

Grid Compatibility of Variable Speed Wind Turbines with Directly Coupled Synchronous Generator and Hydro-Dynamically Controlled Gearbox

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Abstract-- This paper analyzes grid integration aspects of a new type of variable-speed wind turbine, the directly coupled synchronous generator with hydro-dynamically controlled gearbox. In contrast to existing wind generators using synchronous generators, the generator of this concept is directly connected to the AC grid, without the application of any power electronics converter. Variable speed operation of the turbine is mechanically achieved by a gear box with continuously controllable variable gear box ratio.

For this purpose, a detailed dynamic model of a 2 MW wind turbine with a Voith WinDrive® has been implemented using the modelling environment of the simulation software *DIgSILENT PowerFactory*. For investigating grid compatibility aspects of this new wind generator concept, a model of a 50 MW wind farm, with typical layout, based on 25 wind turbines of the 2 MW-class has been analyzed.

This paper focuses on the compatibility of the new concept with existing connection standards, such as the E.ON grid code. Of special interest are typical stability phenomena of synchronous generators, such as transient and oscillatory stability as well as power quality issues like voltage flicker.

The results of stability studies are presented and possible advantages of the new concept with special focus on offshore applications are discussed.

Index Terms-- Variable Speed Wind Turbines, Wind Turbine Modelling, Wind Park, Hydro-dynamically Controlled Gearbox, Synchronous Generators, Power System Transient Stability, Oscillatory Stability, Voltage Flicker.

I. INTRODUCTION

Wind generator technology is steadily advancing and the existing concepts are constantly enhanced. Different concepts of wind generators have been developed over the last

years and are widely used for converting wind energy into electrical energy. Due to the varying wind speeds, and thus the changing rotational speeds of the rotor, variable speed drives are normally applied, increasing the efficiency of the wind turbines.

The main technologies used today are doubly-fed induction generators (DFIG) and converter-driven synchronous generators (CDSG). The DFIG generator can operate at different speeds due to different slip values and is controlled by a PWM converter feeding the wound rotor of the machine via slip rings. The CDSG uses a synchronous generator, which is decoupled from network by a full scale PWM converter.

In this paper a newly developed concept of variable speed wind turbine is described, the directly grid coupled synchronous generator with hydro-dynamically controlled gearbox (WinDrive®), which is developed and manufactured by Voith Turbo.

In this concept the generator rotates at synchronous speed and therefore has the same behaviour as conventional synchronous generators. For achieving variable speed operation of the turbine, a speed-controlled gearbox has been developed that will now be tested for the first time in a D8.2 plant with a rated power of 2 MW (Fig. 1).

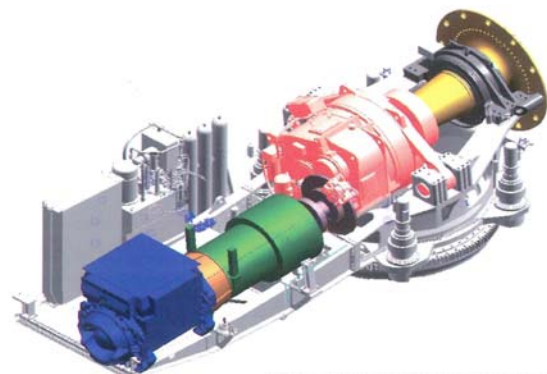


Fig. 1. Drive train of a D8.2 wind turbine with the WinDrive® as a speed controlled gear (Source: EU Energy)

Due to the special applications of wind turbines in remote areas far from load centres, at weak interconnection points or for off-shore applications, several operational aspects have to be analysed. E.g. the ability of the turbine to stay connected

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after severe network faults has to be investigated (fault ride-through capability). Also badly damped oscillations and voltage flicker emissions can have a negative impact on the connected network and have thus to be analysed.

This paper is dealing with the behaviour of the new concept of wind power conversion in a wind farm network. Due to the large differences in the technology a grid impact study has been carried out by DIgSILENT and Voith Turbo to ensure that the wind generator concept is able to operate according to international grid codes.

For this purpose, a detailed dynamic model of a 2 MW wind turbine with a Voith WinDrive® has been implemented using the modelling environment of the simulation software DIgSILENT *PowerFactory*, considering the mechanical turbine model with shaft dynamics, hydro-dynamically controlled gearbox, synchronous generator and the different mechanical and electrical controls. A model of a typical 50 MW wind farm based on 25 wind turbines of the 2 MW-class has been used for analyzing grid compatibility aspects of this new wind generator concept.

Different operational conditions have been assumed, such as:

- Short-circuit level at the wind farm connection point (PCC)
- Wind condition

The main focus of the investigations is on possible interactions of the wind generators with the main grid and interaction between the generators within the wind farm grid. This report covers the following stability aspects, which are important when analysing the behaviour of directly-coupled synchronous generators:

- Transient stability and Fault ride through capability – wind farm stability in the case of severe disturbance, e.g. faults in the supplying network.
- Oscillatory stability – damping of oscillations resulting from interactions between the wind generators and between the entire wind farm and the main grid.
- Voltage flicker resulting from wind turbulence.

