An Evaluation of Fault Tolerant Wind Turbine Control Schemes applied to a Benchmark Model

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Abstract— **Reliability and availability of modern wind turbines increases in importance as the ratio in the world's power supply increases. This is important in order to increase the energy generated per unit and their lowering cost of energy and as well to ensure availability of generated power, which helps keeping the power grids stable. Advanced Fault Tolerant Control is one of the potential tools to increase reliability of modern wind turbines. A benchmark model for wind turbine fault detection and isolation and fault tolerant control has previously been proposed, and based on this benchmark an international competition on wind turbine fault tolerant control has been proposed. In this article the top three solutions from this wind fault tolerant control competition are introduced and evaluated. The evaluation presented in this paper shows that the winner of the competition performs very well on this benchmark and is especially good accommodating sensors faults. The two other evaluated solutions do also well accommodating sensors faults, but have some issues which should be worked on, before they can be considered as a full solution to the benchmark problem.**

I. INTRODUCTION

Power grids around in the world, depend in higher and higher degree on power generated by renewable energy sources, wind turbines play a large part among these renewable energy sources. Wind turbines should consequently be as available and reliable as possible, not considering impact from the uncertain wind. Meaning that the all other sources to availability losses of wind turbines than low wind speed should be minimized by design and construction of the wind turbines. One of the areas to focus on in the process of obtaining this is to design the wind turbines as tolerant towards faults as possible. One of the relevant methods obtaining this is advanced Fault Tolerant Control (FTC), and it is consequently relevant to apply FTC Schemes to modern wind turbines.

The research on fault tolerant control applied to wind turbines have until now mainly been focused on Fault Detection and Isolation (FDI), which is the normal first step in an active fault tolerant control strategy. The fault detection and isolation can also be used in non automatic fault accommodation and repair approaches for the wind turbine manufacturers and operators. A few paper has been published on fault tolerant control of wind turbines, see [1] and [2]. FDI schemes applied to the wind turbine application are reported in a number of publications, some examples on these are introduced in the following. In [3] a Kalman filter based diagnosis system to detect faults in the blade root bending moment sensors was presented. An unknown input observer was designed for detection of sensor faults around the wind turbine drive train in [4]. In [5] active and passive fault tolerant control schemes were applied to a wind turbine model.

In [6] a wind turbine benchmark model for fault detection and isolation and fault tolerant control was proposed. In [7] this benchmark model was described in more details together with description and evaluation of some proposed solutions to the FDI problem. These evaluated FDI solutions were the top contributors to an International Competition. The evaluated solutions can be found in [8], [9], [10], [11] and [12]. A number of other FDI solutions have also been applied to this benchmark model; among these are: [13], [14], [15], [16], [17], [18] and [19].

In this paper a the top three contributions to an International Competition on the fault tolerant control problem proposed in the previously mentioned benchmark. These solutions can be seen in details in [20], [21] and [22]. These solutions will be first be shortly introduced, and subsequently evaluated and compared on the wind turbine FDI and FTC benchmark model.

In addition to the evaluated solutions a number of other FTC solutions have been applied to the benchmark model, some examples are: [23], [24], [25], [26] and [27].

The wind turbine FDI and FTC benchmark model is shortly introduced in Sec. II, in this Section metrics for the evaluation of the fault tolerant control schemes applied to the benchmark model are as well proposed. Section III presents the evaluated FTC schemes. The schemes are evaluated in Sec. IV, and the paper is finalized with a conclusion in Sec. V.

II. WIND TURBINE BENCHMARK DESCRIPTION

This paper considers a generic wind turbine of 4.8 MW described in [6], this paper only shortly introduces this model, more details on it can be found in the mentioned paper. This turbine is a variable speed three blade pitch controlled turbine, with a front horizontal axis rotor.

