MODEL VALIDATION AND VOLTAGE DEVIATION ANALYSIS OF AN EXISTING WIND FARM USING HIGH FIDELITY REAL TIME DIGITAL SIMULATION

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ABSTRACT

This paper reports on the validation of a high-fidelity transient model of an existing wind farm with directly grid connected fixed-speed induction generators implemented on a real-time digital simulator. The model will be used to test the controller hardware of a novel STATCOM, which is planned to be field-tested at the wind farm location, in a hardware-in-the loop setup. The model is described in detail, including the control system model implemented for a realistic replication of the wind farm operation. Comparisons of simulation results with field data, both at the steady state and during transients, are used for validation. In addition, the paper provides insight into the effect of aggregating a large number of turbines into a single equivalent model which is often necessary to reduce the computational burden associated with high fidelity transient simulations.

INTRODUCTION

Operating wind farms with fixed-speed induction generators (FSIGs) may pose challenges if the magnitude of the generation is over the surge impedance loading at the utility point of interconnection. In particular, excessive reactive power drawn by the wind farm, if not properly compensated by power factor correction measures, may cause significant voltage disturbances. Several standards and recommended practices exist for interconnecting and operating wind farms [1], [2]. However, real-life experience may demonstrate severe operating conditions, which require special measures to achieve proper voltage control. A 50 MW wind farm with FSIGs connected to the 69 kV distribution system of the Bonneville Power Administration (BPA) network, a utility in the northwest United States, exhibited such voltage regulation problems over an extended period of time.

Analysis of SCADA records revealed two distinct operating characteristics of the wind farm as illustrated in Figure 1. The record with 5 min resolution in August 2004 shows the real power to ramp up to nearly full capacity without any voltage problems for two days while on the third day the system experienced a voltage depression of almost 9%. Higher resolution data, taken every 2 seconds in 2006, further illustrates this behavior. Meanwhile, the origin of this behavior was attributed to a problem with the local control system operating the switched power factor correction capacitor banks installed at the wind farm substation.

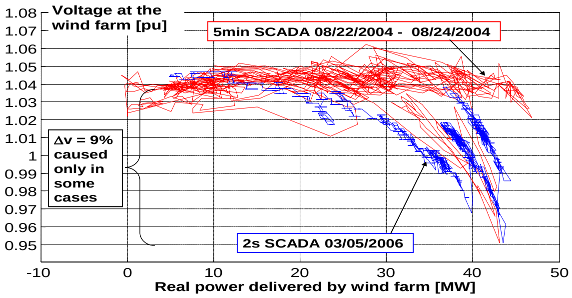

Figure 1 PV-characteristic of the wind farm from SCADA data

Due to the typical transient reactive power variations on FSIG wind farms this site was identified as a potential candidate location to install and field test a prototype of a novel STATCOM for more dynamic voltage control. It utilizes a new power electronic device, the Emitter Turn-Off thyristor (ETO), developed by North Carolina State University, for enhanced high-power switching performance, simplified triggering technology, and overall reduced device and system costs [3].

The main motivation for the work presented in this paper is the desire to develop a high fidelity transient simulation model of the wind farm in a real-time simulation environment, in this case an RTDS [4], to serve as a precursor for rigorous hardware-in-loop (HIL) simulation testing of the STATCOM controller. Especially with the introduction of new software and hardware in the RTDS [5] it becomes feasible to test controllers of self commutated converters which operate at switching frequencies of several kHz. Therefore, the model shall assist in such testing in the lab at the Center for Advanced Power Systems (CAPS) at Florida State University (FSU), Florida, USA. This unique facility includes a 14-rack RTDS installation which allows the simulation of a substantially large power system (756 electrical nodes) and its components (machines, transformers, cables, converters, controls) in real-time with typical time steps of 50 μs for the major portion of the system and typically 1.5 μs for power electronic converter sub-systems. The facility also includes an electric power test lab designed for controller HIL (CHIL) and power HIL (PHIL) testing of equipment up to 5 MW. A more detailed description of these CHIL and PHIL capabilities can be found in [6].

This paper first describes the wind farm model and specifics of implementation on the RTDS. Thereafter, preliminary simulation results are compared with field data for model validation. These results also reveal some of the issues associated with aggregation of a large number of FSIGs into a single machine equivalent. Such detailed comparisons requre a large number of simulations of the high fidelity model and become feasible only by utilizing the computational power of the RTDS or similar simulators.

HIGH-FIDELITY WIND FARM MODEL

Figure 2 shows the system layout which is used for developing the high fidelity model of the wind farm and the surrounding utility power system. A more elaborate 21-bus utility system model, similar to the 12-bus system described in [7], has initially been developed on the RTDS and validated against steady-state SCADA data. However, in the present model, only the most essential features of the utility system are represented by the 4-bus system (DM, CW, FS and MP) shown in Figure 2. It consists of two stiff voltage sources (ES_{DM} and ES_{MP}), their respective substation transformers (T_{DM} and T_{MP}), the 69 kV transmission lines, and two power factor correction capacitors (C_{aFS} and C_{bFS}) at the substation FS. Static PQ-loads (L_{DM}, L_{CW}, L_{FS}, L_{MP},) are applied so the system exhibits proper PV and QV sensitivities as observed with the 21-bus system. One of the locations planned for installation of the ETO based STATCOM is indicated in Figure 2. Some relevant model parameters of the system used in this study are given in Table 1.

