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Wind turbine model validation with measurements

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Abstract

The objective of this work is to validate wind turbine models available in commercial simulation tools with measurements. Results are shown for two turbines located in two different wind farms; wind turbine 1 is a fixed speed turbine with induction generator, and wind turbine 2 is a variable speed turbine with converter-interfaced synchronous generator. Simulated active and reactive power transient responses to voltage dips have been compared to measured responses, as suggested by IEA Wind Annex 21. For the fixed speed turbine quite good agreement between measurement and simulation is obtained. Shaft parameters are seen to have significant influence on the simulated active power response. For the variable speed turbine the active and reactive power responses are to a high degree determined by the power electronics interface and corresponding controllers, and particularly the control strategy applied during voltage dips. Wind turbine manufacturers are generally very restrictive on giving out this type of information, and thus typical configurations and parameters have been used in this work. The agreement between measurement and simulation can to some degree be improved by changing the inverter controller parameters by trial-and error, but detailed knowledge on the control of the converter would be required in order to achieve a very good agreement.

Keywords: voltage dip; measurements; simulation model validation; fixed speed wind turbine;variable speed wind turbine

1. Introduction

With increasing amounts of wind power generation it is important, especially for grid owners, to predict the grid interaction of wind turbines. This paper describes validation of wind turbine simulation models available in commercial software, using measurements from two wind farms with different turbine technologies. A benchmark test procedure, as suggested by the IEA Wind Annex 21 [1] is used. The focus

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is on voltage dips, and the capabilities of the models to simulate the behaviours of real wind turbines during voltage dips are investigated. Validation is important in order to create confidence in the simulation models, as use of non-validated models in power systems studies may lead to inaccurate results and possibly wrong conclusions. Measured voltage time series, in the form of positive sequence voltage amplitude and phase angle, are used as input to the simulations. The simulated responses of active and reactive power to the applied voltage dip are then compared to corresponding measured responses.

Using real measurements for validation of wind turbine models have been reported in some previous literature, e.g. [2] and [3], where simulations results are compared with data measured in field tests on a wind turbine generator. The aim of [4] is to investigate the modelling requirements of wind turbines for power system studies, and to verify the simulation results through on-site measurements. According to the paper, the response of a fixed-speed turbine to a grid disturbance is mainly governed by the induction generator. For variable-speed wind turbines, the response to minor grid disturbances depends on the details of the control system of the specific wind turbine, which are generally not provided by the manufacturers. This makes it very difficult to construct a generally valid model for handling of grid disturbances for these types of turbines. [5] deals with development of generic positive sequence wind turbine generator models for large-scale power system transient stability analyses. The fact that dynamic wind turbine models developed by wind turbine manufacturers are confidential, and only available for use within specific projects, is discussed. In the paper, a reference wind farm with 136 1.5 MW doubly fed induction generators is used for the model validation. Measurements are input to the simulation via a generator model capable of holding terminal voltage and frequency as specified in an input file. A direct comparison between the simulated and measured real and reactive power at the can provide some evidence of model performance. The paper states that validation requires multiple tests across different system conditions and different wind power plants of the same type of generators.

This paper is organized in three chapters, in addition to the introduction in Chapter 1. The benchmark test procedure used for validation of wind farm models is explained in Chapter 2. This also includes description of the measurement system and measurement locations, as well as wind turbine modelling. Chapter 3 gives results of the model validation in the form of curves comparing measured and simulated responses in active and reactive power. Finally some discussion and conclusions are given in Chapter 4.

2. Benchmark test procedure

The IEA Wind Annex 21 has suggested a benchmark test procedure for validation of wind turbine models for voltage dip studies [1]. Three-phase measurements of instantaneous voltages and currents are required as inputs, which are then transformed to RMS fundamental positive sequence values of voltage, active power and reactive power. The measured positive sequence voltage time series (magnitude and phase angle) are input to the simulation, and this applied voltage dip causes a transient response in the simulated active and reactive power. These responses are then compared to the measured positive sequence active and reactive power, in order to validate the wind turbine model.