An overview of the model can be seen in Fig. 1, in which v_w denotes the wind speed, τ_r denotes the rotor torque, ω_r denotes the rotor speed, τ_g denotes the generator torque, ω_g denotes the generator speed, β_r denotes the pitch angle control reference, β_m denotes the measured pitch angles, $\tau_{w,m}$ denotes the estimated rotor torque, $\omega_{r,m}$ denotes the measured rotor speed, $\tau_{g,m}$ denotes the measured generator torque, $\omega_{g,m}$ denotes the measured generator speed, P_g

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The first author is supported by the Vestas Wind Turbine Control program at Aalborg University

denotes the measured generated electrical power, $\tau_{g,r}$ denotes the generator torque reference, and P_r denotes the power reference. Each element of the model is subsequently shortly

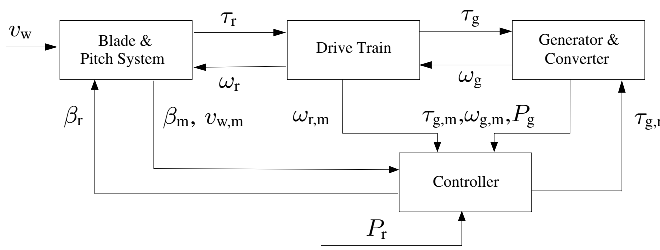

Fig. 1. This figure shows an overview of the benchmark model. It consists of four parts: Blade and Pitch Systems, Drive Train, Generator & Converter, and Controller. The variables in the figure are defined in the text.

described.

1) Wind Model: The wind speed is given by a wind model including mean wind trends, turbulence, wind shear and tower shadow.

A. Aerodynamic and Pitch Actuator Model

Aerodynamics and pitch actuators are modeled in Blade and Pitch System model, the pitch actuator is modeled as a second order transfer function with constraints. The aerodynamics are modeled by a static mapping from the pitch angle, rotor and wind speeds to the torque acting on the wind turbine rotor.

B. Drive Train Model

The drive train, which is used to increase the speed from rotor to generator, is modeled with a flexible two-mass system. The drive train model includes the inertia of the rotor (which includes blades and the main shaft) and generator.

C. Converter Model

The converter which controls the generator torque is modeled by a first order system with constraints. This model covers both the electrical behavior of the generator and converter.

D. Sensor Models

This model is not shown on the figure, since models of each sensors in the figure are included in the relevant part models. The model contains a number of sensors: generator and rotor speed, pitch angles, wind speed, converter torque, electrical power. All the sensors are modeled as the measured variable added with random noise.

E. Controller

The wind turbine operates in principle in 4 regions: Region 1 in which wind speeds are too low for the wind turbine to operate, Region 2 in which the turbine operates up to a nominal wind speed (partial load), Region 3 between nominal and rated wind speed, where the nominal power can be produced, Region 4 above rated wind speed, where the wind turbine is closed down in order to limit extreme loads on the wind turbine.

The controller is active in Region 2 & 3. In Region 2, the optimal rotor speed is obtained by using the converter torque as control signal. In Region 3 the rotor speed is kept at a given reference value by pitching the blades, (the converter keeps the power at the reference taking care of fast variations in the speed). The basic controller in the different regions is described in [28].

F. Fault Scenarios

In the test signal definition described in [7] the defined faults are present at a predefined time. In this bench model setup a predefined wind speed sequence is used. This wind sequence consists of real measured wind data from a wind farm and can be seen in Fig. 2. The benchmark contains 8

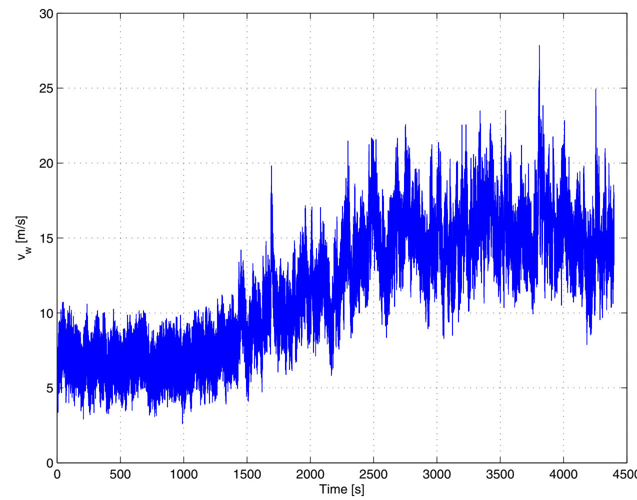

Fig. 2. Illustration of the wind speed sequence used in the benchmark model. It can be seen that the wind speed covers the range from 5 m/s to 20 m/s, with a few spikes at 25 m/s, which is good coverage of normal operational of a wind turbine.

faults, 5 sensor faults and 3 actuator faults. In the following Test Set 1 is defined and the different measurement signals are plotted as well. The fault used are defined as.

