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Technical Disclosure[1]

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Automated Wind Turbine Blade Sequence Validation During Startup

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Technical Disclosure

5. Abstract

Disclosed is a system and method for automatically validating wind turbine blade sequence during a turbine startup phase before the turbine enters production operation. The disclosed approach uses existing blade strain-related sensor or accelerometer signals and rotor azimuth position information to determine whether the blades are mechanically arranged in the expected sequence. During startup, the system acquires sensor measurements associated with individual blades, correlates sensor extrema with rotor azimuth angle, and determines a sequence relationship for the blades based on the azimuth positions at which characteristic maximum and minimum sensor values occur. The detected ordering is compared against an expected blade sequence or valid cyclic permutation. A multi-sensor consensus or majority-vote decision logic may be used to improve robustness. If the detected sequence is inconsistent with the expected blade arrangement, the turbine may be prevented from entering production and may instead be safely stopped and flagged for inspection. The disclosed approach enables early detection of reversed or incorrectly phased blades without requiring additional dedicated hardware, thereby reducing risk of structural loading issues, fatigue damage, downtime, and associated operational cost.

6. Technical field

The present disclosure relates generally to wind turbine diagnostics, commissioning, startup monitoring, and control validation. More specifically, the disclosure relates to automated validation of blade sequence or blade phasing in a wind turbine rotor using blade strain or acceleration sensing and rotor position information during startup or other low-speed operating conditions prior to normal production entry.

7. Background

In utility-scale wind turbines, correct mechanical blade installation and correct phase relationship among rotor blades are important for proper load distribution, rotor balance, and long-term structural integrity. It was observed that some turbines could be operated with a blade condition equivalent to a reversed blade or a blade operating approximately 180 degrees out of phase relative to its correct position. There are instances where swapped signals between blades that would lead to related

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systems to malfunction (blade strain or acceleration measurement, individual pitch actuators, blade condition monitoring systems). Such a condition may result in elevated imbalance, asymmetric loads, increased fatigue, reduced performance, safety concerns, and risk turbine integrity.

Existing checks did not reliably detect such conditions before the turbines entered operation. For example, prior approaches include pitch accelerometer-based approaches, rotor imbalance monitoring, pitch homing procedures, and offline post-event analysis. However, these approaches suffer from limitations. Some are not available or not practical in offshore implementations, some only become reliable at full power or after substantial imbalance is already present, some require manual action, and some merely detect the issue after the event has already occurred.

Offline analysis of blade strain or accelerometer related data was able to identify certain events after occurrence, but such retrospective detection does not prevent defective turbines from operating. Accordingly, there is a need for an automated, online, startup-integrated mechanism capable of verifying blade sequence before the turbine enters production mode.

8. Summary of the disclosure

The present disclosure provides an automated startup validation process that determines whether a wind turbine's blades are arranged in the correct sequence prior to production operation. The process uses sensor data already available in the turbine, such as "fiber optic sensor measuring strain" in different positions of the blade/airfoil, together with rotor position or azimuth information.

In one implementation, the system monitors sensor outputs during a startup transition while the rotor accelerates at low speed. Sensor values are associated with rotor azimuth angle, and characteristic extrema, such as maxima and minima, are detected for each blade over a revolution or another observation window. Because blade reversal or incorrect phasing changes the load behavior and corresponding order of detected extrema, the azimuth sequence of these events can be used to infer blade order.

