Abstract — Two different online parameter identification methods for doubly fed induction generators (DFIG) are investigated in this paper. A model reference adaptive system (MRAS) and a new approach for estimation of the inductances are introduced. Lyapunov stability theory is applied to the adaptive law of the MRAS method. This method requires a test signal which excites all systems eigenvalues. Therefore stator and rotor have to be excited by a test signal. However, not all eigenvalues are excited if the stator of the DFIG is directly connected to the grid. In contrast to common methods the new approach presented here needs no excitation signal. This method estimates the inductances by a set of equations which are based on the description of the DFIG neglecting the stator and rotor resistances. It yields to good results for the mutual inductance and the stator leakage inductance also for the grid connected stator. Both methods are analysed by simulations. The new approach for estimation of the inductances is also tested by measurements at a laboratory setup and yields to good results of the stator leakage and the mutual inductances.

I. INTRODUCTION

Doubly fed induction generators (DFIG) are generally used for applications with high power and limited speed range. They are especially used as wind turbine generators with variable speed for on- and off-shore wind farms. Other actual applications are aviation generators [1], pump storage plants [2] as well as flywheel energy storage systems [3].

Condition monitoring and fault detection has become very important for electrical drives. Detection of sudden or developing faults which occur in actuators, sensors, or other components may be economically reasonable and may contribute to a safe operation or provide fault ride through capabilities. For a model based fault tolerant control, observers are required to estimate the states and the input values of the system. A bilinear Luenberger state observer is developed by the authors to estimate the stator and rotor currents and a bilinear unknown input observer with input reconstruction is developed to estimate the stator voltage. These observers are described in [4], [5], [6] and [7]. The performance of the observers depends on the accuracy of the used parameter. The better the parameters of the observer models agree with the parameters of the system, the better the performance of the observers. Normally the parameters of the system are not known exactly. Moreover, the parameters are not constant during operation. The inductances have a nonlinear magnetization characteristic and the resistances depend on the operation temperature. For a better performance of the observers during operation, varying parameters should be estimated continuously.

Parameter estimation methods have been covered by [8], [9], [10] in general. In [11] various estimation methods have been explored for applications with electrical machines. This paper presents parameter estimation methods for doubly fed induction generators to improve performance of the observers. As far as the authors know, this paper presents the MRAS identification methods for a doubly fed induction generator for the first time. As well as a new method for online estimation of the inductances which needs no additional excitation signal is introduced.

The paper is structured as follows:
An introduction was given in this section. The system of the DFIG is described in the second section. The third section presents the MRAS identification method and a new approach to estimate the inductances of the DFIG which needs no additional excitation signal. Section four presents a sensitivity analysis of the considered observers due to parameter inaccuracies. Section five shows measurement results of the observers with feedback of the estimated parameters. The paper is finished by a conclusion, an appendix and a list of references.

II. SYSTEM DESCRIPTION

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.

The general control scheme of a doubly fed induction generator is shown in figure 1. The stator of the DFIG is directly connected to the grid and the rotor is fed by an inverter from a DC voltage link. Thus the rotor can be fed by a variable voltage and frequency. Field oriented control is used for rotor current control loops. The observers which are used for fault tolerant control are adjustable. They are updated by the identified parameters.
III. ONLINE PARAMETER ESTIMATION

A. Model Reference Adaptive System (MRAS)

Identification methods with a parallel adaptive model are called model reference adaptive systems (MRAS). The model reference adaptive system uses a reference model to generate the desired output, which is compared with the actual output of the system. Adjusting the parameters in the adaptive model minimizes the error signal [12]. The identification scheme can be used for nonlinear multivariable systems with continuous signals [13].

This identification method is described in [13] for the estimation of all squirrel cage induction motor parameters used in state space description. The measurability of all system states is required. States of the squirrel cage induction motor in [13] are stator current and rotor flux. It is necessary to use in state space description. The measurability of all squirrel cage induction motor parameters, are not known exact. Therefore an adaptive model (2) of the considered system is introduced:

\[ \dot{x}(t) = A f[x(t)] + Bu(t) \]  

(1)

The parameters of matrices A and B, i.e. the machine parameters, are not known exact. Therefore an adaptive model (2) of the considered system is introduced:

\[ \dot{x}_M(t) = A_M f[x_M(t)] + B_M u(t) \]  

(2)

The matrices \( A_M \) and \( B_M \) of the adaptive model have to be of the same structure as the system matrices \( A \) and \( B \). Stability of this approach can be verified by a Lyapunov function. Convergence conditions of this identification method are shown in [15].

