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Wind turbine fault detection and fault tolerant control - an enhanced benchmark challenge

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Abstract— **Wind turbines are increasingly growing larger, becoming more complex, and being located in more remote locations, especially offshore. Interest in advanced controllers for normal operation has expanded in recent years, but fault detection and fault tolerant control for wind turbines is a less well-developed area of interest. In this benchmark challenge, we have reworked a previous challenge paper to present a more sophisticated wind turbine model - a modern 5 MW turbine implemented in the FAST software - and updated fault scenarios. These updates enhance the realism of the challenge and will therefore lead to solutions that are significantly more useful to the wind industry. This paper presents the challenge model and the requirements for challenge participants. In addition, it provides additional information about the faults selected for the challenge and their basis in field data.**

I. INTRODUCTION

Detecting wind turbine faults and controlling turbines even when such faults occur are important aspects of decreasing the cost of wind energy and increasing penetration into electrical grids. Improvements in fault detection and isolation (FDI) and fault tolerant control (FTC) should increase reliability and decrease operation and maintenance costs, especially as wind turbines are installed in less accessible locations such as offshore. However, the complexity of MW-scale modern wind turbines makes it difficult to transfer advanced FDI and FTC methods from the realm of control theory to control application, and it is not always clear how to simulate realistic faults or what sensors and models are available for use.

The past few years have seen a rapid growth in interest in wind turbine FDI and FTC. References [1] and [2] provide overviews of the recent status and practical aspects of wind turbine condition monitoring systems. Wind turbine blade sensors and actuators are frequently the topic of the FDI and FTC research focus. For example, an H-infinity-based FDI technique to detect and estimate the magnitude of blade bending moment sensor and pitch actuator faults is given in [3]. Blade root bending sensor measurements are used with a Kalman Filter and CUSUM algorithm to detect pitch misalignment in [4]. Model-based and system identification techniques are used for pitch actuator faults in [5]. A technique for detecting additive and multiplicative actuator faults is developed in [6], with simulation results for a wind turbine blade pitch actuator fault. FTC in the case of faulty blade load measurements is implemented in [7].

FDI and FTC for a wind turbine's generator and converter systems is described in [8], which uses an unknown input observer to isolate faults as either actuator- or sensor-based with the unknown input being the wind speed. Both model-based and signal-based FDI for Doubly Fed Induction Generator (DFIG) sensor faults are examined in [9]. DFIG sensor FDI is also the focus of [10], where the focus is on both isolation and reconfiguration. Finally, a H-infinity based algorithm for power sensor FDI is described in [11].

A previous benchmark paper [12] and competition inspired two sessions of papers at the 2011 IFAC World Congress and another two sessions at the IFAC Safeprocess Symposium in 2012. To motivate this second benchmark challenge, we summarize the results of the previous competition. The first part of the competition was on FDI and inspired both model-based and data-based methods. Observer based schemes were provided in [13], [14], [15]. Support vector machine based scheme were used in [16] and [17]. An automated fault detection and isolation scheme design method was presented in [18]. References [19] and [20] are based on parity equations. Data driven methods are used in [21], [22] and [23]. Finally, [24] is based on a generalized likelihood ratio method.

Results from the FTC portion of the previous benchmark can be found in the Safeprocess papers. A set value based observer method was proposed in [25], and [26] proposes a control allocation method for FTC of the pitch actuators. A virtual sensor/actuator scheme was applied in [27]. Takagi-Sugeno Fuzzy based methods for FTC for operation below rated wind speed were presented in [28] and [29], and a fuzzy logic based FTC scheme was proposed in [30]. Reference [31] presents an active FTC scheme based on adaptive methods and a model predictive control scheme was used for FTC in [32].

The challenge presented in this paper differs from the previous challenge [12] in several ways. First, a higher-fidelity, more realistic wind turbine model based on the wind turbine modeling software FAST [33] is used. FAST is an aeroelastic wind turbine simulator designed by the U.S. National Renewable Energy Laboratory's (NREL) National Wind Technology Center and widely used for studying wind turbine control systems. Since FAST is used by wind turbine researchers around the world, results based on this platform are more likely to be used by the wind industry than those based on a simpler model.

