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Large-Scale Real-Time Simulation of Wind Power Plants into Hydro-Québec Power System

Richard Gagnon, Gilbert Turmel, Christian Larose, Jacques Brochu, Gilbert Sybille, Martin Fecteau

***Abstract*-- This paper is a synthesis of the work done at Institut de Recherche d'Hydro-Québec for modeling and simulating wind power plants for power system studies. The electromagnetic transient model of a wind generator using a doubly-fed induction generator is presented. Modeling techniques for simulating large wind power plants are described. Model validation using field measurements and simulation study are presented. Real-time simulation of 25 aggregate wind power plants into the series-compensated Hydro-Québec power systems is finally presented and illustrates the feasibility of using large-scale electromagnetic transient simulations for power system studies.**

***Index Terms*—Wind generator, wind power plant, modeling, model validation, simulation, real-time simulation.**

I. NOMENCLATURE

WPP	wind power plant
WG	wind generator
IREQ	Institut de Recherche d'Hydro-Québec
DFIG	doubly-fed induction generator
POI	point of interconnection
EMT	electromagnetic transients
MATLAB/SPS	MATLAB/SimPowerSystems
HVDC	high voltage direct current
WFMS	wind farm management system

II. INTRODUCTION

BY 2015 Hydro-Québec will be carrying about 4000 MW of wind power over its transmission system. Integrating WPPs generation under optimal conditions requires extensive modeling and simulation. Modern WGs use sophisticated conversion systems including power electronics and advanced control systems. The diversity of actual WG technologies, the rapidity with which these technologies are developing and the difficulties to obtain technical data from WG manufacturers due to intellectual properties have for consequence that there is not any standard WG models for power system studies. Furthermore, WGs are generally grouped together to form WPPs. A typical large WPP may count several tens of WGs connected to a collector system comprising overhead lines and cables. Due to power computation limitations, it remains unrealistic to simulate each WG of each WPP of a power system. Simplified or aggregate models of WPPs are thus required for power system studies. A major research project on WPP modeling for Hydro-Québec power system studies was therefore undertaken at IREQ.

The project objectives were:

- To develop a model of a type-III WG (DFIG) for EMT studies
- To validate the model with field measurements
- To develop or validate methods to form aggregate models of WPPs for load flow, stability and EMT studies
- To validate the aggregate model of an actual WPP with field measurements
- To develop methods for large-scale EMT simulation of WPPs.

This paper is a synthesis of the work done in this project. Most of the topics presented here have already been published or are submitted for publication. Nevertheless, none has been published on the integration of the diverse methods and results issuing from this project for large-scale real-time simulation of WPPs in the EMT domain. This last achievement of the project is presented at the end of the paper.

Knowing that a huge number of simulations would be required to reach the project objectives we chose Hypersim simulator with MATLAB/SPS models of WGs as simulation environment. Hypersim is a fully digital simulator developed by Hydro-Québec for real-time and off-line simulation [1]. Hypersim can import the code generated from a MATLAB/Simulink model through the MATLAB Real Time Workshop (RTW) [2].

The paper is divided into four sections. The MATLAB/SPS models of WGs and the modeling techniques for simulating large WPPs with Hypersim are respectively presented in sections III and IV. Section V presents model validation. This includes validation of type-III WG and WPP models using on-line disturbance monitoring, validation of aggregation techniques for WPP modeling and generic equivalent collector system parameters for large WPPs. The last section presents the real-time simulation of 25 generic WPPs connected to a Hypersim 643-bus (3-phase bus) model of the Hydro-Québec power system. This simulation illustrates the feasibility of using EMT large-scale simulation for integrating wind power and to study possible interactions between series-compensated power system, real HVDC controls, and massive wind power generation.

