Educational Experimental Rig for Doubly-Fed Induction Generator based Wind Turbine

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Abstract—An experimental rig for grid-connected Doubly-Fed Induction Generator (DFIG) based wind turbine is presented. The experimental rig was developed for educational and research purposes at the University Duisburg Essen. The goal here is to give an overview of the structure, control and operation of the developed DFIG system. Independent control of active and reactive power of the generator is achieved by applying voltage-oriented control schemes. In the laboratory set up, a 9kW slip ring induction generator is used. The generator is driven by a torque-controlled squirrel cage induction motor. The control program of the wind turbine emulator generates the torque reference value for the drive. The commissioning procedure through the PC user interface is described. The performance of the developed rig is demonstrated through experimental results during nominal load operation.

Index Terms — wind power, doubly-fed induction generator, line side converter, machine side converter, emulator.

I. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$i_s$, $i_R$</td>
<td>Complex stator and rotor currents</td>
</tr>
<tr>
<td>$v_s$, $v_R$</td>
<td>Complex stator and rotor terminal voltages</td>
</tr>
<tr>
<td>$v_{LSC}$, $i_{LSC}$</td>
<td>Complex LSC voltage and current</td>
</tr>
<tr>
<td>$v_{DC}$, $i_{DC}$</td>
<td>Converter DC-link voltage and current</td>
</tr>
<tr>
<td>$l_{sl}$, $l_{rl}$</td>
<td>Stator and rotor leakage inductances (per unit), they correspond with the reactances $x_{sl}$, $x_{rl}$</td>
</tr>
<tr>
<td>$l_{fs}$</td>
<td>Main-field inductance (per unit), it corresponds with the reactance $x_f$</td>
</tr>
<tr>
<td>$r_s$, $r_R$</td>
<td>Stator and rotor resistances</td>
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<tr>
<td>$\omega_s$, $\omega_R$</td>
<td>Rotor angular speed, synchronous speed</td>
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<tr>
<td>$v_w$</td>
<td>Wind speed</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Pitch angle</td>
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<tr>
<td>$t_{el}$, $t_m$</td>
<td>Electrical/mechanical torque</td>
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</tbody>
</table>

Superscripts/Subscripts

d, q | Direct, quadrature axis component

$\angle$, $\angle^*$ | Reference frame, $\angle$: arbitrary, $\angle V_g$: grid voltage oriented, $\angle V_s$: stator voltage oriented

II. INTRODUCTION

In the recent years renewable energy sector enjoyed worldwide a rapid capacity growth. Being by far the most promising and technically advanced renewable power source, wind energy generation related projects and studies have scaled up significantly. Therefore there is a growing academic interest in practically demonstrating technologies of wind power conversion systems. One of these technologies is the DFIG. Compared to the full rated converter system, the DFIG is still having appreciable economic advantages in several applications.

Various papers dealt with developing DFIG experimental systems as early as [1]. However most of the papers did not highlight the educational competencies in developing such a system. This paper offers an overall description of the developed experimental rig with its adequate user interface programmed in a graphical simulation environment.

The main motivations behind this work are to demonstrate the control and operation concept of the DFIG and to conduct tests for power system stability studies by applying simulated grid faults. The DFIG system was developed in stages throughout students undergraduate and graduate projects. Presently, the experimental rig is used in the lab for education and research purposes, and undergoes continuous improvements through student projects.

The basic concept of the DFIG is described briefly in the next section. Section IV offers an overview of hardware and software components of the developed rig. The main control concepts of the DFIG are discussed in section V. In section VI, the emulation concept is presented based on a modern strategy for wind turbine control. The paper ends with the demonstration the PC user interface with test results and concluding remarks.

