Dynamic Interaction
of large Offshore Wind Farms with the
Electric Power System

F. W. Koch, I. Erlich, *Member, IEEE,* F. Shewarega and U. Bachmann

Abstract -- The paper explores the influence of large off-shore wind farms on the performance of the system to which they are connected. To meet the emerging requirements of the power system with regard to voltage and frequency, controllers with extended features have been used that enable the control of the terminal voltage and the participation of large wind farms on system frequency control. The models of the wind turbine and the electrical machines together with the proposed control structure are integrated into a power system simulation environment. Then, the impact of planned off-shore wind farms on the transient stability performance of parallel operating conventional power plants and the bus voltage profile of the network during fault for alternative wind generator types are investigated. Additionally, the response of the wind farm to a major load change in a large multi-machine network is simulated and the results discussed.

Index Terms -- Control systems, Dynamics, Induction generators, Power systems, Simulation software, Transient stability, Variable speed drives, Wind power generation.

I. NOMENCLATURE

A_R Swept area
c_p Power coefficient
$\underline{i}$ Complex current
l_h Main-field inductance
l Inductance
m_W Torque at the turbine-shaft
r Resistance
T_m Inertia constant
$\mathbf{u}$ Voltage phasor
v_W Wind speed
$\chi, c_{1..6}$ Parameters of the wind turbine geometry
α Pitch angle
λ Tip speed ratio
ρ Air density
$\underline{\psi}$ Complex flux-linkages
ω_K Angular velocity of the reference frame
ω_0 Synchronous angular velocity

Superscripts and subscripts

'   Transient variable
S, R   Stator, rotor
d, q   Direct, quadrature axis component

F. W. Koch, University of Duisburg, Germany,
   (e-mail: friedrich.koch@uni-duisburg.de).
I. Erlich, University of Duisburg, Germany,
   (e-mail: erlich@uni-duisburg.de).
F. Shewarega, University of Duisburg, Germany,
   (e-mail: shewarega@uni-duisburg.de).
U. Bachmann, Vattenfall Transmission Ltd., Germany,
   (e-mail:Udo.Bachmann@vattenfall.de).

II. INTRODUCTION

The total installed wind generation capacity worldwide is expected to rise from 14,000 MW in 2002 to 47,000 MW in the year 2004. The wind generation in Europe alone is projected to reach approximately 33,600 MW by the year 2004 [1]. Due to the lack of appropriate onshore locations and the problem of acceptance by the population of wind turbines in their backyards, offshore sites will attain more and more significance in the future [2].

As a result of the magnitude of the power to be delivered, the practice of connecting wind units to the local medium voltage network will also change. Offshore wind farms (OWF) with the anticipated output power reaching several hundred MW have to be treated like the conventional power plants for all intents and purposes, and consequently several systemic issues are raised by the interconnection of such large wind parks to the electric power system that need to be addressed.

This paper sets itself the task of analyzing and comparing the dynamic behavior of alternative types of wind generators during a disturbance. For this purpose, five wind farms with the combined output of 1,500 MW supplying a network are simulated. The machines considered for the OWF are pitch-controlled doubly-fed induction machines (DFIM) and stall-controlled squirrel-cage induction machines (SCIM). For comparison purposes, an ordinary synchronous machine (SG) at the same bus in place of the OWF is also simulated. Each of the induction machines is assumed to have a power rating of 2 MW. The network to which the wind farms (or alternatively the SG) are connected is a 282-bus system comprising 73 synchronous generators, 128 transformers and 200 transmission lines. Its overall nominal power is 55,000 MW[3].

First, a systematic procedure for the development of reduced order state space equations for the induction machine operating as wind power generators is shown. This model forms the basis for the design of a multivariable, non-interacting control system, which will be made use of in this study.

