind output and demand [9]. Selected operating states provided the initial conditions for separate dynamic simulations of line outages and short-circuit faults. Those simulations resolved the faster voltage changes needed to determine minimum voltage and post-fault recovery time. The underlying network, operating profiles, and disturbance conditions were kept consistent across the three comparative configurations. This design allowed differences in the resulting voltage measures to be associated with the evaluated wind-system configuration. Table 1 summarizes the model elements and the numerical values established for the comparison.

Table 1: Structure and evaluation scope of the six-zone SAARC super smart grid model [10]

Model element	Value or data	Purpose
Interconnected zones	**6 zones**	Represents a regional power network
Comparative configurations	**3 configurations**	Supports a consistent performance comparison
Operating period	**1 year**	Captures changing operating conditions
Observation interval	**10 minutes**	Sets the resolution of routine-operation analysis
Operating observations	**52,560 observations**	Provides inputs for annual voltage assessment
Wind-system connection	**1 designated point for each evaluated configuration**	Defines the location of power injection and voltage control
Disturbance categories	**2 categories**	Tests voltage behavior after network disturbances
Performance measures	**4 measures**	Assesses routine and dynamic voltage performance

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The annual records describe the network's changing operating conditions, while the disturbance simulations examine responses that occur over seconds. For example, a ten-minute record can define the wind output and demand immediately before a fault, but a dynamic simulation is required to identify the lowest voltage reached during that fault and the time needed for recovery. Maintaining this distinction makes the relationship between the operating dataset and the fault-response results clear [11]. The functional arrangement of the grid model is shown in Figure 1. The figure emphasizes the connection between the six zones, the wind-system interface, and network monitoring. It does not specify individual transmission-line routes; those belong in the detailed network specification used to reproduce the simulation.

