

Modeling and Real-Time Simulation of a Doubly-Fed Induction Generator Driven by a Wind Turbine

Richard Gagnon, Gilbert Sybille, Serge Bernard, Daniel Paré, Silvano Casoria, Christian Larose

Abstract—This paper presents the modeling and real-time simulation of a doubly-fed induction generator driven by a wind turbine in large power systems. The Matlab/Simulink/SimPowerSystems software is used to develop the model for simulation of electromagnetic transients in power systems. The code generated by the Real-Time Workshop of Simulink is linked to the Hypersim digital real-time simulator. A case study example of real-time simulation of wind turbines in a generic series-compensated power system is presented.

Keywords: Doubly-Fed Induction Generator, Wind Turbine, Modeling, Real-Time Simulation, Power Systems, Electromagnetic Transients

I. INTRODUCTION

MASSIVE use of wind turbines in large power systems is becoming a reality. Modern wind turbines use complex technologies including power electronic converters and sophisticated control systems. Electromagnetic transients in power systems need to be simulated and analyzed in order to study the impact of these new power generators on the power systems. Methods and tools for simulation (either fast or real-time) of wind turbines in large power systems are therefore needed. Real-time simulation is also required for field and in-plant testing in order to evaluate performance of control and protection systems.

This paper presents the modeling and real-time simulation of a generic wind-turbine doubly-fed induction generator (WT_DFIG) in a power system [1,2,3]. Matlab/Simulink software is used to develop the WT_DFIG model. The generated code of the Simulink model is linked to the Hypersim digital real-time simulator [4] in order to simulate the power system together with wind turbines.

The paper is divided into three parts. The Matlab/Simulink model is developed in the first part. The implementation of the model in Hypersim is presented in the second part. The third part presents a case study of real-time simulation of wind turbines in a generic power system.

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II. MODELING OF THE WIND-TURBINE DOUBLY-FED INDUCTION GENERATOR

The Simulink discrete-time WT_DFIG model, presented here, is based on the Wind Turbine Doubly-Fed Induction Generator (Phasor Type) available in version 4.0 of Matlab/SimPowerSystems library [5].

The wind turbine and the doubly-fed induction generator are shown in Fig. 1. The AC/DC/AC converter is divided into two components: the rotor-side converter (C_{rotor}) and the grid-side converter (C_{grid}). C_{rotor} and C_{grid} are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source. A coupling inductor L is used to connect C_{grid} to the grid. The three-phase rotor winding is connected to C_{rotor} by slip rings and brushes and the three-phase stator winding is directly connected to the grid.

The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals V_r and V_{gc} for C_{rotor} and C_{grid} respectively in order to control the power of the wind turbine, the DC bus voltage and the voltage at the grid terminals.

An average model of the AC/DC/AC converter is used for real-time simulation [6]. In the average model power electronic devices are replaced by controlled voltage sources. V_r and V_{gc} are the control signals for these sources. The DC bus is simulated by a controlled current source feeding the DC capacitor. The current source is computed on the basis of instantaneous power conservation principle: the power that flows inside the two AC-sides of the converter is equal to the power absorbed by the DC capacitor. With the average model, the high frequency components of the voltage, generated by the PWM switching of electronic devices, are not simulated. This allows to simulate with a relatively large sample time (typically 44 μ s), which is about ten-times larger than would be required to simulate PWM switching.

A. Operating principle of the wind-turbine doubly-fed induction generator

The power flow, illustrated in Fig. 2, is used to describe the operating principle. Parameters used in this figure are described in Table I.