III. MODELING AND SIMULATION

A. Wind turbine-generator model

The generated power by wind (p_W) is given by the following equation [4]:

$$p_W = \frac{\rho}{2} c_p(\lambda, \alpha) A_R v_W^3 \qquad (1)$$

with: $\quad c_p = c_1 \left(c_2 - c_3 \alpha - c_4 \alpha^x - c_5 \right) e^{-c_6(\lambda, \alpha)} \qquad (2)$

The mechanical/electrical energy conversion process is described by the equations of induction machines given in equations (3)-(7) [5]:

$$\underline{u}_S^{\angle K} = r_S \underline{i}_S^{\angle K} + \frac{d\underline{\psi}_S^{\angle K}}{dt} + j\omega_K \underline{\psi}_S^{\angle K} \qquad (3)$$

$$\underline{u}_R^{\angle K} = r_R \underline{i}_R^{\angle K} + \frac{d\underline{\psi}_R^{\angle K}}{dt} + j(\omega_K - \omega_R)\underline{\psi}_R^{\angle K} \qquad (4)$$

$$\underline{\psi}_S^{\angle K} = l_S \underline{i}_S^{\angle K} + l_h \underline{i}_R^{\angle K} \qquad (5)$$

$$\underline{\psi}_R^{\angle K} = l_h \underline{i}_S^{\angle K} + l_R \underline{i}_R^{\angle K} \qquad (6)$$

$$\frac{d\omega_R}{dt} = \frac{1}{T_m} \left(m_W + \left(\psi_{Sd} i_{Sq} - \psi_{Sq} i_{Sd} \right) \right) \qquad (7)$$

In the above equations, all values are in per unit and $\angle K$ stands for an arbitrary rotating reference frame.

The time frame and the dynamic phenomena on which this paper focuses allow the use of algebraic model equations for the network including the stator circuits of electrical machines. This means that stator transients can be neglected. After eliminating stator flux linkages it follows for Equation (3):

$$\underline{u}_S^{\angle K} = r_S \underline{i}_S^{\angle K} + j\omega_K l' \underline{i}_S^{\angle K} + j\omega_K \cdot k_R \cdot \underline{\psi}_R^{\angle K} \qquad (8)$$

where $\quad l' = l_S - \frac{l_h^2}{l_R} \quad$ and $\quad k_R = \frac{l_h}{l_R}$

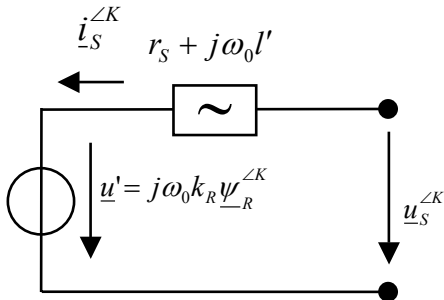Equation (8) corresponds to the equivalent circuit given in Fig. 1 below.

Fig. 1. Equivalent circuit of a DFIM

Re-writing equation (4) in a state space form and eliminating the rotor current using (6) together with the relationship for the stator current in (8) yields:

$$\frac{d\underline{\psi}_R^{\angle K}}{dt} = -(\underline{T}_{L0}^{-1} + j\frac{\omega_0 k_R^2 r_R}{\underline{z}'})\underline{\psi}_R^{\angle K} + \frac{r_R k_R}{\underline{z}'} \underline{u}_S^{\angle K} + \underline{u}_R^{\angle K} \qquad (9)$$

where $\quad \underline{z}' = \omega_0 \cdot l' \quad$ and $\quad \underline{T}_{L0}^{-1} = \frac{r_R}{l_R} + j \cdot (\omega_K - \omega_R)$

The equation of motion becomes:

$$\frac{d\omega_R}{dt} = \frac{1}{T_m} \left(m_W + k_R \cdot \left(\psi_{Rd} i_{Sq} - \psi_{Rq} i_{Sd} \right) \right) \qquad (10)$$

Eq. (9) and (10) constitute the quasi stationary dynamic model of the machine and form the basis on the one hand for the simulation and on the hand for the design of the core control system.

To characterize the operational behavior of the induction machine in steady state, all derivatives in Equations (3)-(7) are set to zero. The resulting relationship translates into the equivalent circuit, which is given in Figure 2.

The complex rotor voltage $\underline{u}_R^{\angle K}$ is zero for the SCIM, and for the DFIM a variable $\underline{u}_R^{\angle K}$ is provided by the inverter. Because $\underline{u}_R^{\angle K}$ is a complex quantity, two variables can be controlled from this input. Usually it is accomplished by the field-oriented approach, which allows the control of active and reactive power on the stator side independently. In general, however, the system represents a multi-variable control task, to which different methods can be applied.
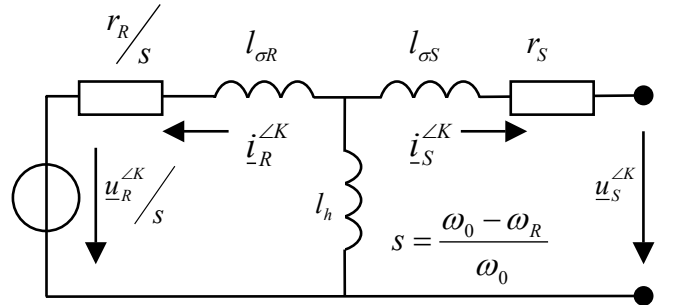

