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EMT Model Validation of DFIG Wind Turbine Using Full-Scale Electrical System Lab Tests

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SUMMARY

The objective of this report is to benchmark the Electromagnetic Transient (EMT) unit model for a GE DFIG type 3 onshore wind turbine with measurements from the lab tests and validate the fidelity of the model to the actual hardware performance. The benchmarking tests are conducted in state-of-art lab facilities, designed to test the response to both small and large-signal disturbances utilizing a multi-megawatt programmable voltage source used as a grid simulator. Various disturbance tests have been performed in both the EMT simulation environment and on the full-scale wind turbine electrical hardware in the lab. The results from the following tests have been presented in this paper:

- Large voltage disturbance Voltage Ride Through (VRT) tests at multiple grid strengths
- Sub-synchronous impedance characterization

KEYWORDS

Onshore Wind Turbine, Model Validation, Model Benchmarking, EMT model, Small signal stability, Large-signal stability, Voltage ride-through, Sub-synchronous Impedance

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1. INTRODUCTION

The grid transformation toward integration of more carbon neutral energy resources and the challenges associated with increasing penetration of Inverter Based Resources (IBR), has driven a fast and ongoing evolution in the IBR technologies. Due to the increasing complexity of the control algorithms and electrical hardware design to overcome these challenges, more complex and detailed analysis is often required for IBR plant interconnection studies and performance evaluations. Electromagnetic Transient (EMT) analysis has proved to be the most accurate tools to perform detailed studies capturing the full range behavior of the IBR plant and potential interactions with other components of the grid, including the adjacent IBR facilities.

The objective of this paper is to benchmark the EMT model of a GE DFIG onshore wind turbine unit with measurements from lab tests and validate the fidelity of the model against the actual hardware performance. The benchmarking tests are conducted in a state-of-art lab facilities, designed to test the response to both small and large-signal disturbances utilizing a multi-megawatt grid simulator.

2. LIMITATIONS AND ADVANTAGES OF DIFFERENT MODEL BENCHMARKING METHODS

The backbone of any reliable design evaluation is a validated IBR unit model that gives an accurate estimation of the IBR behavior when subjected to a wide range of grid events and operating conditions. To ensure the accuracy of the EMT models, the model simulation results are needed to be benchmarked against the actual hardware performance. Various model validation practices have been used in recent years to this end, including field (container) tests, Real Time Digital Simulator (RTDS) tests, and full-scale hardware lab tests. Although field tests are currently the most commonly available way for model benchmarking, the measurement results are often impacted by the events and operating conditions of the utility grid where the IBR is connected to. It could become extremely challenging to account for all the events and variations of the grid operation when benchmarking the simulation model against the field measurements. In addition, for some disturbance tests such as impedance characterization, the IBR unit needs to be connected to a controllable voltage/current source, thus only feasible to be performed in the lab. The RTDS based model benchmarking provides a more controlled environment for model benchmarking tests but is often limited to merely including the control system hardware rather than the entire electrical system. Previous experiences with model EMT benchmarking have shown that the most crucial part of the simulation model uncertainties in fact come from the hardware component models (e.g. transformers, filters, generator machine in wind turbines, etc) [1] that cannot be benchmarked using RTDS. Thus, the full-scale IBR unit lab testing is the most reliable and accurate method, especially for EMT model benchmarking.

3. LAB SETUP AND EMT SIMULATION MODEL

The lab testing facilities utilize a grid simulator (power-electronics controlled voltage source) which can be used to test the wind turbine in various configurations and operating conditions. The grid simulator is a multi-Megawatt programmable voltage source, consisting of a 20 MVA cascaded H-bridge converter, large enough to test a full-scale wind turbine electrical hardware in transient condition while subjected to wide range of small-signal and large signal disturbance types and durations. In addition, the grid simulator is capable of emulating virtual impedance, facilitating testing the unit at various grid strengths. Figure 1 shows a schematic diagram of the grid simulator lab setup and the wind turbine hardware used for the tests and measurements.

Corresponding test cases are set up in the PSCAD EMT simulation platform, using the turbine-level black-box model. The standard graphical user interface of the EMT black-box model is shown in Figure 2 as an example. The simulation is configured to match lab test conditions such as wind turbine converter control parameters, operating point of the wind turbine, test circuit impedances, and grid disturbance type and duration. The set up includes the full-scale electrical hardware of the turbine. The wind control and mechanical details of wind turbine, turbine control and wind plant level controller function are not included in this paper.