The mechanical power and the stator electrical power output are computed as follows:

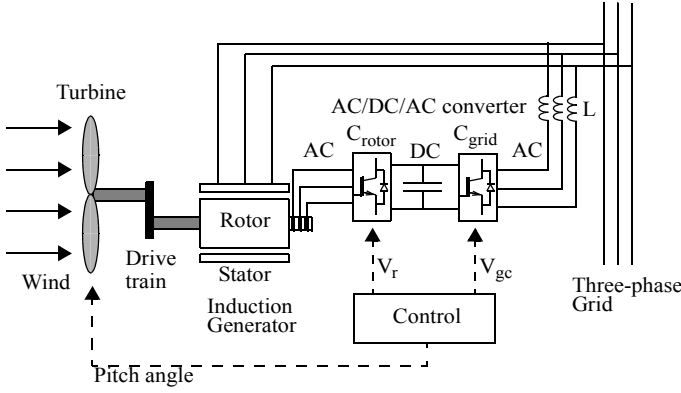


Fig. 1. The wind turbine and the doubly-fed induction generator system

$$P_m = T_m \omega_r \quad (1)$$

$$P_s = T_{em} \omega_s \quad (2)$$

For a lossless generator the mechanical equation is:

$$J \frac{d\omega_r}{dt} = T_m - T_{em} \quad (3)$$

In steady-state at fixed speed for a lossless generator

$$T_m = T_{em} \text{ and } P_m = P_s + P_r \quad (4)$$

It follows that:

$$P_r = P_m - P_s = T_m \omega_r - T_{em} \omega_s = -s P_s \quad (5)$$

where $s = (\omega_s - \omega_r)/\omega_s$ is defined as the slip of the generator.

Generally the absolute value of slip is much lower than 1 and, consequently, P_r is only a fraction of P_s . Since T_m is positive for power generation and since ω_s is positive and constant for a constant frequency grid voltage, the sign of P_r is a function of the slip sign. P_r is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super-synchronous speed operation, P_r is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage. C_{grid} is used to generate or absorb the power P_{gc} in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter P_{gc} is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by C_{rotor} . The power control will be explained below.

The phase-sequence of the AC voltage generated by C_{rotor} is positive for sub-synchronous speed and negative for super-synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip.

C_{rotor} and C_{grid} have the capability for generating or absorbing reactive power and could be used to control the

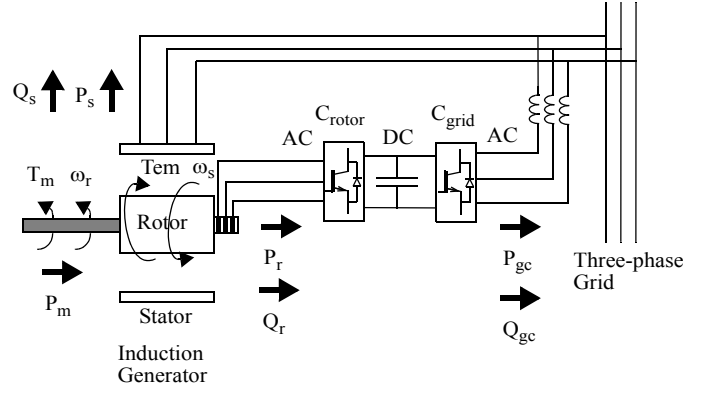


Fig. 2. Active and reactive power flows

reactive power or the voltage at the grid terminals.

TABLE I
PARAMETER DEFINITIONS

P_m	Mechanical power captured by the wind turbine and transmitted to the rotor
P_s, Q_s	Stator active and reactive power output
P_r, Q_r	Rotor active and reactive power output
P_{gc}, Q_{gc}	C_{grid} active and reactive power output
T_m	Mechanical torque applied to rotor
T_{em}	Electromagnetic torque applied to the rotor by the generator
ω_r	Rotational speed of rotor
ω_s	Rotational speed of the magnetic flux in the air-gap of the generator. This synchronous speed is proportional to the frequency of the grid voltage and to the number of generator poles.
J	Combined rotor and wind turbine moment of inertia

B. C_{rotor} control system

The rotor-side converter is used to control the wind turbine output power and the voltage measured at the grid terminals.

