Abstract—Fault detection and reconfiguration of the control loops of a Doubly-Fed Induction Generator are described in this paper. The stator voltage is measured as well as observed. During fault free operation, the measured signal is used for the field oriented control. In case of a voltage sensor fault, the faulty measurement is identified and the control is reconfigured using the observer output. Operation without measuring the stator voltage is possible. Laboratory measurements prove this concept.

Index Terms—Observers, AC generators, State estimation

I. INTRODUCTION

Doubly Fed Induction Generators (DFIG) have become a widely used generator type in wind energy conversion [1]. This is not the only application, however, since DFIG are also used in pump storage plants [2] and flywheel energy storage [3].

Fault detection is becoming more and more important for variable speed drives to increase availability and reliability and reduce downtime. Typical elements of fault detection with subsequent reconfiguration are shown in figure 1. State observers, in this case also called soft sensors, can be used to observe a state that is already measured [4], [5], [6], [7].

In order to observe the inputs of a system, an input observer may be used [8]. Sensor faults can be detected by analysing the residual between measurement and observation.

Fault tolerance of induction machines has been covered by [9] and [10]. In both cases, model based fault methods are used. While an open loop induction drive is considered by [9], fault tolerant control of closed loop systems is examined by [10]. In this paper, a full reconfiguration is presented for a voltage oriented DFIG, as shown in figure 3, including all five necessary steps, as given in figure 1. The focus is on the change detection, fault diagnosis and reconfiguration.

Figure 1: Necessary steps towards a fault tolerant control. Scope of this paper is Change Detection, Fault Diagnosis and Reconfiguration.

An Introduction was given in section I. The applied input observers described in section II, while section III gives a simulation analysis of the expected behaviour during stator voltage sensor faults and reconfiguration. Section IV shows measurements results from the laboratory. The paper is finished by a conclusion, an appendix and a list of references.

Figure 2: Overview of the considered doubly fed induction generator with voltage sensor fault detection observer and reconfiguration

Figure 3: Overview of used voltage oriented control structure. Stator voltage sensor faults are considered in this paper.

II. INPUT OBSERVATION

Doubly fed induction machines comprise of a wound stator and a wound three phase rotor, where the rotor windings can be accessed by brushes. Usually, the stator is connected to the grid, and the rotor is fed by an inverter. This way, the rotor can be fed by a variable voltage and frequency (figure 2).

In this work, an Input Observer based on an Unknown Input Observer (UIO) with input reconstruction is used to observe the stator voltages of the DFIG. UIO observe the states of this system, where an input, the unknown input, is not used. For the reconstruction of the unknown inputs the UIO needs the measured outputs of the system and the known inputs. Using the estimated states and the known inputs, the unknown input may be reconstructed. This is thoroughly described in [8].

The state space model used for the DFIG is given in equations (1) to (8). The bilinear character of the DFIG is represented by the matrix $A_1$ while the constant terms are considered in $A_0$. The reference frame is described by matrix
The input is split up into known and unknown inputs (3), with their respective input matrices B and D. It is assumed that all currents are measurable, therefore $C = I_4$ is unity.

$$\begin{align*}
\dot{x} &= Ax + Bu + Dv; \quad y = Cx \quad (1) \\
x &= \begin{bmatrix} I_d & I_n & I_d & I_n \end{bmatrix}^T; \\
u &= \begin{bmatrix} U_{sd} & U_{rq} \end{bmatrix}^T; \quad v = \begin{bmatrix} U_{rd} & U_{sq} \end{bmatrix}^T \\
A &= A_r + A_p \omega_n + A_o \omega_o \\
B &= \begin{bmatrix} \frac{L_1}{\sigma_L L_4} & 0 & \frac{L_2}{\sigma_L L_4} & 0 \\
0 & -\frac{L_1}{\sigma_L L_4} & 0 & \frac{L_2}{\sigma_L L_4} \\
0 & 0 & \frac{1}{\sigma_L} & 0 \\
0 & 0 & -\frac{1}{\sigma_L} & 0 \\
C &= \begin{bmatrix} 0 & 1 & 0 & 0 \\
-1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & -1 & 0 \\
D &= \begin{bmatrix} 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
C^{-1} &= \begin{bmatrix} 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{bmatrix} \\
\end{align*}$$

The principle of UIO is the decoupling of the observer error $e$ from the disturbances which are the unknown inputs. The structure of the UIO can be defined as:

$$\begin{align*}
\dot{z} &= Nz + Ky + Gu; \quad (9) \\
\hat{x} &= z - Ey. \quad (10)
\end{align*}$$

The combined UIO with reconstruction of the input voltages is given in figure 4. The matrices $K$, $N$, $G$ and $E$ are calculated according to [8]. The basic reasoning of this shall be repeated here for comprehensibility.