III. DFIG TECHNOLOGY

Fig. 1 shows the basic concept of a wind turbine based on DFIG technology. The mechanical torque generated at the wind turbine shaft drives the DFIG. As the generator rotates mechanical power will be converted into electrical power through its rotor and stator windings feeding the connected grid. The DFIG system ensures efficient power conversion due to variable rotor speed. According to the prevailing wind speeds, the rotor speed is adjusted (or limited) using speed and pitch control. Basically the control of the DFIG can be separated into the line side converter (LSC) and the machine
side converter (MSC) controls. The functions and control concepts of both converters are described in section V.

- Function overview:

  - **Pitch and Power Control:**
    - \( P, \cos(\phi) \cdot V \)
  - **MSC Control:**
    - \( U_{DC} \cdot (Q, \cos(\phi), V) \)
  - **Fast Current Control:**
    - Flow through the system

**Fig. 1. Basic concept DFIG-based wind turbine system**

Variable speed operation of the DFIG is made possible by directionally dependent transfer of slip power via the frequency converter [2]. Thus two operation modes are possible: subsynchronous and supersynchronous operation modes. In the subsynchronous mode (partial load range), the stator of the DFIG supplies power to the grid and also the slip power to the rotor via slip rings and the converters. While in the supersynchronous mode (nominal load range), both the stator output power and the rotor slip power are fed to the grid. Usually the nominal generator speed is specified well above the synchronous speed (supersynchronous mode) in order to operate with maximum efficiency; this speed point corresponds to the rated wind velocity. By choosing a higher speed operation point, more power will be transferred through the rotor. Due to the voltage limit of the converters, the operation speed is limited to a certain range. Therefore at full load, the active power passing through the rotor circuit amounts to roughly 17% of total power, while the speed range is +/−33% around the synchronous speed.

**IV. EXPERIMENTAL RIG STRUCTURE**

**A. Hardware Components**

Fig. 2 shows the three-phase circuit diagram of the experimental rig. Basically [3] the rig setup can be separated into five parts: a) Drive train, b) transformer, c) power electronics, d) Digital Signal Processor (DSP) and e) Fault Ride Through (FRT) testing set up.

In this experimental rig, a 50Hz, 11kW, 400V, 2-pole pair slip ring induction generator is driven by a standard squirrel cage asynchronous motor emulating the wind turbine prime mover (Fig. 3). The driving motor is controlled by a commercial variable-frequency converter; the emulation concept is discussed in section VI. The voltage level of the DFIG is limited to 200V due to the saturation effects in the generator. Thus the whole DFIG system has a rated power of 9 kW including the LSC.

A Dyn5 transformer is connected to the low voltage level through its primary winding, while the voltage level of the secondary winding can be adjusted. During grid side faults, the \( \Delta-Y \) connection of the transformer decouples the zero sequence system. Therefore only positive and negative sequence quantities will remain on the generation unit side.

**Fig. 2. Circuit diagram of the experimental rig**

In the state of the art wind turbines as well as in the experimental rig 2-level IGBT converters are used. These back-to-back PWM voltage-source converters were assembled at the university laboratory. The functions of these converters are a) converting AC to DC and back to AC at variable frequency, b) controlling DC-link voltage level and c) controlling amplitude, frequency and phase angle of rotor voltage. The switching frequency of the IGBT’s (here 5 kHz) should be chosen in a way that the balance between switching losses and accuracy of the desired signals is achieved.

The DSP is one of the core elements of the experimental rig because it contains the control and thus the technical know-how. The DSP sends the PWM signals to each IGBT.

**Fig. 3. Drive train of the experimental rig**

An inductive voltage divider is used to produce voltage dips with defined depths and durations, and the FRT capability of the DFIG can be tested to determine whether it meets certain grid code requirements. Fig. 4 describes the basic set up for FRT testing.