The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. This characteristic is illustrated by the ABCD curve in Fig. 3 superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine ω_r is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power

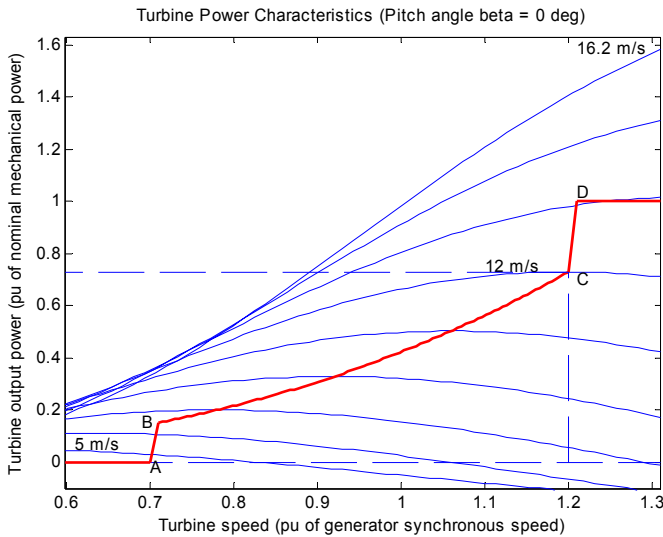


Fig. 3. Turbine characteristics and tracking characteristic

vs turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit (1 p.u.). Beyond point D the reference power is a constant equal to one per unit (1 p.u.).

The generic power control loop is illustrated in Fig. 4b). For the rotor-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with air-gap flux. The actual electrical output power, measured at the grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic. A Proportional-Integral (PI) regulator is used to reduce the power error to zero. The output of this regulator is the reference rotor current I_{qr_ref} that must be injected in the rotor by converter C_{rotor} . This is the current component that produces the electromagnetic torque T_{em} . The actual I_{qr} component is compared to I_{qr_ref} and the error is reduced to zero by a current regulator (PI). The output of this current controller is the voltage V_{qr} generated by C_{rotor} . The current regulator is assisted by feed forward terms which predict V_{qr} .

The voltage at grid terminals is controlled by the reactive power generated or absorbed by the converter C_{rotor} . The reactive power is exchanged between C_{rotor} and the grid, through the generator. In the exchange process the generator absorbs reactive power to supply its mutual and leakage inductances. The excess of reactive power is sent to the grid or to C_{rotor} . The generic control loop is illustrated in Fig. 4b).

The wind turbine control implements the V-I characteristic illustrated in Fig. 5. As long as the reactive current stays within the maximum current values ($-I_{max}$, I_{max}) imposed by the converter rating, the voltage is regulated at the reference voltage V_{ref} . A voltage droop is used for the V-I characteristic shown on Fig. 5 (3% at maximum reactive power output).

C. C_{grid} control system

The converter C_{grid} is used to regulate the voltage of the DC bus capacitor. The control system is illustrated in Fig. 4c). For

