

Modeling, simulating and validating wind turbine behavior during grid disturbances

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Modeling, Simulating and Validating Wind Turbine Behavior During Grid Disturbances

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Abstract—Due to the liberalized energy market Distributed Generation, DG, is increasing. At this moment, most of the power produced by DG, is generated by CHP-plants and variable speed wind turbines. Integration of wind turbines have impact on several aspects of power systems such as power system stability, protection and power quality. This paper focusses on the effect of wind farms on power quality phenomena during and after a grid disturbance. A dynamic model of a modern wind turbine will be presented in order to simulate grid disturbances. The results of the simulations are validated by measurements.

Index Terms—Distributed Generation, Power Quality, Dynamic Modeling

I. INTRODUCTION

In the past decades the use of electronic equipment have grown rapidly. Due to the sensitivity of the end-use equipment the quality of the supply voltage becomes more and more important [1]. However the use of electronic equipment also causes problems such as harmonic distortions. Common used terms in this respect are voltage quality, current quality and power quality. Voltage quality is concerned with deviations of the voltage from the ideal which is a single frequency sine wave with constant amplitude and frequency. Current quality is the complementary term of voltage quality and is concerned with the deviation of the current from ideal which is also a single frequency sine wave with a certain amplitude and constant frequency. Current quality is fully determined by the currents (non-linear) consumer loads taken from the grid while voltage quality is determined by the utilities. In Figure 1 the relationship between voltage quality, current quality and network quality are shown graphically. Power Quality is in disrespeck the quality the customers encounter

Power Quality can be divided in a number of phenomena:

- Voltage magnitude
- Supply voltage variations
- Flicker
- Harmonics and inter-harmonics

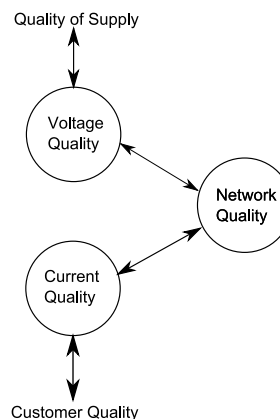


Figure 1. Relationship between voltage quality, current quality and network quality

- Unbalance
- Grid frequency

Power Quality also comprises grid events such as short and long term voltage interruptions, voltage dips and transient over-voltages. As stated in [2] distributed generation can have a significant effect on power quality phenomena as well as grid events. The main potential impacts of embedded generation on power quality are voltage flicker and harmonic voltage distortion. For instance, connection of synchronous machines alters the harmonic impedance of the grid and respond to other harmonic sources. Due to the connection of these synchronous machines the short circuit level is increasing which can improve the power quality of the network. On the other hand DG-units connected by a power electronic converter can inject harmonic currents which deteriorate the power quality of the network. This paper concentrates on power quality issues of a power system including wind farms during and after grid disturbances. In the next section a brief introduction of the power quality issues is given.

II. IMPACTS OF WIND FARMS ON POWER QUALITY

As stated earlier distributed generation influences power quality issues. In weak grids connection of distributed generation has to be limited due to exceeding of Power Quality standards. In this section the effect of wind farms on main power quality phenomena is described.

A. Voltage Fluctuations and Flicker

Electric flicker is a measure of the voltage variation which may cause disturbance for the customer. Especially distributed generation with non-controllable energy sources can cause flicker. Two types of flicker are associated with wind turbines [3, 5]:

1. Flicker emission during start-up
2. Flicker emission during continuous operation

Flicker during start-up is caused for instance due to capacitor switchings and cut-ins of wind turbines. During normal operation flicker emission is set up by variations in the produced power due to fluctuating wind-speed and tower shadow [9]. Partly the problem is solved due to the change of technology of the wind turbines (variable speed wind turbines including power electronic converters) [9]. In the past small constant speed wind turbines were connected to the LV-network. Nowadays modern wind turbines are aggregated in wind farms and connected to the MV-grid or HV-grid with a dedicated connection. In this case variation in injected power will be less perceptible.