Compared to the wind turbine model in the original bench-

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mark challenge, the FAST-based model includes a higher fidelity model of the wind turbine structural behavior with up to 24 degrees of freedom. FAST also allows the use of more realistic "full field" wind inputs that vary spatially across the rotor plane. Each plane consisting of a set of three-dimensional wind speed vectors marches toward the turbine, creating a realistic turbulent input to the turbine. We expect the FAST model with such realistic wind input cases to result in a more complex challenge, since the turbine's nonlinear aerodynamic behavior is more fully modeled and since more complex relationships among faults, sensors, and actuators are simulated.

The final difference between this second FDI/FTC challenge compared to [12] is that the fault scenarios have been updated and additional information motivating their relevance has been provided.

II. Benchmark Model Description

Several FAST models of real and composite wind turbines of varying sizes are available in the public domain, including NREL's 5 MW "baseline" turbine made up of composite pieces and representative of a real utility-scale turbine.[1] This three-bladed, variable speed turbine with full span blade pitch control is available in both onshore and offshore versions, including four variations of offshore structures. The turbine's hub height is 89.6 m and its rotor radius is 63 m. Its rated rotor speed is 12.1 rpm. A baseline controller consisting of a PI pitch controller and $K\omega^2$ torque controller is available with the model. The maximum pitch rate is limited to 8 deg/s. In this wind turbine FDI and FTC challenge, we augment this 5 MW turbine by incorporating various faults within the Simulink environment, as we will describe in Section III.

FAST can utilize either uniform or full-field turbulent wind input files, with the turbulent files generated by the NREL software TurbSim [34]. TurbSim generates turbulence using one of several atmospheric turbulence models. In the wind input files supplied with this challenge, the mean wind speeds at the 90-m hub height are 11, 14, and 17 m/s and an IEC von Karman turbulence model is used to generate the wind input files. The hub-height measurement from the 14 m/s file is shown in Fig. 1. Additional wind input files will be used for testing the challenge results.

Figure 2 shows the major components of the Simulink-based model. The baseline feedback loop uses information from sensors as input to the pitch, torque, and yaw controllers. Actuator models for the pitch drives, generator, and yaw drive are implemented within the Simulink environment. Faults are shown corrupting both actuators and sensors. Note that all faults are implemented within Simulink and there are no changes to the underlying FAST code. Figure 2 also shows a FDI subsystem block that is to be used for FDI; FTC can be implemented in both the FDI subsystem and within the pitch, torque, and yaw controllers. Compared to the original FDI/FTC benchmark challenge [12], this model gives a more straightforward platform so that researchers who are not experts on wind turbine systems can easily determine which sensor and actuator signals are typically available for use. Asking researchers to implement FDI and FTC solutions entirely within the specified blocks will also make it easier to test and compare the solutions fairly.

[1]Available at `http://wind.nrel.gov/public/jjonkman/NRELOffshrBsline5MW`

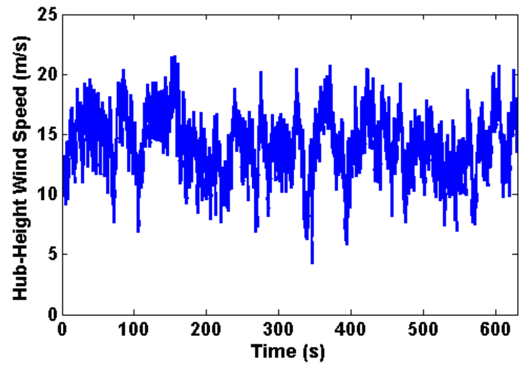

Fig. 1. Hub-height wind speed for 14 m/s sample wind input file for simulation tests.

The remainder of this section gives more information about the sensor, actuator, and controller subsystems.

A. Sensor Models

In this enhanced benchmark model, sensors are modeled in Simulink by adding signals from Band Limited White Noise blocks, which are parameterized by noise power, to the actual variables provided by FAST. These random noise blocks represent measurement noise either due to the measuring principle or due to electrical noise in the system. The sensors provided in the benchmark model are shown in Table I. These models are based on the same concept as used in [12]. More detailed sensor models, for example incorporating low pass filtering or time delays, could in principle be considered. However, in general measurement noise is considered the largest problem with non-faulty wind turbine sensors and is therefore the focus of this challenge's sensor models.