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III. WIND GENERATOR MODEL

The Matlab/SPS model of the type-III WG is shown in Fig. 1. The AC/DC/AC converter is divided into two components: the rotor-side converter (Crotor) and the grid-side converter (Cgrid). Crotor and Cgrid 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 Cgrid to the grid. The three-phase rotor winding is connected to Crotor 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 transmitted to the drivetrain modeled as a two-mass system. The turbine model is illustrated in Fig. 2. Turbine and drivetrain parameters are given in [3]. The drivetrain mechanical power 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 systems in Fig. 3 to 5 generate the pitch angle command and the voltage command signals Uctrl_rotor and Uctrl_gc for Crotor and Cgrid respectively. These output signals are used to control the speed of the generator, the DC bus voltage and the reactive power at the grid terminals.

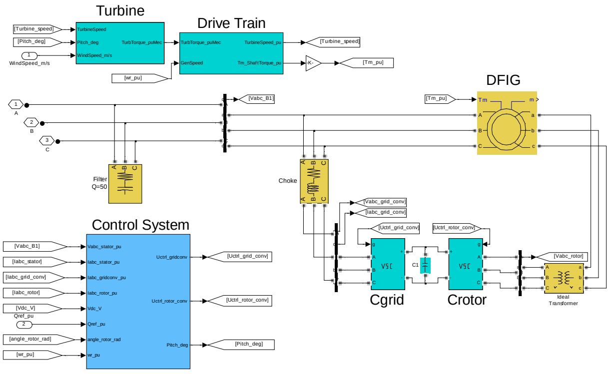


Fig. 1. Matlab/SPS model of the type-III WG

A. *Crotor control system*

The rotor-side converter controls the generator speed and the reactive power measured at the grid terminals. The speed regulator is illustrated in Fig. 3. The pitch and the pitch compensation control loops are also illustrated in the same figure. See [3] for more details.

The speed is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. The actual power Pmeas is measured at the grid terminals of the WG and the corresponding speed of the tracking characteristic is used as the reference speed for the speed regulator. The output of the regulator is the electromagnetic torque (Tem cmd) that must be generated by the generator.

Fig. 4 illustrates control of the electromagnetic torque and of the reactive power. The d-axis of the rotating reference frame, used for d-q transformation, is aligned with the positive-sequence of stator voltage using a phase-locked loop. The reference torque (Tem cmd) is divided by a scaled value of the q-axis flux of the generator in order to obtain the reference rotor current Id_ref that must be injected in the rotor by converter Crotor. The actual Id component is compared to Id_ref and the error is reduced to zero by a current regulator. The output of this current controller is the voltage Vdr that will be generated by Crotor.

As for the reactive power, it is measured at the grid terminals of the WG and it is compared to its reference value (Qref). The error is reduced to zero by an integral regulator (var regulator). Qref is the output of the wind farm management system (WFMS) that regulates the voltage at the POI of the WPP and the power system. The WFMS is not described in this paper. The output of the var regulator is the reference voltage Vref at the grid terminals of the WG. The actual voltage is regulated to its reference value Vref by an integral regulator. The output of this regulator is the rotor current Iq_ref that must be injected in the rotor by converter Crotor. The same current regulator as for the electromagnetic torque control is used to regulate the actual Iq component to its reference value. The output of the current controller is the voltage Vqr that will be generated by Crotor. The 3-phase voltage (Uctrl_rotor) of Crotor is obtained from a d-q to ABC transformation.