The influence of a wind farm on the grid voltage is directly related to the short circuit power, S_k'' , at the point of common coupling (PCC). In strong grids (high S_k'' , low Z_{grid}) the effect of voltage fluctuations due to varying generated power is small while in weak grids (low S_k'' , high Z_{grid}) the voltage fluctuations can become quite cumbersome. In [3] it is stated that the grid can be considered strong if the ratio $\frac{S_k''}{P_{wf}}$ is above 20 (P_{wf} is the total capacity of the connected wind farm).

B. Harmonics

In modern variable speed wind turbines power electronic converters are applied. Most of the grid connected converters are based on Pulse Width Modulation (PWM) with switching frequencies in the range of a few thousand Hz. This switching frequency shifts the injected harmonics to higher frequencies where the harmonics can easily be removed by small filters [3]. For this purpose the output filter of the converter can be used. Manufacturers try to reduce the cost of the output filter by reducing the size of the filter inductor. To keep the cut-off frequency the same the capacitor size have to be increased. This results

in an increasing capacitance of grids where the wind turbines are connected to. The increased grid capacitance lowers the resonance frequency of the grid which can be excited by the injected harmonics. In [4] it is shown that via an active damping controller, which is implemented in the converter, reduction of the harmonic distortion can be obtained. In general the harmonic standards can be met by modern wind turbines.

C. Voltage Dips

Voltage dips occur during grid disturbances. A voltage dip is a short duration reduction in rms voltage. These voltage dips can lead to disconnection of loads and generating units. The propagation of a voltage dip depends on the location of the disturbance. Severe disturbances in transmission systems will lead to a voltage dip in the complete grid connected to the faulted component. However, disturbances in medium or low voltage grids causes voltage dips which are noticed in only a small part of the distribution system and stay undetected in the transmission system. In [1] it is concluded that in voltage dip studies not faults all voltage levels have to be taken into account. Only faults at one voltage level down from PCC are considered.

To quantify the the voltage dip magnitude in radial systems, (1) can be used.

$$V_{dip} = \frac{Z_f}{Z_f + Z_s} \cdot E \quad (1)$$

This equation is based on the network equivalent of a radial distribution system which is shown in Figure 2.

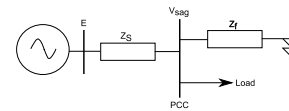


Figure 2. Network equivalent for quantifying a voltage dip

In (1) is stated that the voltage dip becomes deeper for faults closer to PCC (small Z_f) and for faults for weaker systems (large Z_s).

In grid codes requirements are taken up which distributed generation have to meet when connected to the power system. These requirements can affect the normal operation of the wind turbines. One of those requirements was immediate disconnection of wind turbines during disturbances in order to prevent malfunction of the protection system. This can result into a disconnection of the wind turbines during voltage dips even when the feeders of the wind turbines are not involved. The disconnection of wind farms during a voltage dip can lead to grid instability due to a difference in produced and consumed

power. To ensure grid stability including large penetration of wind farms, grid operators have defined various fault ride-through curves [9]. These curves allow disconnection of the wind turbine only when the voltage dip exceeds a certain level. This means that during a disturbance most wind turbines stay connected to the grid which influences the grid recovery. In order to determine grid recovery including large penetration of wind farms, dynamic simulations are carried out. The modeling, validation and results are presented in the next sections.

III. GRID MEASUREMENTS

As a manufacturer of wind turbines and grid operator it is important to know the behavior of wind turbines during grid disturbances. In order to determine the behavior of wind turbines during voltage dips tests are carried out. In 3 the test grid is shown. The tests are carried out in

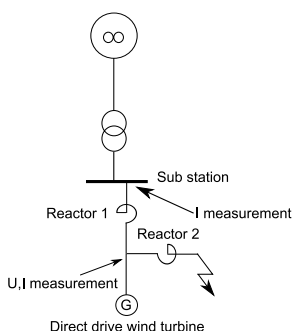


Figure 3. Test grid including a direct drive wind turbine

an existing medium voltage grid and in order to minimize the voltage dip at the point of common coupling (PCC) reactors are placed. Reactor 1 mitigates the voltage dip at PCC and reactor 2 is adjustable in a few taps so the terminal voltage of the wind turbine is controllable. The wind turbine in the test system is a direct drive wind turbine. The goal of the test is to determine if the wind turbine survives voltage dips following the curve defined by E.on. The voltage dip is created by short circuiting the three phases of reactor 2. During the tests the grid contribution as well as the voltage and current contribution of the wind turbine are measured. These measurements are taken as an input to validate the model of the direct drive wind turbine which is modeled in MatLab/Simulink.

