Technical Disclosure[1]

1. Title

Gain-Scheduling of Closed-Loop Control Loops for Wind Turbines

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Technical Disclosure

5. Abstract

Disclosed is a control-tuning framework for wind turbines in which a user or supervisory system specifies target closed-loop behavior rather than directly tuning raw controller gains. A controller estimates or otherwise determines a model of the wind turbine plant dynamics and uses that model, together with operating-condition information, to calculate or recalculate controller gains that achieve the selected closed-loop response targets. The approach may be applied dynamically as a gain-scheduling or loop-calibration process in which operating condition, model parameters, and desired response parameters are updated, and the control gains are correspondingly recalculated. The disclosed framework simplifies tuning of wind-turbine feedback loops, improves transparency between tuning inputs and control objectives, and facilitates troubleshooting when controller settings are incorrect.

6. Technical field

The present disclosure relates to control systems for wind turbines, and more particularly to calibration, tuning, and gain-scheduling techniques for closed-loop control loops such as proportional-integral-derivative (PID), model-based, and model predictive control (MPC) loops used in wind-turbine operations.

7. Background

Wind turbines employ multiple interacting control loops to regulate operational variables such as speed, torque, pitch, power, and other dynamic behaviors. Conventional tuning of such loops is often performed by directly selecting controller gains. In practice, this indirect approach can be difficult because the tuning knobs available to an engineer do not always map clearly to the intended closed-loop performance. As a result, obtaining a desired transient or steady-state response can be cumbersome, time-consuming, and difficult to troubleshoot.

When PID loops, MPC loops, or other model-based controllers are tuned by directly manipulating gain values, an incorrect setting may not immediately reveal which performance objective has been compromised. For wind-turbine systems, this issue is exacerbated by the fact that plant dynamics

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vary with operating condition, turbine configuration, and environmental inputs. Accordingly, a more transparent and adaptive tuning method is desirable.

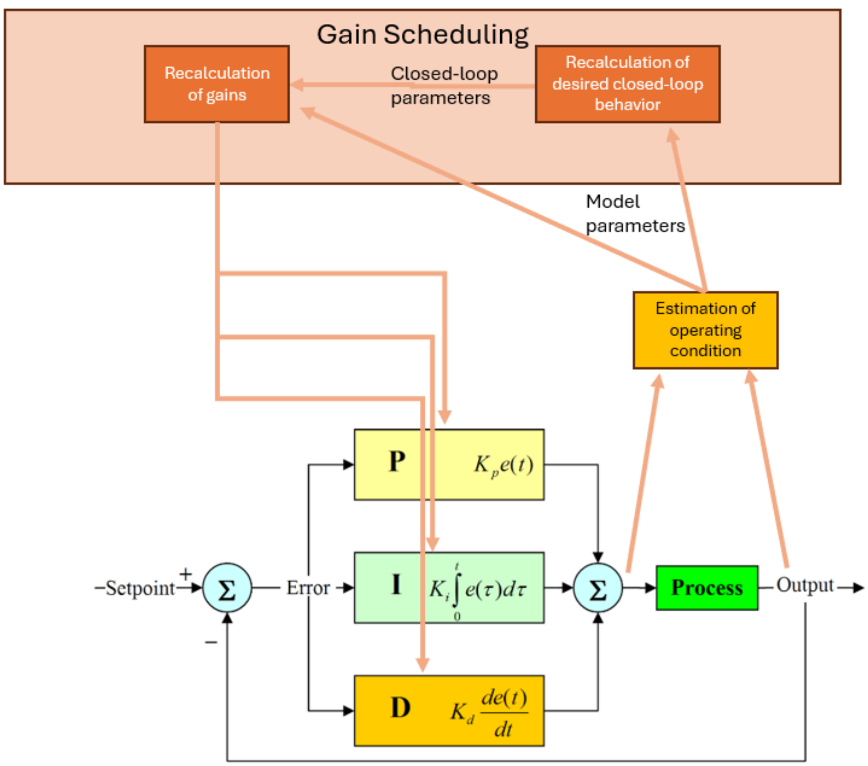
8. Summary of the disclosure

The disclosure provides a mechanism for tuning wind-turbine control loops by specifying desired closed-loop behavior and calculating the controller gains needed to realize that behavior. Instead of requiring a user to directly tune gain values, the system accepts closed-loop performance targets and determines gains based on an estimated or identified model of the wind turbine dynamics.

In some embodiments, the system performs dynamic loop calibration or gain scheduling. The controller or an associated supervisory module estimates the current operating condition of the turbine, obtains or updates model parameters corresponding to that operating condition, and recalculates controller gains so that the closed-loop response remains aligned with the desired closed-loop targets. The desired closed-loop behavior itself may also be recalculated or adjusted based on operating context.

This framework improves the usability of controller calibration for different wind-turbine configurations and provides a more intuitive correspondence between tuning inputs and actual control goals.

9. Brief description of drawings



[FIG. 1] illustrates a dynamic loop calibration or gain-scheduling workflow including estimation of operating condition, updating of model parameters, recalculation of desired closed-loop behavior, and recalculation of controller gains.

10. Detail description

A wind turbine includes one or more feedback control loops for regulating turbine operation. These loops may include, for example, pitch control loops, torque control loops, rotor-speed control loops, generator-related loops, drivetrain damping loops, power regulation loops, or other loops used to govern turbine behavior. The present disclosure provides a tuning and calibration mechanism in which the operator, designer, or supervisory system selects desired closed-loop characteristics rather than directly entering gain coefficients.