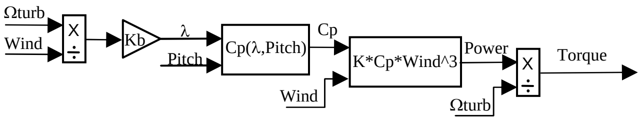


Fig. 2. Turbine model

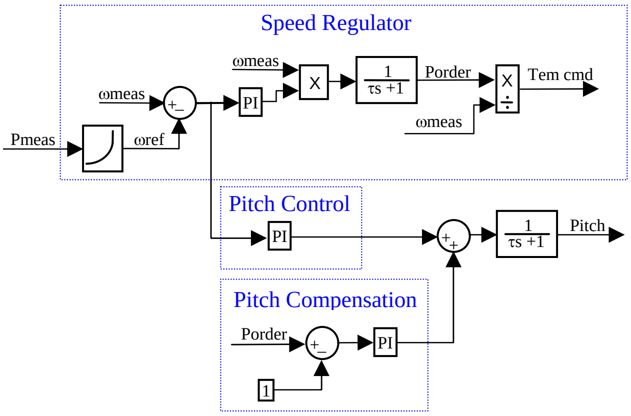


Fig. 3. Speed regulator, pitch control, and pitch compensation control loops

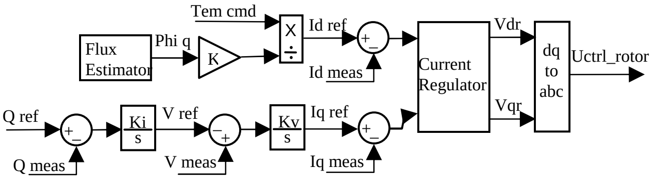


Fig. 4. Control system for rotor-side converter

B. *Cgrid control system*

The converter Cgrid is used to regulate the voltage of the DC bus capacitor and to keep grid converter reactive current to zero. The control system, illustrated in the Fig. 5 consists of a DC voltage regulator and a current regulator. The rotating reference frame used for d-q transformation is the same as for Crotor control system. The output of the DC voltage regulator is the reference current Id_ref for the current regulator. The current regulator controls the magnitude and phase of the voltage generated by converter Cgrid (Vgc) from the Id_ref produced by the DC voltage regulator and Iq_ref = 0.

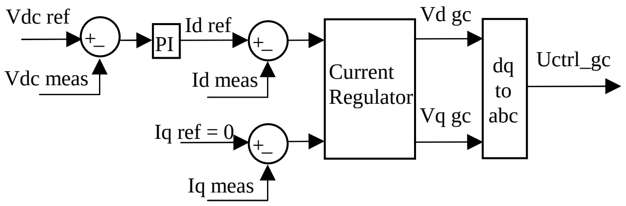


Fig. 5 Control system for grid-side converter

IV. MODELING TECHNIQUES FOR SIMULATING LARGE WWPS

A detailed EMT model of WPP, with all WGs represented with the collector system, is required to validate any aggregate model of WPP.

However, using traditional EMT simulation tools, it is unrealistic to simulate each WG of a large WPP since simulation time becomes extremely long as the network size and number of WGs increase. On the other hand, progress in simulator and supercomputer now allow real-time simulation of large networks using EMT models.

IREQ's real-time simulation expertise has been used to develop efficient modeling techniques for WPPs. As a result, a large WPP can now be simulated in detail, with each WG individually represented, in real-time or close to real-time. The resulting EMT simulation, performed on a parallel supercomputer, is fast enough to fulfill simulation needs in the time frame of EMT and transient-stability for validating aggregate model of WPPs. The next sections present a brief overview of the modeling techniques developed for large WPPs. More details are available in [4].

A. Modeling of power electronics in a wind generator

Modern WGs (type-III and IV) use power electronic converters with PWM switching frequencies in the 1- to 5-kHz range. The simulation of PWM switching is very demanding for EMT simulation, since each switching implies matrix manipulation that is very costly in computation time. Instead of using detailed switch model, two different approaches were implemented. These are identified as the average model and the switching-function model.

In the average model, the converter is represented by a 3-phase controlled voltage source. These sources are driven by the control voltages of the PWM converters. The capacitor voltage variation is also considered in this representation, since the AC power flowing in or out the converter must be kept equal to the DC power. The average converter model implies no switching and no change in circuit topology, offering very fast simulation speed. As harmonics are not represented, time step as large as 20-50 µs can be used to conduct various power system studies. Fig. 6 depicts the implementation of the average model for back-to-back PWM converters of the type-III WG.

