Project title	Frequency characterization and model verification of wind turbines systems by VSC-based testing equipment.
Project number	TG1-4
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Ola Carlson
Other participants	Nicolas Espinoza (PhD student)
Report for	2015-10-01 – 2016-09-30
Participating companies	ABB, Göteborg Energi, GE

Project description

The goal of the project is to investigate the application of VSC-based testing equipment for model validation of wind turbines.

The advantages and limitations of the use of VSC-based testing equipment for model validation and testing of wind turbine will be investigated in Stage 2. That includes frequency characterization of wind turbine to detect possible control interaction between wind turbine and the interconnecting system i.e.: HVDC or AC collector grid, and testing of the generating unit for different scenarios for both normal and faulty condition of the grid. The project includes a comprehensive comparison between the developed simulation model and small scale wind turbine laboratory model in terms of electromagnetic transient behavior and frequency characteristics in order to assess verification methodology of wind turbines system by means of VSC-based testing equipment.

In particular, the research project in Stage 2 will cover the following aspects: Frequency characterization of both DFIG and full-size converter wind turbines by VSC-based testing equipment; Development of a small scale full-size wind turbine drive train for frequency characterization by LV prototype of VSC-based testing equipment and comparison of frequency characteristic between simulation and laboratory model. In addition, the development of testing methodology of wind turbines during normal and faulty condition of the connecting grid includes: Testing of control strategy during LVRT event and grid code compliance; Testing of frequency control during grid frequency fluctuations; Testing of power oscillation damping capabilities of wind turbine by emulating an oscillatory grid in the test equipment.

The investigation conducted during Stage 1 was mainly focusing on grid code testing of wind turbines by using a VSC-based testing equipment. The control of the 2-level VSC both for the wind turbine and for the testing equipment was studied in detail. That includes the classical control algorithms (such as current controller, phase-locked loop, ac and dc voltage controllers) as well as the implementation of control strategies for the wind turbine during fault conditions and hardware protection. In addition, the ability of the modeled generating unit to provide additional features such as voltage control and reactive power support (both during normal and faulty condition of the grid) has been also verified thorough laboratory experiment. The knowledge acquired during Stage 1 will be the basis for the continuation of the project.

Finally, part of the work will be laboratory experiment including the use of LV prototypes for model validation and full power test at the 4 MW wind turbine in Göteborg. Finally, results will be reported through scientific papers, including a PhD-thesis in November 2016. The activities of the project during stage II will be divided in work packages, in correlation with the description given above:

1. **Reporting** of by seminars, scientific papers and Licentiate thesis and PhD thesis. Collaboration and communication with other projects within the SWPTC is also included in this task.
2. **Laboratory work** as continuation of stage 1. That includes laboratory experiment of VSC representation of two area mode power oscillation at the PCC; and frequency spectra characterization of the test object carried out by VSC. Full power test at the 4 MW wind turbine in Göteborg is also included in this task.
3. **Study of wind power systems:** Study of the impact of non-linear conversion systems in the drive-train electromechanical dynamics. Study of possible interactions between wind turbines and interconnecting systems e.g.: control interaction with HVDC systems, sub-synchronous resonances in AC collector systems.

4. **Simulation** of the wind turbine system model including its control system and modulator and grid interface. Research activities conducted in WP5 will be also supported by modeling and simulation. In particular, frequency characterization of both DFIG and full-size converter wind turbines by VSC-based testing equipment.
5. **Validation of wind turbine model:** Development of a small scale full-size wind turbine drive train for frequency characterization by LV prototype of VSC-based testing equipment; Comparison of frequency characteristic between simulation and laboratory results; The development of testing methodology of wind turbines during normal and faulty condition of the connecting grid includes: Testing of control strategy during LVRT event and grid code compliance; Testing of frequency control during grid frequency fluctuations; Testing of power oscillation damping capabilities of wind turbine by emulating an oscillatory grid in the test equipment.