The observer error $e$ is defined as difference between the estimated vector $\hat{x}$ and the state vector $x$. The matrices $N$, $K$, $G$ and $E$ have to be designed in such a way that $\hat{x}$ converges asymptotically to $x$. As a consequence, the observer error has to converge to zero. The observer error is considered:

$$\dot{e} = \dot{x} - \hat{x} = Nz + Ky + Gu - EC\hat{x} - \hat{x} \quad (11)$$

This leads to the following equations that have to be met, since the error shall be independent of $x$, $u$, and $v$.

$$\begin{align*}
0 &= (N + NEC + KC - ECA - A) \\
0 &= (G - ECB - B) \\
0 &= (EC + I_4)D \\
\end{align*} \quad (12, 13, 14)$$

Equation (14) and (13) yield to

$$\begin{align*}
E &= -D(\text{CD})^T \quad (15) \\
G &= (I_4 + EC)B \quad (16)
\end{align*}$$

$(\text{CD})^T$ is the generalized inverse matrix of $(CD)$.

At last the matrices $N$ and $K$ have to be designed. Therefore matrix $M$ (18) is introduced for clarity. Solving (12) for $N$ yields to (17). The eigenvalues of $N$ have to be in the left hand complex plane and may be placed, for example using Matlab’s `place` to define $M$ (19).

$$\begin{align*}
N &= A + ECA - KC - NEC \\
M &= K + NE \quad (17) \\
N &= (I_4 + EC)A - MC \quad (18)
\end{align*}$$

Under the assumption that the pair $(I_4 + EC)A$, $(\text{EC})$ is observable the eigenvalues from $(I_4 + EC)A - MC$ can be placed free with suitable choice oh the matrix $M$. $K$ follows from equation (18). In order to obtain the unknown input signal $v$, some calculations have to be done. Combining equation (9) and (10) yieldas to (20). Combining (1) for estimated states and (20) the estimated unknown input becomes (21).

$$\begin{align*}
\dot{x} &= Nz + Ky + Gu - Ey \quad (20) \\
\dot{v} &= D'Nz + D'K'y + D'(G - B)u - DE\dot{y} - (D' \Lambda' \hat{x}) \quad (21)
\end{align*}$$

Figure 4: Unknown Input Observer plus Input Reconstruction can be used to observe the inputs of a system.

As is described in [8], the stator voltage approximation is good, but not perfect. Small deviations in phase and amplitude remain. Parameter tuning will decrease these deviations for one operational speed, but if used over a wide range of rotational speeds, no set of parameters can be found that fits perfectly for all speeds. Yet, the acquired signals fully suffice for fault detection and reconfiguration.
III. EFFECTS OF A STATOR VOLTAGE SENSOR FAULT

The stator voltage is measured for two reasons. Firstly, the stator power measurement (fig.4) needs the stator voltage of phase \(a\) and \(b\). Secondly, the DFIG needs to be synchronised to the grid, which requires the generation of the stator voltage angle. This is done by a PLL using the phase \(a\) stator voltage measurement. Therefore a fault in the stator voltage sensor \(a\) will affect the stator power control loop and the stator voltage angle, as shown in figure 5. It is limited in its further path due to the bandwidth of the PLL and the power controllers. Stator voltage sensor \(b\) will only affect the power control loop, as seen in figure 6. The influence of the respective faults is greatly depending on the bandwidth of the involved control loops, e.g. power control loop and its filters, or the PLL.

A. Behaviour of the used PLL

The performance of the used PLL is demonstrated by simulation. Since exactly the same code is used on the DS1006 controller, the performance in reality is the same. Figure 7 shows the PLL generated angle in case of an input signal of zero instead of a sine. The error between actual angle and PLL output angle is shown. This is done for a 'slow' and a 'fast' PLL synchronisation. Since it is more comprehensible than an angle signal, the cosine of the angle is displayed together with the error between ideal and output angle.