- Fault 1: fault type 1a) a fixed value on $\beta_{1,m1}$ equal to $5°$ in the time period from 2000 s to 2100 s.
- Fault 2: fault type 1b) a gain factor on $\beta_{2,m2}$ equal to 1.2 in the time period from 2300 s to 2400 s.
- Fault 3: fault type 1a) a fixed value on $\beta_{3,m1}$ equal to $10°$ in the time period from 2600 s to 2700 s.
- Fault 4: fault type 2a) a fixed value on $\omega_{r,m1}$ equal to 1.4 rad/s in the time period from 1500 s to 1600 s.
- Fault 5: fault type 2b) and 3b) gain factors on $\omega_{r,m2}$ and $\omega_{g,m1}$ respectively equal to 1.1 and 0.9 in the time period from 1000 s to 1100 s.
- Fault 6: fault type 5a) change in the dynamics due to hydraulic pressure drop of the pitch actuator 2, the fault is assumed to be abrupt and it is present in the time period from 2900 s to 3000 s.
- Fault 7: fault type 5b) change in the dynamics due to increased air content in the oil on pitch actuator 3. The fault is slowly introduced during 30 s with a constant rate; afterward the fault is active during 40 s, and again

decreasing during 30 s. The fault begins at 3400 s and ends at 3500 s.

- Fault 8: fault type 4b) an offset on τ_g of the value 100 Nm, the fault is active from 3800 s to 3900 s.

In [7] six additional Test Series were defined to test the schemes robustness towards different operational points of the fault. These Test Series are defined as. Test Series 2: +100s for all faults, Test Series 3: -100s for all faults, Test Series 4: -200s for all faults, Test Series 5: -300s for all faults, Test Series 6: -400s for all faults, and Test Series 7: -500s for all faults.

It should be noticed that the proposed schemes are not designed on the basis of Test Series 2 to 7.

The benchmark model package contains a wind speed sequence, a Simulink model with a parameter file. The package can be obtained at [29].

G. FTC Requirements

In the original Benchmark model formulation the requirements to the FTC solutions were not specified in details. It was required that the system performance during faults should be as like the non-faulty performance as possible. It should be noticed that the model do not include models of the physical structures like blades and tower, consequently it cannot be evaluated how the solutions influences the fatigue and extreme loads of the wind turbine.

In the evaluation of the proposed schemes a metric for comparison were developed. The evaluation metric will be described and explained in this section.

Firstly each Test Set, k, is repeat 5 times with different random noise seeds, j. For each time interval in which the faults, f, occurs and for each Test Set and noise seed a number of values are computed of some of the relevant states in the model. Notice that the actual system state value is used in order to use the physical value. Mean of generated power, $P_{\text{mean},j,k,f}$, Mean, Min and max of each pitch angle, $\beta_{\text{min},i,j,k,f}$, $\beta_{\text{max},i,j,k,f}$, $\beta_{\text{min},i,j,k,f}$, where i is the blade number, and the mean of the generator speed, $\omega_{\text{mean},j,k,f}$. Finally a mean of the different variables are computed over the different noise seeds.

The next step is to compute the these values for each Test Set defined as.

$$P_{\text{mean},k,f} = \sum_{j\in\{1,2,3,4,5\}} P_{\text{mean},j,k,f}, \tag{1}$$

$$\beta_{\text{min},i,k,f} = \sum_{j\in\{1,2,3,4,5\}} \beta_{\text{min},i,j,k,f}, \tag{2}$$

$$\beta_{\text{max},i,k,f} = \sum_{j\in\{1,2,3,4,5\}} \beta_{\text{max},i,j,k,f}, \tag{3}$$

$$\beta_{\text{mean},i,k,f} = \sum_{j\in\{1,2,3,4,5\}} \beta_{\text{mean},i,j,k,f}, \tag{4}$$

$$\omega_{\text{max},k,f} = \max_{j\in\{1,2,3,4,5\}} (\omega_{\text{mean},j,k,f}). \tag{5}$$

The fault free Test Set is number as $k = 0$.