Results

The setup shown in Fig. 1 has been modeled in the time-domain simulation software PSCAD

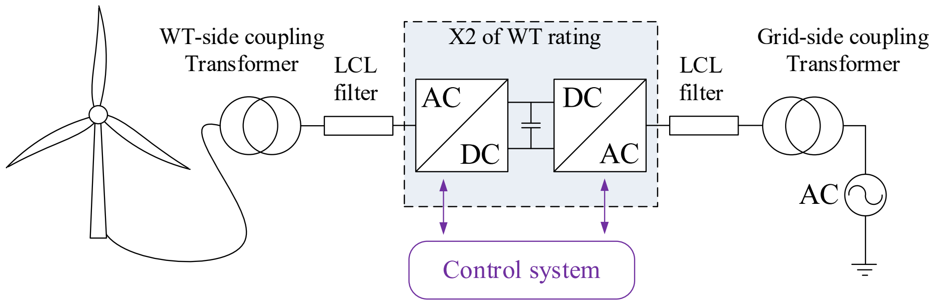

Fig. 1: Wind turbine connected to a Back-to-back VSC –based testing equipment.

A discrete control algorithm has been developed in order to control both the testing equipment and the wind turbine model. A stability analysis has been carried out to identify sensitive settings of these two objects. Laboratory experiment has been carried out to validate the results included in the Licentiate thesis. New results included in a new scientific paper and also in the PhD thesis includes the calculation of the wind turbine admittance. The admittance is calculated as an average of the phase admittance. The system is exited with a reduced voltage at the frequency of interest, while the current at that frequency is retrieved by FFT analysis. The test has been carried out in simulation, laboratory and field test environment.

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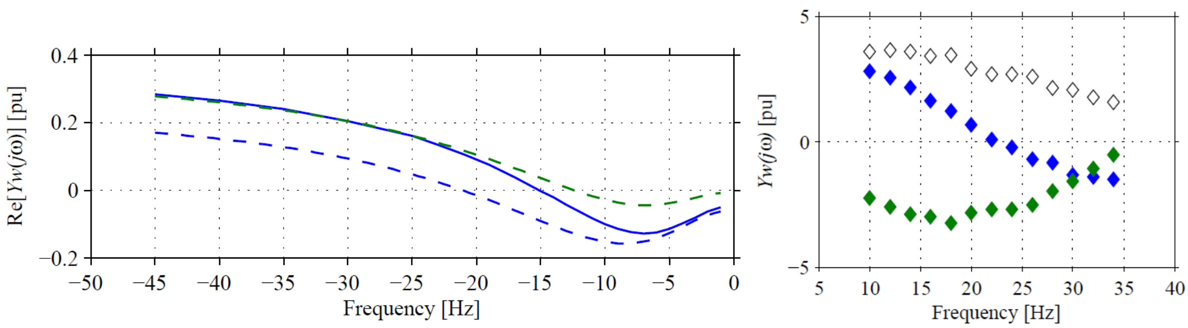

(a) (b)

Fig. 2: Wind turbine admittance: Plot (a): real part of the admittance given by analytical model (dashed) and simulation model (solid). Plot (b): measured at Big Glenn by HVDC (blue: real part, green: imaginary part, and white: magnitude of the admittance).

The admittance of the wind turbine system has been calculated using analytical model (dashed curves in Fig. 3a) where the system has been evaluated to match the admittance of the simulation model (solid curves in Fig. 3b). The admittance has been also measured on the Big Glenn wind turbine by using the VSC-HVDC fully rated testing equipment. The results are shown in Fig. 3b.

Both dashed curves in Fig 2a correspond to the evaluation of the mathematical model with slightly different parameters. Observe, however, that the simulation model match with the analytical model. The real part of the admittance of Big Glenn wind turbine is given in Fig 2b in blue curves. The shape follows the admittance of the simulated models. Positive value of the real part of the admittance means that the system is passive against a distribution at that frequency. In other words, the system behaves as a resistor, dissipating the energy of the oscillation. Negative real part means that the system behaves as a current source and that is giving energy into the system.