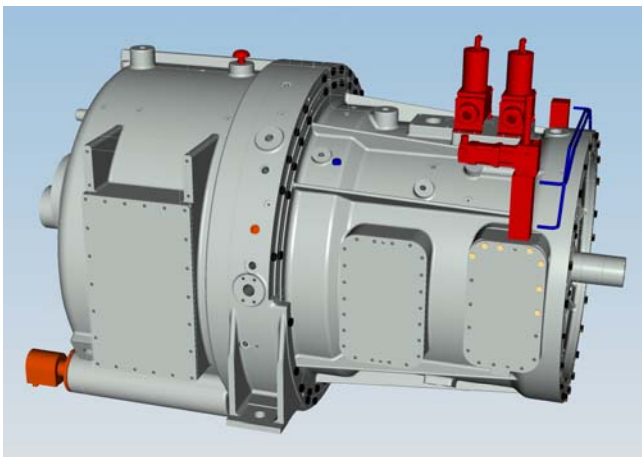


Fig. 2. 3D view of a superimposing variable speed gear (WinDrive®).

II. DESCRIPTION OF THE WIND TURBINE MODEL

A. The Function of the Variable Speed Gear

The variable rotor speed is adapted to the constant grid frequency in a superimposing variable speed gear (Fig. 2).

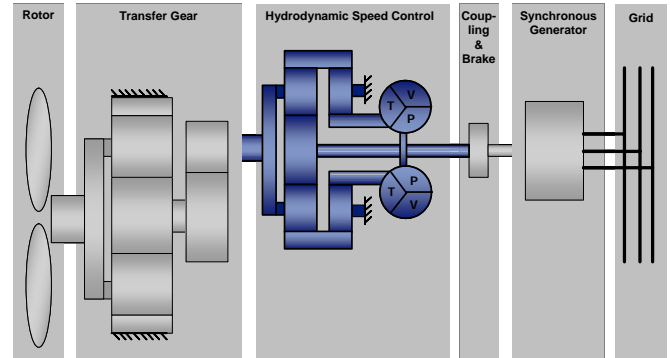


Fig. 3. Drive train of a wind turbine with a superimposing planetary gear between main gear and synchronous generator.

In the superimposing gear unit, the input power is supplied to the carrier of a planet gear stage. Simultaneously, a hydrodynamic circuit drives the annulus gear via the control drive. The planet gear stage operates as superimposing gear unit leading both power flows via the sun gear to the output shaft towards the outside. In the hydraulic circuits, the control power is taken from the output shaft with an impeller and returned to the superimposing gear via the turbine wheel (Fig. 4).

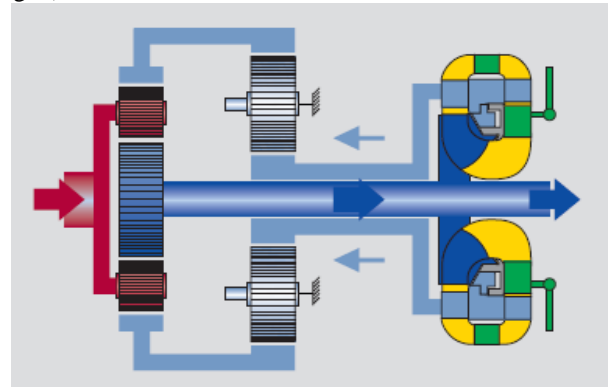


Fig. 4. Power flow in a variable speed gear unit consisting of a revolving planetary gear, a fixed planetary gear and a torque converter

The fluid-machine just takes the regulating power required for speed control from output shaft that, relative to the drive power, is small ensuring thus a high total efficiency. The mechanical power of two shafts is superimposed in the revolving planet gear stage and thus is called superimposing gear unit. Between annulus gear and fluid-machine it is necessary to adapt speed and direction of rotation by means of another gear stage. The planet gear unit used is provided with fixed planets and that's why it is also called fixed planetary gear.

Hydrodynamic circuits in the superimposing gear damp vibrations and reduce load peaks, having the function of a low-pass filter in the drive train. Decoupling the input and

output side as to vibration has a positive effect on the load collective of the whole turbine. The use of such a gearbox enables to manufacture dynamically loaded components in the wind turbine smaller and cheaper.

The torque converter is provided with adjustable guide vanes and can thus be used as actuator (Fig. 5). Dependent on the opening angle, the upwind angle and thus the power consumption of pump can be varied. The energy content of the fluid and the torque generated by the turbine wheel change with the power consumption of pump. The control power is transmitted from the turbine via the fixed planetary gear to the annulus gear and the input power superimposed in the revolving planetary gear.

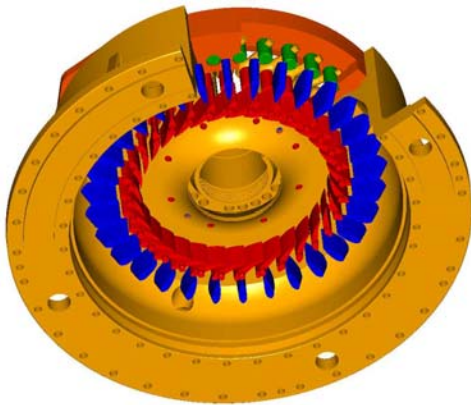


Fig. 5. Torque converter with adjustable guide vanes

The design of the torque converter and the ratios in the gear stages determine the performance diagram of the machine (Fig. 6). A prime goal in the design phase is to maximize the annual energy production. At the same time, the system efficiency of the whole wind power plant is being assessed with the respective time portions. A reversal in the secondary train has to be beyond the regular operating range. Also the gear ratios must not exceed certain limits for design reasons. Fig. 6 shows such a performance diagram.