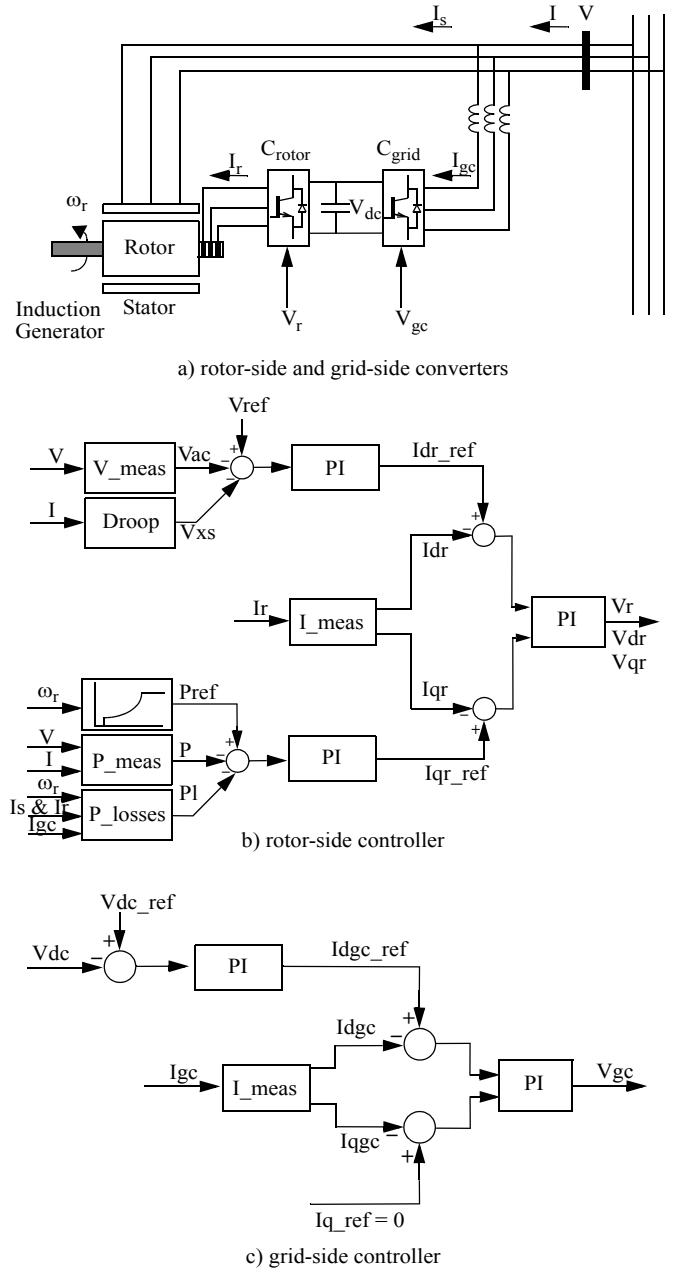


Fig. 4. Rotor-side and grid-side converters and control systems

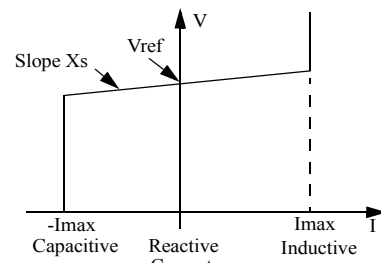


Fig. 5. Wind turbine V-I characteristic

the grid-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with the positive-sequence of grid voltage. This controller consists of:

- 1- a measurement system measuring the d and q components of AC currents to be controlled as well as the DC voltage V_{dc}
- 2- an outer regulation loop consisting of a DC voltage

regulator. The output of the DC voltage regulator is the reference current I_{dgc_ref} for the current regulator (I_{dgc} = current in phase with grid voltage which controls active power flow).

3- an inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by converter C_{grid} (V_{gc}) from the I_{dgc_ref} produced by the DC voltage regulator and specified I_{q_ref} reference. The current regulator is assisted by feed forward terms which predict the C_{grid} output voltage.

D. Pitch angle control system

The pitch angle is kept constant at zero degree until the speed reaches point D speed of the tracking characteristic. Beyond point D the pitch angle is proportional to the speed deviation from point D speed.

For electromagnetic transients in power systems the pitch angle control is of less interest. The wind speed should be selected such that the rotational speed is less than point D speed.

E. Turbine model

The turbine model is the one provided in the Matlab/SimPowerSystems library [5].

III. HYPERSIM IMPLEMENTATION

The Simulink model of the WT_DFIG has four inputs and three outputs. The inputs are the wind speed and the three phase-to-ground voltages at the bus bar of the WT_DFIG. The outputs are the three line currents absorbed by the WT_DFIG.

In Hypersim, the WT_DFIG is modeled by a three-phase controlled current source connected between the ground and the bus bar of the WT_DFIG. This current source is controlled by the current output of the WT_DFIG Simulink model.