**Fig. 4. Basic set-up for RFT testing set up**
The programming of the DSP is done using MATLAB/Simulink, where the program is translated in C-code using the Automatic Code Generation tool integrated in MATLAB. The code is then transformed further into Assembly language level and finally to binary code that is sent to the DSP. This programming approach of the DSP and its benefits are discussed in details in [3]

Fig. 5 illustrates the main interfaces and data flow of the experimental rig. First, voltages and currents required for the control of the system are measured. Through transducers and signal conditioners the measured data are parameterized and processed so that it can be digitalized by the analog to digital converter (ADC) in the DSP as well as the Data Acquisition (DAQ) device. The received data in the DSP are further processed and control signals of the output variables are generated and modulated using the PWM technique. These PWM signals are the control signals of the IGBT’s of both LSC and MSC.

For visualizing different measurements, adjusting setpoints and operation modes of the experimental rig the software LabVIEW is used. LabVIEW is a G-code based programming environment which offers a distinctive user interface through its “Front Panel”. LabVIEW is commonly used for data acquisition, signal processing and visualization applications [4].

For the grid voltage oriented control are as follows:

\[
\theta_g = \int \omega_0 dt = \arctan \left( \frac{v_{g,0}^{\omega,0}}{v_{g,\beta}^{\omega,0}} \right)
\]

Where \( \omega_0 \) is the synchronous angular speed corresponding to the speed of the rotating reference frame \( \omega_g \). According to Clarke transformation, \( v_{g,\alpha}^{\omega,0} \) and \( v_{g,\beta}^{\omega,0} \) are the phasor components in the fixed coordinate system (denoted by \( \angle 0 \)). Fig. 7 illustrates the complex phasor diagram of the LSC. In grid voltage-oriented rotating reference frame it can be concluded that \( v_{g,1}^{\omega,0} = 0 \).

The reference voltages of the LSC by adjusting both (2) and (3) will be:

\[
\begin{align*}
 v_{LSC,d,\text{ref}}^{\omega,0} &= v_{g,d}^{\omega,0} - v_{LSC,d}^{\omega,0} + \omega_0 i_{LSC,q}^{\omega,0} \\
 v_{LSC,q,\text{ref}}^{\omega,0} &= v_{g,q}^{\omega,0} - v_{LSC,q}^{\omega,0} - \omega_0 i_{LSC,d}^{\omega,0}
\end{align*}
\]
The active and reactive power of the LSC are expressed as:

\[ P_{LSC} = v_{g,d}i_{LSC,d} + v_{g,q}i_{LSC,q} \quad (9) \]

\[ Q_{LSC} = v_{g,q}i_{LSC,d} - v_{g,d}i_{LSC,q} \quad (10) \]

Since the q-component \( v_{g,q} \) of the LSC in symmetrical case is zero, we can conclude, that the d-component \( i_{LSC,d} \) and the q-component \( -i_{LSC,q} \) of the LSC are proportional to the active and reactive power respectively. By neglecting converter power losses the power flow between the DC and AC sides can be expressed as:

\[ P_{LSC} = v_{DC}i_{DC} = v_{g,d}i_{LSC,d} \quad (11) \]

Consequently it can be concluded, that the DC-link voltage is controlled through adjusting the d-component \( i_{LSC,d} \) of the LSC. The reference value for the corresponding d-component current is given by:

\[ i_{LSC,d,ref} = k_p \left( 1 + \frac{1}{sT} \right) (v_{DC,ref} - v_{DC}) \quad (12) \]

Equations (7), (8) and (12) form the basic control scheme for the LSC. The reactive current characteristic function in Fig. 8 sets the reference value of the q-component \( i_{LSC,q,ref} \) to support the grid with reactive power during short-time grid faults. This is required in certain grid codes. The LSC has always active current priority in order to preserve the power balance in the dc-link.

### B. MSC Control

Independent control of active and reactive power of the generator can be achieved through the MSC. Here likewise voltage-oriented control is used based on stator voltage-oriented reference frame. Flux-oriented control is a common practice in electrical drives. However, power system engineers are more familiar with the terms active and reactive currents instead of electrical torque and excitation current.