Fig. 2. Equivalent circuit of a DFIM in steady state

As a result of its control capabilities, the DFIM allows a more versatile and flexible operation than the SCIM. However, to make use of this capability a converter/inverter is required, which has to provide a voltage source with variable magnitude and frequency supplying the three-phase rotor windings through collector rings. Another alternative is to use synchronous machines instead of the asynchronous machines. However, in this case the total generated power must be transferred through a converter, which is located now on the stator side. The rated power of converter in case of DFIM is approximately 20-30% of the total power, which makes this solution more suitable for wind turbines. On the other hand synchronous machines for wind turbines are built for low speed and therefore a gearbox is not necessary. It is not clear at this stage which solution will be able to assert itself in the future.

In this paper wind turbines with synchronous machines are not considered further.

B. Control system

The mechanical power output of a wind turbine depends on the wind speed and the pitch angle. The pitch angle in a stall-controlled turbine is fixed. The rotor is designed in such a way that it stalls at wind over-speed thereby protecting the turbine from mechanical damage. Within the normal range of wind speeds, the power generation is determined by the actual wind speed. In pitch-controlled turbines the pitch angle enables the continuous control of the power output despite the stochastically varying wind speed. Normally the pitch angle is adjusted for maximum output except under conditions of wind over-speed during which the output power is limited to the rated value by the pitch angle control.

DFIM encompasses two control systems, a mechanical pitch-angle and an electronic controller, which acts through the converter/inverter unit that supplies the rotor circuit. The electronic part contains two decoupled control channels. The reader may be referred to [5] for details pertaining to the derivation of the control algorithms. Fig. 3 shows the outline of the applied control structure. Characteristic for this scheme is the fact that the speed control is basically realized by the pitch control. The converter is utilized for active power and voltage control. As the share of wind power in the system increases, additional requirements commensurate with this growth is likely to be imposed on wind farms by system operators. The proposed voltage control, in addition to helping to address this emerging issue in the future, can offer more operational flexibility.

The OWF simulated in this study have a capacity in the range of conventional power plants, which raises the issue of participation by these wind farms on frequency control. As to the required control structure, there are two basic possibilities as can be seen in Fig. 3. A sustained support of the system frequency presupposes a power reserve that can be called upon when the need arises. This can be achieved by adjusting the pitch-angle accordingly. The PI frequency controller increases an additional reference power to the power controller according network frequency requirements. Because this controller is an electronic one it works very fast and also utilizes partially the kinetic energy in the rotating masses in the initial phase. The second option for frequency control is unique to variable speed machines like the doubly-fed induction machine. It – equipped with a derivative controller - is capable of supporting the system frequency in the immediate aftermath of a major frequency change utilizing purely the kinetic energy of the rotating masses. This approach presupposes that the primary control sources of the power system will come along and replace the power in the ensuing period.
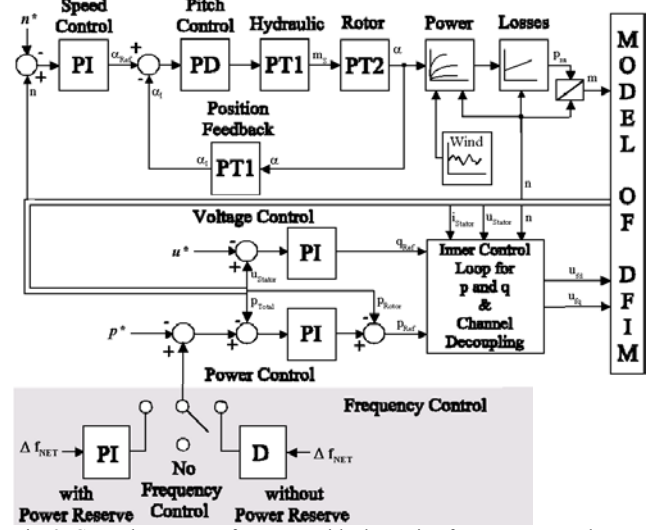

Fig. 3. Control structure of a DFIM with alternative frequency control

C. Simulation of the entire system

The simulation was carried out with the software package Power System Dynamics (PSD) as a platform.