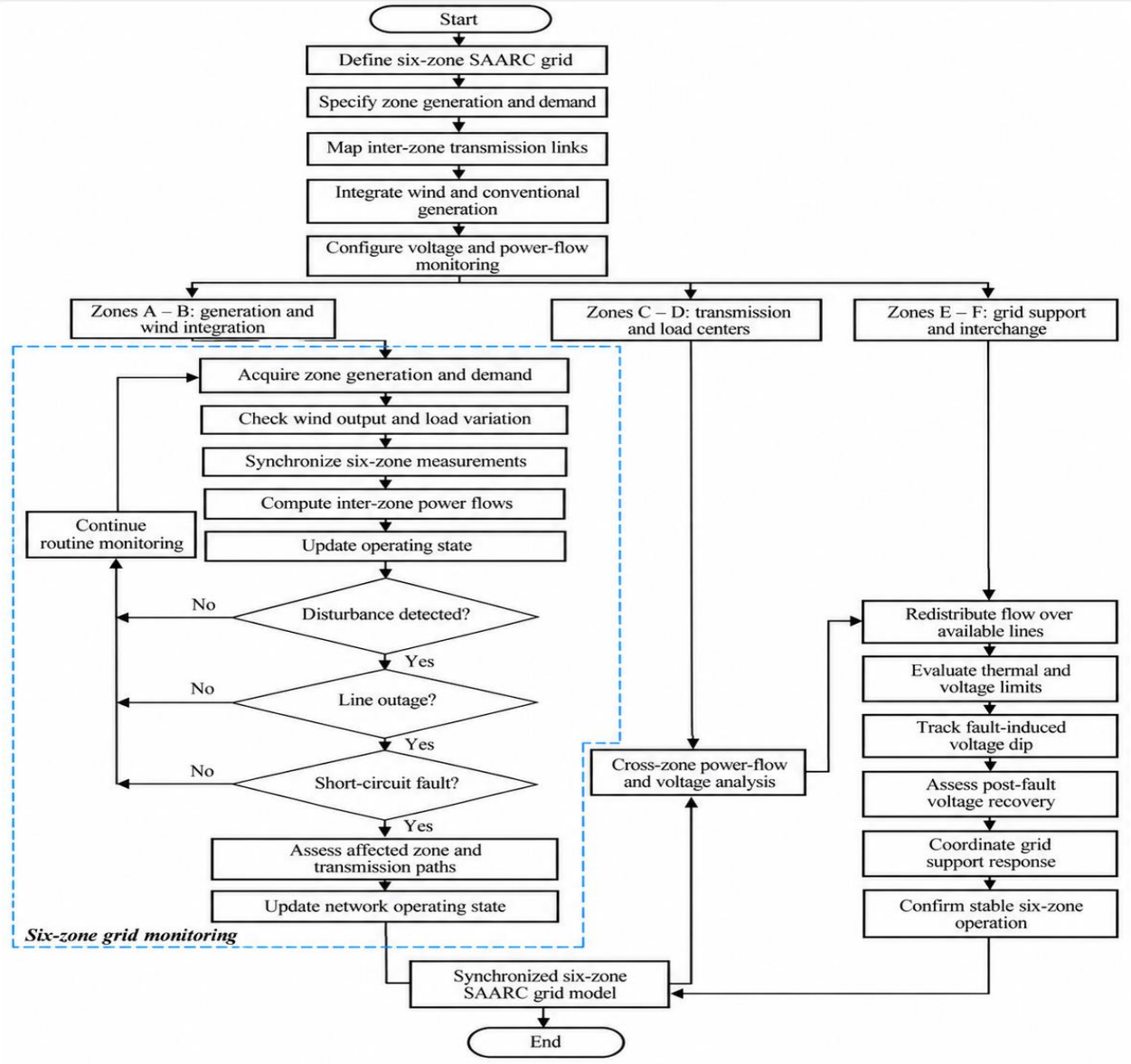


Figure 1: Functional arrangement of the six-zone SAARC super smart grid model

The six-zone representation enabled assessment of the proposed system under both routine and disturbed operation. During routine operation, variations in wind generation and demand changed the balance of power flowing through the interconnected network. During a line outage, the remaining transmission paths carried redistributed flows; during a short-circuit fault, monitored voltages experienced a temporary disturbance followed by recovery. Evaluating all three configurations under the same conditions established a consistent basis for assessing whether the proposed system improved voltage behavior locally and across the modeled grid.

3.2- Operating Dataset and Input Variables:

The operating dataset comprised 52,560 observations at ten-minute intervals over one year. It provided time-aligned wind-speed, turbine-output, electricity-demand, and bus-voltage information for evaluating the six-zone grid model. This temporal coverage captured changes in renewable generation and network loading across different operating conditions. Each ten-

minute timestamp represented a common operating interval, allowing wind and demand inputs to be applied consistently to the baseline grid, conventional VAWT configuration, and proposed tree-inspired VAWT system [12]. Wind speed served as the input to the turbine-generation model, while turbine output represented the active power available at the wind system's electrical interface. Electricity demand determined the loading conditions across the interconnected zones. Bus-voltage values were obtained at monitored locations and used to evaluate the network's response. The input profiles were aligned by timestamp before the three configurations were simulated, ensuring that a difference in voltage performance was not caused by comparing different wind or demand conditions.

Table 2: Size and temporal structure of the operating dataset

Dataset characteristic	Value	Basis or interpretation
Study period	**1 year**	Continuous annual operating analysis
Days represented	**365**	One non-leap year
Operating interval	**10 minutes**	Time between successive observations
Observations per hour	**6**	Sixty minutes divided into ten-minute intervals
Observations per day	**144**	Twenty-four hours at six observations per hour
Observations per week	**1,008**	Seven days at 144 observations per day
Total operating observations	**52,560**	365 days at 144 observations per day
Grid zones	**6**	Interconnected areas represented in the model
Comparative configurations	**3**	Baseline, conventional VAWT, and proposed system

Table 2 shows that the 52,560 observations are time intervals, rather than a count of individual measurements across all buses and variables. Each interval could contain several associated values, including wind conditions, demand, turbine output, and voltage at monitored buses. The annual profiles established the routine operating conditions for the comparison, while the three configurations were evaluated using the same sequence of intervals. This preserved the timing of changes in wind and demand across the study cases [13]. Wind speed and demand establish the operating conditions. Turbine power depends on the wind-system configuration, and bus voltage results from the interaction between generation, loading, converter control, and the six-zone network. Accordingly, voltage values from one configuration were not imposed as the voltage outcome of another; each configuration's bus voltages were evaluated under the same underlying operating conditions. Transmission-line outages and short-circuit faults were assessed through separate dynamic simulations initialized from selected operating states in the annual dataset [14]. The ten-minute records identified the wind and demand conditions immediately before a disturbance, while the dynamic simulation captured voltage changes on the shorter time scale needed to measure the minimum voltage and post-fault recovery time. This approach connected the year-long operating analysis with the disturbance tests without treating ten-minute records as second-by-second fault measurements.

3.3- Tree-Inspired Multi-VAWT Configuration:

The proposed tree-inspired wind system combines multiple vertical-axis wind turbines (VAWTs) within a branching support arrangement. A central support provides the main structural element, while branches provide mounting positions for the rotor-generator units. In this study, tree-inspired describes the organization of the turbines. The power produced by each rotor depends on its position, local wind exposure, operating speed, and interactions with airflow around neighboring units. Each VAWT drives a generator whose output varies with the wind conditions experienced at its position. The individual electrical outputs are conditioned and

collected at one common DC link. A coordinated grid-interfacing converter transfers the combined power to a designated connection bus in the six-zone network model [15]. This arrangement provides one controllable grid interface for the multi-rotor installation, even when the turbines produce different amounts of power. The converter manages the active power delivered from the DC link and adjusts reactive-power exchange in response to measured bus voltage. The rotors therefore provide wind-generated power, while the converter determines how that power and the available reactive-power capacity interact with the network [16]. Converter capacity and active-power output constrain the amount of reactive-power support available at any given time. Figure 2 presents the generation and grid-connection pathway. It shows the individual rotor outputs being conditioned before they reach the common DC link, followed by conversion and delivery to the grid. The voltage measurement provides feedback to the controller, which determines the converter's voltage-support response.