The basic setup is to give credit for the accommodation of each fault in each Test Set. In order to make the description and formulation of the evaluation metric easier to understand, the metric is described for fault number f.

First the ratio of mean generated power during the fault relatively to the mean generated power in the fault free case for the same time interval is computed. A number of multiplicative reductions are subsequently introduced to deal with a number of constraints and objectives which should be enforced by the control solutions.

This means that the metric, $C_{f,k}$ for fault f in Test Set k can be formulated as

$$C_{f,k} = \frac{\sigma_1}{\sigma_0} \cdot r_1(\sigma_1) \cdot r_2(\sigma_2) \cdot r_3(\sigma_3) \cdot r_4(\sigma_4) \cdot r_5(\sigma_5) \cdot r_6(\sigma_6), \tag{6}$$

in which

$$\sigma_0 = P_{\text{mean},0,f}, \tag{7}$$

$$\sigma_1 = P_{\text{mean},k,f}, \tag{8}$$

$$\sigma_2 = \begin{bmatrix} \beta_{\text{mean},1,k,f} \\ \beta_{\text{mean},2,k,f} \\ \beta_{\text{mean},3,k,f} \\ P_{\text{mean},k,f} \end{bmatrix}, \tag{9}$$

$$\sigma_3 = P_{\text{mean},k,f}, \tag{10}$$

$$\sigma_4 = \omega_{\text{max},k,f}, \tag{11}$$

$$\sigma_5 = \begin{bmatrix} \beta_{\text{min},1,k,f} \\ \beta_{\text{min},2,k,f} \\ \beta_{\text{min},3,k,f} \end{bmatrix}, \tag{12}$$

$$\sigma_6 = \begin{bmatrix} \beta_{\text{mean},1,k,f} \\ \beta_{\text{mean},2,k,f} \\ \beta_{\text{mean},3,k,f} \end{bmatrix}. \tag{13}$$

In the following all the functions r_1 - r_6 are defined, explained and motivated. In these a number of weights are used, and these are elements in a vector W. The different weights are found by trial and error, with objective of punishing very critical operation during faults higher than less critical behavior. In additions they are adjusted such that a clear conclusion can be drawn from the comparison.

The function r_1 is included to enforce a constraint on the max power which is equal to 4.8MW. If the power increased with more than 20 % a penalty is inferred. Such a large overproduction is not allowed and will result in a full reduction of gained points.

$$r_1(P_{\text{mean},k,f}) = \begin{cases} 0 & \text{if } P_{\text{mean},k,f} > 1.2 \cdot 4.8, \\ 1 & \text{else} \end{cases} \tag{14}$$

The function r_2 is included to ensure that the power production is optimal, i.e. that the mean pitch angle is below 1 degree if the mean power is below 4.6 MW, which is slightly lower than the rated power, in order to allow a slight power reduction for obtaining other objectives, as they might lead to power drop, W(1)=0.75.

$$r_2 \begin{pmatrix} \beta_{\text{mean},1,k,f} \\ \beta_{\text{mean},2,k,f} \\ \beta_{\text{mean},3,k,f} \\ P_{\text{mean},k,f} \end{pmatrix} = \begin{cases} W(1) & \text{if } \alpha_1 > 0, \\ 1 & \text{else.} \end{cases} \tag{15}$$

α_1 is equal if $\text{mean}_{i\in\{1,2,3\}}(\beta_{\text{mean},i,k,f}) > 1 \wedge P_{\text{mean},k,f} > 4.6$ and is equal 0 in if not.

