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Erratum: Global versus local Lyapunov approach used in disturbance observer-based wind turbine control

Frontiers Production Office*

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KEYWORDS

global and local Lyapunov approach, Takagi–Sugeno framework, model-based controller and observer design, feedforward-feedback control, linear-matrix-inequality and pole region-based controller design, wind turbine application, elaborated wind turbine simulation model, load analysis

An Erratum on
Global versus local Lyapunov approach used in disturbance observer-based wind turbine control

by Gauterin E, Pöschke F and Schulte H (2023). Front. Control. Eng. 3:787530. doi: 10.3389/fcteg.2022.787530

Due to a production error, the equation in section **2.2.1 Global Controller** was incorrect.

$$\text{The incorrect equation was: } X: \ = P^{-1}\left(\Rightarrow \overset{10}{=} X \right)$$

$$\text{The correct equation is: } X: \ = P^{-1}\left(\Rightarrow \overset{Eq. 10}{=} X \right)$$

Due to a production error, the equations in section **Discussion**, subsection **Pole Locations** were incorrect.

$$\text{The incorrect equations were } s_{P,i}^{OL,3} \text{ and } s_{P,i}^{OL,1/2}$$

$$\text{The correct equations are } s_{P,i}^{OL,1} \text{ and } s_{P,i}^{OL,2 \vee 3}$$

Due to a production error, the equation in section **Error-feedback gains** (page 16) was incorrect.

$$\text{The incorrect equation was: } \left| L_{\bar{i}B}^{w,\bar{j}} \right|_2 (\forall w \in [B, D]) > \left| L_{\bar{i}B}^{w,\bar{j}} \right|_2 (\forall w \in [G, I])$$

$$\text{The correct equation is: } \| L_{\bar{i}B}^{B,\bar{j}} \|_2 > \| L_{\bar{i}B}^{G,\bar{j}} \|_2, \| L_{\bar{i}B}^{C,\bar{j}} \|_2 > \| L_{\bar{i}B}^{H,\bar{j}} \|_2 \text{ and } \| L_{\bar{i}B}^{D,\bar{j}} \|_2 > \| L_{\bar{i}B}^{I,\bar{j}} \|_2$$

Due a production error, the first paragraph in section **Wind speed reconstruction and actuation** signals was incorrect. You can find the correct paragraph below:

With the mitigated error-feedback gains $L_{\bar{i}B}^{w,\bar{j}}$, the reconstructed states $\hat{\underline{x}}$, especially the reconstructed wind speeds $\hat{v}$, are mitigated, too (see **Eq. 7**[11]): While the reconstructed wind speed $\hat{v}^{w}(t_1)$ of a single and arbitrary time point t = t$_1$ decreases *steadily* for the wind speed observer design with a local Lyapunov approach (i.e., $\hat{v}^{F}(t_1) \approx \hat{v}^{G}(t_1) > \hat{v}^{H}(t_1) > \hat{v}^{I}(t_1)[> \hat{v}^{J}(t_1)]^{10}$, see left column in **Figure 6**), the reconstructed wind speed

$\hat{v}^w(t_1)$ for the wind speed observer design with a global Lyapunov approach decreases *unsteadily* (i.e., $\hat{v}^A(t_1) > \hat{v}^D(t_1)[> \hat{v}^E(t_1)] > \hat{v}^C(t_1) > \hat{v}^B(t_1)$, corresponding to the unsteady decrease of the mean Euclidean norm of the wind error state gains $\|L_{\bar{i}\mathcal{B}}^{w,\bar{3}}\|_2$ of the global wind speed observers (with (w [A, E], see **Table 3**; i.e., $\|L_{\bar{i}\mathcal{B}}^{A,\bar{3}}\|_2 > \|L_{\bar{i}\mathcal{B}}^{D,\bar{3}}\|_2 > \|L_{\bar{i}\mathcal{B}}^{C,\bar{3}}\|_2 > \|L_{\bar{i}\mathcal{B}}^{B,\bar{3}}\|_2$)[10]

In the same section, **footnotes** 12 and 13 were assigned incorrectly, and these have been replaced with footnote 10 in the updated article.