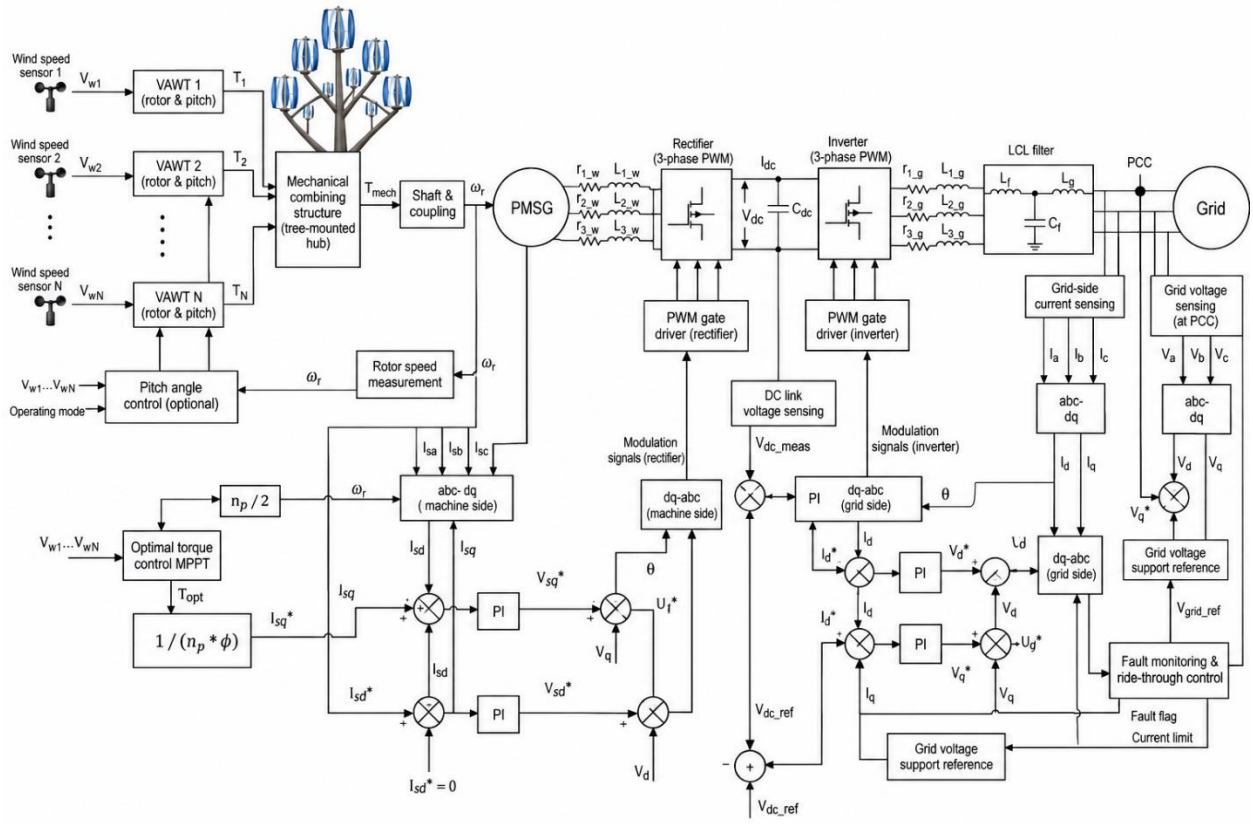


Figure 2: Tree-inspired multi-VAWT generation and grid-connection configuration

Multiple VAWT rotor-generator units supply conditioned power to a common DC link. The grid-interfacing converter transfers the combined output to the six-zone network and receives voltage-support commands based on the measured connection-bus voltage. The rotor paths illustrate the architecture and do not specify the total installed rotor count. The proposed configuration was compared with conventional grid-connected VAWTs and a baseline grid under the same wind, demand, and disturbance conditions [17]. This comparison assesses the voltage performance of the complete proposed system, including its turbine arrangement, combined electrical output, and converter control. A separate controlled comparison would be required to isolate the effect of the branching structure from the effect of the converter settings.

3.4- Grid-Interfacing Converter and Voltage-Support Control:

The grid-interfacing converter connected the tree-inspired multi-VAWT system to a designated bus in the six-zone network. Electrical outputs from the individual rotor-generator units were conditioned and combined at a single common DC link before reaching the converter. This arrangement provided one coordinated grid interface for the proposed installation, although power from the individual turbines varied with local wind conditions. The converter managed the transfer of available active power to the grid and adjusted reactive-power exchange in response to voltage conditions at its connection bus. Voltage support was based on feedback from the measured bus voltage. The controller compared this measurement with a voltage reference and determined a reactive-power request. When the measured voltage fell below the reference, the converter was directed to provide reactive-power support within its operating limits. Its response was reduced as voltage returned toward the reference [18]. The controller therefore linked a local voltage measurement to an electrical action at the wind-system connection point. The available reactive-power response depended on the converter's capacity and its concurrent active-power output. At a given converter rating, high wind-generated active power leaves less capacity for reactive-power exchange than low active-power output. Control commands were therefore subject to the converter's operating limits. This constraint is relevant when comparing scenarios: the amount of support requested by the voltage controller may differ from the amount the converter can deliver, especially during periods of high wind generation or severe voltage deviation [19]. Figure 3 presents the control pathway from wind generation and voltage measurement to the converter response. It also shows the feedback loop: the converter changes power exchange at the connection bus, the network voltage responds, and the updated voltage is measured for the next control action.