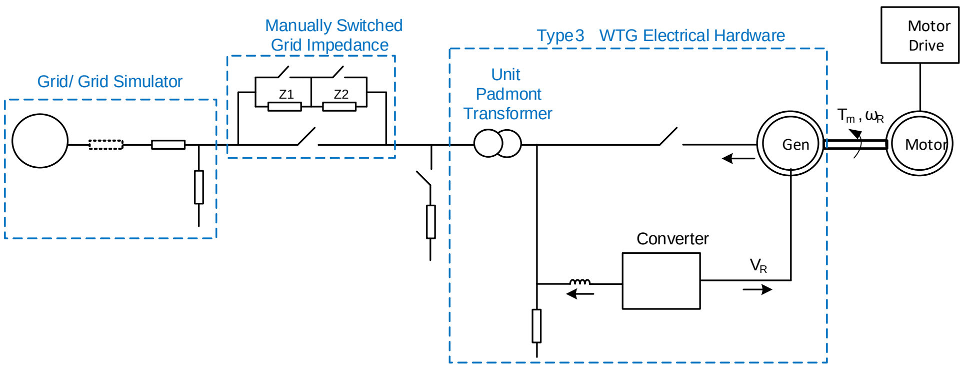

Figure 1. Schematic diagram of the GE lab test facilities

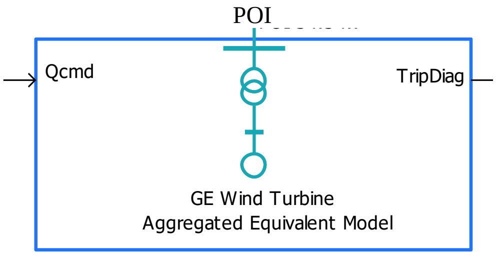

Figure 2. Example of PSCAD user-interface of GE turbine-level blackbox model

4. MODEL BENCHMARKING

The results from various disturbance tests in both the EMT simulation environment and the full-scale turbine electrical lab measurements have been performed in section with the aim to validate the model response with the lab measurement for both large-signal and small-signal disturbances.
In the first step after performing the lab tests, the control parameters are matched between the EMT model and the unit in the lab. A representation of the grid simulator and the lab test setup is included in the EMT simulation environment in addition to the wind turbine unit model. The pre-disturbance steady-state operating point including terminal voltage, active and reactive power outputs is closely aligned between the simulation model and the lab measurements in all cases. Furthermore, the simulations have been configured to closely match the disturbance type, duration and point-on-wave at inception and clearance of the disturbance performed in the lab.

I. Large Voltage Disturbance

Three-phase High Voltage Ride Through (HVRT), Low Voltage Ride Through (LVRT), and three phase and line to line Zero Voltage Ride Through (ZVRT) tests have been conducted under strong grid (SCR = 60) and weak grid (SCR = 1.7) conditions in both lab and EMT simulation setups to benchmark the EMT model fidelity against lab measurements. The results for the benchmarking tests are presented in Figure 3. For all the tests, the unit is initialized to the same target pre-disturbance operating point at rated power, rated speed, and near unity power factor. The instantaneous voltage is shown in the first three plots, followed by the rms voltage, active power, and reactive power in each case. All quantities are measured at the high voltage terminals of the turbine transformer.
It can be observed from the plots in Figure 3 that the EMT model and the lab results match closely in all large voltage disturbance tests.

II. Sub-synchronous Impedance Characterization

Sub-synchronous control interaction (SSCI) is a phenomenon including the interaction of fast power-electronic converter controls with series-compensated transmission systems. The main purpose of sub-synchronous impedance characterization is to derive the equivalent resistance and reactance of the wind turbine to be used in system level small-signal stability analysis performed at the wind plant point of interconnection to quickly identify potential resonance modes, and subsequently SSCI risk, for various grid contingencies [2].