[10]The global and local wind speed observers E and J are not taken into account, because of their (closed-loop) pole locations, which are moved beyond the open-loop pole locations, as explained before in the subsection Pole locations.

Footnote 12 was also incorrect, the correct version is:

[12]with two exceptions for the tower *side-to-side*-bending moments $S_{eq}^B(TwrBsMxt) < S_{eq}^J(TwrBsMxt)$ and $S_{eq}^C(TwrBsMxt) < S_{eq}^J(TwrBsMxt)$ (see **Figure 8B** and line 7 in **Table A9** as well as line 7 in **Table A10**.

Due to a production error, section **Load Mitigation**, paragraph number 3, appears to be interrupted and broken into two parts. This has been corrected into one single paragraph.

In the Appendix, part of section **Specification of the LMI constraints** was not included in the article. The corrected entire section appears below:

To calculate the *mean* Euclidian norm $\|L_{i\mathcal{B}}^{w,\bar{j}}\|_2$ of the error-feedback gains $L_{i\mathcal{B}}^{w,j}$ [see (26)] and the *average, mean* Euclidian norm $\|L_{\bar{i}\mathcal{B}}^{w,\bar{j}}\|_2$ [see (27)] the worksheet *Uebersicht_L_Matrizen_Pitchwinkel-YYYY_MM_DD.xlsx* is used.

In the Appendix, the section **Load Analysis** was not included in the article. This has now been added to the article, you can find it below:

Load analysis

For the ultimate loads max^w and fatigue loads S_{eq}^w resulting from five different wind speed observers (i.e., for the $w \in [A, E]$ global wind speed observers and $w \in [A, E]$ local wind speed observers; see **Figure 8**), the steady increase or decrease of the loads is evaluated separately for each of the two observer approaches (see **Table A9**) and in comparison to each other (see **Table A10**).

Due to a production error, **Tables A9 and A10** in the Appendix were not included in the article, and the layout of **Tables A1–A8** in the Appendix was incorrect. The corrected Tables are listed below:

The font color has been corrected in the table captions and in the body of the text, throughout the article.

The publisher apologizes for this mistake. The original version of this article has been updated.

TABLE A1 States of the i steady state operations points OP_i of the NREL FAST 5MW reference wind turbine with the wind speed $v_{c,i}$, rotor rotational speed $\omega_{\mathcal{R},c,i}$, generator torque $T_{G,c,i}$ and pitch angle $\beta_{c,i}$.

i	$v_{c,i}$	$\beta_{c,i}$	$T_{G,c,i}$	$\omega_{\mathcal{R},c,i}$
1	3	0	2.912	3.4
2	4	0	5.193	4.6
3	5	0	8.079	5.7
4	6	0	11.646	6.9
5	7	0	15.843	8.0
6	8	0	20.671	9.2
7	9	0	26.128	10.3
8	9.5	0	29.094	10.9
9	10	0	32.267	11.4
10	10.5	0	35.547	12.0
11	11	0	40.433	12.1
12	11.5	2.2	43.094	12.1
13	12	4.1	43.094	12.1
14	12.5	5.5	43.094	12.1
15	13	6.6	43.094	12.1
16	14	8.6	43.094	12.1
17	15	10.4	43.094	12.1
18	16	12.0	43.094	12.1
19	17	13.4	43.094	12.1
20	18	14.8	43.094	12.1
21	19	16.1	43.094	12.1
22	20	17.4	43.094	12.1
23	21	18.6	43.094	12.1
24	22	19.7	43.094	12.1
25	23	20.8	43.094	12.1
26	24	22.0	43.094	12.1
27	25	23.0	43.094	12.1

TABLE A2 State matrices $A_{i\mathcal{B}}$ and augmented state matrices $\tilde{A}_{i\mathcal{B}}$ of the $\mathcal{B}$lade model (for the submodels $i \in [15,18]$).