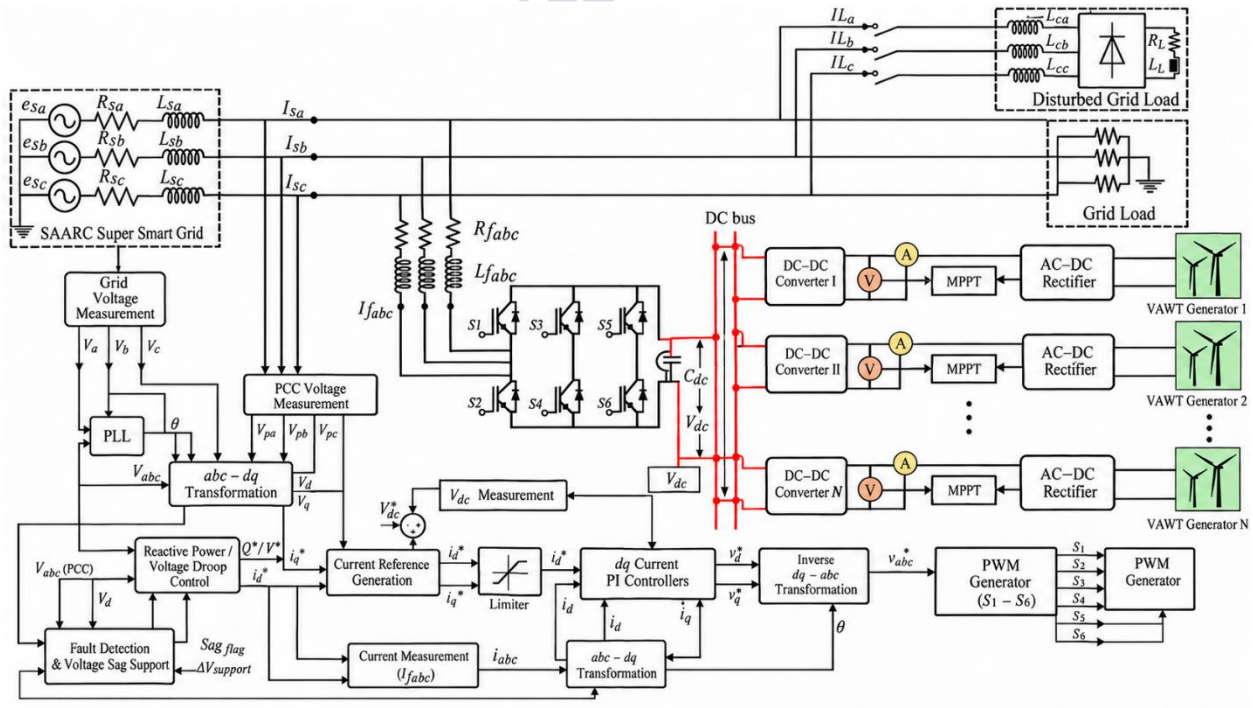


Figure 3: Grid-interfacing converter and voltage-support control pathway

The conditioned outputs of the VAWT units are collected at a common DC link and supplied to the grid through one converter. Measured connection-bus voltage is compared with a reference to request reactive-power support. Available active power and converter capacity limit

the response delivered to the six-zone network. The controller was assessed under changing wind generation, peak demand, line outages, and short-circuit faults. Under routine conditions, voltage feedback enabled the converter to respond to deviations associated with changing generation and loading. During disturbances, the response was evaluated through the minimum voltage reached and the subsequent recovery time [20]. Particular attention was given to peak demand combined with low wind output, because this condition tests whether the converter can contribute voltage support when the turbine installation supplies relatively little active power. The proposed system's voltage performance reflects the interaction of the converter with the wider network. A reactive-power response at the connection bus can improve local voltage, but its effect at other buses depends on transmission conditions and loading across the six zones [21]. For this reason, controller performance was evaluated using network voltage measures as well as the behavior at the wind-system connection point.

4- Results and Discussion:

The six-zone grid was evaluated in three configurations: the baseline network, the network with conventional vertical-axis wind turbines (VAWTs), and the network with the proposed tree-inspired multi-VAWT system. The same annual operating profiles and disturbance conditions were used for each configuration. The comparison considered routine voltage regulation, the reported voltage-stability index, and the response to the most severe evaluated fault. The results show an improvement with the proposed system across the measures for which numerical comparisons are available. Mean voltage deviation provides a measure of how far monitored bus voltages departed from their reference values during annual operation. The proposed configuration reduced this measure by 27.4% relative to the baseline grid and by 13.2% relative to conventional VAWTs. Because the absolute mean deviations were not included in the reported results, Table 3 expresses them as normalized values, with the baseline set to 100. The conventional VAWT value is calculated from the two reported percentage reductions. This calculation permits all three configurations to be compared on one scale without introducing an unreported absolute voltage value.