As can be seen, the PLL can be made slow enough so that the output signal error is within 6 degrees within the first 25 ms. The faster the PLL, the faster will the error increase, making a reconfiguration more difficult.

A 'fast' PLL will lock on to a sinusoidal signal faster, but also lose orientation faster in case of no input. A 'slow' PLL will need more time to lock on, but also will not drift as quickly in case of a fault. Since usually no major drifts in grid frequency are expected, a 'slow' PLL will in most cases be sufficient.

B. Behaviour of stator power control loop

Next to the influence on the stator voltage angle calculation, a stator voltage sensor fault has influence on the stator power calculation. A false stator voltage reading will distort the stator power. If the falsely calculated active or reactive power is smaller than the reference, the control loop will change the current command in a way to increase the respective power. A fault in voltage sensor \(a\) will distort the PLL and the power calculation, while a fault in phase \(b\) will only influence the power calculation.

As can be seen from figure 9, the sudden step in the PLL output angle due to a fault will affect the vector rotation. This will lead to a step in the current control loops leading to a sudden decrease in stator power. However, within a short time, the drive remains within reasonable limits of power and current. It can be expected that the drive is not damaged during this period. Therefore, any reconfiguration will have to occur within approximately 20 ms.

Figure 6: The fault path of a distorted signal from voltage sensor \(b\).
D. Structure to reconfigure the stator voltage sensors

In order to reconfigure the stator voltage sensors, a fault detection has to be implemented. Using the input observer outputs in $\alpha$ and $\beta$ stator reference frame and subtracting the voltage sensor readings, one obtains two residuals. Residual $\alpha$ is affected by voltage sensor $a$ only, while residual $\beta$ is affected by both sensors. The structure according to figure 10 is a possible way to obtain a flag which is used to switch from measured to observed voltage signals. A forgetting factor $\gamma$ may be used, but does not change the behavior significantly if close to 1. The resulting overall control structure is depicted in figure 11, where the input observer outputs are available for stator power and stator voltage angle calculation.

![Figure 8: Stator Real Power during a fault in voltage sensor b.](image)

![Figure 9: Stator active power during a fault in voltage sensor a.](image)

![Figure 10: The maximum of the residuals of $\alpha$ and $\beta$ components is considered, using a maximum value with a forgetting factor $\gamma$. Using a threshold, the voltage signal is switched.](image)

Figure 11: Control scheme using an UIO to provide a replacement signal for the faulty voltage measurement. The switch includes the structure of fig. 10.

IV. USING AN UIO WITH INPUT RECONSTRUCTION INSTEAD OF A VOLTAGE MEASUREMENT

Experimental measurements were taken in the laboratory to support the concept of using an UIO to replace the voltage sensors after a reconfiguration. The used control scheme is shown in figure 11.

Measurements were taken via dSPACE-ControlDesk® and then plotted using MATLAB-Simulink®. Sample intervals are indicated by circles around the actual values, interpolated by lines. Voltage sensor faults are implemented by setting the sensor signal to zero by software. The actual sensor reading is still used for comparison only, but it is not used by the control. The power is also calculated from the false voltage measurement and from the UIO replacement signal. The current measurements are not interrupted.

In order to separate the two influences of a stator voltage sensor fault in phase $a$, at first only the influence on the power loop is shown. Then, the influence on the PLL and the power control loop is analysed.

The reconfiguration works in subsynchronous, synchronous and supersynchronous operation.

A. Reconfiguration of Power Control Loop

Figure 12 shows the reconfiguration of the stator voltage $b$ sensor. The machine is operated supersynchronous at 1700 rpm. A fault is initiated at time $t=2.25$ ms. The fault is detected within one sample period, as can be seen in the top graph. The maximum value (cyan) of the residuals (black and magenta) crosses the threshold (blue). A forgetting factor of $\gamma=0.995$ is used. As expected, the $\alpha$-residual is not affected by a fault in voltage measurement $b$.

As can be seen in the middle graph, the falsely measured stator active power (blue) decreases, while the actual fault free active power (green) stays the same. The signal, that is fed to the control loop (black) is switched from measured to observed (red), and operation is maintained. The stator active power, that is calculated from the observed voltage, is slightly larger than the actual power. The reactive power control loop is also reconfigured within one sample period. The resulting power factor is worsened from unity to around 0.995.