PSD is a multi-purpose software package developed for the investigation of dynamic phenomena of large electric power systems from short to long time intervals. The simulation of the dynamic response of large systems over such a broad time spectrum requires efficient numerical methods for the solution of the algebraic and differential equations describing the system. Furthermore, modelling details should be adaptable to the time interval for which the dynamic phenomenon is being investigated. For components such as generator controllers, where alternative technical solutions are commonplace, user-defined models can be used. The PSD is an outgrowth of several years of research aimed at meeting these requirements.

As a result of the rapid growth of wind power generation in the recent past, it was necessary to expand the features of the PSD so that the simulation of the transient behavior of wind parks operating on an interconnected system is also possible. Fig. 4 gives the overall structure of the PSD including these additional features.

IV. RESULTS OF THE SIMULATION

The wind farms, whose performance during fault is to be simulated, are connected to the network as shown in Fig. 5. It will be recalled that the OWF are five in all and have a combined rated capacity of 1500 MW.
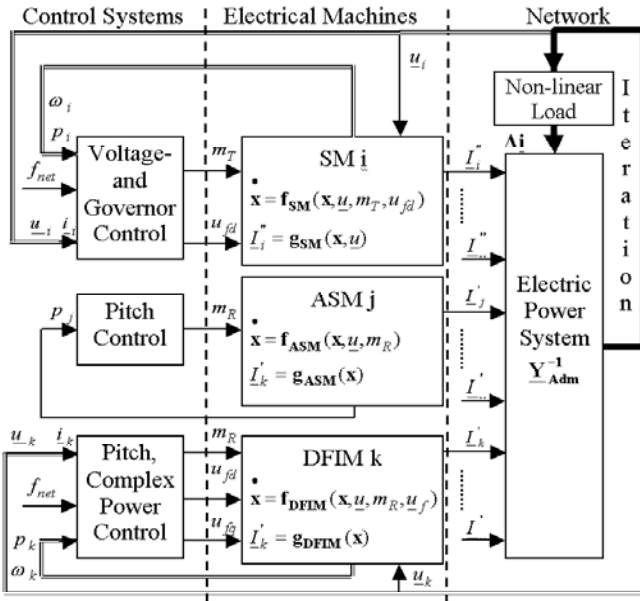
Fig. 4. Structure of the Simulation Model

They are connected to bus 4 of the network through sea cables ranging from 40 to 60 km length. Please note that in Fig. 5 only one of the five wind farms is given in detail since the situation in the other four is more or less similar.
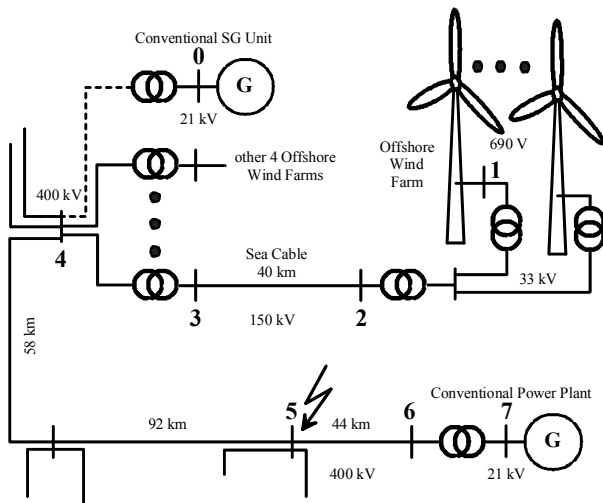

Fig. 5. Section of the network Relevant sector of the power system with measurement points

For a symmetrical three-phase fault at the high voltage bus 5, the performance of alternative induction machine types used in the wind farms was investigated. Additionally, the behavior of a conventional synchronous generator located at the same bus was simulated as another alternative. The study focused on the impact of the OWF machine type on the transient stability behavior of the synchronous machines and voltage profiles of the network buses during short-circuit. Finally, the response of these alternative scenarios to a major load change in the system was simulated and the results were compared.