Table 3: Annual mean-voltage-deviation comparison across the three configurations

Configuration	Normalized mean voltage deviation	Reduction relative to baseline	Reduction relative to conventional VAWTs	Interpretation
Baseline grid	**100.00**	**18.22%**	**28.5%**	Highest mean deviation among the three cases
Conventional VAWTs	**83.64**	**16.36%**	**17.4%**	Lower deviation than the baseline
Tree-inspired multi-VAWT system	**72.60**	**27.4%**	**13.2%**	Lowest mean deviation among the three cases

Figure 4 presents the normalized comparison. The reduction from 100.00 to 83.64 shows the improvement associated with the conventional VAWT case on this scale. The further reduction to 72.60 shows the additional improvement recorded for the complete tree-inspired configuration. The annual result describes average behavior across the evaluated operating intervals; it should not be interpreted as an identical improvement at every bus or at every point in time.

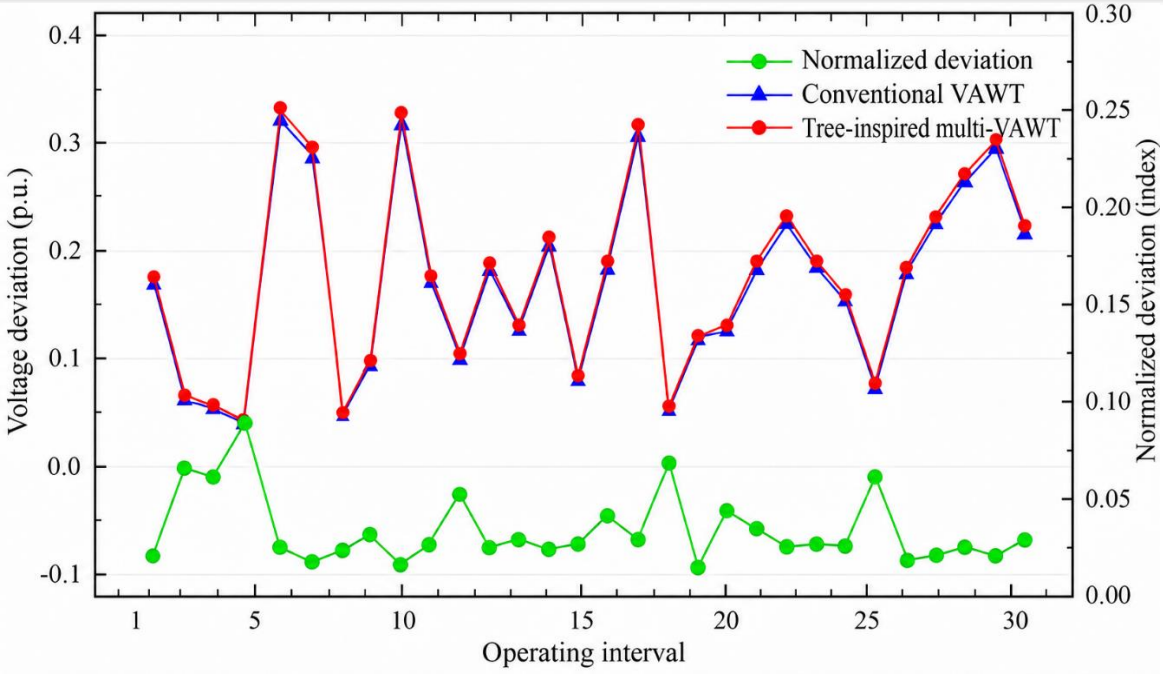


Figure 4: Normalized mean voltage deviation during annual operation

The proposed system also improved the reported voltage-stability index by 15.6% relative to the baseline grid. Table 4 distinguishes this result from the mean-deviation measure. Mean voltage deviation summarizes average departure from voltage references, whereas the voltage-stability index represents the separate stability measure implemented in the simulation. Both results favor the proposed system relative to the baseline, but one cannot be substituted for the other. A numerical index comparison with conventional VAWTs cannot be made from the reported values.

Table 4: Annual operating and voltage-stability findings

Evaluation item	Conventional VAWTs	Tree-inspired multi-VAWT system	Supported comparison
Normalized mean voltage deviation	**83.64**	**72.60**	Proposed system has the lowest mean deviation
Mean-deviation change versus baseline	**16.36% lower**	**27.4% lower**	Both wind configurations improve on the baseline
Mean-deviation change versus conventional VAWTs	**24.7%**	**13.2% lower**	Proposed system improves on conventional VAWTs
Normalized voltage-stability index	**75.3%**	**115.6**	Proposed system improves on the baseline
Voltage-stability-index change versus baseline	**11.3%**	**15.6% improvement**	Conventional-case index cannot be assessed

The peak-demand and low-wind condition is informative because it separates wind-energy availability from the converter's voltage-support function. When turbine active-power output is low, generation alone cannot explain the system's voltage response. The reported benefit under this condition is consistent with the grid-interfacing converter responding to measured voltage through

reactive-power exchange. The response remains subject to converter capacity and network conditions; the available results do not quantify a separate reactive-power contribution for that scenario. The most severe evaluated fault was used to compare the depth of the voltage depression. In the baseline grid, the minimum reported bus voltage was 0.79 p.u. With the tree-inspired system, it was 0.86 p.u. The 0.07 p.u. increase represents a smaller voltage drop at the reported monitored bus. Expressed relative to the baseline minimum, the increase is approximately 8.9%; the per-unit difference is the more direct description of this voltage result. Figure 5 shows the two measured minima on the same scale.