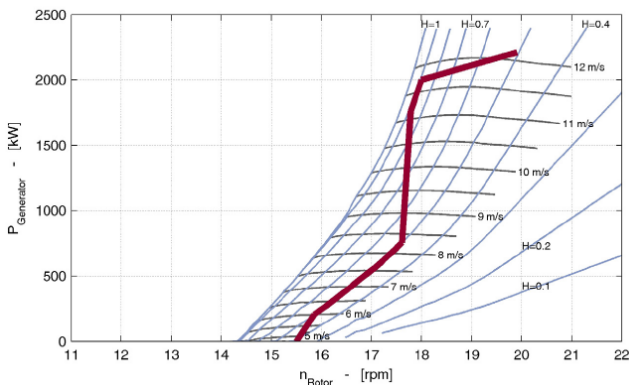


Fig. 6. Performance diagram showing electric power as a function of rotor speed with curves of same guide vane position H and curves of same wind speed.

In case of weak wind, the plant is connected to the grid at low rotor speed. At constant guide vane position, the variable speed gear form the first part of the characteristic curve. On

reaching rated speed, for reasons of strength and noise, the rotor speed is not increased further on. Now the guide vanes are opened permanently until reaching rated power. When the wind velocity continues to rise, the gearbox regulates hydrodynamically the torque in the drive train.

B. Model Description

The drive train of wind power turbines is modelled in its main components as block diagrams using DIGSILENT PowerFactory (Fig. 7).

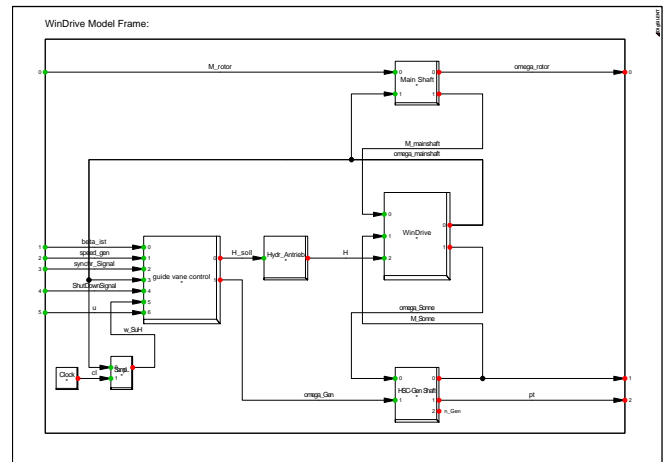


Fig. 7. Block diagram of the drive train in a wind turbine with variable speed gearbox.

The control loops for the rotor blade angle, the guide vane position in the torque converter and the excitation in the generator were integrated into the rotational vibration system. During the simulation, sensors detect the controlled variables leading them to the respective control loops. The pitch hydraulic, the actuator for guide vane adjustment as well as the generator excitation voltage act as manipulated variables.

The variable speed gear model comprises the revolving planetary gear, the torque converter and the hydraulic actuator (Fig. 8). The torque converter is modelled with its hydrodynamic behaviour based on the characteristic curves and by timely transfer function.

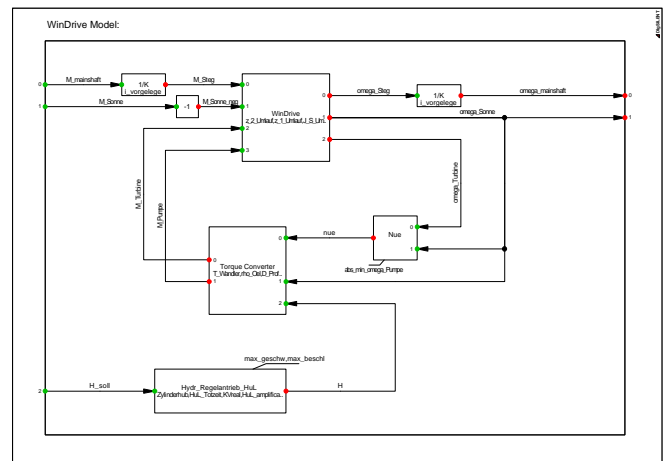


Fig. 8. Block diagram of variable speed gear with planet gear stage, torque converter and hydraulic actuator.

The revolving planetary gear is modelled as a subsystem with the transfer functions for its kinematics and dynamics (Fig. 9).

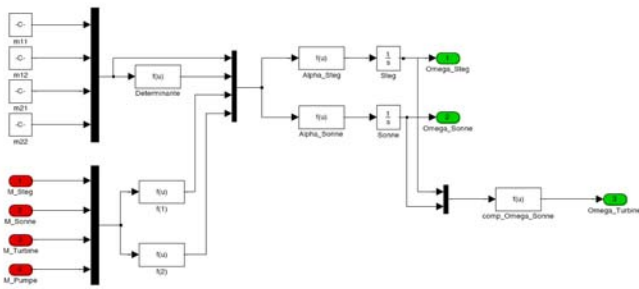


Fig. 9. Block diagram of the planet gear stage with transfer functions for input, output and superimposing gear system.

Besides the controller itself (Fig. 10a), the control loop for guide the vane adjustment also comprises the dynamic transfer elements of the hydraulic actuator (Fig. 10b).