A. Effect on the transient stability performance of a parallel operating synchronous machine

In a preliminary step, the critical fault clearing time for the most affected generator in the system (for a fault at bus 5) without any wind power generation was determined. It was around 320 ms. Subsequently, a wind power generation of 740 MW in OWF was introduced and the selected fault with 320 ms duration was introduced again. Three alternative scenarios were investigated: OWF with DFIM, OWF with SCIM and a conventional SG unit in place of the OWF. The interest in all cases focused on the transient behavior of the parallel-operating synchronous generator.
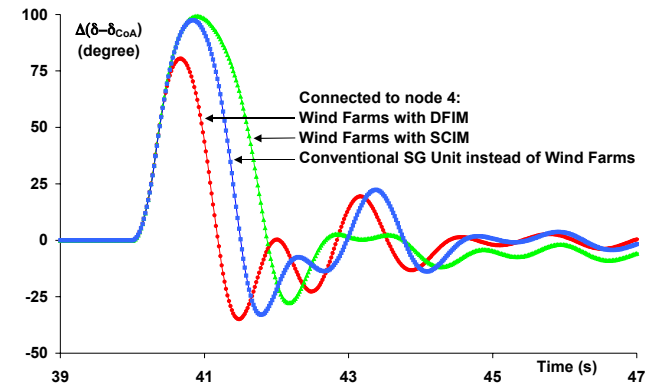

Fig. 6. Swing curve of a SG in a conventional power plant operating in parallel with three alternative types of generators

The results are given in Fig. 6, which reveals that the transient stability performance of the synchronous machine is improved when it operates in parallel with a DFIM. The performance of the SCIM in this regard is the least favorable.

As can be seen in Fig. 7, the voltage controller keeps the terminal voltage of the DFIM almost constant during the fault. This causes the voltage at bus 4 (the point of interconnection to the network) to remain at around 60% of its pre-fault value. The voltage at the same location for the other two machines is well below 40%. This leads to the conclusion that the synchronous machine being investigated will have the largest terminal voltage when DFIM are used in the OWF. Consequently, its output power during the fault remains larger than what it would be, when it operates together with another SG unit or SCIM, and a more stable transient behavior is achieved as demonstrated in Fig. 6. In addition to its lack of voltage control capability, the SCIM draws the excitation current from the network, giving rise to additional voltage drops in the network.

The alternative SG causes the parallel operating generator to become less stable than the DFIM does. However, a comparison between the two alternatives is only conditionally possible, since the SG is located closer to the fault electrically than the OWF generators. The OWF are connected to bus 4 via sea cables and intermediate transformers. Furthermore, the SG operates near the nominal power and thus it has a smaller inertial constant as opposed to the OWF generators, which work in part load mode.

B. Effect of the wind generator type on bus voltage profile during fault

For the fault at the location described above, the voltages for buses 1 to 7 are plotted in Fig. 7. With regard to the two alternative types of induction machine, one observes a fundamental difference. Whereas the voltage at the terminals of the DFIM recovers quickly after an initial dip and remains around the rated value even during fault, the terminal voltage of the SCIM drops significantly. This voltage recuperates slowly after the fault but the SCIM is not capable of lifting the voltage to the pre-fault operating point on its own long after the fault is cleared.
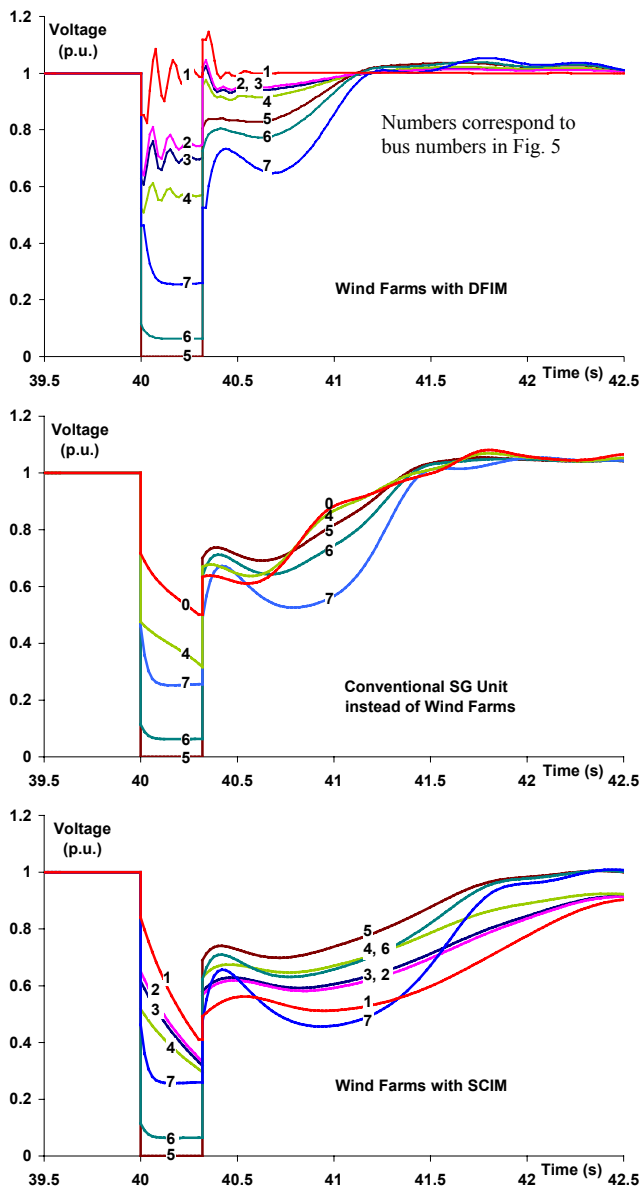