IV. WIND TURBINE MODELING

Three wind turbine types are mostly widely used nowadays: squirrel-cage induction generator (SCIG, known also as fixed speed wind turbine), doubly-fed induction generator (DFIG) and direct-drive synchronous generator (DDSG). The structure of generic model for all types of

wind turbines is shown in Figure 4. Black color represents

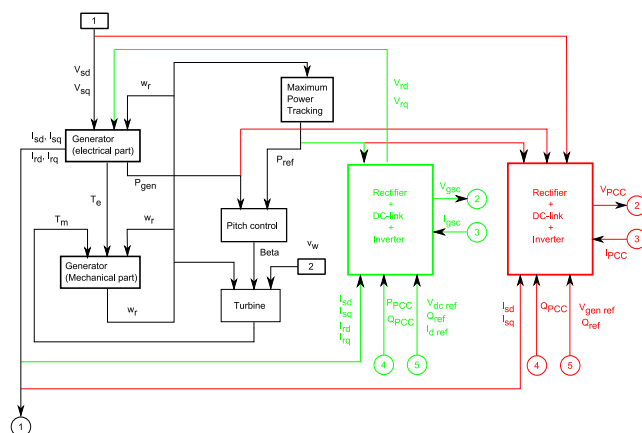


Figure 4. Generic block scheme of the wind turbine models

the part, which is common for all wind turbine types (at the same time, it is complete structure of SCIG model), green color - DFIG structure, and red color - DDSG structure. There are the following major differences between these three wind turbine types:

1. SCIG and DFIG use induction machine as a generator, while DDSG can be implemented with permanent magnet or electrically excited synchronous machine.
2. SCIG does not contain any power electronics, while the other concepts use rectifier, DC link and inverter: DFIG - in rotor circuits, DDSG - in stator circuits of the machine.
3. Control circuits of DFIG and DDSG converters are slightly different due to the reason mentioned in the previous item.

It is also necessary to mention that certain variations in the control concepts can be introduced, but they are not shown in the generic model in order to keep it readable. The more detailed description of generic model and structure of converters control blocks for different turbine types will be given in the full paper.

V. MODELING OF DIRECT DRIVE WIND TURBINE

In this section a brief description of the model of the direct drive wind turbine is given. Detailed information can be found in [6, 7]. The model is set up in MatLab/Simulink. A direct drive variable speed wind turbine is based on a rotor which is directly mounted on the generator shaft and a power electronic converter which is placed between the generator and the grid. Due to the

power electronic converter the wind turbine can operate at a variable speed. An overview of this concept is shown in Figure 5. In the subsequent sections the main parts of

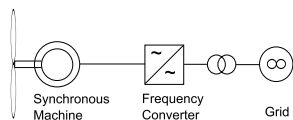


Figure 5. Direct-drive wind turbine

the wind turbine model are described.

A. Synchronous Generator

The model of a synchronous machine is normally described in a d-q reference frame. For detailed calculations of stator transients a 7th order model is used. In stability studies however, transient phenomena are usually not considered [8]. By neglecting the stator transients the 7th order model reduces to a 5th order model. In the d-q reference frame the stator and rotor voltage equations are:

$$\begin{aligned} v_d &= R_a i_d - \omega \psi_q \\ v_q &= R_a i_q + \omega \psi_d \end{aligned} \quad (2)$$

Rotor voltages:

$$\begin{aligned} v_E &= R_E i_E + \frac{d\psi_E}{dt} \\ 0 &= R_D i_D + \frac{d\psi_D}{dt} \\ 0 &= R_Q i_Q + \frac{d\psi_Q}{dt} \end{aligned} \quad (3)$$

For completing the synchronous machine model the flux linkage and mechanical equations are required.