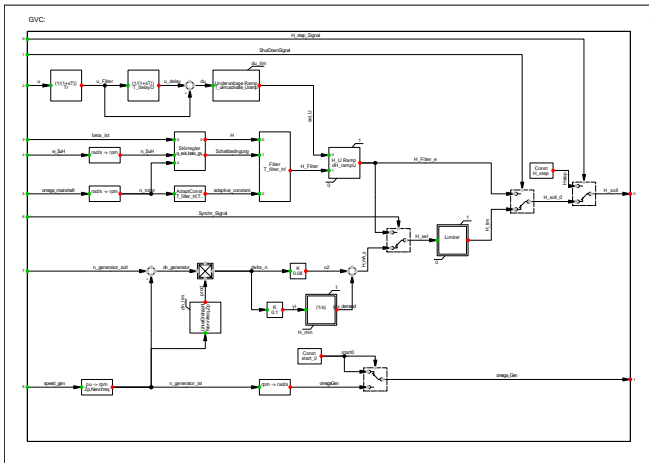


Fig. 10a. Block diagram of controller for guide vane adjustment in the torque converter.

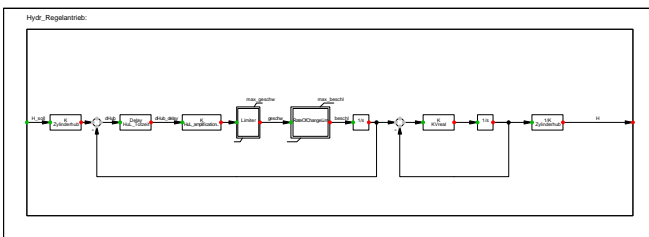


Fig. 10b. Block diagram showing the controlled system for the hydraulic actuator.

With the measurement system, the controllers and actuators, the drive forms a closed, dynamic system by means of which the influences of mechanics, hydraulics, electrics and the control system can impressively be investigated. Natural frequencies, modes, stability behaviour and time responses are methods which are used to optimize the parameters in an early design stage.

III. WIND FARM LAYOUT

The dynamic performance of wind farm with directly grid-connected synchronous generators and variable speed gearbox is analyzed on the basis of a typical wind farm layout with a total rated power of 50 MW and a nominal frequency of 60 Hz.

The wind generators are arranged in 5 strands each connecting 5 wind turbines. The synchronous generators have a rated power of 2 MW each and a rated voltage of 13.6 kV.

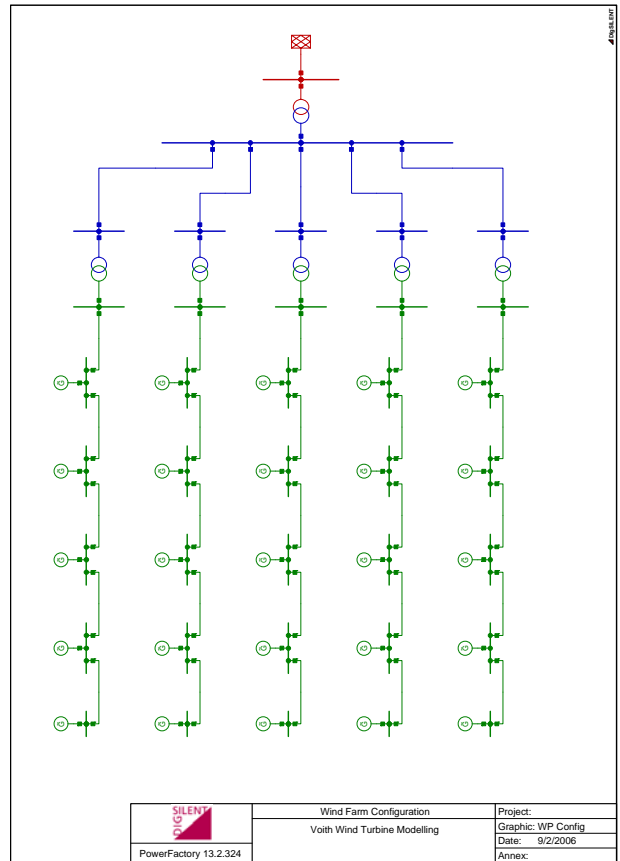


Fig. 11. Typical wind farm layout with 25 wind turbines used for analysing behaviour and possible interactions of the wind turbines.

Each strand with 5 wind turbines is operated at a voltage of 13.6 kV. The distance between the turbines is varying, having an average value of about 700 m. Each strand is connected by AC cables to a step-up transformer to 34 kV (one per strand). These transformers are then connected at 34 kV to one 60 MVA, 110 kV/34 kV step-up transformer. The wind farm configuration is shown in Figure 11.

Other wind farm layouts, e.g. using a single MV-voltage level in the wind-farm distribution grid and step-up transformers for each individual generator, have been analyzed as well but it could be shown that the layout according to Fig. 11 has great advantages compared to other layouts.

For all investigations performed in the following chapter, a complete dynamic model, including the mechanical parts and the controllers is been used for each of the 25 wind turbines.

IV. LOCAL WIND-FARM STABILITY

In this chapter the performance of the generator when affected by large faults or small disturbances is analyzed. Especially, the following effects are investigated:

- Transient stability and fault ride-through capability
- Oscillatory stability

In the study three different wind scenarios were used for the investigation of the wind generator behaviour:

- Strong wind conditions
- Medium wind conditions
- Low wind conditions

In the strong wind scenario it is assumed that all wind generators are operating above nominal wind speed, thus all generators are providing rated active power of 2 MW to the grid. The total power output of the farm is about 50 MW.

During low wind conditions the generators are loaded only by 10%, having a total power output of only 5 MW.

In the medium wind scenario a typical wind speed variation inside the wind farm is assumed. In this case, the total resulting power output of the farm is 26 MW.