Fig. 7. Voltage characteristics selected nodes

Both DFIM and SCIM draw the excitation current from the network, but in the case of the SCIM the lack of voltage control capability makes it impossible for the machine to actively head towards the pre-fault operating point. The DFIM stands out with a remarkable performance as far as maintaining the voltage is concerned. The SG also experiences a strong voltage drop. But this is due to its vicinity to the fault location compared to the OWF, and as opposed to the SCIM, the pre-fault voltage profile is restored after some time.

It is interesting to observe the variation of the reactive power output of the DFIM during fault, which is given in Fig. 8. The pre-fault lagging power factor changes rapidly to a value demanded by the actual situation in the network to maintain a constant voltage.
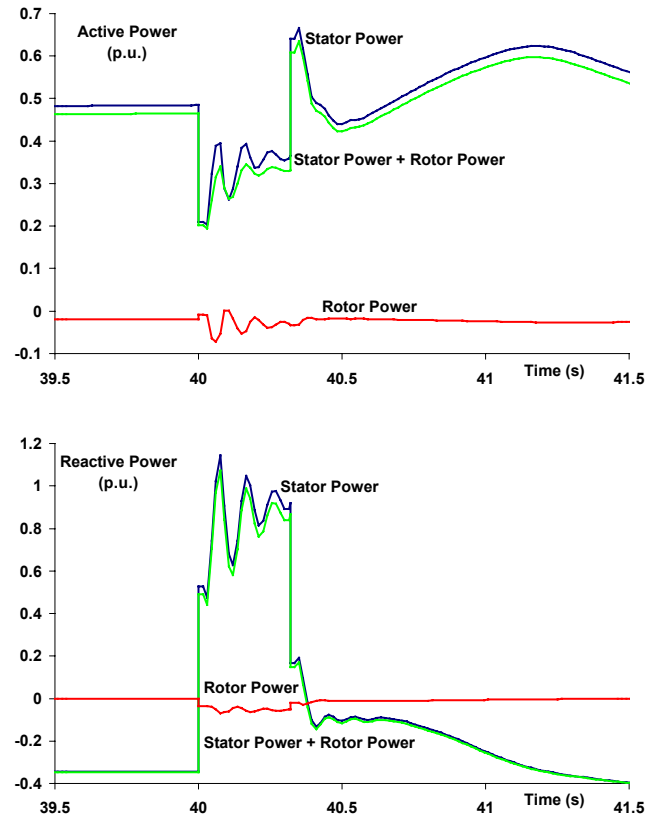

Fig. 8. Power characteristics of the DFIM

C. Machine response to a major load/generation change

Next, the response of the alternative types of machines to a loss of generation involving 900 MW was simulated. The issue of interest under this condition is the ability of each type of machine to counter the dip in system frequency resulting from the loss of generation. The schemes simulated are the following:

A - DFIM without frequency control ,
B - DFIM with a derivative frequency controller,
C - DFIM with a PI frequency controller together with a 4% power reserve,
D - SCIM and
E - Synchronous generator.

To recap on what was already discussed earlier, the reserve power (Scheme C) in effect entails that at any given wind velocity the wind farm maintains 4% of the nominal power as a reserve to be used for frequency control in a manner reminiscent of a conventional power plant.