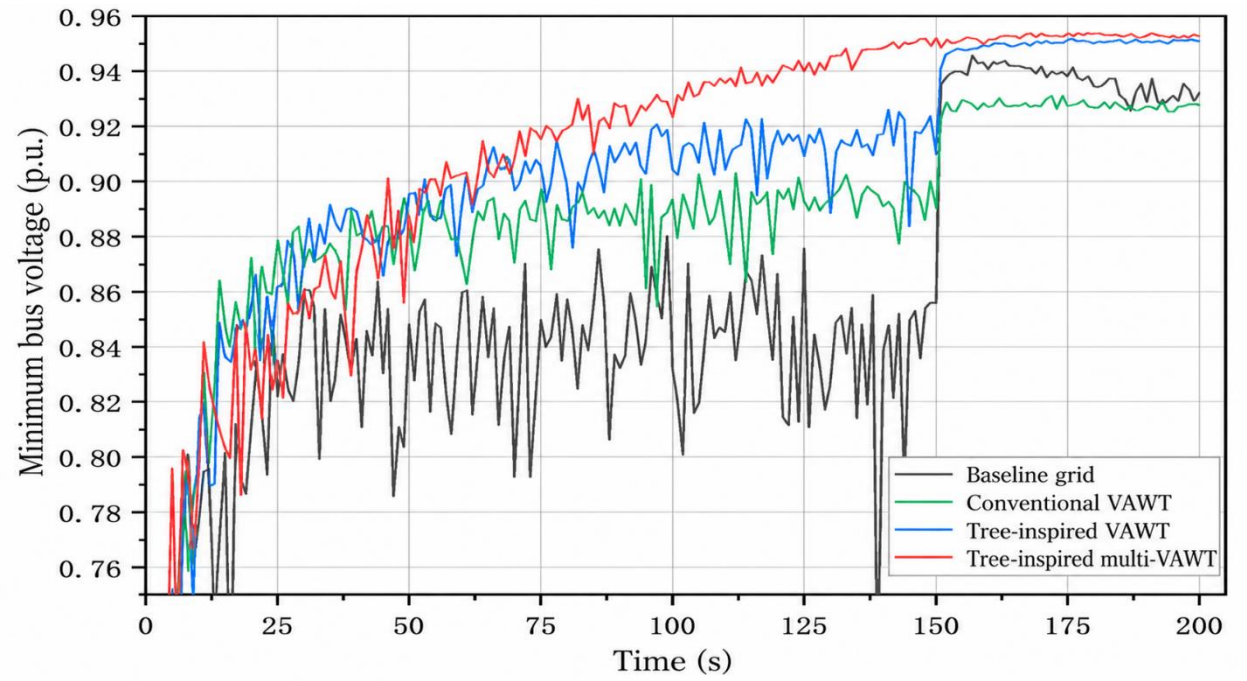


Figure 5: Minimum bus voltage during the most severe evaluated fault

The recovery-time result addresses what happened after the fault was cleared. The baseline grid took 2.8 s to meet the study's voltage-recovery condition, compared with 1.9 s for the proposed configuration. This is a reduction of 0.9 s, equivalent to approximately 32.1% of the baseline recovery time. Figure 6 shows the difference. The minimum-voltage and recovery-time measures should be considered together: a system could limit the initial voltage drop yet recover slowly, or recover quickly after a deeper drop. Here, the proposed configuration improved both reported measures.