Especially when assessing the dynamic behaviour of the turbines, the short circuit level at the point of common coupling (PCC) has a high influence. Therefore, stability impact is analysed for two different short-circuit levels at the 110 kV PCC:

- Strong network: $SK''=1000$ MVA (SCR=20)
- Weak network: $SK''=100$ MVA (SCR=2)

The “strong network” represents a typical case for weak conditions in European grids. The assumed “weak network” with SCR of 2 represents extreme conditions, which might be found in remote areas in the US or Australia.

A. Transient Stability and Fault Ride Through Capability

The grid code of most countries requires wind generators to stay connected in the case of network faults (Low voltage ride-through capability (LVRT) or fault ride through capability (FRT)). It is of particular importance to transmission system operators, that wind farms stay connected in case of faults at major transmission levels leading to a voltage depression in a wide area, which could lead to a major loss of wind generation if wind farms were not equipped with LVRT-capability.

Therefore, LVRT-capability is a definite requirement for all larger wind farms.

The main issue of synchronous generators with direct grid connection (without power electronics converters) is their ability to remain in synchronism during and after major voltage sags. The corresponding effect is named ‘Transient Stability’ in [1].

The main parameters influencing transient stability are:

- Rotor inertia/turbine power during the fault.
- Depth of the voltage sag.
- Duration of the voltage sag.
- Short circuit impedance of the grid to which the generators are connected.

For two different short-circuit levels at the 110kV PCC and for different wind conditions, various faults are applied to the wind farm. The following fault scenarios at the PCC are simulated:

- Solid 3-phase short-circuit with 150 ms clearing time (0% remaining voltage)
- 3-phase short-circuit with 150 ms clearing time, 20% remaining voltage
- 3-phase short-circuit with 150 ms clearing time, 80% remaining voltage
- Solid 2-phase short-circuit with 150 ms clearing time
- Voltage profile according to grid connection code of E.ON Netz GmbH (Version April 2006 [4])

The fault duration was chosen to be 150ms, which represents a worst case assumption in the UCTE system for first-zone fault clearing times. Additionally a voltage profile (Fig. 12), according to the grid connection conditions from E.ON [4] for synchronous machines, is applied to the PCC and the generator response is studied.

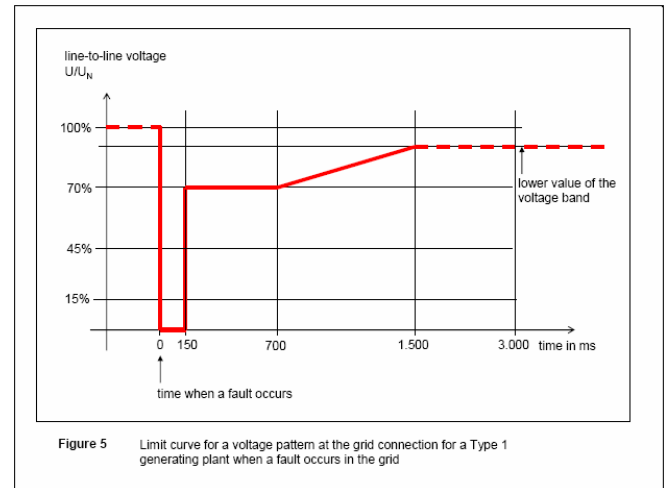


Fig. 12. Voltage profile according to the requirements for LVRT capability of synchronous generators according to [4].

Figure 13 shows simulation results of a solid three-phase fault with 150 ms duration at high wind conditions for a strong network. The figures show the voltage at the PCC as well as the voltage at the generator terminals and generator speed.

The results of the simulations are listed in table I and II.

TABLE I
RESULTS FROM THE SIMULATIONS FOR THE TRANSIENT STABILITY AT A STRONG PCC

Fault	Strong Network (SCR=20)		
	Strong Wind	Medium Wind	Low Wind
3ph Short-Circuit, 0%	stable	stable	stable
3ph Short-Circuit, 20%	stable	stable	stable
3ph Short-Circuit, 80%	stable	stable	stable
2ph Short-Circuit	stable	stable	stable
Voltage Profile E.ON	stable	stable	stable

TABLE II
RESULTS FROM THE SIMULATIONS FOR THE TRANSIENT STABILITY AT A WEAK PCC

Fault	Weak Network (SCR=2)		
	Strong Wind	Medium Wind	Low Wind
3ph Short-Circuit, 0%	unstable	stable	stable
3ph Short-Circuit, 20%	stable	stable	stable
3ph Short-Circuit, 80%	stable	stable </td <td>stable</td>	stable
2ph Short-Circuit	stable	stable	stable
Voltage Profile E.ON	unstable	stable	stable