The MSC control concept is based mainly on the asynchronous machine equations. The system of equations for the DFIG consists of two voltage equations, two flux equations and an equation of motion which are given by the following:

**Voltage equations:**

\[ \sigma_s = r_s i_s + \frac{d\psi_s}{dt} + j\omega_k \psi_s \quad (13) \]

\[ \sigma_r = r_k i_r + \frac{d\psi_r}{dt} + j(\omega_k - \omega_r) \psi_r \quad (14) \]

---

Fig. 7. LSC complex phasor diagram

Fig. 8. Structure for generating LSC current reference values

Fig. 9. LSC current control
The inductances in (15), (16) are defined as:

\[
\psi_{S,d} = l_S i_{S,d} + l_h i_{R,d} \\
\psi_{S,q} = l_h i_{S,q} + l_R i_{R,q}
\]

Equation of motion:

\[
\frac{d\omega_R}{dt} = \frac{1}{\theta_m} \left( \psi_{S,d} i_{S,q} - \psi_{S,q} i_{S,d} + t_m \right)
\]

The inductances in (15), (16) are defined as:

\[
l_S = l_h + l_{es} \\
l_R = l_h + l_{eh}
\]

In the steady-state, from (13), (15), and by neglecting the stator resistance, the stator voltage equation can be rewritten as:

\[
V_S = j \omega_k (l_S i_{S,d} + l_h i_{R,d})
\]

Hence the complex phasor of the rotor current is defined as:

\[
i_{R,d} = -\frac{x_s}{x_h} i_{S,d} + j \frac{v_S}{x_h}
\]

In stator voltage oriented coordinates (denoted by \(\angle v_S\)):

\[
i_{R,d} = -\frac{x_s}{x_h} i_{S,d} \\
i_{R,q} = -\frac{x_s}{x_h} i_{S,q} - \frac{|v_S|}{x_h}
\]

The stator active and reactive power equations are given by:

\[
P_S = V_{S,d} i_{S,d} + V_{S,q} i_{S,q} \\
q_S = V_{S,q} i_{S,d} - V_{S,d} i_{S,q}
\]

Assuming that the reference values for stator active and reactive power outputs are known, and by substituting the voltage values in the stator oriented reference frame \((v_{S,d} = v_S, v_{S,q} = 0)\), we get:

\[
i_{R,d,ref} = -\frac{P_{S,ref}}{|v_S|} \frac{x_s}{x_h} \\
i_{R,q,ref} = -\frac{q_{S,ref}}{|v_S|} \frac{x_s}{x_h}
\]

From the rotor voltage in (14) and the stator voltage equation (20) we obtain the following:

\[
V_R = r_R i_{R} + j \omega_k \left( \frac{v_S - j x_S i_{S,d}}{x_S} + x_h i_{R,d} \right)
\]

In stator voltage oriented coordinates (denoted by \(\angle v_S\)), rotor voltage can be written in dq components as:

\[
V_{R,d,ref} = s \frac{x_h}{x_S} V_{S,d} + r_R \frac{i_{R,d}}{x_h} - i_{R,q} \sigma x_R \\
V_{R,q,ref} = r_R i_{R,q} + i_{R,q} \sigma x_R
\]

Here a leakage coefficient \(\sigma = (1 - x_h^2 / x_h x_S)\) is introduced.