The C code of the WT_DFIG model is generated by the Real-Time Workshop of Simulink. Then it is included in Hypersim using a «Simulink block» of the SYSTEM TOOLS palette [7].

IV. CASE STUDY

The case study illustrates three 750 MW wind farms connected to a transmission system with a total of 25000 MVA of hydro power generation (Fig. 6). Each wind farm is simulated by a single wind turbine block with the appropriate ratings of generator (835 MVA), turbine (750 MW) and converter (375 MVA). The capacitance value of the DC link is related to the WT_DFIG rating and to the DC link nominal voltage. The energy stored in the capacitance (in joules) divided by the WT_DFIG rating (in VA) is a time duration which is usually a fraction of a cycle at nominal frequency. In this particular case this time duration is 4.3 ms (0.26 cycle at 60 Hz). The corresponding capacitance is 5F (10000 μ F is a typical value for a 1.5 MW wind turbine). The DC link nominal voltage is 1200 V. The stiffness of the drive train is infinite (torsion modes not simulated) and the friction factor and the inertia of the turbine are combined with those of the generator. The inertia constant is $H = 5.4$ s.

The wind farms are connected to a 735 kV radial power system divided into three geographical zones (North-West, North-East and South-West) and including five identical (13.8 kV, 5000 MVA) synchronous generators and their regulators. The hydraulic plant models include detailed representation of turbine, generator, exciter, speed regulator and stabilizer. A total of fifteen transmission lines (distributed parameter models) are used to transmit power to two 25 kV loads (total $P = 19000$ MW, total $Q = 2500$ Mvar) in the South-West region. Most lines are series compensated (capacitive compensation from 18% to 47%). Shunt reactive power compensation is also used.

The Hypersim diagram of Fig. 6 is simulated in real-time using a SGI-Origin-350 supercomputer using seven processors MIPS R16k 800MHz, at a 44 μ s time step.

In steady-state the generator NW1 produces 3000 MW and the four others produce 3650 MW each. The wind speeds for each wind turbine are such that the North-West Wind Farm produces 544 MW at a speed of 1.2 p.u. (synchronous speed is 1 pu), the North-East Wind Farm produces 680 MW at a speed of 1.21 p.u. and the last one produces 230 MW at a speed of 0.9 pu.

Simulation results shown in Fig. 7, Fig. 8 and Fig. 9 illustrate the system response to a 6-cycle double-line-to-ground fault. The fault is applied at $t = 0.1$ s at SW7_4 bus and it is eliminated at $t = 0.2$ s. The three-phase voltage at bus bar SW7_4 and the A-phase voltage and current of the North-East Wind Farm are illustrated in Fig. 7. Fig. 8 shows a superposition of the speeds of the five synchronous generators (trace 1) and the speed of the three wind turbines. The DC bus voltages of each wind turbine are illustrated in Fig. 9.

Speeds of all synchronous generators and wind turbines recover after fault clearing. This particular power system configuration is therefore stable for this particular wind farm location.

Fig. 9 shows that the DC bus voltages of the wind turbines are strongly affected by the fault even if this one is far from the wind farms. This suggests that nearby faults should be simulated to study their impacts on the wind farms and also on the power system. In this case a model of the protection systems of the wind turbine, as a crowbar, should be developed and included in the Simulink model.

V. CONCLUSION

The modeling of a doubly-fed induction generator driven by a wind turbine has been described. The model is a discrete-time version of the Wind Turbine Doubly-Fed Induction Generator (Phasor Type) of Matlab/SimPowerSystems. The paper also describes the method used to include the model into the Hypersim digital real-time simulator for fast and real-time simulations of wind farms in large power systems. A case study illustrates the simulation of an unbalanced fault in a large power system including three wind farms.

Different wind turbine models and other power devices could be developed in Simulink and included in Hypersim for real-time simulation. Real-time simulation is required for field and in-plant testing and evaluation of equipment performance.