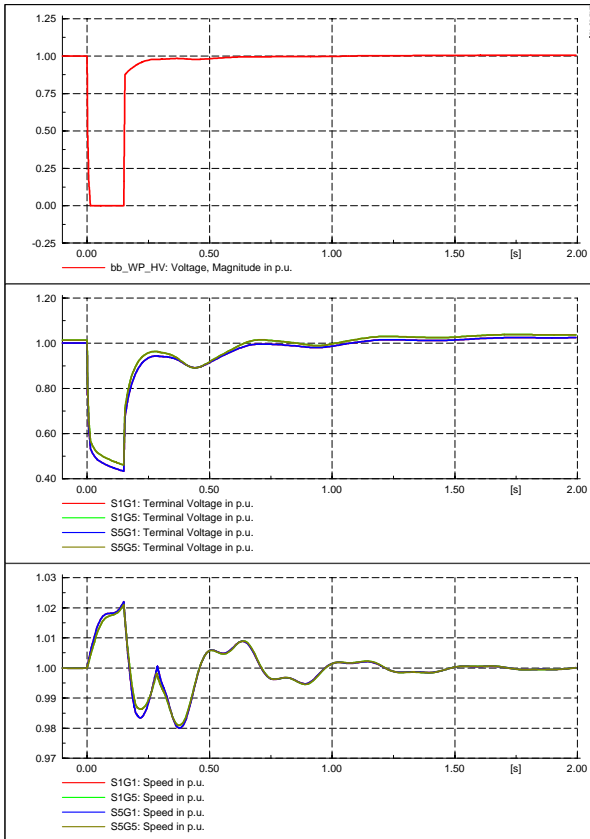


Fig. 13. Voltages at the PCC, at the generators and the generator speeds during a solid three-phase fault for 150 ms at high wind conditions for a strong network for 2 s.

The results show, that the generators do not face instability when the wind farm is connected to a sufficiently strong network in relation to the total rated wind farm power. Also at low or medium wind conditions, i.e. at a low loading of the generators, no unstable behaviour was shown. Only in the case of an extremely low short circuit level and full load operation, transient stability can be a problem.

Transient stability can further be supported using the ability of the hydro-dynamic control of the WinDrive® to reduce mechanical torque during grid faults.

During the fault, the synchronous generator supports the voltage by large reactive currents, which are much higher than reactive current support that can be achieved by other wind generator concepts. The voltage supporting properties might even allow other wind farms in the area to better ride-through network faults.

Also, the influence of the layout of the wind farm grid on transient stability has been analyzed. In the analysed case a SCR value of 3 would be sufficient to ride-through a solid 3-phase fault. A different layout can further improve transient stability.

The connection of the generators to the MV level is advantageous compared to a layout with LV-generators and step-up transformers, because it reduces the effective impedance between the generators and the external grid.

B. Oscillatory Stability

Minor disturbances, like changes in the voltage due to switching of lines or capacitors near the wind farm or load changes in the transmission network, are continuously present in electrical power systems. In addition to these random effects periodically occurring influences like torsional sampling and tower shadow could possibly have an influence onto the turbine behaviour. It has to be ensured, that due to these small disturbances no oscillations between the wind farm and the main network or oscillations between the different generators within the farm are excited.

The oscillatory modes of the wind-farm are analyzed using eigenvalue analysis in *PowerFactory*. Using this analysis technique, characteristic modes of a system are obtained in terms of damping and characteristic frequency.

For each combination of short-circuit level at the PCC (SCR=20, SCR=2) and wind scenario (strong, medium, low wind), frequency and damping of each mode is calculated and analyzed. Fig. 14 shows the eigenvalue plot of a medium wind case at a weak network. The plot is visualizing the eigenvalues in the complex plane.

From the results of the eigenvalue analysis it can be derived, that there are oscillatory modes in basically three different frequency ranges:

- 2-3 Hz
- 5-7 Hz
- 29-30 Hz

The modes at around 2...3 Hz are generator oscillations related to the turbine inertia. These modes are sufficiently damped.

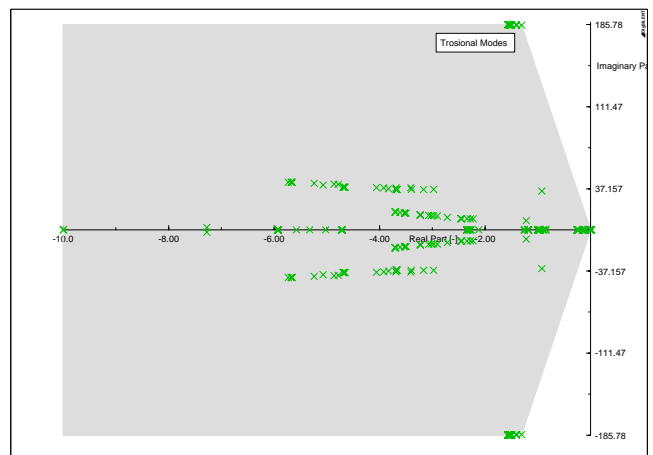


Fig. 14. Eigenvalues in the complex plain indicating the frequency (imaginary part) and damping (real part) of the eigenfrequencies.

The lowest damped mode at around 6Hz represents oscillations of the wind generator masses against the external 110 kV network. The speed-participation factors of this mode are shown in Fig. 15. These oscillations show sufficient damping during strong wind conditions. At a weak network and under low or medium wind situations, the damping gets slightly lower.

The other modes in the frequency range between 5...7 Hz are related to generator oscillations within the wind farm. The speed-participation factors of the mode with the lowest damping are shown in Fig. 16.

If further damping of these modes has to be ensured, power system stabilizers (PSS) are often applied to the synchronous generators and can be designed for his purpose. The effect on the damping has not been analysed in this paper.