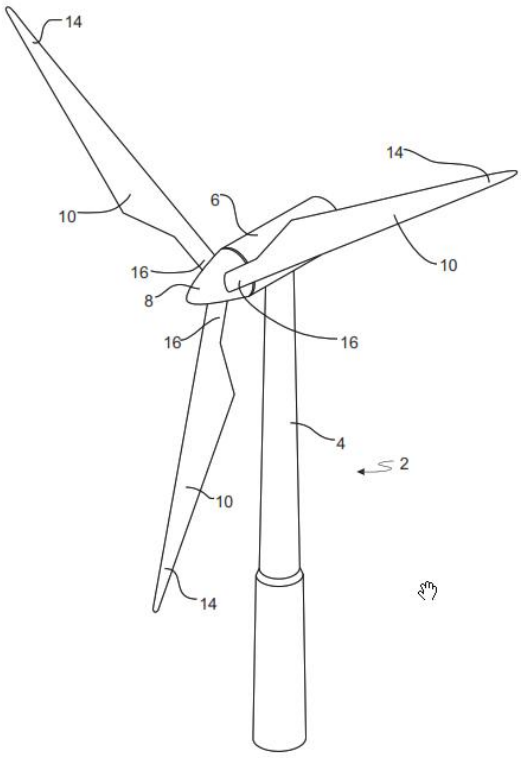
The inferred order from multiple sensors is evaluated against the expected blade sequence, optionally allowing valid cyclic permutations depending on the blade reference convention. A majority-vote or other consensus logic across multiple sensor channels may be applied to reduce susceptibility to noise, calibration drift, or isolated sensor anomalies. If the blade sequence is validated, the turbine is permitted to proceed toward production. If the sequence is not validated, the turbine is safely stopped, flagged, and diagnostic information is logged.

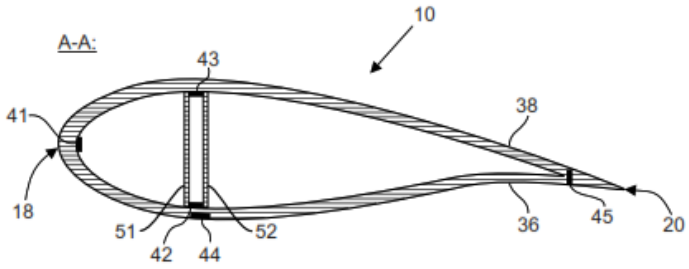
9. Brief description of drawings

In example drawings, one or more figures may illustrate:

- a wind turbine system including rotor blades, blade strain sensors or accelerometers, controller, and azimuth position input;

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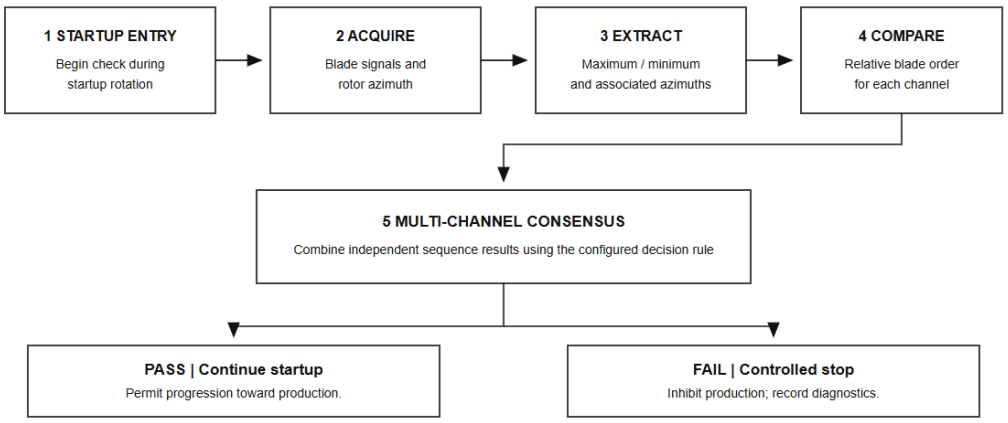