Although the magnitude is quite different between Big Glenn and the simulation models, this example show that with the proposed methodology it is possible to retrieve the admittance of the generating unit. Note that here Big Glenn is treated as a black box, meaning that there is no information about the control strategy on the actual wind turbine, while the simulated wind turbine includes common current control and grid synchronization strategies given in the literature. These results can be of use in a second stage where the stability of the system constituted by wind turbines and the grid is evaluated. Especially if the frequency scan is performed on an actual wind turbine, such as Big Genn.

Other test carried out on Big Glenn was testing for voltage dip. During this test, the voltage is reduced to 0.7 pu for 200 ms. From the voltage waveform given in Fig. 3a, it is possible to observe that the HVDC controls the applied voltage in a smooth way. At the moment of the dip, the wind turbine reacts by injecting reactive power into the grid, as seen from the green curves in Fig. 3c. The test was carried out in a non-windy day, therefore the active power (blue curve in figure) is set to 0 pu. As soon as the voltage is restored, the wind turbine brings back the reactive power to its pre-fault set point. This example demonstrate the use of the investigated testing equipment in evaluating the behavior of the wind turbine against voltage dip.

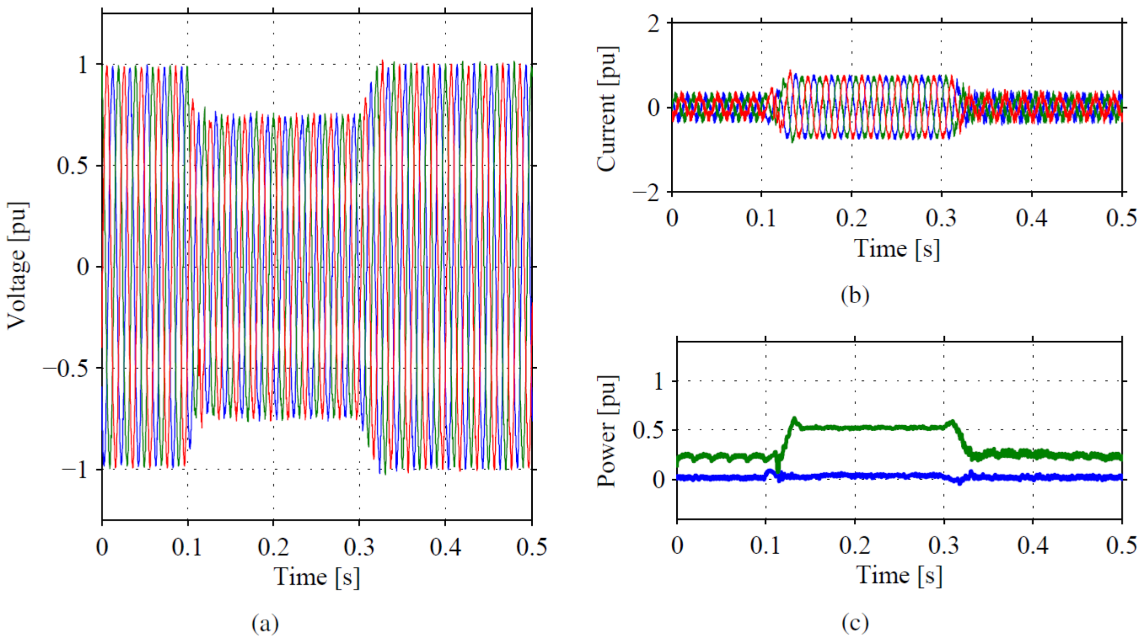

Fig. 3: Wind turbine under voltage dip test at low power production. Plot (a): three-phase voltage; Plot (b): three-phase current; Plot (c): active (blue) and reactive (green) power.