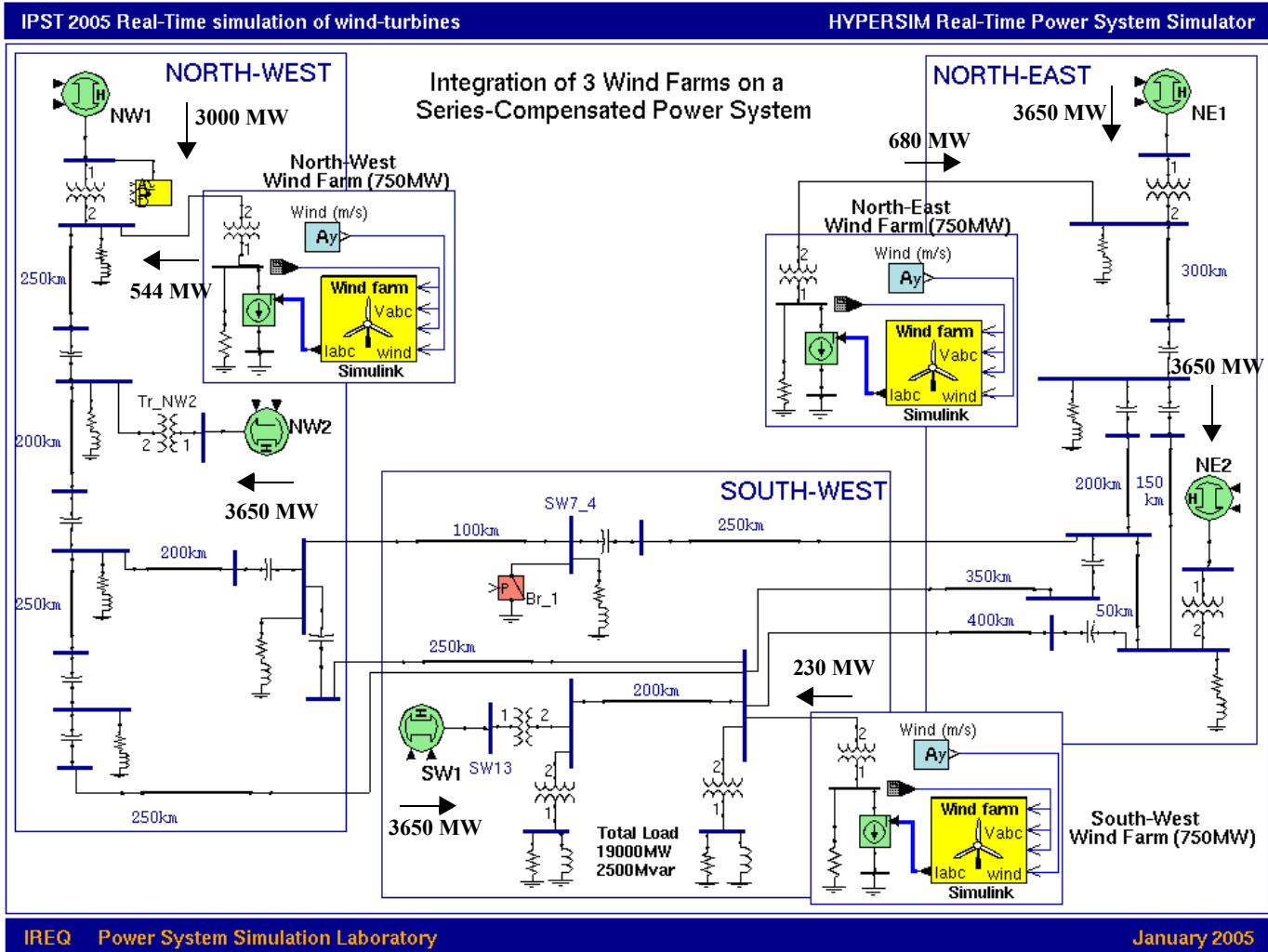


Fig. 6. Hypersim diagram of the power system with three 750-MW wind farms

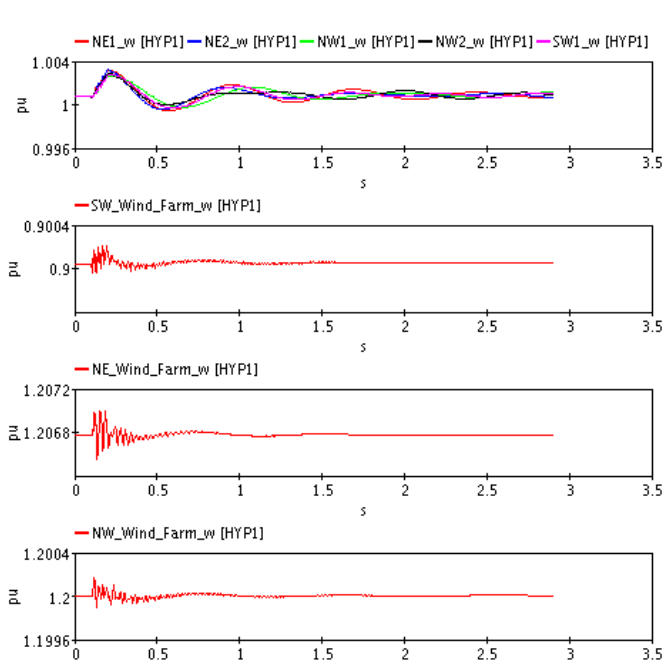


Fig. 8. Synchronous generator speeds and wind turbine speeds

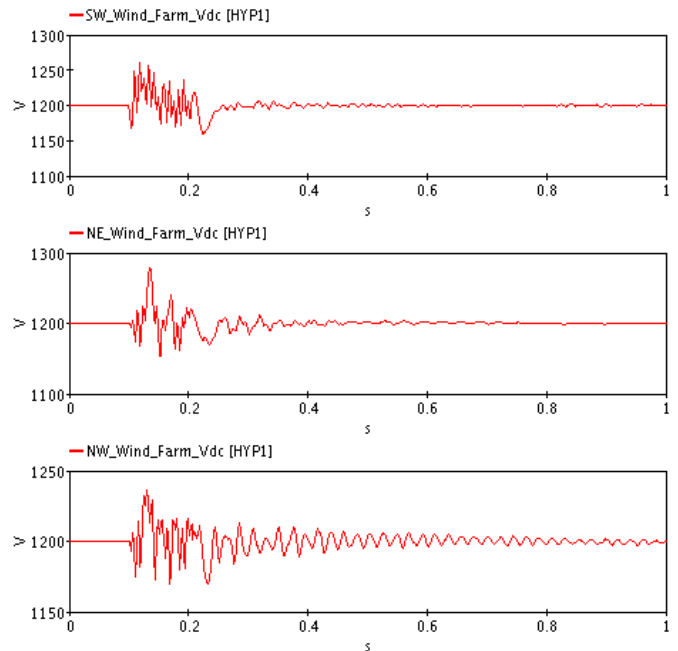


Fig. 9. DC bus voltages of each wind turbine

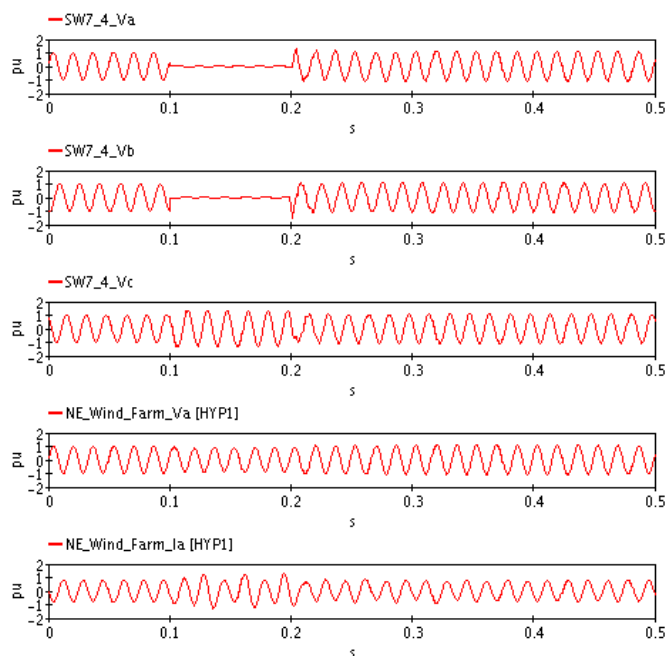


Fig. 7. Three-phase voltage at bus bar SW7_4 and A-phase voltage and current of the North-East Wind Farm

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VII. BIOGRAPHIES

Richard Gagnon was born in Québec, Canada in 1966. He obtained his B.Sc. degree in physics engineering in 1990, his M.Sc. degree in electrical engineering in 1992 and his Ph.D. degree in electrical engineering in 1997, all from Université Laval (Québec). Since 2001, he is with the Laboratoire Simulation de réseaux of Institut de Recherche d'Hydro-Québec as a research engineer. His area of professional interests includes modeling and simulation of power system devices and wind turbines. He is a beta tester and developer of several SimPowerSystems blocks, demos, and documentation. SimPowerSystems is jointly developed by The Mathworks and Hydro-Québec.

Gilbert Sybille obtained his electrical engineering degree in France in 1970 and his M.Sc. from Université Laval (Québec) in 1978. In 1978 he joined the