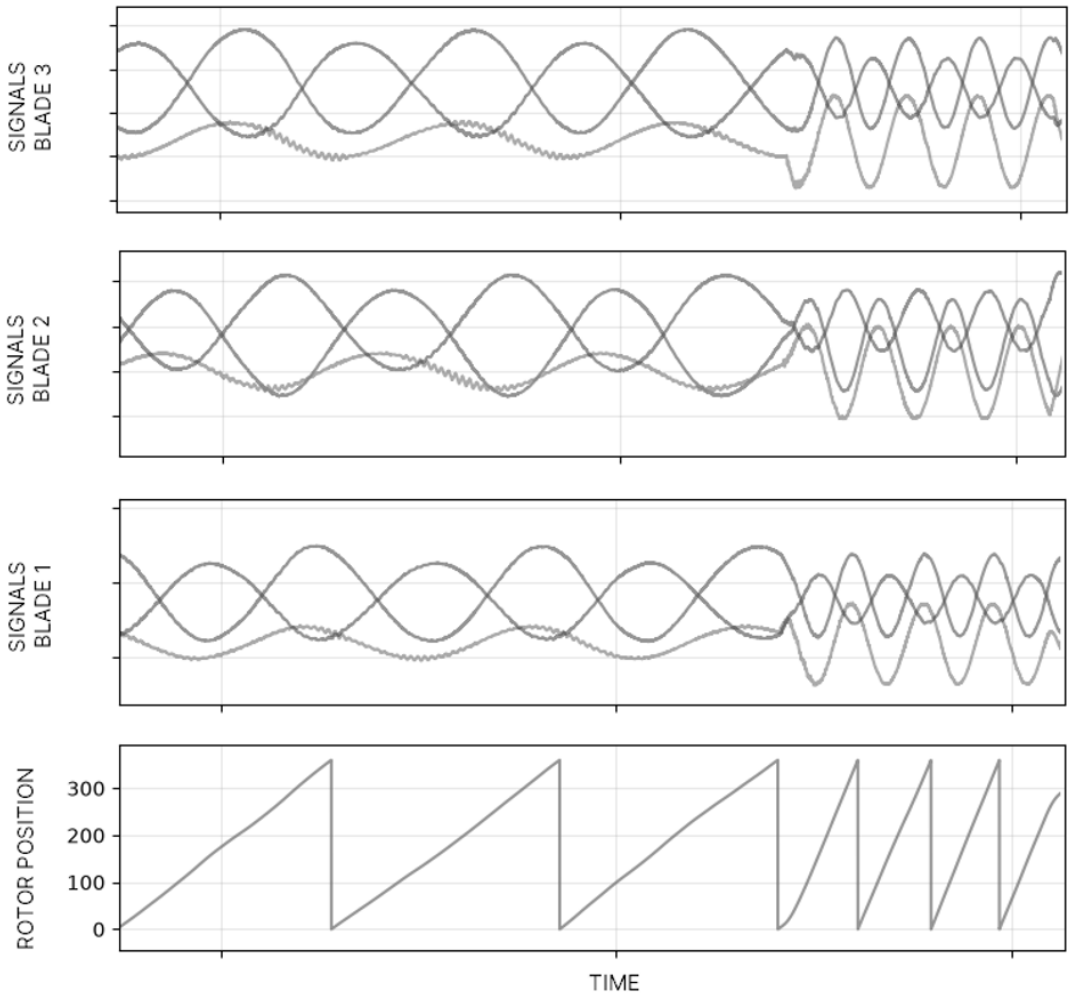
2 – Wind turbine
4 - Tower
6 – Nacelle
8 - Hub
10 – Blade
14 – Blade tip
16 – Blade root
18 - Leading edge
20 – Trailing edge
36 – Pressure side
38 – Suction side
41, 42, 43, 45 – Strain sensors or Accelerometers
44 – Spar cap
51, 52 – Shear web

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- a startup monitoring sequence showing acquisition of blade strain sensor or accelerometer data and rotor azimuth data;

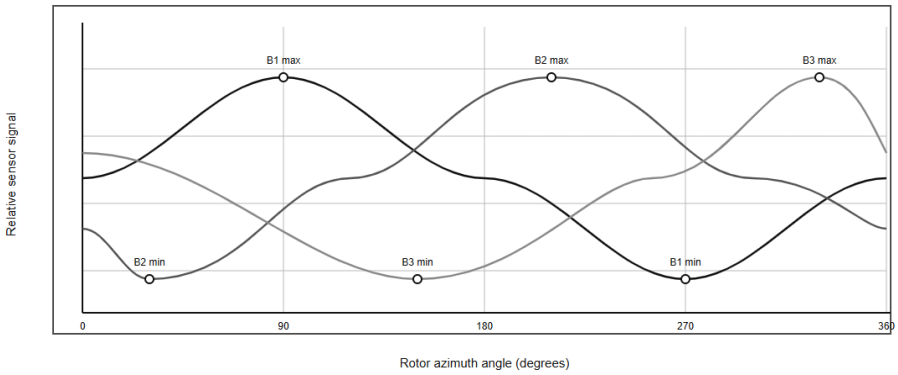


- plots of sensor values versus time or azimuth for multiple blades during startup;