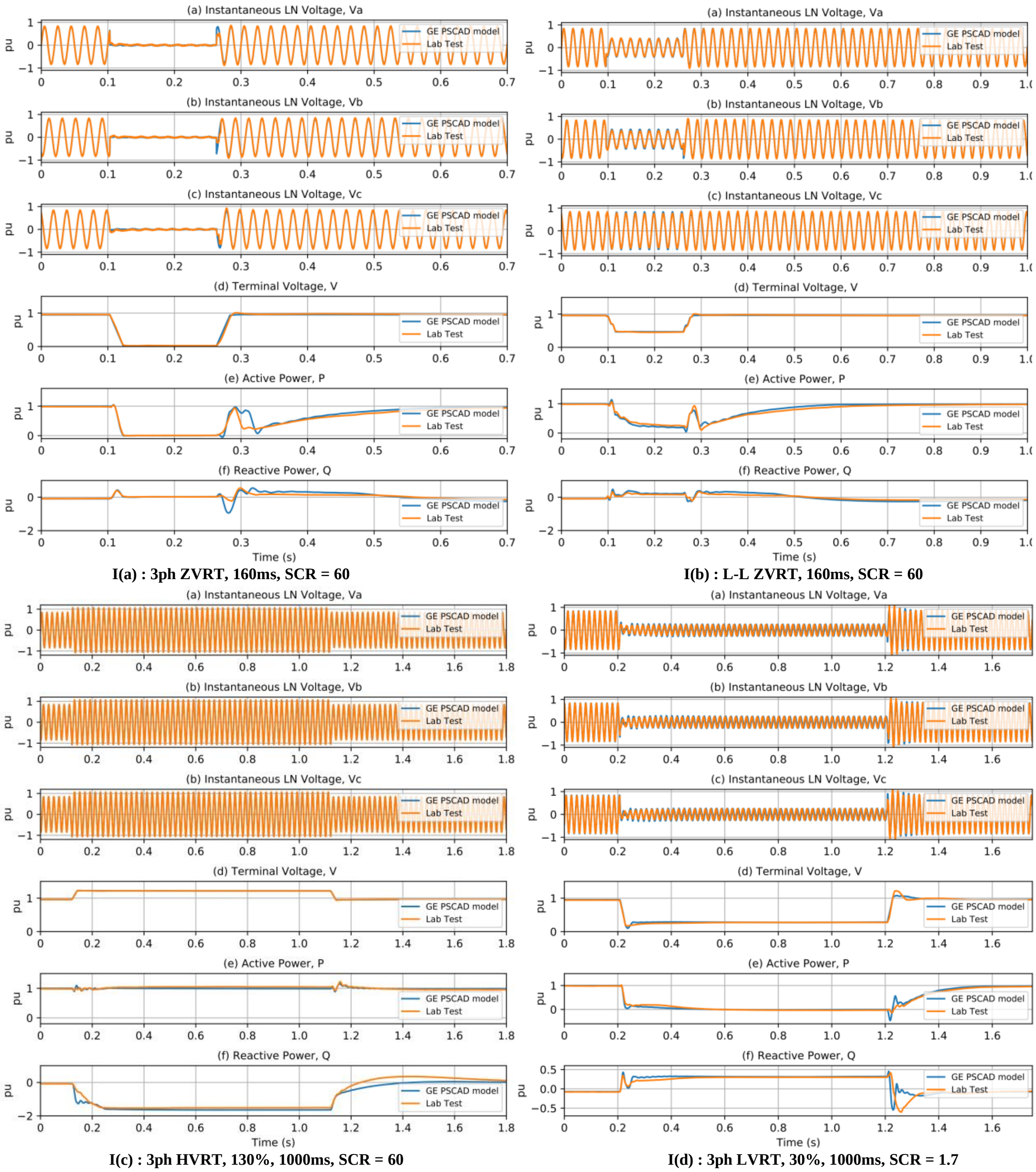

Figure 3 –EMT model benchmarking results for large voltage disturbance tests

To validate the fidelity of the model for small signal disturbance, sub-synchronous impedance tests have been performed in the 5 to 40 Hz range with 1 Hz steps with the turbine operating at 100% power output and unity power factor, in both lab and EMT simulation setups. For these tests, the grid simulator is directly connected to the wind turbine and the test setup SCR at the turbine terminal is approximately 60.

The frequency scan methodology and principles used to obtain the sub-synchronous impedance of the turbine are very similar in the lab and the simulation environment [3]. A simple test circuit setup is created in the simulation tool similar to the test setup as illustrated in Figure 5. The setup includes the DFIG generator and converter connected to an equivalent model of the grid including a programmable voltage source and the grid impedance.

The sub-synchronous impedance for a specific frequency f is derived by adding a three-phase voltage test signal with the frequency f and small amplitude on top of the nominal fundamental frequency grid voltage V_{Grid}. A separate simulation is done for each frequency. The terminal voltage (V_{WTG}) and current (I_{WTG}) of the wind turbine in each test for a specific frequency is obtained through lab measurement or simulation (Figure 4). The f Hz component of the terminal voltage V_{WTG}^{f} and terminal current I_{WTG}^{f} are obtained using post processing the V_{WTG} and I_{WTG} with fast Fourier transform (FFT). Finally, the impedance of the wind turbine generator (WTG) at sub-synchronous frequency f (Z_{WTG}^{f}) can be calculated as,

$$Z_{WTG}^{f} = \frac{V_{WTG}^{f}}{I_{WTG}^{f}}$$

where f is the sub-synchronous frequency ranging from 5 Hz to 40 Hz.