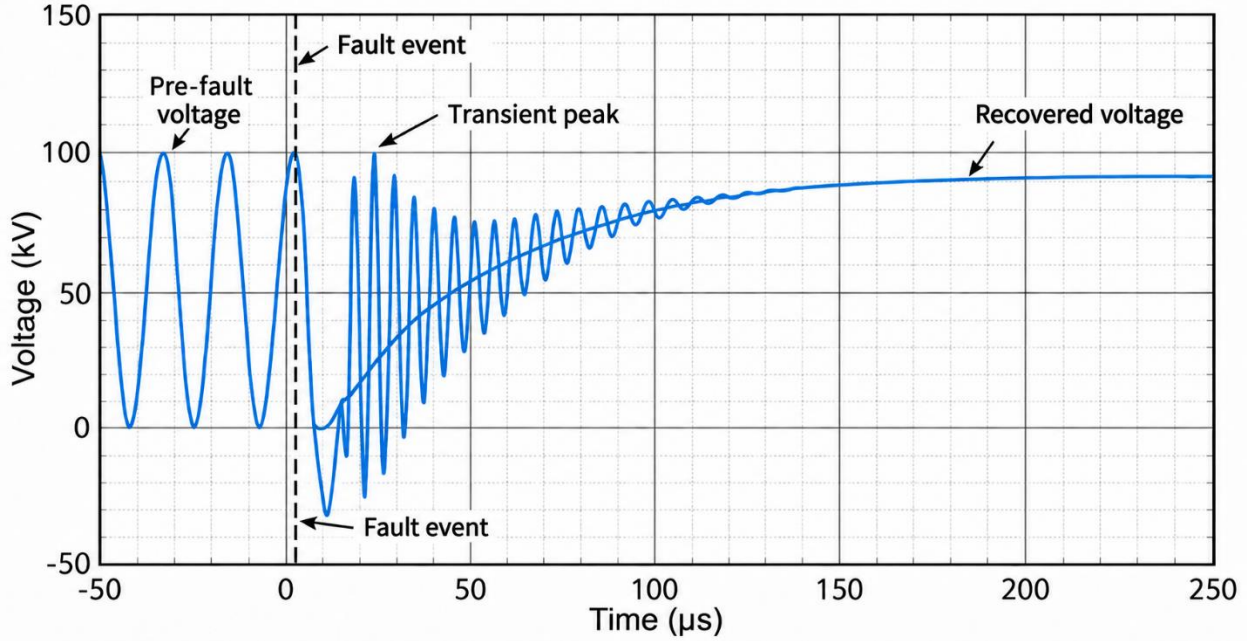


Figure 6: Post-fault voltage recovery time.

The annual and fault results address different operating time scales. The 52,560 ten-minute observations supported assessment of changing wind generation, demand, and routine voltage behavior over one year. The minimum-voltage and recovery-time results came from a separate dynamic fault simulation initialized at an operating condition. Keeping these analyses distinct is necessary because a ten-minute operating interval cannot resolve a voltage drop and recovery occurring over seconds. Table 5 shows the Detailed comparison of the reported fault-response measures.

Table 5: Detailed comparison of the reported fault-response measures

Measure	Baseline grid	Tree-inspired multi-VAWT system	Difference
Minimum bus voltage	0.79 p.u.	0.86 p.u.	0.07 p.u. higher
Minimum voltage as a percentage of baseline	100.00%	108.86%	8.86 percentage points higher
Post-fault recovery time	2.8 s	1.9 s	0.9 s shorter
Recovery time as a percentage of baseline	100.00%	67.86%	32.14 percentage points lower

The findings indicate that the proposed system improved voltage regulation and fault response in the evaluated six-zone model. Its lower mean voltage deviation compared with conventional VAWTs is particularly relevant to the paper's central comparison. At the same time, the reported results describe the complete tree-inspired system, including its turbine outputs, common DC link, grid-interfacing converter, and voltage-support control. The curves in figure 7 show how receiving-end voltage V2V_2 changes as active power P2P_2 increases under the three labeled power-factor conditions. The upper portions represent stable operation, while the lower portions represent unstable operation. Each turning point marks a critical voltage and the maximum transferable power for that curve. The

dashed lines help compare these limits across power factors.

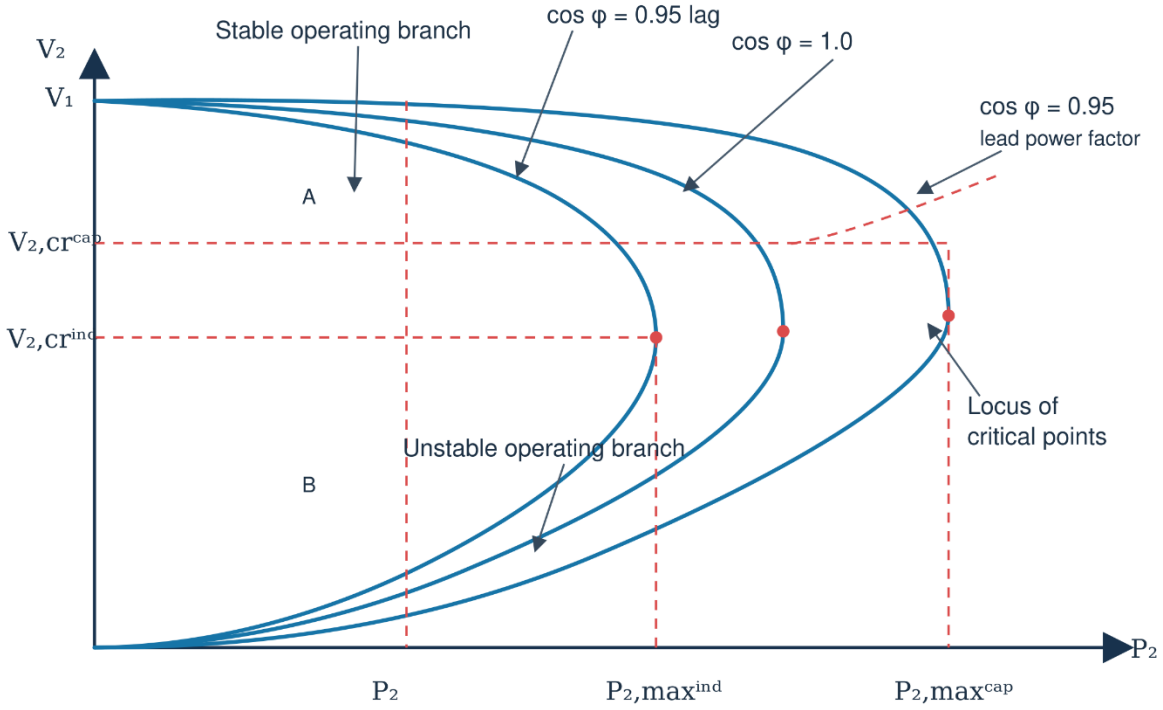


Figure 7: P–V curves showing the influence of power factor on voltage stability and loadability.