A transformer (T_{CW}) connects the utility CW bus to the wind farm main bus (WF). There, eight power factor correction capacitors ($C_1 \ldots C_8$) are switched by vacuum breakers automatically to maintain the WF bus voltage at the nominal value of 34.5 kV. The individual wind power generation units are represented by their unit transformer (TT_i), a soft starter (SS_i), a pole-switched induction generator ($FSIG_i$) and a wind turbine model that include generic pitch control and typical turbine aerodynamic characteristics. The mechanical aspects of the turbines were modelled broadly according to [8]. Each unit is also equipped with two capacitors (C_{aTi} and C_{bTi}). During low speed (6-pole) operation of the FSIG, only C_{aTi} is turned on while in high speed (4-pole) operation both capacitors are switched in. The actual layout of the wind farm is closely represented by connecting the units through underground cabling. It provides approximately 2 MVAr of reactive power support through shunt capacitance.

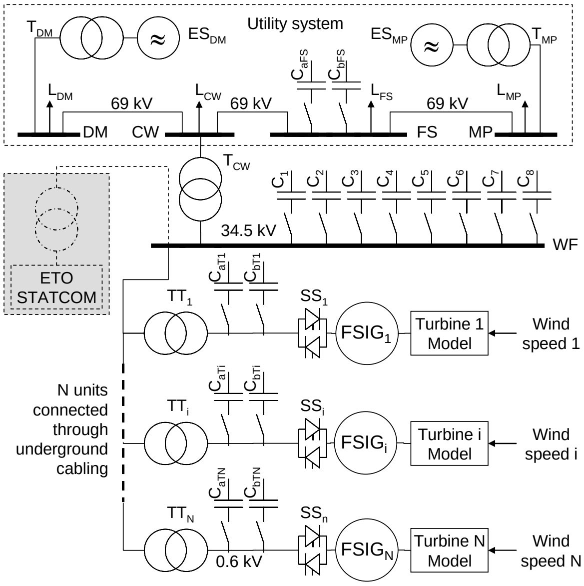

Figure 2 System layout used for RTDS model

Table 1 Significant system parameters

Item	Parameter	Value	Unit
T_{CW}	Rated power Impedance	50 7.6	MVA % @ 30 MVA
C_{aFS}, C_{bFS}	Rated power	2.75	MVAr
69 kV lines	Length	180	km
C_1, C_2	Rated power	2	MVAr
$C_3 \ldots C_8$	Rated power	1	MVAr
C_{aTi}, C_{bTi}	Rated power	90	kVAr
$FSIG_i$	Rated power No of poles	660 4 or 6	kW -
TT_i	Rated power Impedance	650 5.75	kVA %

Specifics of the RTDS implementation

Due to the real-time constraints, the size of one electrically closely coupled sub-system that can be simulated on one RTDS rack is limited [4]. Considering all the modelling details contained within one individual wind power generation unit, including the necessity to implement two FSIG models per generation unit to account for the pole-switched machines, a maximum of four units could be modelled per RTDS rack. Therefore, the wind farm was represented by a maximum of 40 units, each scaled by a factor of 2.075 to account for the 83 units actually in the field. This leaves 4 racks for the representation of the utility system and the STATCOM system. The model is constructed with maximum flexibility in the scripted input of parameters to allow for fast re-scaling of the units to investigate further model aggregation ($N < 40$).

In order to avoid excessive inrush currents from individual turbine start-up, thyristor based soft starters are installed at each unit. Since the purpose of this model is to realistically reproduce transients of the real-time wind farm operation it became necessary to model the soft starters in sufficient detail (i.e. with six individual switches per generation unit). In the absence of on-site wind speed data for this study, typical wind speed data based on a notional wind farm layout was created synthetically according to [9] with 1 s time resolution for realistic representation of operating conditions.

Overall control of the wind farm operation

All the essential control functions of the wind farm such as the pole-switching of the FSIGs, the ramp-rates of the soft starter and the controls for the three different levels of power factor correction capacitors are included in the model. Due to the page limit of this paper only the salient characteristics of these controls are described. A turbine goes on-line in 6-pole mode when the average wind speed exceeds 3.5 m/s. When the FSIG reaches 1100 rpm the soft starter engages and smoothly connects the machine to the grid. At the same time, one local capacitor bank (C_{aTi}) is switched in. If the wind speed exceeds 8 m/s for at least 10 minutes the FSIG switches to 4-pole mode. This requires a sequence of pitching the blades out (to remove torque), disconnecting the FSIG from the grid, speeding up the turbine by pitching the blades back in, and finally re-energizing the FSIG with the soft starter. In this mode, both unit capacitor banks (C_{aTi} and C_{bTi}) are connected.