Based on PI controllers, the control transfer function for the rotor current controller is given as:

\[
v_{R,d} = k_p \left( 1 + \frac{1}{s T} \right) (i_{R,d,ref} - i_{R,d}) \\
v_{R,q} = k_p \left( 1 + \frac{1}{s T} \right) (i_{R,q,ref} - i_{R,q})
\]

To be able to pass the outputs of the rotor current controller \(v_{R,d}\) and \(v_{R,q}\) as reference values into the MSC, the signals have to be transformed into the rotor reference frame. This will require the knowledge of the rotor (position) angle \(\Theta_R\), which could be obtained by measuring the rotor position using a position encoder sensor. Alternatively the rotor transformation angle \(\Theta_R\) and the slip transformation angle are obtained mathematically using the measured stator and rotor currents as follows:

\[
\Theta = \arctan \left( \frac{i_{R,Q}}{i_{R,D}} \right), \quad \Theta_R = \arctan \left( \frac{i_{R,Q}}{i_{R,D}} \right)
\]

The coordinate system \((a^R, b^R)\) is a fixed reference frame (stationary) with respect to the rotor. From the definition of the slip speed: \(\omega_s = \omega_R - \omega_k = \frac{d\Theta}{dt}\), the slip transformation angle is defined as \(\Theta_s = \Theta - \Theta_R\). The MSC complex phasor diagram in Fig. 10 is based on this sensorless approach.

![MSC complex phasor diagram](image-url)
VI. WIND TURBINE MODELING, CONTROL AND EMULATION

A control model for the wind turbine emulator is implemented in a software environment. The model consists of a wind turbine mechanical model with pitch and speed control. Recorded wind speed data are the input. The model generates the mechanical torque setpoint for the drive and the reference value of active power for the MSC. Depending on the rotor speed, the reference value of the active power is derived using typical power characteristics of a wind turbine.

A. Wind Turbine Mechanical Model

The mechanical power extracted from the wind can be calculated as:

\[ p_m = \frac{1}{2} \rho A_{rot} c_p (\lambda, \beta) v_w^3 \]  

(33)

Where \( \rho \) is the air density, \( A_{rot} \) is the cross-section through which the air mass is streaming, \( c_p \) is the power coefficient and \( v_w \) is the wind speed. Wind turbine manufacturers give the specific value for a turbine as a function \( c_p (\lambda, \beta) \) and tip-speed ratio \( \lambda \). The tip-speed ratio is defined as:

\[ \lambda = \frac{\omega_r R}{v_w} \]  

(34)

Where \( R \) is the radius of rotor blade and \( \omega_r \) is the speed of the turbine. There is a fixed relationship between \( \omega_r \) and \( \omega_t \) given by the gear transmission ratio. The turbine model is based on the steady-state power characteristics of the turbine; the function \( c_p (\lambda, \beta) \) was modeled based on [5].

B. Pitch and Speed Control

The main task of pitch (rotor blade) control is to limit wind turbine mechanical power (torque) at high wind speeds to the nominal value and to keep the rotor speed inside the desired range. Using a PI controller the speed error is compensated, when the generator speed exceeds the nominal speed (see bottom part of Fig. 14). Usually the chosen nominal speed for the generator is \( 1.2 \omega_r \) or \( 1.2 \) per unit. Fig. 13 shows a typical power curve of a wind turbine.

C. Emulation Technique

Various papers [1], [6] discussed in details different techniques of wind turbine emulation. The technique applied at the experimental rig is based on Fig. 14.
In this control structure, the mechanical torque $t_m$ of the wind turbine model is sent as a setpoint to the driving motor. Simultaneously, the wind turbine reference power $P_{WT,ref}$ is generated through the wind turbine speed-power characteristics. The optimum power is stored in a look-up table. When the speed exceeds the nominal speed the pitch controller is activated. Thus the mechanical power of the wind turbine model will be reduced and consequently the shaft speed will therefore decrease. The actual wind turbine emulator control is implemented in LabVIEW. A further paper will discuss in details the theoretical concept, technical implementation and features of the existing emulator.

VII. USER INTERFACE, COMMISSIONING AND EXPERIMENTAL RESULTS

A. PC User Interface

The Front Panel of the software LabVIEW is the user interface for operating the experimental rig. The Front Panel consists of three subpanels. Fig. 15 shows the DFIG control subpanel. For educational and illustrative purposes, setpoints for LSC and MSC control are manually adjustable with certain limitations during manual speed control operation. These setpoints are sent to the DSP through a serial interface. During emulator operation, the “Control Power Curve” button is activated and consequently manual adjustments of setpoints are deactivated. Measured and calculated currents, voltages and powers are visualized flexibly on the Front Panel. Fig. 16 shows the FRT testing subpanel. The user can choose the fault type and perform short-circuit tests with adjustable durations.