Stator flux linkage:

$$\begin{aligned} \psi_d &= (L_{hd} + L_\sigma) i_d + L_{hd} i_E + L_{hd} i_D \\ \psi_q &= L_{hq} + L_\sigma i_q + L_{hd} i_Q \end{aligned} \quad (4)$$

Rotor flux linkage:

$$\begin{aligned} \psi_E &= L_{hd} i_d + (L_E) i_E + (L_{hd} + L_{\sigma L}) i_D \\ \psi_D &= L_{hd} i_d + (L_{hd} + L_{\sigma L}) i_E + (L_D) i_D \\ \psi_Q &= L_{hq} i_q + (L_{hd} + L_{\sigma Q}) i_Q \end{aligned} \quad (5)$$

with for L_E and L_D :

$$\begin{aligned} L_E &= (L_{hd} + L_{\sigma L} + L_{\sigma E}) \\ L_D &= (L_{hd} + L_{\sigma L} + L_{\sigma D}) \end{aligned} \quad (6)$$

The mechanical equations of the synchronous machine are:

$$\begin{aligned} J \frac{d\omega}{dt} &= T_t + T_e \\ \frac{d\theta}{dt} &= \omega \end{aligned} \quad (7)$$

B. Power Electronic Converter

The direct drive wind turbine makes use of power electronic converters. In modern wind turbines the grid-side converter is normally realized by well known self commutated pulse-width modulated circuits [6]. For the wind turbine model a build in model of Power Factory is used. When an ideal DC voltage is assumed the AC and DC voltage can be related by (8).

$$|V_{AC}| = \frac{\sqrt{3}}{2\sqrt{2}} m V_{DC} \quad (8)$$

The pulse-width modulation index, m , is the control variable of the PWM-converter and (8) is valid for $0 \leq m < 1$. The converter model is completed by the power conservation equation:

$$V_{DC} I_{DC} + \sqrt{3} \operatorname{Re}(V_{AC} I_{AC}^*) = 0 \quad (9)$$

C. Power Electronics Controllers

The controllers of the applied power electronic converters are based on a current control loop. Each converter have an own controller which build of two stages:

1. Fast current controller
2. Slow outer control loop

The fast current controller regulate AC currents in an AC-voltage oriented reference frame. Hence the d-axis current is the active current and the q-axis current is the reactive current. A schematic diagram of the both current controllers is depicted in Figure 6. The fast current controller

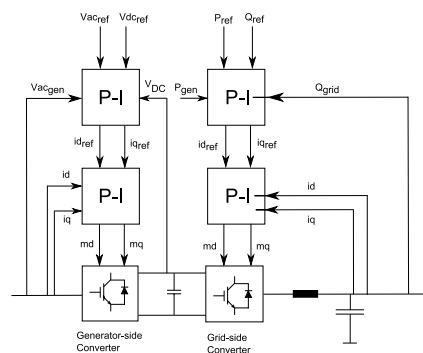


Figure 6. Power Electronic Converter including controllers [6]

is based on a PI controller and controls i_d and i_q . The reference currents are obtained from the slower outer control loop which regulate the active and reactive power. Modern wind turbines make use of a maximum power tracking (MPT) strategy. This means that the power dispatched to the grid is permanently optimized and depended of the

actual wind speed. The MPT-characteristic determines the reference value, P_{ref} , of the optimal power generated by the wind turbine and P_{ref} is used as an input value of the slower control loop. The output of the slower controller are the reference values for i_d and i_q . The generator side controller regulates the DC voltage. Here the current references are defined by the AC and DC voltages. Detailed information of the controller concepts can be found in [4, 6, 7].

VI. RESULTS

The current measured during short circuit from grid side is represented by the blue curve on Figure 7. From the curve it appears that parameters of wind turbine controllers were not properly adjusted. Although there is no DC-component present in the curve, the current is not symmetrical in respect to axis of abscissas (negative half-wave of the current is cut). Simulations have been shown that such a behavior cannot be achieved with simplified fundamental frequency model of the converters. However, positive half-wave of the current can be fitted well even with simplified model. To achieve better approximation, more elaborate modeling of converters is required. After readjustment of controller parameters the current measured from the grid side has symmetrical form (sinusoidal wave with presence of exponentially decaying component, positive and negative half-waves are symmetrical). The analytical expression, which is the best fit of the curve, was found (see green curve on Figure 7) and shown in (10).