$A_{15\mathcal{B}}$	0 -21.82 -	1 -5.41 -	$\tilde{A}_{15\mathcal{B}}$	0 -21.82 0	1 -5.41 0	0 9.58 -0.25
$A_{16\mathcal{B}}$	0 -21.88 -	1 -5.36 -	$\tilde{A}_{16\mathcal{B}}$	0 -21.88 0	1 -5.36 0	0 9.51 -0.25
$A_{17\mathcal{B}}$	0 -21.92 -	1 -5.35 -	$\tilde{A}_{17\mathcal{B}}$	0 -21.92 0	1 -5.35 0	0 9.48 -0.25
$A_{18\mathcal{B}}$	0 -21.95 -	1 -5.30 -	$\tilde{A}_{18\mathcal{B}}$	0 -21.95 0	1 -5.30 0	0 9.38 -0.25

TABLE A3 Input matrices $B_{i\mathcal{B}}$ and augmented input matrices $\tilde{B}_{i\mathcal{B}}$ of the $\mathcal{B}$lade model (for the submodels $i \in [15,18]$).

$B_{15\mathcal{B}}$	0 -563.53 -	0 0 -	$\tilde{B}_{15\mathcal{B}}$	0 -563.53 0	0 0 0
$B_{16\mathcal{B}}$	0 -589.16 -	0 0 -	$\tilde{B}_{16\mathcal{B}}$	0 -589.16 0	0 0 0
$B_{17\mathcal{B}}$	0 -606.41 -	0 0 -	$\tilde{B}_{17\mathcal{B}}$	0 -606.41 0	0 0 0
$B_{18\mathcal{B}}$	0 -628.21 -	0 0 -	$\tilde{B}_{18\mathcal{B}}$	0 -628.21 0	0 0 0

TABLE A4 Common output matrix $C_{\mathcal{B}}$ and augmented common output matrix $\tilde{C}_{\mathcal{B}}$ of the $\mathcal{B}$lade model (for all submodels).

$C_{\mathcal{B}}$	1	0	$\tilde{C}_{\mathcal{B}}$	1	0	0

TABLE A5 Steady states $\underline{x}_{c,i\mathcal{B}}$ and augmented steady states $\tilde{\underline{x}}_{c,i\mathcal{B}}$ of the $\mathcal{B}$lade model (for the submodels $i \in [15,18]$).

$\underline{x}_{c,15\mathcal{B}}$	3.61 0 -	$\tilde{\underline{x}}_{c,15\mathcal{B}}$	3.61 0 13
$\underline{x}_{c,16\mathcal{B}}$	3.15 0 -	$\tilde{\underline{x}}_{c,16\mathcal{B}}$	3.15 0 14
$\underline{x}_{c,17\mathcal{B}}$	2.73 0 -	$\tilde{\underline{x}}_{c,17\mathcal{B}}$	2.73 0 15
$\underline{x}_{c,18\mathcal{B}}$	2.44 0 -	$\tilde{\underline{x}}_{c,18\mathcal{B}}$	2.44 0 16

TABLE A6 Steady state pitch angle $\beta_{c,i}$ and generator torque $T_{G,i}$ (for the submodels $i \in [15,18]$).

$\beta_{c,15}$ $T_{G,15}$	6.6 43.094
$\beta_{c,16}$ $T_{G,16}$	8.6 43.094
$\beta_{c,17}$ $T_{G,17}$	10.4 43.094
$\beta_{c,18}$ $T_{G,18}$	12.0 43.094

TABLE A7 State feedback matrices $K_{i\mathcal{R}}$ of the (rigid body) $\mathcal{R}$otion drive train model (for the submodels $i \in [15,18]$).