The response of the system in terms of system frequency drop for the loss of generation mentioned-above is given in Fig. 9. The variations in power output during this period is given in Fig. 10, and the voltage deviation at an arbitrarily chosen intermediate location in the power system in Fig. 11.

It follows from Fig. 9 that the DFIM without a frequency control (Scheme A) offers the least support to limit the frequency drop. This is due to the fact that the output power of the machine is kept almost constant by the power control (Fig. 10). On top of this the voltage is also controlled, which renders the power drawn by the load to remain almost constant.

Control scheme B with a derivative frequency control allows a very fast increase of the output power at the beginning. However, it drops to the value determined by the wind after a short backswing. This is because the increase in output was achieved by tapping into the kinetic energy of the rotating masses and, in the absence of any replenishment from an external source, this cannot be sustained. On the contrary, the rotor must be accelerated again for which the energy is supplied from the network. This causes (Fig. 10, curve B) a backswing period, which follows after the deepest system frequency has been reached. Therefore, this control schema can provide a worthwhile contribution to maintain system frequency even without any power reserve, i.e. without the need for forgoing energy yield.

The DFIM with the power reserve (Scheme C) continues to increase its output in supporting system frequency and can hold it on a level that corresponds to the actual power reserve.

The SCIM (Scheme D), on the other hand, is capable of increasing its output only temporarily after the loss of generation, which is caused by the slip change. But its performance in support of the system frequency, as depicted in Fig. 9, goes beyond what one could have deduced from the output power increase. In fact, for this particular load configuration this scheme can be characterized as the second best. The reason for this behavior is its lack of voltage control capability. While all the other machines try to counter the voltage drop in the network caused by the loss of generation, the SCIM does not possess the ability to do so (Fig. 11). As a result of the reduced voltage, the power absorbed by the loads in the various network buses will also decrease. In this simulation, a quadratic relationship between power (both real and reactive) and the voltage magnitude has been assumed. As far as the frequency is concerned, a desirable effect may be achieved, albeit at a cost of unfavorable voltage profile.

In the conventional plant (Scheme E) the output power rises continuously and settles at a higher operating point, which is caused by the primary governor control. However, also in this case the generator voltage control affects the frequency behavior negatively by increasing the voltage level and thus the network load demand.
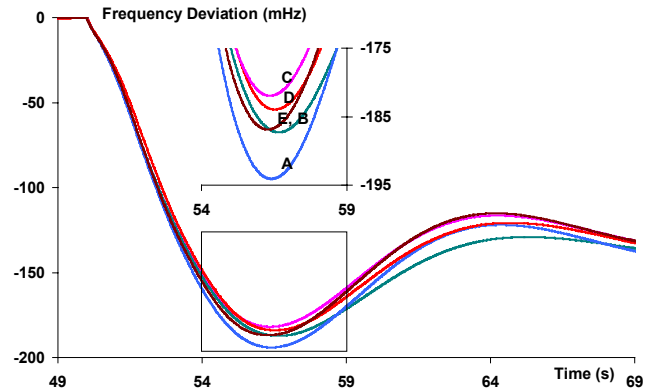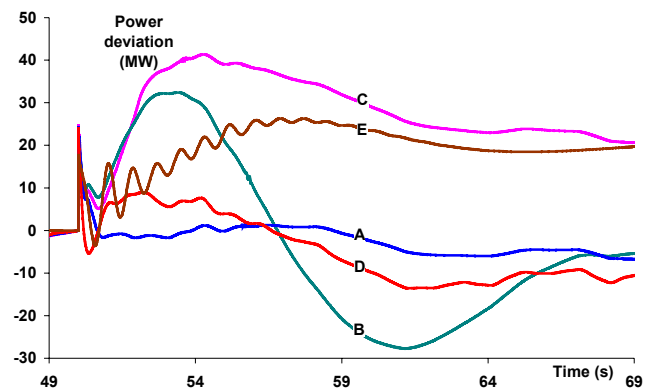