The next function r_3 is introduced to ensure optimal power production, in the case that the generator torque is used to lower the production, W(2)=0.75.

$$r_3(P_{\text{mean},k,f}) = \begin{cases} W(2) & \text{if } P_{\text{mean},k,f} < 4.8, \\ 1 & \text{else.} \end{cases} \tag{16}$$

The next function, r_4 is introduced to punish generator over-speed. The nominal speed is 162 rad/s, over-speed is weighted with two scales one for 16 %, W(3)=0.75, and one for 28 % over-speed, where the later results in a higher reduction, W(4)=0.5.

$$r_4(\omega_{\text{max},k,f}) = \begin{cases} W(3) & \text{if } 207 \geq \omega_{\text{max},k,f} > 186, \\ W(4) & \text{if } \omega_{\text{max},k,f} > 207, \\ 1 & \text{else.} \end{cases} \tag{17}$$

r_5 punishes pitch angle requests below -2 degree, which is the lowest possible pitch angle the actuator can provide. The used weight W(5) is set equal to 0.5 for this.

$$r_5 \begin{pmatrix} \beta_{\text{min},1,k,f} \\ \beta_{\text{min},2,k,f} \\ \beta_{\text{min},3,k,f} \end{pmatrix} = \begin{cases} W(5) & \text{if } \min_{i\in\{1,2,3\}}(\beta_{\text{min},i,k,f}) < -2, \\ 1 & \text{else.} \end{cases} \tag{18}$$

r_6 evaluates the correction of the pitch system faults, and since the wind turbine is controlled with collective pitch all three pitch angles should be alike. If the difference is larger than 10 degrees it is punished, W(6)=0.5, if it is lower than 2 degrees it is rewarded, (W(7)=1.1) and if lower than 1 degree it is rewarded even more (W(8)=1.2).

$$r_6 \begin{pmatrix} \beta_{\text{mean},1,k,f} \\ \beta_{\text{mean},2,k,f} \\ \beta_{\text{mean},3,k,f} \end{pmatrix} = \begin{cases} W(6) & \text{if } , \alpha_2 > 0, \\ W(7) & \text{if } , \alpha_3 > 0, \\ W(8) & \text{if } , \alpha_4 > 0. \end{cases} \tag{19}$$

and α_2 is equal 1 if $\|\max_{i\in\{1,2,3\}}(\beta_{\text{mean},i,k,f}) - \min_{i\in\{1,2,3\}}(\beta_{\text{mean},i,k,f})\| > 10$ and 0 if not. α_3 is equal 1 if $\|\max_{i\in\{1,2,3\}}(\beta_{\text{mean},i,k,f}) - \min_{i\in\{1,2,3\}}(\beta_{\text{mean},i,k,f})\| < 2$ and 0 if not, α_3 is equal 1 if $\|\max_{i\in\{1,2,3\}}(\beta_{\text{mean},i,k,f}) - \min_{i\in\{1,2,3\}}(\beta_{\text{mean},i,k,f})\| < 1$ and equal 0 if not.

The weight vector W is defined in (20), based on the parameter values assigned in the description of each of the metric function.

$$W = \begin{bmatrix} 0.75 \\ 0.75 \\ 0.75 \\ 0.5 \\ 0.5 \\ 0.5 \\ 1.1 \\ 1.2 \end{bmatrix} \tag{20}$$

All these metrics are subsequently summarized over the different faults and Test Series.

Even though that stability of the FTC solutions are not directly dealt with, it is indirectly taken into account by r_1, r_4 and r_6, as they considers maximal values of specific key turbine states which would be violated in case of unstable operation. It must be said that the wind turbine operation do not need to be unstable for these values to be violated, but unstable operation will lead to violation of these.

III. Evaluated Fault Tolerant Control Methods

In this section the three FTC solutions, applied to the benchmark model presented in [6], are introduced before they are evaluated in Section IV.

A. Virtual Sensor and Actuator based FTC

This solution has been published in [20], it will in the following be denoted VSA.

This solution proposes a fault tolerant control scheme based on a virtual sensor and actuator concept, which in principle encapsulates the actual sensors and actuators in a software module which compensates for the faults in the sensors and actuators respectively. This can be seen as an annihilating signal to the fault being introduced in the virtual sensor/actuator such that the effect of the fault is mitigated.

This means that the wind turbine and the nominal controllers would in principle not see any differences from the non-faulty sensors and actuators. This in turn implies that the nominal controller can be used. This is especially relevant and important for industrial applications, like a wind turbine.