Matrices \( A_M \) and \( B_M \) are adjustable and the dynamics are given by the following equations (3) and (4).

\[ \dot{A}_M(t) = \left[ \dot{x}(t) - \dot{x}_M(t) - A_M(t)(f[x(t)] - f[x_M(t)]) \right] \cdot f^T(x(t))K_A \]  

(3)

\[ \dot{B}_M(t) = \left[ \dot{x}(t) - \dot{x}_M(t) - A_M(t)(f[x(t)] - f[x_M(t)]) \right] \cdot u^T K_B \]  

(4)

The advantage of the DFIG is the measurability of all states using the stator and rotor currents as system states. The system of the DFIG is nonlinear and can be described using a state space model. The stator and rotor voltages \( U_s \) and \( U_r \) as well as the currents \( I_s \) and \( I_r \) are space vectors with real and imaginary parts. The state space model of the electrical system is shown in equation (1).

\[
\begin{align*}
A = & \begin{bmatrix}
-R_s \frac{d}{dt} & 0 & \frac{L_R R_s}{L_s} & 0 & 0 & 0 & 0 & 0 & \frac{L_H I_R}{L_s} & 0 & \frac{L_H}{L_s} \\
0 & -R_s \frac{d}{dt} & \frac{L_R R_s}{L_s} & 0 & 0 & -\frac{L_H I_R}{L_s} & 0 & 0 & -\frac{L_H}{L_s} & 0 & 0 \\
\frac{L_R R_s}{L_s} & 0 & -R_s \frac{d}{dt} & 0 & 0 & 0 & 0 & -\frac{L_H I_R}{L_s} & 0 & -1 \frac{1}{\sigma} & 0 \\
0 & \frac{L_R R_s}{L_s} & 0 & -R_s \frac{d}{dt} & 0 & 0 & \frac{L_H I_R}{L_s} & 0 & 0 & \frac{1}{\sigma} & 0 \\
\frac{1}{\sigma} & 0 & -\frac{L_H I_R}{L_s} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{\sigma} & 0 & -\frac{L_H I_R}{L_s} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{L_H I_R}{L_s} & 0 & \frac{1}{\sigma} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{L_H I_R}{L_s} & 0 & \frac{1}{\sigma} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\end{align*}
\]

(7)

\[
B = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

(8)
The matrices $K_A$ and $K_B$ influence the decay characteristic of the identification process and are designed to ensure a convergence that follows \[13\]:

\[
\lim_{t \to \infty} x_M(t) = x(t) \quad (9)
\]

\[
\lim_{t \to \infty} A_M(t) = A \quad (10)
\]

\[
\lim_{t \to \infty} B_M(t) = B \quad (11)
\]

Defining the error vector $e(t)$ as stated in equation (12) tends to a nonlinear integral feedback as can be seen in equation (13) and (14).

\[
e(t) = \frac{\dot{x}(t) - \dot{x}_M(t) - A_M(t)[f[x(t)] - f[x_M(t)]]}{\Delta f(x(t), x_M(t))} \quad (12)
\]

\[
A_M(t) = \int e(t)f[x(t)]^T K_A \, dt + A_M(t_0) \quad (13)
\]

\[
B_M(t) = \int e(t)x^T K_B \, dt + B_M(t_0) \quad (14)
\]

This time variable matrices $A_M(t)$ and $B_M(t)$ are used for online calculation of the state vector $x_M(t)$ of the parallel adaptive model. The block diagram of the MRAS method is shown in figure 2.

The error vector $e(t)$ defined in (12) can be used as the input of an adaptive parameter estimator [16]. The challenge of this method is the design of the matrices $K_A$ and $K_B$. If the entries are too small, the decay characteristic will be too slow and a convergence cannot be guaranteed. If they are too large, the adaptive model is very sensitive concerning disturbances and a risk of instability exists. The success of this method depends mainly on the choice of the excitation signal [14]. The signal must be selected in such a way that all eigenvalues of the system become excited. A good excitation of the system can be obtained with a signal, which comprises different high amplitudes and frequencies.