B. Actuator Models

Three actuators for the pitch, generator and converter, and yaw systems are considered and modeled in this benchmark model.

a) Pitch Actuator Model: The hydraulic pitch system is modeled as a closed loop transfer function from the pitch angle reference β_{r} to the actual pitch angle β. This model is essentially the same as used in [12]. In principle it is a piston servo system which can be modeled well by the second order transfer function (see [35])

$$\frac{\beta(s)}{\beta_{\mathrm{r}}(s)} = \frac{\omega_{\mathrm{n}}^2}{s^2 + 2\cdot\zeta\omega_{\mathrm{n}}\cdot s + \omega_{\mathrm{n}}^2} \tag{1}$$

where ζ is the damping factor and ω_{n} is the natural frequency. A transfer function is associated with each of the three pitch systems, which are identical when no fault exists. For the no-fault case, we use the parameters $\zeta = 0.6$ and $\omega_{\mathrm{n}} = 11.11$.

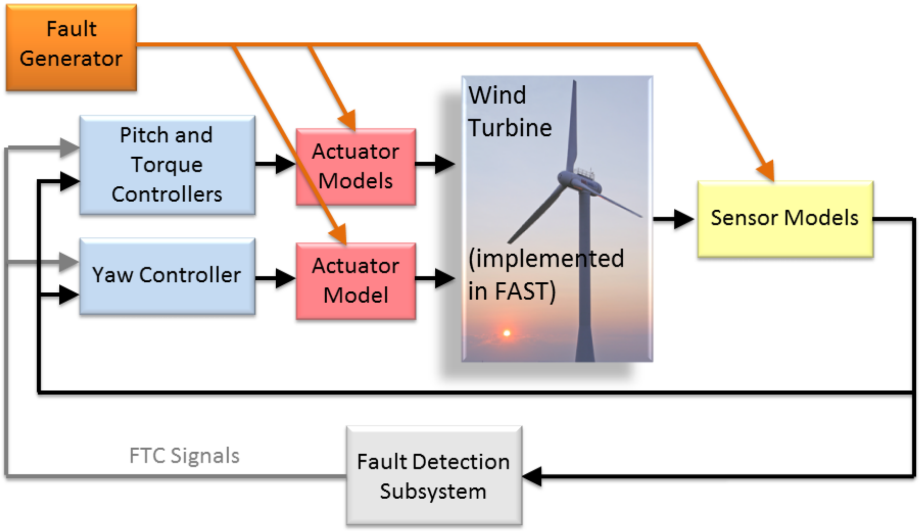

Fig. 2. Block diagram showing major elements of the FAST- and Simulink-based FDI and FTC benchmark model. The 5 MW wind turbine is simulated by FAST, while the sensor and actuator faults are implemented within the Simulink environment.

TABLE I

SENSORS AVAILABLE FOR THE BENCHMARK CHALLENGE. THESE SENSORS AND ASSOCIATED NOISE LEVELS ARE REPRESENTATIVE OF THE TYPES OF SENSORS THAT ARE AVAILABLE ON A MW-SCALE COMMERCIAL WIND TURBINE, WHICH FOR THE MOST PART ARE NOT HIGHLY REDUNDANT.

Sensor Type	Symbol	Unit	Noise Power
Anemometer - Wind speed at hub height	$v_{\mathrm{w,m}}$	m/s	0.0071
Rotor Speed	$\omega_{\mathrm{r,m}}$	rad/s	10^{-4}
Generator Speed	$\omega_{\mathrm{g,m}}$	rad/s	$2 \cdot 10^{-4}$
Generator Torque	$\tau_{\mathrm{g,m}}$	Nm	0.9
Generated Electrical Power	$P_{\mathrm{g,m}}$	W	10
Pitch Angle of i th Blade	$\beta_{i,\mathrm{m}}$	deg	$1.5 \cdot 10^{-3}$
Azimuth angle low speed side	ϕ_{m}	rad	10^{-3}
Blade root moment ith blade	$M_{\mathrm{B},i,\mathrm{m}}$	Nm	10^{3}
Tower top acceleration (x and y directions) measurement	$\begin{bmatrix} \ddot{x}_{\mathrm{x,m}} \\ \ddot{x}_{\mathrm{y,m}} \end{bmatrix}$	m/s^2	$5 \cdot 10^{-4}$
Yaw error	$\Xi_{\mathrm{e,m}}$	deg	$5 \cdot 10^{-2}$

The dynamics of the pitch actuator are determined by the stiffness of the hydraulic oil it contains, but this actuator is typically underdamped. When the actuator is requested to move, pressure builds up in the oil before the blade moves. The oil will always have some air content, which makes the hydraulic system even more underdamped, and the system damping decreases as the air content increases.