The sensor and actuator faults are compensated by estimating the faults and then using the estimates in compensating them. This scheme relies on fault detection and isolation such that the fault is identified. For the sensor faults in case of fixed sensor values, the measurement is replaced by estimations based on models and other sensors. The gain fault is compensated by estimating the fault gain and subsequently compensate the measurement by it.

The pitch actuator fault is compensated by estimating the fault dynamics and using the inverse of it to compensate the changed dynamics. The converter fault is compensated by subtracting the estimated offset from the control signal sent by the controller.

B. T-S Fuzzy based FTC

[22] proposes this solution to the FTC problem, it is denoted as TSF.

This solution was only designed for partial load control of the wind turbine. In this article the solution is nevertheless evaluated on the full test sequences.

The first step in this approach is to model the wind turbine with Takagi-Sugeno multi models representing the nonlinear behavior of the wind turbine. An effective wind speed estimator is used to select the relevant model. The generator speed sensor faults are estimated using a Proportional Multiple Integration Observer and as well provide a robust estimate of the effective wind speed. Based on these estimates in which the fault is compensated by a Takagi-Sugeno Fuzzy Dynamic Output Feedback Controller. Lyapunov stability is proven with respect to H_∞ performance and D-stability constraints.

C. Adaptive FTC

The adaptive FTC scheme is proposed in [21] and [30], and is in the following denoted ADA.

This fault tolerant control strategy is based on an adaptive scheme, in which the online identification of the system is used. In this way, the controller reconfiguration mechanism exploits an adaptive regulator implementation, depending on the online estimate of system model. This system model is achieved using a recursive identification method exploiting an adaptive directional forgetting scheme. Modified Ziegler-Nichols rules are applied to the online adapted model to adjust the PI controller parameters in the control scheme. One of the advantages of this strategy is that, for example, the original structure of the logic-based switching digital controller scheme already implemented for the wind turbine benchmark can be almost preserved. Note also that this scheme does not require any FDI schemes.

IV. Evaluation of Methods

In this section the three methods are evaluated. The evaluation metrics proposed in Sec. II-G are computed and the results of this is presented in this section. Based on these data the fault accommodation of the different methods of the different faults can be seen, and as well robustness of the schemes can be evaluated as well.

The results of the evaluation of the VSA scheme can be seen in Table I, from which it can be seen that it handle faults # 1, 4 and 5 very well, and the rest well. This indicates that this scheme is better for accommodation of sensor faults than actuator faults. It can also be seen that it handles the different Test Series with almost the same performance, but it do actually scores a higher number for Test Series # 4, 5, 6 and 7 than for the nominal Test Series which it was designed for, which is mainly due a better accommodation of pitch actuator faults in the later Test Series. Compared with the two other schemes, their results can be seen in Table II for the TSA scheme and in Table III for the ADA scheme, the VSA scheme performs much better. The TSA scheme accommodates faults 4 and 5 very well and fault 2 and 3 well. It is expected that the actuator faults (fault # 6-8) would be handled poorly due to the fact that they occurs in full power, which this scheme was not designed for. It can also be seen that this scheme is some how robust towards changes in the time location of the faults, and thereby the operation condition at which the different faults occur. The TSA scheme is scoring well without being designed for full load control. The ADA scheme accommodates Fault # 4 and 5 very well and # 1 and 2 well. The actuator faults are again not handled as well as the sensor faults. It seems to be a general trend of these solutions, which might indicate that the sensor faults in the benchmark model is easier to accommodate than the actuator faults. The ADA scheme scores at the same level for all Test Series, but the nominal Test Series scores slightly better than the others. Based on these proposed evaluation metrics, it is clear that the VSA scheme performs the best on the used Wind Turbine FDI/FTC Benchmark model. A drawback on this benchmark is that it do not include models of the structural parts of the wind turbine, so fatigue and extreme loads on important components like tower and blades cannot be investigated and evaluated. Future work would consequently be to redesign the schemes for a benchmark including more detailed aerodynamic and structural wind turbine model,

TABLE I
The evaluation metrics for the VSA scheme.