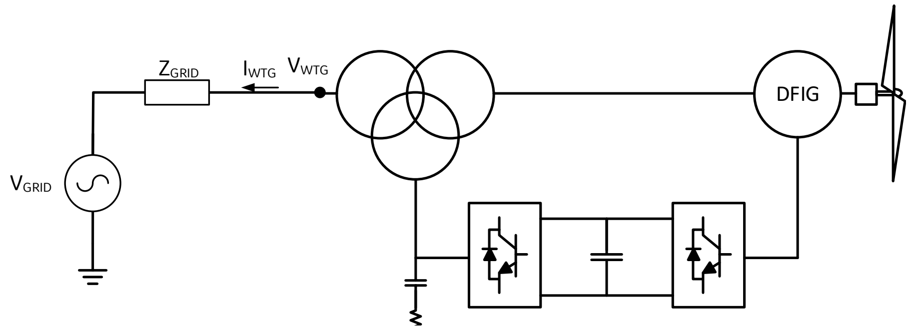

Figure 4 – Simulation and measurement setup for sub-synchronous impedance characterization

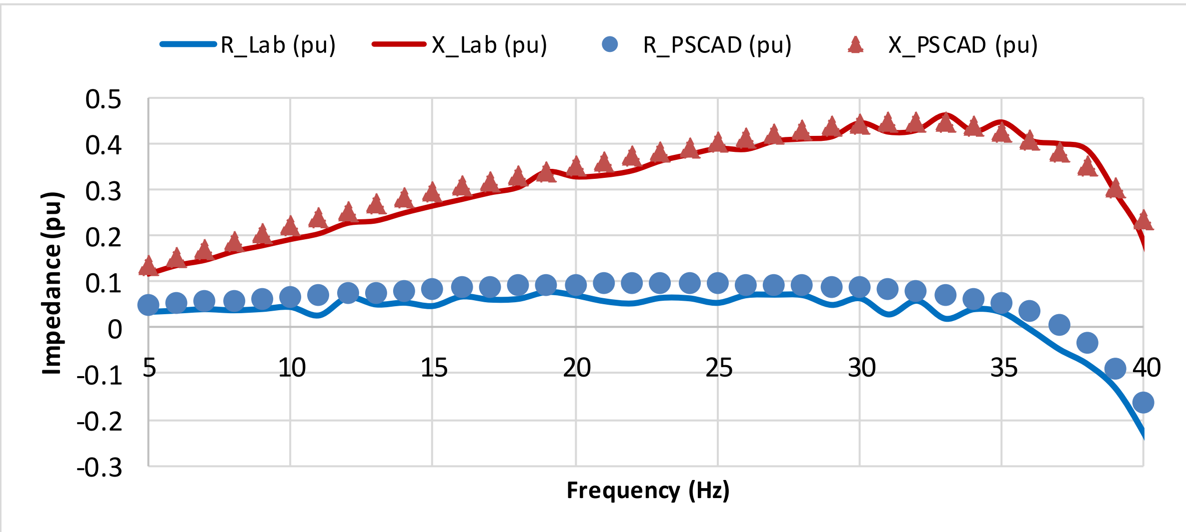

Figure 5 – Benchmarking results for sub-synchronous impedance characteristic

A comparison of the impedance results obtained from the lab test measurements and the EMT model simulations is presented in Figure 5. It can be observed that both resistance and reactance results show a very close match between the lab test and model over the entire target frequency range.

5. CONCLUSION

Multiple large and small disturbance tests have been conducted on a type 3 DFIG GE onshore wind turbine with the aim to benchmark the black-box EMT simulation model against the measurements obtained from a full-scale turbine electrical system set up in a state-of-art lab facility. The results from all test cases show a close matching between the simulation model and the lab measurement during the pre-disturbance steady-state operating condition, disturbance inception and clearance, transient behavior during and after the clearance of the disturbance and the new steady state reached after the disturbance clearance. Furthermore, the unit successfully rides through the large disturbances and stays online in all cases. The small signal behavior of the wind turbine EMT model for sub-synchronous frequency range has been successfully benchmarked against the lab measurements with the sub-synchronous impedance matching closely over the target frequency range.

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