The capacitor banks at the wind farm bus (WF) are switched in when the WF-bus voltage drops below 1 pu and disconnect again at 1.03 pu. Each of the two utility capacitors (C_{aFS} and C_{bFS}) only switch in when the bus voltage at FS drops below 0.96 pu They disconnect again at 1.04 pu. While the SCADA data in Figure 1 shows C_{aFS} and C_{bFS} coming on line they are not intended for reactive power support of the wind farm under normal operating conditions.

MODEL VALIDATION AND AGGREGATION

Validating the model is of great importance to this project since the model eventually will be used to test and tune a real STATCOM controller in the CHIL setup. Therefore, steady-state SCADA data as well as data from a transient recorder temporarily installed at the wind farm is used for comparisons. In addition, a first attempt to study the effect of aggregating a large number of turbines is illustrated. To represent the most extreme case all 40 turbine units were lumped into a single equivalent by appropriately scaling the parameters of the turbines, the FSIGs (4-pole mode only), the unit transformers, the unit capacitors and the capacitance of the cabling. In the following paragraphs the detailed model ($N = 40$) is called Mod40 while the aggregated model is called Mod1.

Steady state results

Figure 3 shows the comparison between steady-state results obtained with Mod40 and Mod1, and 2 s time resolution SCADA data. A case was selected where the WF-bus capacitor control malfunctioned and the wind farm drew excessive reactive power at high real power output (see also Figure 1). As a consequence, the two utility FS substation capacitors (C_{aFS} and C_{bFS}) switched in. This behavior was included in the model Mod40.

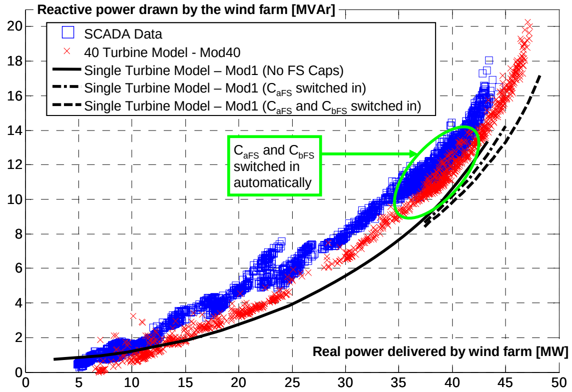

Figure 3 Comparison of results from two models with SCADA data

With Mod1 two additional curves show the characteristics with either C_{aFS} or both, C_{aFS} and C_{bFS}, turned on. The differences between Mod1 and Mod40 originate first in the non-uniform wind speed distribution in Mod40 and second in small discrepancies in the impedances caused by network reduction. These results demonstrate the advantages of representing the wind farm with 40 units. In particular for this project since even small differences in reactive power cause relative large voltage deviations on the utility network under study.

Dynamic and transient results

Figure 4 shows the results obtained with the model Mod40 during two subsequent wind farm capacitor switching operations. It compares well with the RMS value of the instantaneous voltages captured at bus CW. In particular, the relatively slow increase in voltage within approximately 1 s due to the dynamic interactions between the FSIGs and the grid is clearly visible.

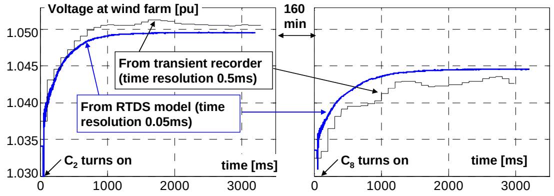

Figure 4 Comparison of RTDS model results with transient recorder data

Finally, Figure 5 compares transient results from the two models during a simulated fault on the utility system resulting in a severe voltage dip on the wind farm. Such an event could normally cause the wind farm to disconnect from the grid which was not simulated in this case. The voltage recoveries (RMS values) of the two models are similar in shape but of different magnitude, as expected. The inset, showing instantaneous bus voltages, further illustrates the fidelity of the model. While the initial operating conditions of the wind farm are the same in both models, those of the individual turbines are not as seen from the plot of selected turbine speeds. More significant deviations are expected when additional details of the mechanical drive train, such as shaft and gear box stiffness, are included in the model.

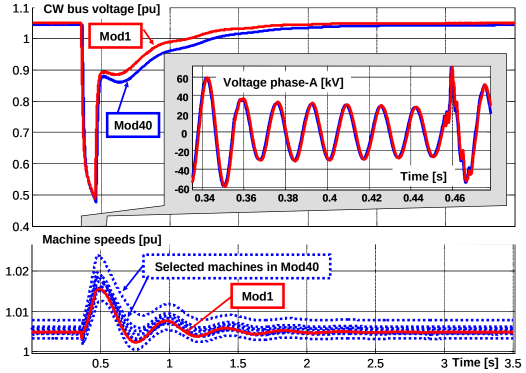

Figure 5 Comparison of bus voltage and turbine speeds during fault transient

CONCLUDING REMARKS

This paper reports on the validation of a high-fidelity transient model of a wind farm implemented on the real-time digital simulator (RTDS). Comparisons of results with field data demonstrate not only the validation process but provide insight into the effect of aggregating turbines into a single equivalent. In the future, the power electronics of the STATCOM will be included in the model to facilitate the CHIL tuning and testing of its controller hardware. In addition, model aggregation will be investigated further.

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