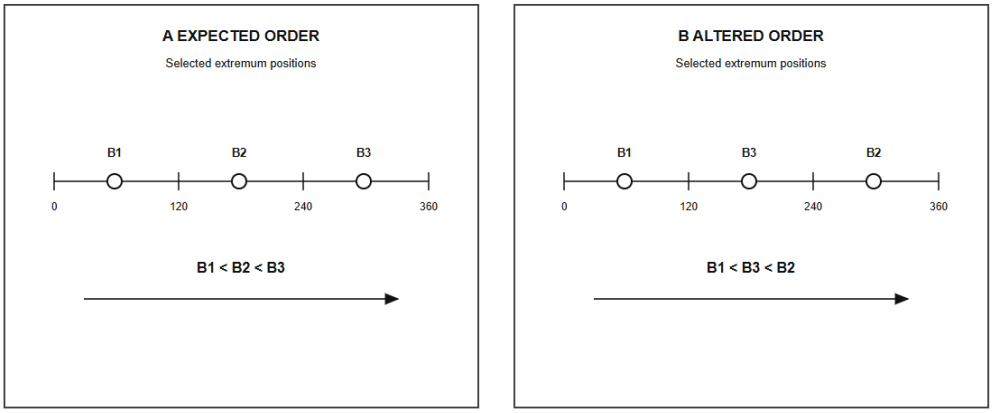


- determination of maximum and minimum sensor values for each blade over one or more revolutions;

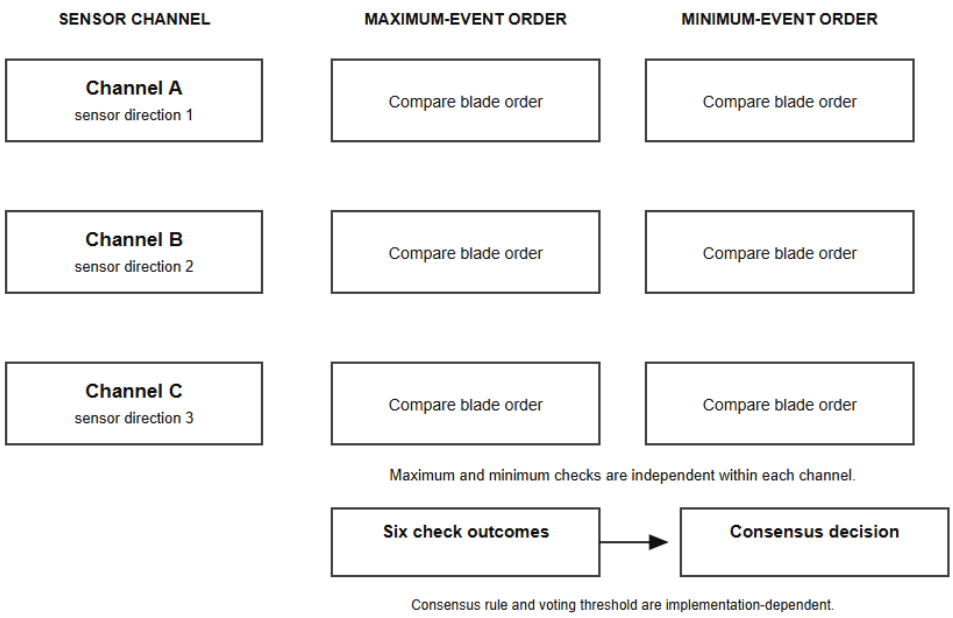
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- comparison of azimuth ordering among Blade 1, Blade 2, and Blade 3;