There are two main reasons for using fundamental positive sequence values. Firstly, perfectly balanced conditions can generally not be assumed, and it is convenient to represent an unsymmetrical voltage dip by the corresponding positive sequence equivalent. Secondly, most power system simulator models are positive sequence phasor type models [1].

2.1. Wind farm measurements

The measurements are recorded using Elspec Blackbox instruments [6]. The instruments continuously samples voltage and current in all three phases, and store the measurements in a central database.

Processing of data is done partly by the instruments and partly by post-processing accessing the database; for the post-processing both Elspec software and Matlab routines developed by SINTEF Energy Research are used.

Measurements are recorded in two wind farms with two different types of wind turbine installed. Wind farm 1 consists of multiple 2.3 MW fixed speed turbines with directly connected induction generators. Reactive power is compensated for by controlled capacitor banks. Wind farm 2 consists of multiple 2.3 MW variable speed wind turbines with synchronous generators and full scale frequency converters. Multi-pole synchronous generators allow for gearless transmission of mechanical power from turbine to generator. There are two measurement points in each of the wind farms; one is located at the terminal of a single turbine, and one is located at the common wind farm connection point to the grid. Only results for validation with measurement from the terminals of the two single wind turbines are shown in this paper.

2.2. Wind turbine modelling and simulations

Both wind turbines have been modelled in the dynamic simulation tool SIMPOW [7], using standard available wind turbine models.. The models generally require a large amount of input parameters, and where parameters were not available for the specific sites or manufacturers default values were used. In addition wind turbine 2 has been modelled in the transient simulation PSCAD [8].

For wind turbine 1, wind, aerodynamic models and blade pitching control are not included in the simulation model. Instead, a constant mechanical torque is used to drive the generator rotor. Each induction generator has two sets of stator windings, with rated power of 0.4 MW and 2.3 MW, respectively. A data sheet of a 2/0.4 MW constant speed turbine from the same manufacturer was available. These parameters have been converted to pu-values based on 2.3 MW, for use in the simulation.

For wind turbine 2 a standard "Full Power Converter Wind Turbine" model available in SIMPOW [9] has been used. The model consist of a wind turbine, standard synchronous machine, PWM rectifier and inverter and control systems for speed, pitch and AC voltage. In PSCAD a converter model developed at SINTEF Energy Research assuming ideal switching have been used. Only the grid side converter was modelled, assuming ideal control of the dc voltage. No data were available for the variable speed turbine except rated voltage and power, and thus the default parameters have been used.

3. Comparisons between measured and simulated responses

This chapter shows results of comparisons between measured and simulated values of active and reactive power to applied voltage dips. Measured values refer to positive sequence components calculated in Matlab from measured instantaneous values of voltage and current. Base values for plotting of active and reactive power is equal to the active power rating of one turbine, 2.3 MVA.

3.1. Wind farm 1, fixed speed turbines

A voltage dip with residual voltage of 0.85 pu and duration about 70 ms in the positive sequence component has been studied. The wind turbine was generating approximately 15 % of nominal power in the pre-fault state. Capacitors provide reactive power compensation, and thus the reactive power is close to zero in the pre-fault state. 15 % of nominal power corresponds to about 0.35 MW, which is less than the rating of the 0.4 MW stator winding. Simulations however show that the magnitudes of the transient peaks become very small when simulating with the generator rating of 0.4 MW, and the agreement between measurement and simulation is best with the generator rating of 2.3 MW. Thus it can be concluded that the 2.3 MW stator winding was in operation in this case.

The impacts of different parameters in the shaft model and the induction generator model on the active power response have been investigated. Fig 1 shows the response (a) when the shaft self damping constant D is increased from the original value of 0.1 to 5, and when the rotor resistance R is decreased changed from the original value of 0.00933 to 0.005.