Other grid-support capabilities of the wind turbine can also be tested. For example, by varying the applied frequency away from the 50 Hz nominal value, it is possible to test frequency support and active power curtailment properties of the generating unit. Here, by using the HVDC station, the frequency is varied upwards by applying two consecutive frequency swells of 1 Hz. The frequency, shown in Fig. 4 in the upper plot is initially controlled at 50 Hz and varied upwards with a ramp of 0.05 Hz/s, or 20 seconds per varied Hz. A frequency of 51 Hz is maintained for 25 seconds approximately. Afterwards, frequency is increased to 52 Hz. The reaction of the wind turbine can be seen in Fig.4 in the lower plots, where the blue curves correspond to the actuve power production and the green curves shows the reactive power set-point, during the moment of the test.

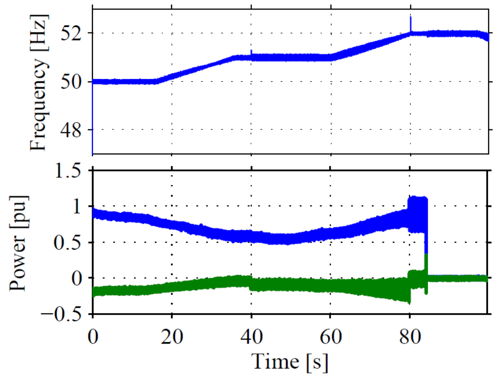

Fig. 4: Frequency variation test consisting of two consecutive frequency swells of 1 Hz (top), and active (blue) and reactive (red) power out of the wind turbine (bottom).

Observe in the lower plot that the upwards and downwards tendency of the output power suggest that the wind turbine is varying its operating point according to the wind speed and not in demand of the applied frequency. In addition, the active power is slightly increased 10 seconds after the frequency reaches 51 Hz, at 40 s, while continues to increase with the increasing of the system frequency at 60 s. Finally, a critical point is encountered at 80 s when the frequency reaches 52 Hz. The wind turbine enters into an operation mode that affects the active power output while experiencing an oscillation at 104 Hz. The wind turbine shuts down by an over-frequency protection relay, 5 seconds after the frequency reaches 52 Hz, at t =85 s. The different power production levels experienced when performing the test are also somewhat reflected on the reactive power output of the wind turbine, as seen in green traces in the lower plot.

During second half of 2015, the Licentiate degree has been achieved. The Phd defense has been set for the 15th of December. The new results includes frequency characterization of wind turbine to detect possible control interaction between wind turbine and the interconnecting system i.e.: HVDC or AC collector grid, and testing of the generating unit for different scenarios for both normal and faulty condition of the grid. The results have been verified by simulation and laboratory experiment and validated through field test results.

Fulfilment of SWPTC’s goals

This work is contributing to the development of testing procedures for high power wind turbines. It also contributes with the Swedish development and production and optimization of components and subsystems. Moreover, the development of reliable technology for wind turbine systems is key factors to improve the overall economy and penetration of wind power nationally.

With the increasing penetration of wind energy into the grid, the use of VSC-based testing equipment can assess the model validation and verification process of wind turbines. Grid support capabilities can be also tested ensuring a more reliable grid interconnection of wind farms. The testing equipment is a power electronic voltage source converter based testing device..

Deviations from project plan

There are no deviations according to the PhD project proposal written on 2015-06-12.

Publications

Espinoza, N.; Bongiorno, M.; Carlson, O., “Grid Code Testing of Full Power Converter Based Wind Turbine Using Back-to-Back Voltage Source Converter System,” in EWEA 2013 Annual Event Conference Proceedings. Feb. 2013.

Espinoza, N.; Bongiorno, M.; Carlson, O., "Novel LVRT Testing Method for Wind Turbines Using Flexible VSC Technology," in Sustainable Energy, IEEE Transactions on , vol.6, no.3, pp.1140-1149, July 2015.

N. Espinoza, M. Bongiorno and O. Carlson, “Frequency Characterization of Type-IV Wind Turbine Systems,” in 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016.