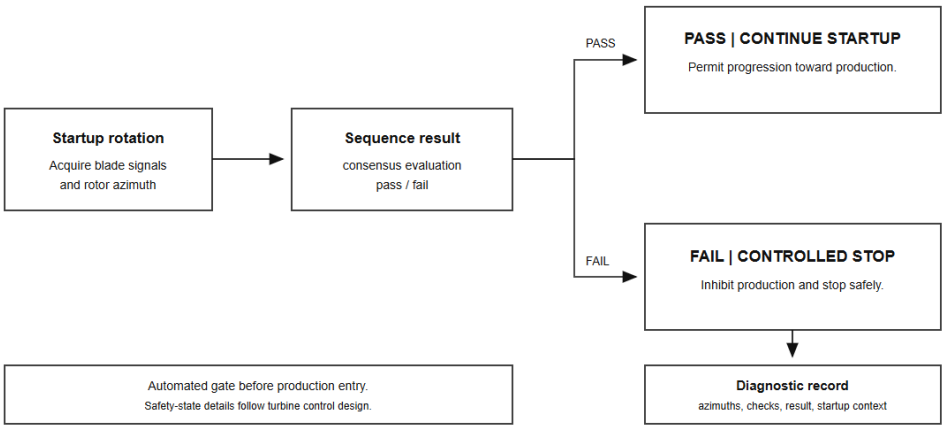


- a consensus or majority-vote decision block for validating blade sequence; and



- turbine control actions corresponding to pass/fail startup gating.

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10. Detail description

A wind turbine includes a rotor having a plurality of blades, such as three blades, mounted to a hub. The turbine further includes one or more controllers configured to receive sensor data from blade-related sensing channels and to receive rotor position information, such as azimuth angle. In some embodiments, the blade-related sensing channels are sensors measuring blade load behavior in multiple orientations, including leading edge, upwind, and downwind directions.

During a startup procedure, the controller initiates or observes a validation routine before the turbine is permitted to enter production operation. The startup phase may include low-speed rotor acceleration produced by converter action, motorized turning, wind-driven rotation, manual spin, or another controlled startup mechanism. Throughout this period, the controller continuously or periodically acquires blade sensor measurements and corresponding rotor azimuth angle values.

For each selected sensor channel and for each blade, the controller identifies characteristic sensor extrema over a rotor revolution or another suitable angular window. In example implementations, the controller identifies the maximum value and the minimum value for a given sensor signal corresponding to each blade and records the azimuth angle at which each extremum occurs. This produces azimuth-tagged extrema for the blades across multiple sensor channels.

The azimuth positions of the extrema are then analyzed to infer the blade order. In an illustrative case for a three-blade rotor, if the blades are correctly arranged in the expected sequence, the azimuth values associated with characteristic extrema may occur in a consistent order, for example Blade 1 before Blade 2 before Blade 3, subject to the selected angular reference and cyclic wraparound convention. If a blade is reversed, mis-phased, or otherwise mechanically out of sequence, the resulting load sign or load pattern changes, causing the relative order of extrema to change. The altered order provides a basis for detecting a blade sequence error.

The sequence decision may be made independently for each sensing direction or channel. Because one channel may occasionally be noisier or less reliable in a particular startup event, the controller may combine the individual sensor-channel determinations using a majority-vote or other consensus logic. For example, if at least two of three sensing directions indicate an incorrect blade sequence, the controller may determine that the turbine has failed the startup blade sequence validation. Conversely, if the required consensus indicates a correct sequence, the controller may permit continued startup progression.

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Upon failure of the validation, the controller may execute a controlled stop, inhibit progression into production mode, create an alarm or fault code, and log relevant diagnostic data. Logged data may include sensor traces, extrema values, azimuth angles, blade-by-blade ordering results, consensus results, timestamps, startup state information, and turbine identification. Such logged information may support investigation, maintenance planning, and root-cause analysis.

The validation may be integrated into a normal startup sequence as an automated gate. In one example, a “pass” result allows startup to continue toward production, while a “fail” result triggers a controlled stop. This approach converts what was previously a manual, limited, or retrospective verification into an online automated commissioning or operational safeguard.

In some embodiments, the disclosed process may also be applied retrospectively to stored fleet data to identify turbines already operating with incorrect blade phasing or reversed blade conditions. Accordingly, the disclosure is applicable both to new turbine startup validation and to retrospective fleet screening.

11. Advantages

The disclosed approach provides several technical and commercial advantages.

Technical advantages include:

- use of existing turbine sensors and rotor position information, thereby avoiding additional dedicated hardware;

- non-invasive implementation through software, firmware, or controller logic integration;

- automated validation during startup, before production entry;

- robust decision-making through multi-sensor consensus or majority voting;

- resistance to isolated sensor issues, noise, or calibration drift; and

- generation of diagnostic information useful for troubleshooting and root-cause analysis.