In addition, constraints on the pitch actuator include the pitch angle being restricted to the interval -2 deg - 90 deg and the pitch rate being restricted to the interval -8 deg/s - 8 deg/s.

b) Generator and Converter Model: The electrical system in the wind turbine and the electrical system controllers are much faster than the frequency range used in the benchmark model; for example, a generator time constant of 0.1 s is used in [36], [37]. It is common practice in wind turbine control to consider the generator and converter control loop separately from the turbine control loop due to time constant separation [38], [39]. On a system level of the wind turbine, the generator and converter dynamics can be modeled by a first order transfer function. This model is essentially the same as used in [12] and is given by

$$\frac{\tau_{\mathrm{g}}(s)}{\tau_{\mathrm{g,r}}(s)} = \frac{\alpha_{\mathrm{gc}}}{s+\alpha_{\mathrm{gc}}},$$

where α_{gc} depends on the generator and converter; for this turbine, $\alpha_{\mathrm{gc}} = 50$.

The power produced by the generator is given by

$$P_{\mathrm{g}}(t) = \eta_{\mathrm{g}}\omega_{\mathrm{g}}(t)\tau_{\mathrm{g}}(t),$$

where η_{g} is the efficiency of the generator and we use $\eta_{\mathrm{g}} = 0.98$.

In the context of this benchmark model the topology of the generator can either be (1) a DFIG in which the stator is directly connected to the grid and the rotor is connected through a converter, or (2) a full scale converter solution where both the generator's stator and rotor are connected to the grid through a converter. For the model resolution and selected faults in this challenge, both topologies are adequately represented by this simple model.

c) Yaw Actuator Model: The yaw actuator model differs from the pitch and generator/converter models because the FAST model includes the yaw dynamics, while the pitch and generator models are implemented in Simulink. FAST requires a yaw angular velocity reference, $\omega_{\mathrm{y,r}}$, and yaw angular position reference, $\Psi_{\mathrm{y,r}}$, as inputs. Since the yaw controller only provides a yaw angular velocity, which is either 0 rad/s or a constant yaw angular speed $\pm\alpha_y$, it can be concluded that the yaw actuator model contains an integrator, given as

$$\Psi_{\mathrm{y,r}}(t) = \int_0^t \omega_{\mathrm{y,r}}(\tau) d\tau. \tag{2}$$

That is, providing a yaw angular velocity into FAST via Simulink results in the determination of the yaw angular position as well as the yaw angular velocity. MW-scale wind turbine have yaw systems with maximum yaw rates of less than 1 deg/s, so higher order dynamics do not need to be included in the model.

d) Yaw Controller: The designed yaw controller is a simplification of an industrial baseline yaw controller. It is basically an on/off controller, which operates with a constant angular speed and a direction given by the sign of the yaw error. First, the measured yaw error $\Xi_{\mathrm{e,m}}$ is filtered via

$$\hat{\Xi}_{\mathrm{e,m}}(z) = \frac{0.1175}{z - 0.8825}\Xi_{\mathrm{e,m}}(z), \tag{3}$$

where $\hat{\Xi}_{\mathrm{e,m}}$ is therefore the filtered version $\Xi_{\mathrm{e,m}}$.

The yaw reference angular velocity, $\omega_{\mathrm{y,r}}$, is zero if the error is less than a threshold value κ_{y} and a constant value if its magnitude is greater than κ_{y}; that is,

$$\omega_{\mathrm{y,r}} = \begin{cases} 0 & \text{if } |\hat{\Xi}_{\mathrm{e,m}}| \leq \kappa_{\mathrm{y}}, \\ \alpha_{\mathrm{y}} & \text{if } |\hat{\Xi}_{\mathrm{e,m}}| > \kappa_{\mathrm{y}} \text{ and } \hat{\Xi}_{\mathrm{e,m}} > 0, \\ -\alpha_{\mathrm{y}} & \text{if } |\hat{\Xi}_{\mathrm{e,m}}| > \kappa_{\mathrm{y}} \text{ and } \hat{\Xi}_{\mathrm{e,m}} < 0, \end{cases} \tag{4}$$

in which $\alpha_{\mathrm{y}} = 0.5$ and $\kappa_{\mathrm{y}} = 4$ for this benchmark challenge.