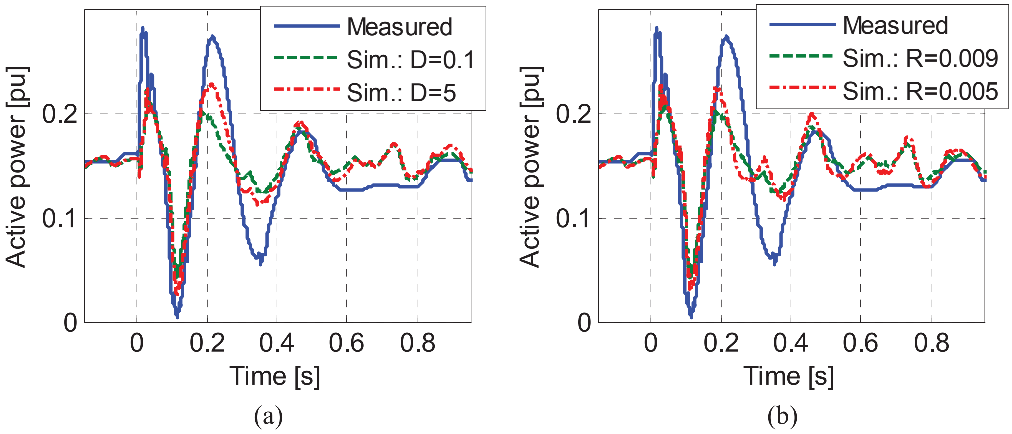

Fig 1 Comparisons between measured and simulated (SIMPOW) active power responses. (a) Shaft damping constant D is changed from 0.1 to 5. (b) Rotor resistance R is changed from 0.009 to 0.005.

Increasing D from 0.1 to 5 leads to increased magnitudes of the transient peaks from the first negative swing. Thus the larger D gives a response closer to the measured. A further increase of D from 5 to 10 (not shown here) gives negligible improvement of the response. The higher transient peaks seen with increased damping may be due to some interaction between generator and shaft responses. The smaller R-value leads to some larger peak values, which is as expected.

The impact of changing other shaft parameters (shaft stiffness constant K and mutual damping DM) has also been investigated. For the generator parameters, a reduction of the rotor reactance X was seen to give responses with higher peaks and faster swings.

Fig 2 shows responses in active and reactive power when both shaft model constants and generator parameters have been modified in order to get a better match between simulation and measurement. For the active power response, no improvement is seen due to the modified parameters for the first positive and negative peaks. In the next peaks, a very good agreement between measurement and simulation is seen. For reactive power the agreement was a bit better with the original set of parameters.

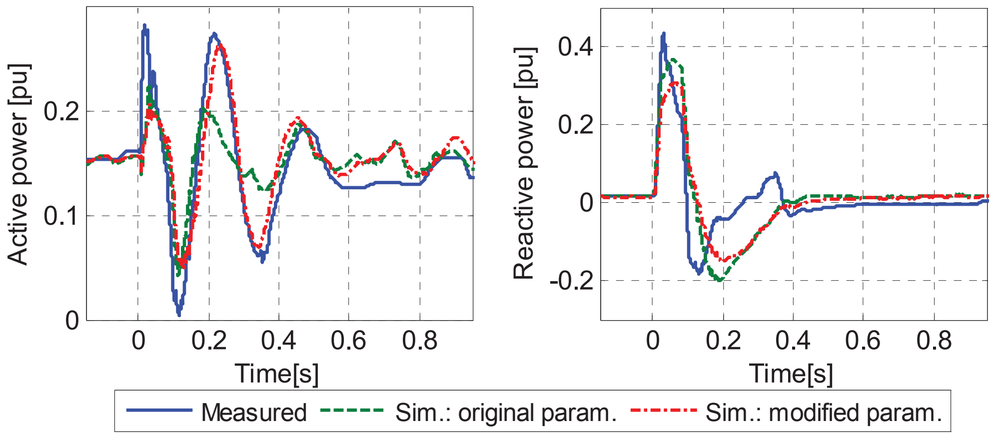

Fig 2 Measured and simulated (SIMPOW) responses in active power with original parameters and with adjusted DM, D, K, R and X

3.2. Wind farm 2, variable speed turbines

A voltage dip with residual voltage of 0.83 pu and duration about 80 ms in the positive sequence component, measured at wind turbine 2, has been studied. The turbine was generating about 15.8 % active power and 5 % reactive power in the pre-fault state, referred to nominal power.