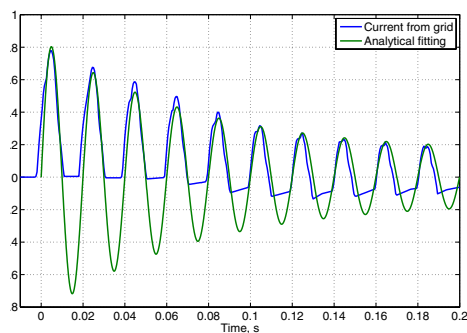


Figure 7. Short-circuit current contribution from the grid and its analytical fitting

$$i_{reactor}(t) = 0.15 \sin(\omega t) + 0.7 \sin(\omega t)e^{-14t} \quad (10)$$

This analytical expression is an approximation of short-circuit current through Reactor 2. After that, the current contribution from the turbine side was estimated by (11):

$$i_{turbine}(t) = i_{grid}(t) - i_{reactor}(t) \quad (11)$$

This current is plotted on Figure 8. From the curve it can be seen that its shape is distorted due to saturation of converter of the turbine (there appears large amount of high order harmonics), and significant DC-component is present in the curve.

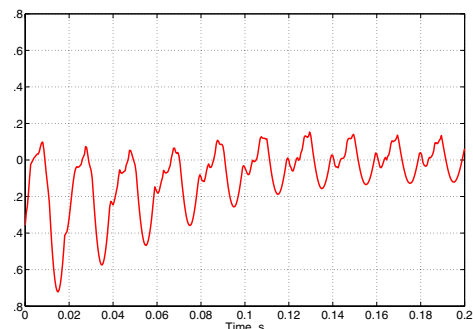


Figure 8. Estimation of short-circuit contribution from wind turbine side

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VIII. BIOGRAPHY

Edward J. Coster was born in Leiden, The Netherlands, in 1972. He received the B.eng degree in electrical engineering from TH Rijswijk in 1997 and the MSc. degree in electrical engineering from Delft University of Technology in 2000. From 2000 he is as a senior specialist for network planning with ENECO NetBeheer. In april 2006 he part-time joined the Electrical Power System group, Eindhoven University of Technology to start a PhD research project. His fields of interest are: Distributed Generation, Power System Protection, Dynamic Behavior and Stability of Power Systems.

Anton Ishchenko was born in Krasnodar, Russia in 1980. He received MSc. in Electrical Engineering from the Kuban State Technological University, Russia in 2002. In 2001 he was honored with Russian Academy of Electrotechnical Sciences Award for outstanding student's paper in the area of "Power and Electrical Engineering". At the same year he received Russian Ministry of Education Award for outstanding student in the area of technical science. In August 2003 he joined the Electrical Power Systems group, Technical University of Eindhoven as PhD student. His major fields of interest are: renewable energy sources, control systems, power system protection and emergency controls, power system transients and stability.

Johanna M.A. Myrzik was born in Darmstadt, Germany in 1966. She received her MSc. in Electrical Engineering from the Darmstadt University of Technology, Germany in 1992. From 1993 to 1995 she worked as a researcher at the Institute for Solar Energy Supply Technology (ISET e.V.) in Kassel, Germany. In 1995 Mrs Myrzik joined the Kassel University, where she finished her PhD thesis in the field of solar inverter topologies in 2000. Since 2000, Mrs Myrzik is with the Eindhoven University of Technology, the Netherlands. In 2002, she became an assistant professor in the field of distributed generation. Her fields of interests are: power electronics, renewable energy, distributed generation, electrical power supply.

Wil L. Kling (M'95) was born in Heesch, the Netherlands in 1950. He received the MSc. degree in electrical engineering from the Technical University of Eindhoven, the Netherlands, in 1978. From 1978 to 1983 he worked with KEMA and from 1983 to 1998 with Sep. Since then he is with TenneT, the dutch Transmission System Operator, as a senior engineer for network planning and network strategy. Since 1993 he is a part-time Professor at the Delft University of Technology and since 2000 he is also a part-time Professor in the Electrical Power Systems group at the Eindhoven University of Technology, the Netherlands. He is leading research programs on distributed generation, integration of wind power, network concepts and reliability. Mr. Kling is involved in scientific organizations such as Cigre and IEEE. He is the Dutch representative in the Cigre Study Committee C1 *System Development and Economics*