Fig. 9. Frequency characteristics
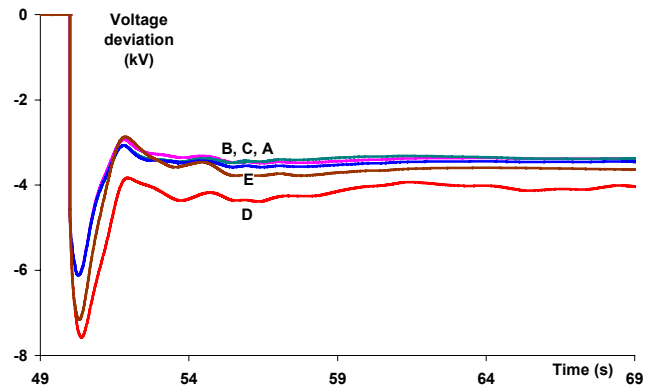

Fig. 10. Power characteristics

Fig. 11. Voltage characteristics at an arbitrary bus

V. CONCLUSION

As the share of the wind power in the system rises, the overall performance of the system will increasingly be affected by the inherent characteristics of wind generating plants. With the objective of addressing some of the emerging issues, a new approach for voltage and frequency control in the DFIM has been proposed. The control system encompasses a mechanical pitch-angle and an electronic controller, which acts through the converter/inverter unit.

To validate the effectiveness of the proposed approach, five offshore farms equipped with alternative types of machines and operating on a realistic, large interconnected

system were modeled and short-circuit and major load changes were simulated.

The results of the simulation reveal that compared to the SCIM, the DFIM leads to a significantly better network voltage profile as well as transient stability performance of the system.

With regard to system frequency, the proposed approach enables the integration of OWF into the overall frequency control regime. With an appropriate provision of reserve power and a frequency controller, the DFIM is capable of supporting the system frequency just like any conventional power plant. Alternatively, the DFIM equipped with a derivative frequency controller can assist the system frequency in the short-term utilizing the kinetic energy of the rotating masses without the need for reserve power. As opposed to the synchronous machine, in which frequency control is possible only using the control reserve power, the DFIM offers at least the above two possibilities. However, the best way to achieve the frequency stability remains a subject of further discussion.

VI. References

[1] BTM Consult: International Wind Energy Development, Ringkobing, Denmark, 03/2000.

[2] Greenpeace: North Sea Offshore Wind – A Powerhouse for Europe, Techn. Possibilities and Ecological Considerations Study, 10/2000.

[3] Koch F., Erlich I.: Dynamic Interaction of wind farms with the electric power system, ew, pp. 60 – 65, 09/2002.

[4] Slootweg J. G.; Polinder H.; Kling W.L.: Initialization of Wind Turbine Models in Power System Dynamics Simulations, IEEE Porto Power Tech Conference, 2001.

[5] Erlich, I.: Analysis and Simulation of the Dynamic Behavior of Electrical Power Systems, Habilitation-Thesis, Technical University of Dresden, Department of Electrical Engineering, 1995.

[6] [6] Grotenburg K.; Koch F.; Erlich I.; Bachmann U.: Modeling and Dynamic Simulation of Variable Speed Pump Storage Units Incorporated into the German Electric Power System, EPE Graz, 2001.

VII. Biographies

Friedrich W. Koch (1969) is presently PhD student in the Department of Electrical Power Systems at the University of Duisburg/Germany. He received his Dipl.-Ing. degree in electrical engineering from the University of Siegen/Germany in 1998. After his studies, he worked in the field of industrial- and power plants. He is a member of VDE.

Istvan Erlich (1953) 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 of Duisburg/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 IEEE.

Fekadu Shewarega (1956) received his Dipl.-Ing. degree in electrical engineering from the Technical University of Dresden, Germany in 1985. From 1985 to 1988 he pursued his postgraduate studies in the same university and obtained his PhD degree in 1988. After graduation, he joined the Addis Ababa University, Ethiopia as the member of the academic staff where he served in various capacities. His research interests are focused on power system analysis and rural electrification options.

Udo Bachmann (1952) received his grad. Engineer degree in electrical power grids and systems from the Leningrad Polytechnic Institute /Russia in 1977. After his studies, he worked in Berlin in the field of development and management by renewal and reconstruction of power grid protection. From 1980 to 1983, he joined the Department of Electrical Power Plant and Systems of the Leningrad Polytechnic Institute again, where he received his Ph.D. degree in 1983. Since 1983 he worked in the National Dispatch Center as Engineer and senior specialist in the field of management of grid protection from system view. During the last 15 years he is responsible for steady state and dynamic stability computation in the Vattenfall Transmission Company (former VEAG Vereinigte Energiewerke AG).