3.2.1. Results from SIMPOW simulation

Fig 3 shows a comparison between measured and simulated active and reactive power at wind turbine 2 for this case. The grid side converter has a voltage controller, and the reactive power is controlled by adjusting the voltage set-point.

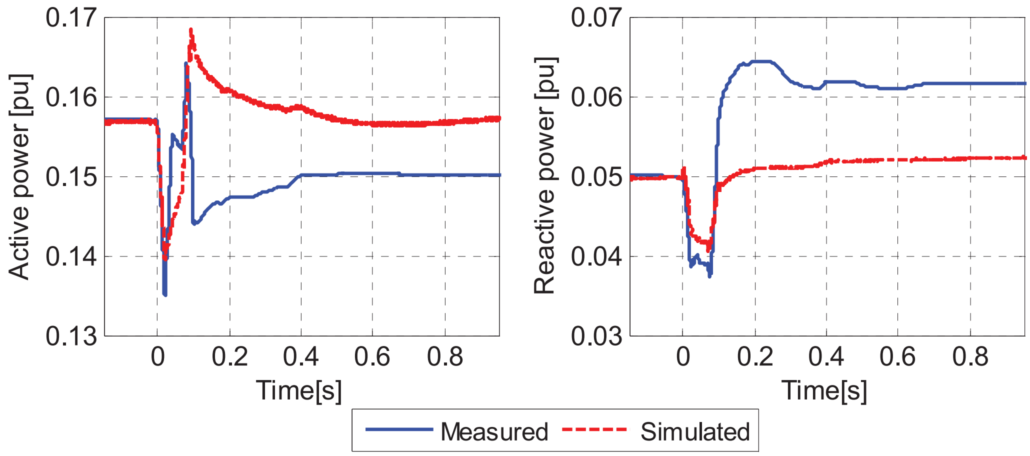

Fig 3 Comparisons between measured and simulated (SIMPOW) responses in active and reactive power for when inverter voltage controller parameters have been changed.

There is not very good agreement between measured and simulated active power responses. The turbine appears to have a different control strategy for active power in reality than what is implemented in the SIMPOW model. In the simulation, the active power goes high after the dip, most likely to decelerate the turbine back to nominal speed after acceleration during the voltage dip. The measured dip in active power is of much shorter duration, and this probably leads to less acceleration of the turbine. For the reactive power, good agreement is seen for the first negative swing, but not for the further response, and the high reactive power after the dip is not reproduced by the simulation. Since the wind turbine is connected to the grid via a power electronics converter, the response is to a high degree determined by the converter control strategies and parameters. Changing the grid side controller parameters had some impact, but did not change the overall shape of the responses.

The reactive power response is determined by the voltage controller for the grid side converter. The measured voltage used as input to the simulation is a controlled voltage, and the high reactive power seen after the first dip is drawn by the inverter in order to keep the voltage at the controller set-point. The amount of reactive power required is governed by the network characteristics, which is not included in the simulation model. Thus it is difficult to reproduce the reactive power response in the simple test applying only a voltage dip in the measurement point. In the simulation model, a constant set-point has been used for the voltage controller, and thus the reactive power goes back to a value close to the pre-fault value when the voltage has restored after the fault.

3.2.2. Results from PSCAD simulation

Fig 4 shows a comparison between measured and simulated active and reactive power at wind turbine 2 for the same case as in Fig 3 with PSCAD. Active and reactive power can be controlled independently, and the steady-state values are determined by the controller set-points (reference values).