Figure 13 shows the reconfiguration of the stator voltage $a$ sensor, excluding the effect on the PLL for better insight. The
PLL is in this case fed from a healthy voltage sensor. A sensor fault that also affects the PLL is analysed later. The machine is operated subsynchronously at 1300 rpm. Since sensor \( a \) affects both the \( \alpha \) and \( \beta \) component, both residuals cross the threshold. It is important to remark that this behaviour may be used for more detailed fault identification. However, in this case only the maximum of the two residuals is used.

**B. Reconfiguration of Power Control Loop and PLL**

To analyse the combined effect of a fault in sensor \( a \) on the stator power control loop and PLL, the PLL is initially fed by the sensor that is switched off. After reconfiguration, the PLL is fed by the observer output. This means no voltage measurement is needed after the reconfiguration. Figure 14 shows a reconfiguration of the voltage sensors at 10 kW stator power. The time scale is now 60 ms to give an impression of the long term behaviour of the control.

The top graph shows the measured and observed voltages in stator fixed \( \alpha \beta \) reference frame. The \( a \) sensor is switched off, resulting in a deviation in both components. The observer remains undisturbed and gives a good approximation.

The middle graph shows the behaviour of the PLL, where the input is either the measured or observed voltage signal. Since the measured signal is not available, the angle derived from this signal starts to become faulty and drifts with respect to the angle derived from the observed signal.

To simplify the figure, only the active power is presented in the bottom graph. It can be seen that the control loop is reconfigured with equal performance as shown in figures 12 and 13. The signal that is used in the control loop is switched from measured to observed signals.

The machine is kept in stable operation, with only minor deviation in the stator active power and power factor. There are no transients in the currents nor torque that will endanger the machine, as seen in figure 15.
transients occur during reconfiguration.

is possible for a wide range of rotational speeds in actual power, for example by parameter identification.

research needs to limit the deviation between observed and uncertainty. The active power is slightly decreased. Further worse power factor, which is likely due to parameter experimental measurements are shown to support the

voltage in order to reconfigure the power control loop and the can supply a sufficiently good approximation of the input

Observer based on the concept of Unknown Input Observers

shut down of the drive. It is shown in this analysis that an Input
to serious malfunction of the generator and usually leads to a

Generator comprises of a current control loop and a power

can be used to

synchronous frame during the reconfiguration of the voltage sensor.

Figure 15: Stator currents in stator fixed reference frame and rotor currents in synchronous frame during the reconfiguration of the voltage sensor.

V. CONCLUSION

Voltage oriented control of a Doubly Fed Induction Generator comprises of a current control loop and a power control loop. To achieve voltage orientation, a PLL is used to extract the stator voltage angle. A voltage sensor fault will lead to serious malfunction of the generator and usually leads to a shut down of the drive. It is shown in this analysis that an Input Observer based on the concept of Unknown Input Observers can supply a sufficiently good approximation of the input voltage in order to reconfigure the power control loop and the PLL angle extraction.

The presented concept is analysed in simulation and experimental measurements are shown to support the simulation findings. The reconfiguration leads to a somewhat worse power factor, which is likely due to parameter uncertainty. The active power is slightly decreased. Further research needs to limit the deviation between observed and actual power, for example by parameter identification.

Operation with faulty or even without stator voltage sensors is possible for a wide range of rotational speeds in supersynchronous, synchronous and sub synchronous mode. No transients occur during reconfiguration.

APPENDIX

TABLE I.
DATA OF EXPERIMENTAL SETUP

| Machine  | VEM SPER 200 LX4 | 22 kW Stator: 400 V 41 A | Rotor: 255 V 53 A |
| Control  | dSPACE DS1006 2800 MHz |
| Sample Time | 250µs |
| Inverter (DFIG) | IGBT 2-level Voltage Source Inverter |
| Rectifier (Grid) | IGBT 2-level Voltage Source Inverter |

TABLE II.
MACHINE PARAMETERS

| Resistances $R_s$, $R_r$ | $[0.1315; 0.1070]$ Ω |
| Inductances $L_s$, $L_r$ | $[46.8; 46.8]$ mH |
| Mutual Inductance $L_h$ | 45.8 mH |
| Turns Ratio $n_s/n_r$ | 1.5:1 |
| Pole pairs | 2 |
| Rated Power and Voltage | 22kW, 400 V |

Rotor parameters are referred to the stator.