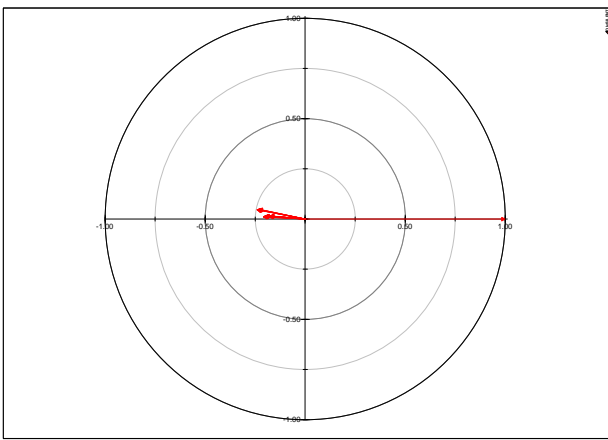


Fig. 15. Speed-participation factors for the generators for a wind farm mode, related to oscillations of the wind generators against the external network.

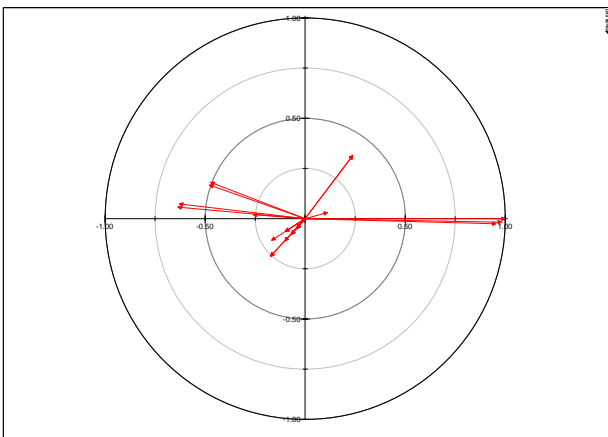


Fig. 16. Speed-participation factors for the generators for a wind farm mode with the lowest damping, related to oscillations within the wind farm.

Oscillatory modes at higher frequencies are torsional modes of the drive trains. These oscillations are always present in case of wind turbines. However, they are not causing interactions between the wind generators and are therefore not considered to be critical.

Additionally it can be concluded that oscillatory modes around frequencies of 0.5-1 Hz are not present in the

eigenvalue spectrum; therefore periodically excited frequencies in this range, e.g. resulting from tower shadow effects, will not result in persisting oscillations.

V. VOLTAGE FLICKER

A. Turbulence Modelling:

Wind turbulence is a stochastic effect. One way of modelling wind turbulence consists of synthesizing stochastic signals on the basis of a given power spectral density (PSD) function. A widely used PSD for wind-turbulence is the Kaimal spectrum. This spectrum is parameterised by the mean wind speed and the standard deviation from the mean wind speed, which is defined by the turbulence intensity [2].

Using the turbulence model described in [3], a signal for the equivalent hub wind speed of each wind turbine is generated. Besides the stochastic turbulence modelling based on a Kaimal-spectrum, the model takes into account the effect of rotational sampling and tower shadow effects.

IEC 61400-21 [5] assumes that fast wind speed variations (200ms-average) are entirely uncorrelated and that slower wind turbulence (60s-average) are fully correlated.

In these studies, a more sophisticated approach has been taken for obtaining most realistic signals. The method applied is named “Complex Cross Spectral Method”, as described in [3], considers frequency dependent correlation.

B. Cases:

For obtaining a scenario with considerably high power variations, the mean wind speed has been set to 9m/s at all wind turbines and the turbulence intensity was set to 15%. This results in partial load operation of all wind turbines, just below rated wind speed, leading to considerable variations of the power output of the turbines due to the high gradient of the wind speed-power curve in this area.

It has to be pointed out that the simulated scenarios neither represent worst-case conditions nor stochastically representative behaviour. The purpose of the analysis is just to verify turbulence impact under typical, medium-wind, high-turbulence conditions.

C. Impact on Voltage Flicker:

Wind turbulences are causing variations in the power output of the wind generators and thus of the complete wind farm. These variations can be divided into three groups:

- Gusts travelling over the complete wind farm.
- Faster variations in wind speed resulting from local turbulences.
- Oscillations at around 1 Hz resulting from rotational sampling and tower shadow effects.

The effect of wind turbulence on the active power output of the wind farm at the PCC when connected to a weak network for a time range of 1000 s can be seen in Fig. 17. It shows the situation for the medium wind case with high turbulence intensity and with correlated wind speed distribution over the wind farm. The figure also shows the impact on the voltage at the PCC and the spectral density plot of the voltage signal.

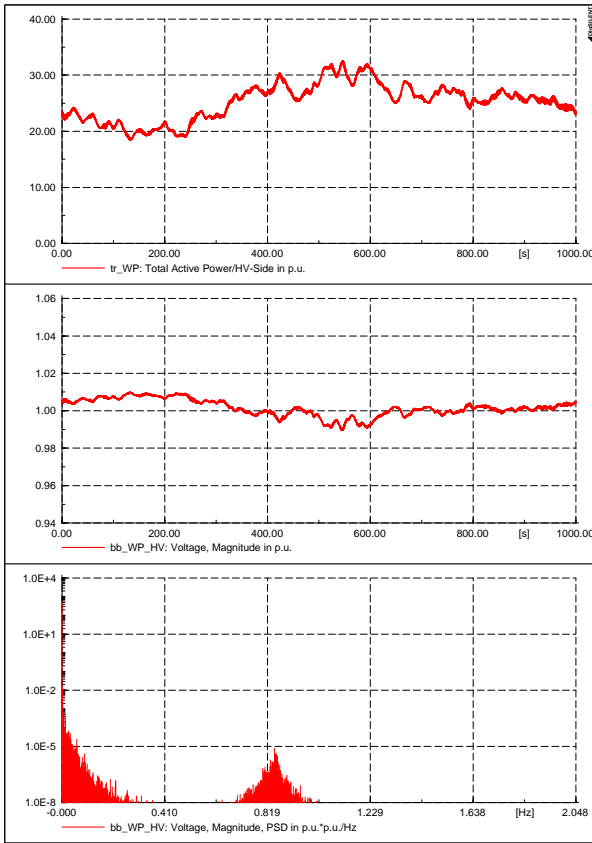


Fig. 17. Active power and voltage of the wind farm at the PCC for a simulation of 1000 s with medium wind speed and high turbulence intensity in combination with a weak network.