Fault No	Series 1	Series 2	Series 3	Series 4
1	**1.2**	**1.23**	**1.2**	**1.2**
2	**0.6**	0.46	**0.6**	**1.2**
3	0.54	0.59	0.42	0.45
4	**1.2**	1.1	**1.2**	**1.2**
5	**1.2**	1.17	**1.24**	**1.21**
6	**0.6**	0.45	0.6	0.59
7	**0.6**	**0.43**	**0.6**	**0.6**
8	**0.6**	**0.6**	0.6	**0.52**
Sum	**6.56**	**6.03**	**6.46**	**6.97**
Fault No	Series 5	Series 6	Series 7	Sum
1	**1.2**	**1.2**	**1.2**	**8.43**
2	**1.2**	**1.2**	**1.2**	**6.46**
3	**0.6**	**0.6**	**1.2**	4.4
4	**1.2**	**1.2**	**1.2**	8.3
5	**1.27**	1.22	**1.22**	**8.53**
6	**0.58**	0.33	0.45	3.6
7	**0.45**	**0.59**	**0.47**	**3.74**
8	0.55	0.6	**0.6**	**4.07**
Sum	**7.05**	**6.94**	**7.54**	**47.55**

TABLE II
The evaluation metrics for the TSA scheme.

Fault No	Series 1	Series 2	Series 3	Series 4
1	0.33	0.34	0.46	0.48
2	0.3	0.3	0.3	0.9
3	**1.19**	**1.1**	**1.09**	**1.1**
4	**1.2**	0.83	**1.2**	**1.2**
5	**1.2**	**1.2**	**1.19**	1.2
6	0.30	0.3	**1.19**	0.3
7	0.30	0.0	0.0	0.0
8	0.27	0.29	**0.9**	0.0
Sum	5.09	4.36	5.62	4.51
Fault No	Series 5	Series 6	Series 7	Sum
1	0.34	0.45	0.45	2.85
2	0.3	1.18	1.19	4.47
3	0.1	0.11	0.29	**4.98**
4	**1.2**	**1.2**	0.23	7.06
5	1.2	**1.25**	1.21	8.45
6	0.29	0.3	**1.25**	**3.93**
7	0.3	0.3	0.29	1.19
8	0.3	0.0	0.30	2.06
Sum	4.43	5.15	5.21	34.37

TABLE III
The evaluation metrics for the ADA scheme.

Fault No	Series 1	Series 2	Series 3	Series 4
1	0.59	0.6	0.46	0.6
2	**0.60**	**0.59**	**0.6**	0.6
3	0.44	0.15	0.12	0.44
4	**1.2**	**1.2**	**1.2**	1.11
5	1.19	1.19	1.15	1.19
6	**0.6**	**0.6**	0.45	**0.6**
7	0.15	0.15	0.15	0.15
8	0.45	0.32	0.6	0.13
Sum	5.22	4.8	4.71	4.81
Fault No	Series 5	Series 6	Series 7	Sum
1	0.6	0.6	0.59	4.04
2	0.6	0.47	0.59	4.05
3	0.44	0.15	0.15	1.89
4	**1.2**	**1.2**	**1.2**	**8.31**
5	1.19	1.19	1.19	8.29
6	0.23	**0.6**	0.6	3.68
7	0.15	0.15	0.15	1.05
8	**0.68**	**0.68**	0.37	3.23
Sum	4.99	4.94	4.84	34.31

like the one proposed in [31]. It could also be relevant to investigate the performance of the schemes for multiple faults. Another observation made is that sensors faults are better accommodated than actuator faults in this benchmark, this might be due to the fact that the in this benchmark all the used sensors are physical redundant, while the actuators are not. Another explanation could be that the used methods are better for sensor fault accommodation than actuator fault accommodation.

V. Conclusion

In this article the top three solutions in an international competition on fault tolerant wind turbine control, where presented and evaluated on a known benchmark model for wind turbine fault tolerant control. The benchmark model were as well used for the evaluation of the solutions in the mentioned competition. Based on this evaluation it can be seen that the winner of the competition performs very well on the benchmark model problem, especially for the sensor faults. The first and second runners up showed some potentials but are not fully usable solutions. The next steps in the area of wind turbine fault tolerant control would be to test the proposed schemes on a high fidelity wind turbine model, and with multiple fault.

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