A state-of-the-art industrial yaw controller has a number of filters like (4) with different time constants which are used in the same manner as the one used in this model. Different thresholds are used as well for the different filters. The yaw control signal would be active (non-zero) if one filter's output crosses its thresholds.

III. Fault Description

As in [12], we consider both sensor and actuator faults. Most faults selected were motivated by research, both in the public domain and from proprietary sources. In this section, we describe the faults and, when permissible, provide sources to data motivating their selection.

A. Sensor faults

Sensor faults include measurements that are stuck, scaled from the true values, or offset from the true values, as indicated by Faults 1-6 in Table III.

When Fault 1 occurs, the blade root bending moment sensor at Blade 2 is scaled by a factor of 0.95. Fault 1 is present between 20s and 45s.

Fault 2 results in an offset of -0.5m/s^2 on the tower top accelerometer in both the fore-aft and side-to-side directions. Fault 2 is present in the time period 75s to 100s. Accelerometers are notoriously difficult to keep calibrated; see, for example, [40] and [41].

Fault 3 causes the generator speed sensor to be scaled by a factor of 0.95. Fault 3 is present between 130s and 155s.

Fault 4 results in Blade 1 having a stuck pitch angle sensor, which holds a constant value of 1 deg. Fault 4 is active from 185s to 210s.

While Fault 5 is occurring, the generator power sensor is scaled with a factor of 1.1. Fault 5 is present in the time interval from 240s to 265s. Precedent for scaled generator power sensor errors can be found in [40].

Fault 6 models a bit error in the low speed shaft encoder, which is another sensor fault documented in [40]. This bit error is modeled by randomly adding an offset to the measurement that corresponds to the bit on which the error is present. Fault 6 occurs from 295s to 320s.

B. Actuator faults

The primary actuators used by the turbine are the blade pitch drives, the generator torque, and the yaw drive.

The two faults in the pitch actuators are Faults 7 and 8. These two faults are modeled by changing the parameters ζ and ω_n in the relevant pitch actuator model (1), and the same parameters are used as in [12]. Motivation for faults in pitch actuators is largely proprietary, but an example of a pitch actuator fault containing unexpected dynamics is given in [40]. The pressure drop in the actuator can be caused by a leakage in the hydraulic system, which allows air to mix with the oil and thus makes the oil more compressible than normal. This increased compressibility alters the eigenfrequency of the actuator and lowers its damping ratio as well. Although the hydraulic system is designed to avoid leakage and to minimize the air content, it is not possible to eliminate it completely. Therefore, the air content is consistently unknown.

To model the pitch actuator's hydraulic power drop and increased air content, the parameters in the transfer function (1) are changed during these faults. Notice here that the hydraulic pressure drop is assumed to be abrupt, while the air content increases slowly. The two parameters for the pressure drop case (Fault 8) are denoted $\omega_{\mathrm{n2}} = 5.73,\ \zeta_2 = 0.45$ and the two parameters for the increased air content model (Fault 7) are denoted $\omega_{\mathrm{n3}} = 3.42, \zeta_3 = 0.9$. Fault 7 is introduced linearly from 350s to 370s, fully active from 370s to 390s, and linearly eliminated from 390s to 410s. Fault 8 is active from 440s to 465s, and linearly introduced and eliminated within 1s.

Fault 9 is an offset on the generated generator torque, which can be caused by an error in the initialization of the converter controller. This fault can occur since the converter torque is estimated based on the currents in the converter. If this estimate is initialized incorrectly it will result in a offset on the estimated converter torque, which leads to the offset on the generator torque. This fault is modeled as in

TABLE II

FAULT SCENARIOS. BOTH SENSOR AND ACTUATOR FAULTS ARE INCLUDED AND MOTIVATION PROVIDED WHEN PERMISSIBLE. FAULT-TOLERANT CONTROL SHOULD STRIVE TO KEEP THE TURBINE OPERATING IN THE CASE OF MOST OF THESE SCENARIOS, THOUGH FAULTS 7 AND 10 REQUIRE A TURBINE SHUT-DOWN.