![Fig. 15. Main subpanel - DFIG control](image)

B. Commissioning Procedure of the Experimental Rig

The operation of the experimental rig starts by connecting the rotor side circuit to the grid through the transformer. First, the LSC is connected and the LSC control is activated. The LSC regulates the DC-link voltage to stabilize it at constant level (here approx. 350V). The next step is to start the motor in manual speed control mode to operate at a subsynchronous speed of 1200 rpm. MSC control is afterwards activated; at this point stator voltage and grid voltage are synchronized. Only then the stator side circuit is connected to the grid. As a result, the DFIG is coupled successfully to the grid.

At this stage, the DFIG can operate in partial load or full load operation depending on the given speed level. The active and reactive power setpoints can be set from the subpanel during manual speed operation. At any point after synchronization and coupling the DFIG to the grid, the emulator control mode can be activated and the DFIG will operate according to the power tracking control algorithms mentioned in the previous section. This is done by pressing the start button in the middle column of Fig. 17 and loading the set of recorded wind speed data.

![Fig. 16. FRT subpanel](image)

![Fig. 17. Motor drive control subpanel](image)

C. Experimental Results

Fig. 18 demonstrates the results during emulator operation. Recorded data of fluctuating wind speed are processed during a period of 100 s. The base wind speed is set to 12 m/s corresponding to the rotor nominal speed of 1.2 pu. The active power value in per units is referenced to the rated total active power (stator and rotor electrical power). The nominal torque can be calculated as follows:

$$t_{nom(pu)} = \frac{p_{nom(pu)}}{\omega_{nom(pu)}} = \frac{1}{1.2} = 0.833pu$$  \hspace{1cm} (35)

Experimental results of FRT capability for the same DFIG system are given in [3].
Fig. 18. Behavior of the DFIG system during emulator operation using variable wind speed data input.

VIII. CONCLUSION

The developed experimental rig focuses on the demonstration of the control and operational principles of a modern DFIG based wind turbine.

The detailed documentation during different implementation phases of the experimental rig offers an open source technical know-how for the students at the university. Based on that experience, the university developed the DFIG control system for a commercial training system of a wind energy generation unit in cooperation with the company Lucas-Nülle. The specifications of the training unit are found on the company website: (http://www.lucas-nuelle.com/316/apg/1226/EWG+1+Wind+power+plants.htm).

IX. REFERENCES


X. BIOGRAPHIES

Mohammad Suwan (1985) received his M.Sc. degree in electrical engineering from the University Duisburg Essen, Germany in June 2011. Since August 2011 he is doing his Ph.D. studies in the department of Electrical Power Systems at the same University. His research interests are focused on grid integration of renewable energy and modeling and control of wind turbine converters and solar inverters. He is a member of VDE.

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Christian Feltes (1979) received his Dipl.-Ing. degree in electrical engineering from the University Duisburg Essen, Germany in 2005. From January 2006 to February 2011 he worked in the research staff of the Department of Electrical Power Systems at the same University. Since March 2011 he is working as grid integration engineer in the Offshore Wind Engineering department at RWE Innogy GmbH in Hamburg. His research interests are focused on wind energy generation, control, integration and dynamic interaction with electrical grid.

Istvan Erlich (SM’06) was born in 1953. He received his Dipl.-Ing. degree in electrical engineering from the University of Dresden, Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he is Professor and head of the Institute of Electrical Power Systems at the University Duisburg-Essen/Germany. His major scientific interest is focused on power system stability and control, modeling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and senior member of IEEE.