Commercial and operational advantages include:

- prevention of operation of mechanically defective or incorrectly assembled turbines;

- reduction in risk of fatigue damage, higher loads, structural wear, downtime, warranty exposure, and remedial field campaigns;

- improved quality assurance and commissioning confidence;

- ability to support field retrofit or firmware deployment for fleet-wide screening;

- enhanced customer confidence and compliance support with mechanical assembly expectations and turbine behavior requirements; and

- achievement of these benefits with little or no additional hardware cost.

12. Example Embodiments

Embodiment 1:

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A method for validating blade sequence in a wind turbine during startup, comprising acquiring blade sensor signals and rotor azimuth values, determining characteristic extrema for each blade, correlating the extrema to azimuth positions, and determining whether the blade order matches an expected sequence before allowing entry into production mode.

Embodiment 2:

The method of Embodiment 1, wherein the blade sensor signals include measurements from “fiber optic sensor measuring strain” in different positions of the blade/airfoil

Embodiment 3:

The method of Embodiment 1 or 2, wherein the method determines both maxima and minima for each blade and uses the azimuth positions of the extrema to evaluate blade sequence.

Embodiment 4:

The method of any preceding embodiment, wherein a majority-vote or consensus logic across a plurality of sensing channels is used to determine whether the blade sequence is valid.

Embodiment 5:

The method of any preceding embodiment, wherein a failed blade sequence validation causes a controlled shutdown, startup inhibition, fault generation, and storage of diagnostic data.

Embodiment 6:

A wind turbine control system comprising one or more processors and memory storing instructions that, when executed, cause the system to perform the method of any preceding embodiment.

Embodiment 7:

A non-transitory computer-readable medium containing instructions that, when executed by a wind turbine controller, perform startup blade sequence validation using load-extrema/azimuth correlation and consensus-based decision logic.

Embodiment 8:

A fleet diagnostic method comprising reprocessing stored startup or operating data from multiple turbines to identify turbines having blade sequence abnormalities based on extrema ordering relative to azimuth position.

13. Industrial Applicability

The disclosure is applicable to utility-scale wind turbines, including offshore and onshore turbines, and particularly to turbines equipped with blade strain or acceleration sensing and rotor position monitoring. The disclosed method can be implemented in turbine control software, supervisory diagnostics, startup logic, commissioning tools, or fleet analytics platforms. It is useful during factory testing, commissioning, restart procedures, maintenance verification, retrofit deployment, and fleet health screening. The disclosure is particularly relevant where incorrect blade installation, blade reversal, or blade phasing error could create elevated structural loads, imbalance, or safety concerns.

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14. Variations and Alternatives

Various modifications may be made without departing from the scope of the disclosure.

For example, rather than using only maxima and minima, the system may use other characteristic signal features, such as zero crossings, slope changes, filtered peaks, phase relationships, pattern matching, harmonic content, or statistical descriptors derived from blade sensor signals.

The disclosed approach may use different sensor combinations, including a subset of “fiber optic sensor measuring strain” in different positions of the blade/airfoil, or other sensors indicative of blade loading, motion, strain, acceleration, or structural response. Rotor position may be derived from encoder feedback, azimuth estimators, blade-1-up reference logic, or other position determination techniques.

The decision logic may use majority voting, weighted voting, confidence scoring, thresholding, rule-based logic, model-based classification, or machine-learning-based classification. The method may validate exact blade order, cyclic permutation consistency, expected phase offsets such as approximately 120-degree spacing, or other sequence conventions defined for a particular turbine architecture.

Alternative approaches for addressing similar problems may include average-difference analysis, standard-deviation-based anomaly detection, transformed coordinate systems for phase interpretation, or direct checking that blade events occur around expected azimuth positions such as about 120 degrees and 240 degrees relative to a reference blade. These alternatives are contemplated as possible variants or design-around concepts, although the presently disclosed implementation emphasizes startup-time extrema/azimuth correlation with multi-sensor consensus.

15. Conclusion

This disclosure describes an automated method and system for validating wind turbine blade sequence during startup using existing strain-related sensors or accelerometers and rotor azimuth information. By correlating characteristic sensor behavior with rotor position and applying a robust multi-sensor decision process, the disclosed approach enables detection of reversed or incorrectly phased blades before a turbine enters production operation. The result is improved safety, commissioning quality, turbine integrity protection, and reduced operational risk, while leveraging existing sensing infrastructure and requiring little or no additional hardware.

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