**Simulation Results with MRAS**

Simulation results presented in figures 3 and 4 show the estimated parameters of the matrices $A_M(t)$ and $B_M(t)$ and the reference values. The simulated system is excited by the stator and rotor with a test signal which includes various amplitudes and frequencies. All initial values are set to zero. The estimated parameters of the adaptive matrix $A_M(t)$ converge within approximately four seconds to the system parameters. Estimated parameters of matrix $B_M(t)$ converge somewhat faster. MRAS identification method yields good simulation results if the input signals excite all eigenvalues of the system, as can be seen in figures 3 and 4. The stator of DFIG is directly connected to the grid. Consequently the used stator excitation signal cannot be used for the laboratory setup. Unfortunately, the excitation only via rotor for a net connected stator excites not all eigenvalues and tends not to a correct identification process. Therefore a new approach for online estimation of the DFIG inductances which needs no additional excitation signal is introduced in the next subsection.
B. New Approach for Online Estimation of the Inductances

A new method for estimation of the inductances \( L_{dH} \), \( L_{sd} \) and \( L_{rd} \) of the DFIG is presented in this subsection. This approach needs in contrast to the common methods no test signal to excite the systems eigenvalues.

Equations (15) and (16) arise from the equivalent circuit diagram of the DFIG in an arbitrary reference system (index ”\( H \)”) for stationary operation as can be seen in figure 5.

\[
\begin{align*}
U^H_s &= R^H_s I^H_s + j \omega_s L^H_s I^H_s + j \omega_s L_{dH} I^H_d \\
U^H_s &= \frac{R^H_s}{s} I^H_s + j \omega_s L^H_s I^H_s + j \omega_s L_{dH} I^H_d
\end{align*}
\]

(15) and (16)

By multiplying (14) with \( s = \omega_p/\omega_s \) yields to (17).

\[
\begin{align*}
U^H_s &= R^H_s I^H_s + j \omega_s L^H_s I^H_s + j \omega_s L_{dH} I^H_d
\end{align*}
\]

By multiplying (14) with \( s = \omega_p/\omega_s \) yields to (17).

\[
\begin{align*}
U^H_s &= R^H_s I^H_s + j \omega_s L^H_s I^H_s + j \omega_s L_{dH} I^H_d
\end{align*}
\]

(17)

Solving the two sets of linear equations leads to following equations in an arbitrary reference frame:

\[
\begin{align*}
L_{dH} &= U^H_s \frac{d}{d} I^H_d - I^H_s I^H_s - I^H_d I^H_d \\
L_{sd} &= \frac{U^H_s}{\omega_s} I^H_s I^H_s - I^H_d I^H_d \\
L_{rd} &= \frac{U^H_s}{\omega_s} I^H_s I^H_s - I^H_d I^H_d
\end{align*}
\]

(22) and (23)

By transforming equations (22) and (23) into a stator voltage fixed reference frame and transforming equation (25) into a rotor voltage fixed reference frame yields to the following three equations:

\[
\begin{align*}
L_{dH} &= U^S_s \frac{d}{d} I^S_d - I^S_s I^S_s - I^S_d I^S_d \\
L_{sd} &= \frac{U^S_s}{\omega_s} I^S_s I^S_s - I^S_d I^S_d \\
L_{rd} &= \frac{U^S_s}{\omega_s} I^S_s I^S_s - I^S_d I^S_d
\end{align*}
\]

(27) and (28)

These equations are implemented in MATLAB-Simulink® in the corresponding reference systems. The leakage inductances \( L_{sd} \) and \( L_{rd} \) can be calculated with the estimated mutual inductance \( L_{dH} \):

\[
\begin{align*}
L_{sd} &= L_s - L_{dH} \\
L_{rd} &= L_r - L_{dH}
\end{align*}
\]

(29) and (30)

Due to zero crossings of the denominator a logic block is implemented which guarantee stability. Lag elements with a cut-off-frequency of 33Hz are implemented to smooth the signals.

Simulations of the estimation of the parameters \( L_{dH} \) and \( L_{sd} \) have shown good results for almost all operating points. The estimation of \( L_{rd} \) yields only to good simulation results if the mechanical speed is not near the synchronous speed. Otherwise the neglected term \( R_d/s \) of equation (14) is no longer negligible. The slip \( s \) becomes zero for a synchronous mechanical speed and therefore \( R_d/s \) becomes infinite. A further condition for an accurate estimation of the inductances is that the active power may not be zero.

Simulation Results with new Approach

Simulation results of the online estimation for one operating point are shown in figure 6. Initial values are set to zero, the mechanical rotor speed amounts to 1000 rpm and the active power to 5 kW.
It can be seen that the mutual inductance $L_H$ and the stator leakage inductance $L_{S\sigma}$ are estimated very well. The rotor leakage inductance $L_{R\sigma}$ doesn’t reach the correct final value in cause of the neglected term $R_S\sigma$. The presented new approach for online estimation is not able to estimate the resistances $R_S$ and $R_R$.