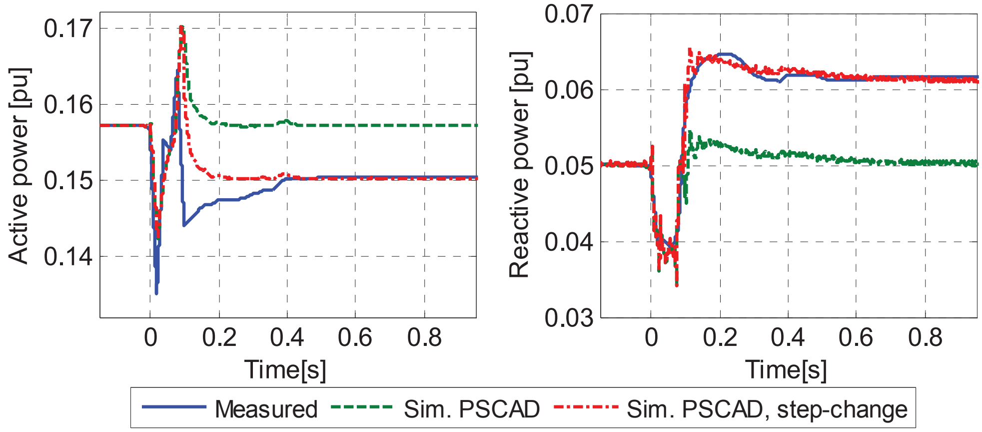

Fig 4 Comparisons between measured and simulated (in PSCAD) responses in active and reactive power. With adjusted inverter controller parameters, and step changes in active and reactive power set-points

After the dip, neither active nor reactive power returns to the same values as before dip, and also the power factor is changed. Thus the measured responses cannot be expected to be reproduced when the controllers have constant set-point values. Step-changes have been applied in both active and reactive power set-points in order to get a better agreement between simulation and measurement, with results shown in the red curve named "Sim. PSCAD, step-change". The green curve named "Sim. PSCAD" shows results with constant set-points for active and reactive power. This curve is comparable with the simulated response in SIMPOW, shown in Fig 3. However, the active power controller parameters have been adjusted to shorten the duration of the first dip in active power in the PSCAD model, which was not possible in the SIMPOW model.

In the model developed in PSCAD all components are accessible, and all parameters can be modified by the user. This is an advantage as compared to the SIMPOW model which is more like a black-box model, and only grid side voltage controller parameters could be modified. An interesting observation is that the simulated responses in SIMPOW and PSCAD have overall similar shapes when the controller set-points are kept constant. Since the SIMPOW model comprise the wind turbine, generator and full back-to-back converter, while the PSCAD model only consist of the grid-side converter, it can be concluded that the response seen on the grid side is mainly determined by the grid side converter.

4. Discussion and conclusions

This work provides some experience in practical use of the benchmark test procedure suggested by IEA Wind Annex 21 [1]. The capabilities of the SIMPOW standard wind turbine and generator models to simulate the transient responses of real wind turbines have been investigated. In addition a converter model developed in PSCAD has been tested. Sensitivities of different simulation model parameters to the active and reactive power responses have been analysed.

For wind turbine 1, a fixed speed turbine with directly connected induction generator, quite good agreements were seen between the simulation results and measured time series, especially in the first swings. By adjusting some parameters in the simulation model, especially wind turbine shaft constants, a response closer to the measurement could be obtained. Thus the benchmark test procedure appears to be suitable for model validation with this type of wind turbine technology.

For wind turbine 2, a variable speed turbine with full power electronics interface, it was more difficult to obtain a good agreement between measured and simulated responses. Since the controllers govern the responses in both active and reactive power, the challenge is to find the correct parameters for components and controls, and deciding the control strategy. Detailed information is required in order to obtain accurate results, however this is difficult to obtain from wind turbine manufacturers. Wind turbine 2 should have some fault-ride-through capability, and the active power response seen from the measurement is probably due to the action of such a control strategy. Such strategies are normally kept as business secrets. Possibly, the control strategy could be guessed based on analysing a number of measured responses. Measurements should then be available for dips with different characteristics (depth and duration), and for different power generation levels. Unfortunately, only a limited number of voltage dips were found in the data from the long-term measurement campaign which this paper is based on. Another possibility for obtaining measured responses is by applying voltage dips at the terminals of a wind turbine, using low voltage ride-through test equipment (test-container).

The higher reactive power generation after the voltage dip is not reproduced by the simulation with a constant set-point for the voltage/reactive power controller. The reason is probably that the voltage applied to the simulation is a result of controller action. It should be investigated further if a correct reactive power response can be achieved by applying a voltage dip at the connection point of a full converter turbine with active voltage/reactive power control. Alternatively, the network has to be represented in the model, and a fault has to be applied instead of a voltage dip.

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