$K_{15\mathcal{R}}$	-1.31 0
$K_{16\mathcal{R}}$	-1.03 0
$K_{17\mathcal{R}}$	-0.85 0
$K_{18\mathcal{R}}$	-0.71 0

TABLE A8 Error state feedback gain matrices $L_{i\mathcal{B}}^{w,j}$ of the blade model based wind speed observers $\mathcal{B}$ for:
- **global** Lyapunov approach with $w \in [A, E]$
- **local** Lyapunov approach with $w \in [F, J]$
- submodels $i \in [15,18]$
- matrix elements $j \in [1,3]$.

	A	B	C	D	E	F	G	H	I	J
$L_{15\mathcal{B}}^{w,1}$	3.87	2.81	2.04	1.28	0.30	4.06	3.02	1.79	0.38	-1.35
$L_{15\mathcal{B}}^{w,2}$	-13.31	-15.30	-9.80	-5.92	-4.22	-14.19	-12.90	-8.78	-5.23	-4.46
$L_{15\mathcal{B}}^{w,3}$	2.56	0.88	1.21	1.43	1.31	2.27	1.90	1.61	1.11	0.39
$L_{16\mathcal{B}}^{w,1}$	3.87	2.81	2.04	1.28	0.30	4.07	3.07	1.84	0.43	-1.30
$L_{16\mathcal{B}}^{w,2}$	-13.44	-15.45	-9.95	-6.05	-4.28	-14.33	-13.14	-9.18	-5.57	-4.85
$L_{16\mathcal{B}}^{w,3}$	2.56	0.88	1.20	1.43	1.31	2.26	1.91	1.61	1.12	0.40
$L_{17\mathcal{B}}^{w,1}$	3.88	2.81	2.04	1.28	0.30	4.07	3.08	1.85	0.44	-1.29
$L_{17\mathcal{B}}^{w,2}$	-13.49	-15.50	-10.01	-6.10	-4.31	-14.39	-13.22	-9.30	-5.68	-4.98
$L_{17\mathcal{B}}^{w,3}$	2.56	0.88	1.20	1.43	1.31	2.26	1.92	1.61	1.12	0.40
$L_{18\mathcal{B}}^{w,1}$	3.88	2.81	2.04	1.28	0.29	4.08	3.13	1.90	0.50	-1.23
$L_{18\mathcal{B}}^{w,2}$	-13.60	-15.62	-10.13	-6.19	-4.33	-14.51	-13.43	-9.70	-6.00	-5.39
$L_{18\mathcal{B}}^{w,3}$	2.56	0.88	1.20	1.43	1.31	2.26	1.93	1.61	1.13	0.40

TABLE A9 Analysis of the ultimate loads $\max^w$ and fatigue loads S_{eq}^w resulting from five different wind speed observers regarding the steady increase or decrease of the loads (evaluated separately for each of the two Lyapunov approaches with $w \in [A, E]$ for the **global wind speed observers** and with $w \in [F, J]$ for the **local wind speed observers;** based on the loads depicted in Figure 8).