In contrast to common methods this approach needs no test signal to excite the system and is appropriate to estimate the inductances $L_H$ and $L_{S\sigma}$ during the controlled operation of the DFIG. A sensitivity analysis of the observers due to parameter inaccuracies has shown that the observers are not sensitive due to inaccuracies of the leakage inductances and the resistances but very sensitive due to inaccuracies of the mutual inductance $L_H$, as can be seen in the following section.

IV. SENSITIVITY ANALYSIS

The approach is not able to estimate the resistances. The estimation of the rotor leakage inductance is not satisfying as well. Therefore a sensitivity analysis due to parameter inaccuracies of the used observers is introduced in this section.

The parameters of a 22 kVA test drive have been identified manually for a fixed operating point ($U_S = 185 V$, $N = 1000 \text{ min}^{-1}$, $P = -3 \text{ kW}$, $Q = 0 \text{ VA}$; induction machine is not saturated). The identified parameters are:

- $L_H = 50 \text{ mH}$
- $L_{S\sigma} = 1 \text{ mH}$
- $L_{R\sigma} = 2 \text{ mH}$
- $R_S = 0.15 \Omega$
- $R_R = 0.15 \Omega$

These parameters are used for the considered observers. For evaluation of the sensitivity of the observers due to parameter inaccuracies every parameter was varied stepwise one by one while the others were kept constant. Every parameter was varied from -80% to +100% around the identified parameters (specified above) consecutively. The difference between estimated states and measured states has been determined for every of this parameter inaccuracy. The results of this sensitivity analysis are shown in figure 7. The measured states at this operating point have been: $I_{Sd} = -10.8 \text{ A}$, $I_{Sh} = 0.01 \text{ A}$, $I_{Rd} = -11.06 \text{ A}$, $I_{Rh} = -11.1 \text{ A}$, $U_{Sd} = 185 \text{ V}$, $U_{Sh} = 0 \text{ V}$, $U_{Rd} = 76.4 \text{ V}$, $U_{Rh} = -0.56 \text{ V}$. The results on the left side of figure 7 show the difference (error) between the estimated currents of the Luenberger state observer and the measured currents for inaccuracies of the parameters $L_H$, $L_{S\sigma}$, $L_{R\sigma}$, $R_S$ and $R_R$ (top-down). The results on the right side show the differences between the estimated voltages of the unknown input observer and the measured voltages for inaccuracies of $L_H$, $L_{S\sigma}$, $L_{R\sigma}$, $R_S$ and $R_R$ (top-down). It can be seen that the estimated currents have an estimation error up to 20 A if the deviation of the mutual inductance $L_H$ is set to 100% (top left). This amounts to a relative error of the real part of the estimated stator current $I_{Sd}$ about 188%. The estimation error of the unknown input observer amounts up to 120 V if the deviation of the mutual inductance $L_H$ is set to 100% (top right). This equates to a relative error of about 64% of the estimated stator voltage real part $U_{Sd}$. Beneath the results for variation of the mutual inductance the results for the stator leakage inductance $L_{S\sigma}$ are shown. It can be seen that both observers yield to a much smaller estimation error for an inaccurate parameter $L_{S\sigma}$. Inaccurate parameters $L_{R\sigma}$, $R_S$ and $R_R$ have also not a mentionable influence on the performance of the observers as can be figured out in the lower pictures.

The most important parameter is the mutual inductance. The considered observers are robust due to inaccurate leakage inductances and resistances. But they are very sensitive due to inaccuracies of the parameter $L_H$. Therefore, the parameter $L_H$ should be estimated and fed back during operation. The fact that only the mutual and the stator leakage inductance can be estimated satisfactory is consequently not a big disadvantage.

This method has been implemented in the laboratory setup. Some results are shown in the following section.

V. MEASUREMENT

The new approach for online estimation of the inductances has been tested on a 22 kVA test drive. Measurements were taken via dSPACE-ControlDesk®. The parameters $L_H$, $L_{S\sigma}$ and $L_{R\sigma}$ are estimated during
A comparison between real system and system model has shown a small difference in the real part of the rotor current \( I_{Rd} \). Therefore a virtual resistance \( R_v \) is introduced to compensate this difference. The adjusted rotor current component used for the new estimation method is shown in equation (31):

\[
I'_{Rd} = I_{Ra} \frac{U_{Sd}}{R_v}
\]

A virtual resistance of \( R_v = 110 \Omega \) led to a good accordance of the considered setup.