In one implementation, a controller receives one or more closed-loop targets. Such targets may define desired response behavior including, by way of example, closed-loop poles, response speed, damping, settling characteristics, overshoot constraints, disturbance rejection characteristics, robustness margins, bandwidth targets, or combinations thereof. The controller also receives or determines a model of the wind turbine plant. The plant model represents turbine dynamics and may include model parameters corresponding to a particular turbine configuration, subsystem state, or current operating condition.

Using the plant model and the selected closed-loop targets, the controller calculates one or more controller gains that produce the desired response. In this way, the gain values are derived quantities rather than the primary tuning inputs. This creates a more direct and transparent link between the engineer's stated performance objective and the resulting controller behavior.

In further embodiments, the system performs gain scheduling or dynamic loop calibration. Operating conditions may vary across wind speed ranges, rotor speeds, power levels, blade pitch angles, drivetrain states, thermal conditions, turbulence levels, or other relevant variables. The controller estimates the current operating condition and based on that condition, updates model parameters associated with the turbine plant. The controller then recalculates the gains required to maintain or approximate the desired closed-loop behavior under the updated conditions.

In some implementations, the desired closed-loop behavior may also be recalculated as a function of operating condition. For example, one set of response targets may be used in one operating region, and another set of response targets may be used in a different region. Accordingly, the disclosed system may perform one or both of: (i) recalculation of closed-loop target parameters; and (ii) recalculation of controller gains.

The gain calculation may be applied to PID controllers, state-space controllers, model-based controllers, MPC implementations, or hybrid control architectures. The system may operate continuously, periodically, or in response to detected condition changes. It may be implemented in turbine-level control hardware, in a supervisory control processor, or in another computational module communicatively coupled to the turbine control system.

The disclosed approach is particularly useful where multiple wind-turbine configurations are supported. Because the tuning input is based on intended closed-loop behavior rather than opaque gain values, the method simplifies transfer of tuning practices across platforms and assists with diagnosis of field issues. If a selected target is incorrect, the mismatch between intended response and actual response is easier to identify than in conventional direct-gain tuning approaches.

11. Advantages

The disclosed system provides several technical and practical advantages, including:

- simpler tuning of wind-turbine feedback loops;
- a clearer relationship between tuning inputs and intended control outcomes;
- easier troubleshooting when a tuning value is set incorrectly;
- improved transparency in controller calibration;
- support for multiple turbine configurations through model-based gain determination;
- adaptability to changing operating conditions through dynamic gain scheduling; and
- applicability to PID, MPC, and other model-based control strategies.

Commercially and operationally, the disclosure can reduce engineering effort associated with commissioning, retuning, and field support while improving consistency of controller behavior across turbine variants.

12. Example Embodiments

In one example embodiment, a wind-turbine controller receives user-selected closed-loop response targets and computes gains for a PID loop regulating a turbine operating variable. The gains are calculated from an estimated model of the turbine dynamics so that the loop behavior matches the selected response target.

In another example embodiment, a model-based wind-turbine controller uses gain scheduling across multiple operating regions. The controller estimates the operating condition, updates plant-model parameters and recalculates controller gains in real time or near real time to maintain desired loop behavior.

In a further example embodiment, a supervisory calibration function stores multiple sets of desired closed-loop parameters for different wind-turbine configurations. When the configuration or operating condition changes, the supervisory function selects or recalculates the appropriate closed-loop targets and causes the control gains to be recomputed accordingly.

In yet another example embodiment, the disclosed method is applied to MPC tuning, where the user specifies desired closed-loop objectives and the controller framework derives the tuning settings or gain-equivalent parameters needed to realize those objectives for a given turbine model.

13. Industrial Applicability

The disclosure is applicable to utility-scale wind turbines, distributed wind systems, prototype turbines, test platforms, and retrofit control upgrades. It may be used during controller development, plant commissioning, field tuning, service troubleshooting, fleet optimization, and adaptation of control software across different wind-turbine platforms.

The disclosed approach is particularly relevant where turbine dynamics vary with configuration or operating state and where conventional direct gain tuning is burdensome or insufficiently transparent.

14. Variations and Alternatives

Numerous variations are possible without departing from the disclosure. For example, the plant model may be estimated online, selected from a library, identified offline, or updated using measured operating data. The controller gains may be recalculated continuously, at scheduled intervals, upon threshold condition changes, or during designated calibration events.

The desired closed-loop behavior may be expressed in different forms, such as time-domain response metrics, frequency-domain targets, pole-placement objectives, robustness constraints, optimization weights, or other response descriptors. The method may be applied to single-loop or multi-loop architecture and may be distributed across local turbine controllers and remote supervisory systems.

Alternative implementations may tune the controllers indirectly by setting gains first and then observing the resulting closed-loop behavior. However, the present disclosure instead emphasizes direct specification of desired closed-loop behavior followed by determination of gains needed to achieve that behavior in the wind-turbine application.

15. Conclusion

This disclosure describes a gain-scheduling and control-loop calibration framework for wind turbines in which desired closed-loop behavior is specified directly and controller gains are calculated from an estimated model of turbine dynamics. By linking tuning decisions to intended control outcomes and by recalculating gains as operating conditions change, the disclosed approach improves transparency, simplifies troubleshooting, and supports more efficient tuning of wind-turbine feedback control systems.

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