Laboratoire Simulation de réseaux of Institut de Recherche d'Hydro-Québec (IREQ) as a research engineer. He has been project leader in many simulation studies where he developed an expertise in real time testing of FACTS controllers. He has also developed various models and softwares for the IREQ's real time simulator. He is the technical leader and one of the main contributors in Power System Blockset which is jointly developed by The Mathworks and Hydro-Québec.

Serge Bernard received a B.S.C.A in electrical engineering in 1980 from Université Laval (Québec City), Québec. Since 1980, he has worked in system planning for Hydro-Québec where he has been involved in several projects concerning control, protection and special protection systems. He has established several criteria and practices for generation integration and distributed generation on Hydro-Québec network. Mr. Bernard is registered professional engineer in the province of Québec.

Daniel Paré obtained his B.Sc. degree in Electrical Engineering from Université Laval (Québec) in 1990. He joined the Institut de recherche d'Hydro-Québec (IREQ) in 1990. He has coordinated and realized several simulator studies related to HVAC, HVDC and FACTS. Currently he is performing power system study on the real-time numerical simulator. He is a member of Ordre des ingénieurs du Québec.

Silvano Casoria was born in Cairo, Egypt in 1953. He received the B.Eng. and M.Sc.A degrees in Electrical Engineering from École Polytechnique de Montréal in 1977 and 1981 respectively. Since 1981, he is with Institut de recherche (IREQ) at Hydro-Québec as a research engineer in the Laboratoire Simulation de réseaux. From 1988 to 1989, he was a trainee at ASEA Brown Boveri (ABB) plant in Ludvika, Sweden. During this period, he developed software subsystems implemented in the control and protection system for the Québec-New England HVDC multi-terminal transmission system. His area of professional interests include simulation and study of FACTS and HVDC transmission and control systems, model development in transient analysis programs like EMTF-RV, EMTDC, HYPERSIM, MATLAB, SPS.

Christian Larose received his B.Eng. degree in Electrical Engineering in 1995 and M.Sc. degree in 1998, both from École de Technologie Supérieure (ÉTS). He joined Institut de recherche d'Hydro-Québec (IREQ) in 1996 as a development engineer in the Power System Simulation Laboratory. His main interest is in the numerical real-time simulation of power systems.