Loads	Global Lyapunov approach	Local Lyapunov approach
TwrBsMyt	$\max^A > \max^B > \max^C > \max^D > \max^E$	$\max^F > \max^G > \max^H > \max^I > \max^J$
TwrBsMxt	$\max^A > \max^B < \max^C < \max^D < \max^E$	$\max^F \approx \max^G > \max^H > \max^I > \max^J$
*RootMxb*1	$\max^A > \max^B < \max^C < \max^D < \max^E$	$\max^F > \max^G > \max^H > \max^I > \max^J$
*RootMyb*1	$\max^A < \max^B > \max^C > \max^D > \max^E$	$\max^F > \max^G < \max^H < \max^I > \max^J$
ΔT	$\max^A < \max^B > \max^C > \max^D > \max^E$	$\max^F > \max^G > \max^H > \max^I \approx \max^J$
TwrBsMyt	$S_{eq}^A > S_{eq}^B < S_{eq}^C < S_{eq}^D < S_{eq}^E$	$S_{eq}^F > S_{eq}^G > S_{eq}^H > S_{eq}^I > S_{eq}^J$
TwrBsMxt	$S_{eq}^A > S_{eq}^B < S_{eq}^C < S_{eq}^D < S_{eq}^E$	$S_{eq}^F < S_{eq}^G > S_{eq}^H > S_{eq}^I > S_{eq}^J$
ΔT	$S_{eq}^A > S_{eq}^B \approx S_{eq}^C > S_{eq}^D > S_{eq}^E$	$S_{eq}^F > S_{eq}^G > S_{eq}^H > S_{eq}^I > S_{eq}^J$
*RootMyb*1	$S_{eq}^A > S_{eq}^B < S_{eq}^C < S_{eq}^D > S_{eq}^E$	$S_{eq}^F > S_{eq}^G > S_{eq}^H > S_{eq}^I > S_{eq}^J$
*RootMxb*1	$S_{eq}^A < S_{eq}^B = S_{eq}^C = S_{eq}^D = S_{eq}^E$	$S_{eq}^F \approx S_{eq}^G \approx S_{eq}^H < S_{eq}^I < S_{eq}^J$

TABLE A10 Analysis of the ultimate loads $\max^w$ and fatigue loads S_{eq}^w resulting from five different wind speed observers regarding the steady increase or decrease of the loads (comparing both Lyapunov approaches with each other with $w \in [A, E]$ for the **global wind speed observers** and with $w \in [F, J]$ for the **local wind speed observers;** based on the loads depicted in Figure 8).

Loads	A ⇔ F	B ⇔ G	C ⇔ H	D ⇔ I	E ⇔ J
TwrBsMyt	$\max^A > \max^F$	$\max^B < \max^G$	$\max^C < \max^H$	$\max^D > \max^I$	$\max^E > \max^J$
TwrBsMxt	$\max^A > \max^F$	$\max^B < \max^G$	$\max^C < \max^H$	$\max^D > \max^I$	$\max^E > \max^J$
*RootMyb*1	$\max^A < \max^F$	$\max^B > \max^G$	$\max^C > \max^H$	$\max^D > \max^I$	$\max^E > \max^J$
*RootMxb*1	$\max^A > \max^F$	$\max^B < \max^G$	$\max^C < \max^H$	$\max^D > \max^I$	$\max^E > \max^J$
ΔT	$\max^A < \max^F$	$\max^B > \max^G$	$\max^C > \max^H$	$\max^D > \max^I$	$\max^E < \max^J$
TwrBsMyt	$S_{eq}^A > S_{eq}^F$	$S_{eq}^B < S_{eq}^G$	$S_{eq}^C < S_{eq}^H$	$S_{eq}^D > S_{eq}^I$	$S_{eq}^E > S_{eq}^J$
TwrBsMxt	$S_{eq}^A > S_{eq}^F$	$S_{eq}^B < S_{eq}^G$	$S_{eq}^C < S_{eq}^H$	$S_{eq}^D > S_{eq}^I$	$S_{eq}^E > S_{eq}^J$
*RootMyb*1	$S_{eq}^A < S_{eq}^F$	$S_{eq}^B < S_{eq}^G$	$S_{eq}^C > S_{eq}^H$	$S_{eq}^D > S_{eq}^I$	$S_{eq}^E > S_{eq}^J$
*RootMxb*1	$S_{eq}^A > S_{eq}^F$	$S_{eq}^B > S_{eq}^G$	$S_{eq}^C > S_{eq}^H$	$S_{eq}^D < S_{eq}^I$	$S_{eq}^E < S_{eq}^J$
ΔT	$S_{eq}^A > S_{eq}^F$	$S_{eq}^B < S_{eq}^G$	$S_{eq}^C > S_{eq}^H$	$S_{eq}^D > S_{eq}^I$	$S_{eq}^E > S_{eq}^J$