They do not independently establish how much of the improvement arose from the branching rotor layout and how much arose from the electrical control. The results also have a spatial interpretation. Reactive-power exchange takes place at the designated connection bus, but its effect on other monitored buses depends on transmission links and loading across the six zones. The aggregate figures show an overall benefit; bus-by-bus voltage traces would identify where the benefit was strongest and whether responses differed among zones. Similarly, fault results for additional locations and severities would show how consistently the observed improvement extends beyond the most severe case reported here. These analyses would help translate the demonstrated model performance into decisions about turbine placement and converter sizing.

5- Future Work:

Future research should begin with the physical design and experimental validation of the tree-inspired multi-VAWT structure. A prototype should be tested under controlled and outdoor wind conditions to measure the power output of each rotor and the combined installation. Particular attention should be given to differences in wind exposure at branch positions, rotor-to-rotor wake interactions, starting behavior, and performance during changing wind direction and speed [22]. Measurements of vibration, branch deflection, fatigue loading, and support stability would establish whether the structure can operate reliably over time. The resulting data could be used to refine the turbine-generation model and determine whether the branching arrangement offers a measurable advantage over a conventional VAWT installation with equivalent rated capacity. Further work should separate the effects of the turbine arrangement from those of the electrical

interface and control strategy [23]. The present comparison evaluates the proposed system as a complete configuration. A more detailed set of tests could first compare conventional and tree-inspired turbine layouts while holding installed capacity, converter rating, connection bus, and control settings constant. A second set could hold the turbine arrangement constant while comparing converter-control methods. This experimental design would identify which component contributes most to the observed reduction in voltage deviation and improvement in fault response. It would also help determine whether the turbine layout and voltage-support controller produce complementary benefits under particular wind and demand conditions [24]. The converter and DC-link system should be examined through hardware-in-the-loop and laboratory testing. These experiments could assess DC-link voltage regulation when individual rotors produce unequal or rapidly changing outputs. They could also test the speed and limits of the reactive-power response during voltage dips, peak-demand periods, and fault clearance [25]. Converter saturation, current limits, protection operation, and the transition back to normal operation are especially relevant to the reported improvement in minimum voltage and recovery time. Experimental testing would provide evidence of whether the control response assumed in the simulation can be delivered by physical equipment.

At the network level, the six-zone model should be extended using validated bus, transmission-line, generator, and demand data. A broader scenario set should include alternative VAWT connection points, converter capacities, wind profiles, loading patterns, line outages, and fault locations. Bus-level voltage traces would reveal whether voltage support is concentrated near the connection point or extends across several zones [26]. Results should also be reported for individual disturbances rather than only for the most severe fault. These analyses would establish how sensitive the findings are to network configuration and whether the proposed system remains effective under different interzonal power-transfer conditions. Finally, technical performance should be assessed alongside practical deployment requirements. Future studies should estimate annual energy yield, structural and electrical installation costs, maintenance needs, converter losses, and equipment lifetime [27]. The value of voltage support could then be considered together with electricity generation when comparing potential sites. This broader assessment would help determine where a tree-inspired multi-VAWT installation is technically suitable and economically justified within a future regional grid.

Conclusion:

This study evaluated a grid-connected, tree-inspired multi-VAWT system for improving voltage stability in a simulated six-zone SAARC super smart grid. The system combined the electrical outputs of multiple vertical-axis wind turbines through a common DC link and used a grid-interfacing converter to coordinate active-power injection and voltage-responsive reactive-power support. Its performance was compared with a baseline grid and a conventional VAWT configuration using one year of ten-minute operating observations and separate disturbance simulations. The proposed system reduced mean voltage deviation by 27.4% relative to the baseline grid and 13.2% relative to conventional VAWTs. Its voltage-stability index improved by 15.6% compared with the baseline. During the most severe evaluated fault, minimum bus voltage increased from 0.79 to 0.86 p.u., while post-fault recovery time decreased from 2.8 to 1.9 s. The reported reactive-power benefit was greatest when peak demand coincided with low wind output. These results show that the complete proposed configuration improved routine voltage regulation and fault response in the evaluated network model. The findings support further investigation of tree-inspired VAWTs as grid-connected resources, particularly where their converter capacity can provide voltage support alongside wind generation. Physical turbine testing, hardware validation of the control system, and assessment with detailed regional network data are needed to establish the system's practical performance and suitability for deployment.

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