The expected oscillations at frequencies around 0.8...1 Hz can be identified in the spectra. However, the spectrum has a very low density indicating only very small magnitudes of oscillations in this frequency range. Also the time domain visualisation of the voltage at individual generators does not show oscillations with considerable magnitudes.

From these simulations, it can be concluded that no oscillatory wind farm modes are excited by wind turbulences, which can be explained by the fact that wind turbulence and rotational sampling effects are in much lower frequency ranges (<1Hz) than the eigenfrequencies of the wind farm (2-3Hz, 5-7Hz). Secondly, oscillatory modes of the wind farm are well damped.

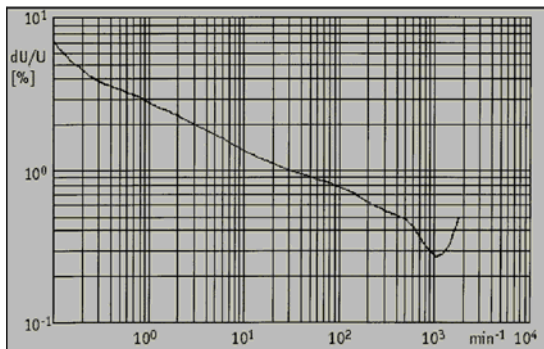


Fig. 18. Short term flicker curve ($P_{st} = 1$) [6].

For assessing the impact of wind turbulences on voltage flicker, voltage variations are analyzed and compared against the flicker limit curve for $P_{st} = 1$ according to IEC 61000-3 [6], which is also shown in Fig. 18.

The flicker impact is assessed by using time domain simulations and comparing the amplitude of the oscillations to the limit of $P_{st} = 1$ for the short term flicker (see Fig. 18). Table III compares the maximum amplitude in the 1 Hz range against the corresponding limit of the flicker limit curve for $P_{st} = 1$ in the case of a low short circuit level (SCR=2) at the PSS, which represents the worst case for flicker emissions. In case of a strong network at the PCC the voltage flicker emissions are negligible.

TABLE III
VOLTAGE OSCILLATIONS AMPLITUDE AND LIMITS FOR A WEAK NETWORK.

f / Hz	Flicker limit / % Ur [3]	Max. Amplitude / % Ur
0.8	0.9	0.07
0.025	2.5	0.5
0.001	7	1

It can be concluded that no flicker problems have to be expected, even at connection points with very low short circuit levels compared to the power output of the wind farm.

This is mainly due to the fast, continuous voltage regulation installed at each generator.

VI. CONCLUSION

In this paper the grid impact of a new technology of variable speed wind turbine is analyzed. The concept of the directly grid coupled synchronous generator with hydro-dynamically controlled gearbox (WinDrive®), which is developed and manufactured by Voith Turbo, is presented and the implementation of a detailed dynamic model 2 MW wind turbine including the Voith WinDrive® in the simulation software DlgSILENT PowerFactory is described.

For investigating the behaviour of the turbine models and its compliancy with existing grid codes, a detailed model of a 50 MW wind farm consisting of 25 individual wind turbines with typical layout is used. The dynamic model is valid over a wide time range from some milliseconds up to several minutes.

Transient stability analysis based on a dynamic model of the Voith wind generator concept show that wind farms equipped with this concept are robust with regard to grid faults. Only in cases, in which such a wind farm is connected to a network with extremely low short circuit level, transient stability might be an issue in case of full load operation.

Oscillatory stability analysis of the wind farm has identified characteristic modes in the range of 2 to 3 Hz and 5 to 7Hz. The modes are generally sufficiently damped. The simulation results show that no sustained power oscillations with considerable amplitude are present in the output power of the wind-farm.

Further, the impact of turbulent wind speed variations on the wind farm behaviour has been analysed. Wind turbulences

have been modelled by synthesising random signals from a given power spectral density (Kaimal spectrum). For considering correlation between different turbines in the wind farm, the cross-spectral density method as described in [3] has been applied. The effect of rotational sampling and tower shadow has additionally been considered.

As a result it can be summarized that there is no risk that oscillatory modes of the wind farm are excited by wind turbulences. Due to the stabilising effect of automatic voltage regulators installed at each wind turbine, flicker impact is very low, also in the case of very weak wind farm connection points.

Compared to the existing technologies of variable speed wind turbines, the WinDrive[®] concept has a number of substantial advantages due to its very high grid compatibility:

- Wind-farms based on directly connected synchronous generators support the voltage and stabilized the system by increasing the short-circuit level. Especially in weak areas, this might be of very high importance.
- The new concept is able to operate in island systems. This is an important aspect for applications in remote areas, remote industrial plants or small islands.
- Finally, offshore wind-farms based on wind turbines with directly coupled synchronous generators can be connected to the main grid using conventional, thyristor-based HVDC technology. This might become a great advantage for connecting large offshore wind-farm clusters to shore.

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