Measurement results are shown in figures 8 and 9. The upper pictures show measured (dashed lines) and estimated (continuous lines) stator voltage (left) and rotor voltage (right) of the unknown input observers. The lower pictures show measured and estimated stator current (left) and rotor current (right) of the state observers. The voltages and currents are space vectors with real and imaginary parts transformed into a rotating stator voltage oriented reference frame. At the time \( t = 0 \) s, the feedback of the estimated inductances is switched on. The fixed parameters for the observer models which are used if the parameters are not fed back, amounts to:

\[
\begin{align*}
L_{H} & = 39 \, \text{mH} \\
L_{S\sigma} & = 1 \, \text{mH} \\
L_{R\sigma} & = 2 \, \text{mH} \\
R_{S} & = 0.12 \, \Omega \\
R_{R} & = 0.12 \, \Omega
\end{align*}
\]

Measurements were taken at various operating points. Figure 8 shows measurement results for the operation at a mechanical rotor speed of 1000 rpm, active power of -3 kW and a phase to phase root mean square voltage of 260V (induction machine is not saturated). During this operation the following inductances have been estimated with the presented approach:

\[
\begin{align*}
\hat{L}_{H} & = 45.7 \, \text{mH} \\
\hat{L}_{S\sigma} & = 0.9 \, \text{mH} \\
\hat{L}_{R\sigma} & = 4.0 \, \text{mH}
\end{align*}
\]

Operation with a phase to phase root mean square voltage of 180 V yields to following estimated inductances:

\[
\begin{align*}
\hat{L}_{H} & = 52 \, \text{mH} \\
\hat{L}_{S\sigma} & = 1.18 \, \text{mH} \\
\hat{L}_{R\sigma} & = 4.9 \, \text{mH}
\end{align*}
\]

Measurement results at this operating point can be seen in figure 9. The real parts of the observed voltages as well as the currents agree with the measured voltages by adjusting the observers with the estimated inductances. The imaginary parts of the observed currents come closer the measured currents as well. The difference between observed states and measured states becomes significantly smaller with the adaption of the estimated inductances, as can be seen in figures 8 and 9.

Measurement results at this operating point can be seen in figure 8. The quality of the observers increases significantly with feedback of the estimated inductances, as can be seen in figure 8. The real parts of the observed stator and rotor voltages come closer to the measured values by adjusting the observer models with the estimated inductances (top). The differences of imaginary parts become somewhat bigger. That may be something to do with the poorly estimated rotor leakage inductance. Both real and imaginary parts of the observed currents come closer to the measured currents (bottom).

\[
\begin{align*}
L_{H} & = 39 \, \text{mH} \\
L_{S\sigma} & = 1 \, \text{mH} \\
L_{R\sigma} & = 2 \, \text{mH} \\
R_{S} & = 0.12 \, \Omega \\
R_{R} & = 0.12 \, \Omega
\end{align*}
\]
VI. CONCLUSION

In this paper parameter estimation technique is used for improvement of a model based fault tolerant control. The model based control uses observers whose quality depends highly on the accuracy of the mutual inductance. A model reference adaptive system and a new approach for online estimation of the DFIG parameters are presented in this paper.

The MRAS identification method shows good simulation results if a test signal excites all relevant eigenvalues of the DFIG. This method yields not to a correct identification of the system parameters, if the stator of the DFIG is directly connected to the grid and only the rotor is excited by a test signal.

A new approach for the estimation of the DFIG inductances is investigated and analysed in this paper. This method needs no additional excitation signal and yields to good simulation and measurement results of the stator leakage and the mutual inductances.

The performance of the considered observers increases with feedback of the estimated inductances.

VII. DATA OF EXPERIMENTAL SETUP

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>Data of experimental setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine VEM SPER 200 LX4</td>
<td>22 kW  Stator: 400 V 41 A  Rotor: 255 V 53 A</td>
</tr>
<tr>
<td>Control</td>
<td>dSPACE DS1104 250 Mhz</td>
</tr>
<tr>
<td>Inverter (DFIG)</td>
<td>IGBT 2-level Voltage Source Inverter</td>
</tr>
<tr>
<td>Converter (Grid)</td>
<td>3-phase Diode Rectifier</td>
</tr>
</tbody>
</table>

ACKNOWLEDGMENT

This work has been funded by Land Schleswig-Holstein (State Schleswig-Holstein) and Deutsche Forschungsgemeinschaft (German Research Foundation).

REFERENCES