No.	Fault	Type	Motivation
1	Blade root bending moment sensor	Scaling	Proprietary
2	Accelerometer	Offset	[40], [41]
3	Generator speed sensor	Scaling	Proprietary
4	Pitch angle sensor	Stuck	Proprietary
5	Generator power sensor	Scaling	[40]
6	Low speed shaft position encoder	Bit error	[40]
7	Pitch actuator	Abrupt change in dynamics	Proprietary
8	Pitch actuator	Slow change in dynamics	[40]
9	Torque offset	Offset	[42]
10	Yaw drive	Stuck drive	Proprietary

[12]; however, it was found based on the evaluation of the contribution to the FDI benchmark problem that the original offset value 100 Nm was too small to be detected (see [42]). Consequently the offset is increased to 1000 Nm. Fault 9 occurs from 495s-520s.

The last fault, which is the stuck yaw actuator (Fault 10), represents the case when the turbine cannot yaw, either due to actuator malfunction or the yaw brake being stuck on. It is modeled by setting the yaw angular velocity to zero rad/s independent of the value of $\Xi_{\text{e,m}}$ and is active in the time interval from 550s to 575s.

IV. REQUIREMENTS

A. Fault Detection and Isolation Requirements

The FDI requirements are listed in this subsection, where the goal is to motivate solutions that are realistic for the wind industry. The detection times T_{D} for the respective faults are defined in terms of the sampling time for the control system T_{s}, which is 0.0125 s in this case.

Time of detection:

- Faults 1 - 6 must satisfy $T_{\text{D}} < 10 \cdot T_{\text{s}}$
- Fault 7 must satisfy $T_{\text{D}} < 8 \cdot T_{\text{s}}$
- Fault 8 must satisfy $T_{\text{D}} < 100 \cdot T_{\text{s}}$
- Fault 9 must satisfy $T_{\text{D}} < 3 \cdot T_{\text{s}}$
- Fault 10 must satisfy $T_{\text{D}} < 50 \cdot T_{\text{s}}$.

Simulations using many wind input files will be applied to test that the detection scheme can detect the specified faults with these requirements. Measurement noise will induce differences between each simulation, and each simulation case is expected to be repeated 100 times.

False detections: the number of false detections is required to be kept low: the interval between false detections is required to be larger than 30000 samples on average. The false detections must last no more than three samples.

Missed detections: the faults included in this benchmark model are of such a size that they all should be detected.

Issues to be aware of: a major problem in wind turbine control in general is that, when viewed from a control theoretical point-of-view, the wind turbine is driven by a disturbance (the wind). The wind speed is, however, measured in a very loose sense including significant noise and risk of offset. This "measurement" is performed both by an anemometer on the nacelle and by the rotor itself (with closed-loop control affecting both of these measurements.) The measurement offset can be calibrated but is expected to be considered in the FDI system. The measurement noise is modeled as a Gaussian white noise with parameters found in the list of parameters.

B. Accommodation Requirements

The benchmark model of the paper contains both faults for which the system can be reconfigured to continue power generation, as well as very severe faults which require a safe and fast shut down of the wind turbine. The severe faults are numbers 7 and 10. In the FTC challenge, all remaining faults must be accommodated in some way and the wind turbine must continue its operation. In all cases detection of faults must be reported to the system operator, and automatic action is required. In case of a single sensor fault, system performance must not deteriorate; in the case of multiple faults, a mild deterioration of the system performance is accepted. Large transients when accommodating the fault must be avoided.

For many aspects of FTC, it is difficult to give hard constraints. A rule of thumb is that for FTC, operation should be as close as possible to the fault-free case. In particular, generator speed should be regulated to no more than 10% of its rated value of 1200 rpm in above-rated wind conditions. Particular attention should also be given to blade root bending moments, nacelle acceleration, drive train torsion, and tower bending moments to avoid structural damage to the turbine.

V. CONCLUSIONS

With this updated challenge model, we have provided a more realistic model for use in designing and testing FDI and FTC algorithms for wind turbines. The turbine model is more realistic, using the well-recognized FAST software, and the faults have been updated to better reflect observed faults in both sensors and actuators.

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