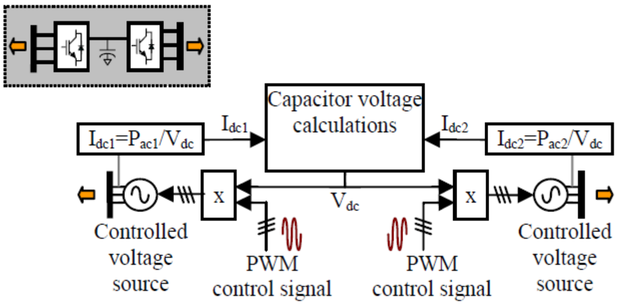


Fig. 6. Average modeling of a back-to-back PWM converter

The second approach is the switching-function model. The same techniques of controlled voltage source is used, except that theses sources inject switched output voltages derived from the PWM control signals and PWM generators. Smaller time step is required for precise results and this representation includes harmonics generated by PWM switching.

B. Decoupling of WPP power system equations for parallel processing on a supercomputer

Real-time digital simulators, based on multi-processor system, have been relying on power system equation decoupling for more than a decade. Using this technique, part of the natural propagation delay of a transmission line is absorbed by the communication time between two processors. As a result, the large system impedance matrix can be divided into multiple smaller matrices and can be solved in parallel on many processors without numerical error. The reduced matrix size drastically diminishes the computation effort, thus improving simulation speed.

This technique is only applicable for overhead (O/H) line or underground (U/G) cable that are long enough, in order to have a total propagation delay that is longer than the simulation time step. Unfortunately, WPP collector networks use short lines, so the technique cannot be applied directly.

It is known that the propagation delay (t_{propag}) of a line involves its length (l) and its propagation speed (v), as in the following equation:

$$t_{propag} = {}^{l}\!/_{v} \quad \text{and} \quad v = {}^{1}\!/_{\sqrt{LC}} \tag{1}$$

In order to decouple WPP collector system, the propagation delay of some selected U/G cables needs to be artificially increased. To do so without affecting the precision of the simulation results, this artificial increase is done by virtually moving and grouping the C from the surrounding power system components. Doing this, the global capacitance of the system is not modified, and only nearby capacitances are grouped to a punctual location.

To minimize the impact on simulation results, the virtual displacement of capacitances should be done in order to preserve the same total positive- and zero-sequence capacitance. Using this technique, the collector system can be decoupled in numerous sub-networks for very fast simulation time. Fig. 7 a) depicts this technique.

Similarly, each WG present on the WPP can be decoupled from the collector system for faster simulation. In this case, decoupling is done at the U/G cable, or at the equivalent collector system impedance of an aggregate WPP, that interconnects the generator transformer to the collector system. If the total capacitance of surrounding U/G cables is not sufficient for decoupling, part of the transformer leakage inductance can be also moved to the decoupling cable. However this virtual displacement of the leakage inductance can only be done with a transformer with delta connection, to avoid impact on the zero-sequence impedance of the system. Fig. 7 b) depicts this technique.

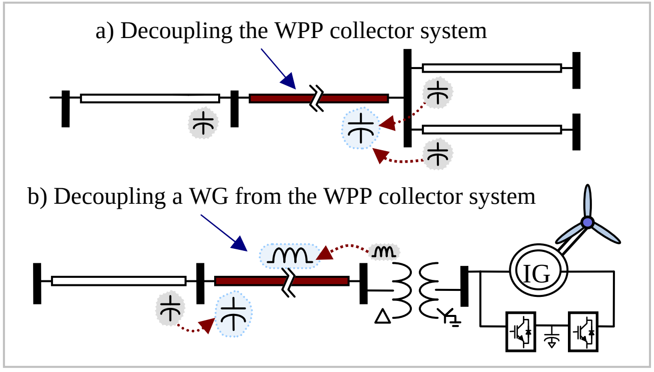


Fig 7. Moving of L and C from surrounding components to allow decoupling of WPP collector system equations.

V. MODEL VALIDATION

A. Validation of type-III wind generator and WWP models using on-line disturbance monitoring

For the purpose of model validation, on-line monitoring equipment has been installed on a typical WPP connected to the Hydro-Québec power system. This WPP is composed of seventy-three 1.5-MW type-III WGs. Fig. 8 shows the WPP, with the voltages and currents monitored and their locations at the generator, feeder and POI levels. From 2007 to 2009, various disturbances (e.g. faults and frequency deviations) were recorded. Those recordings have been used to validate the type-III WG model in the EMT domain.

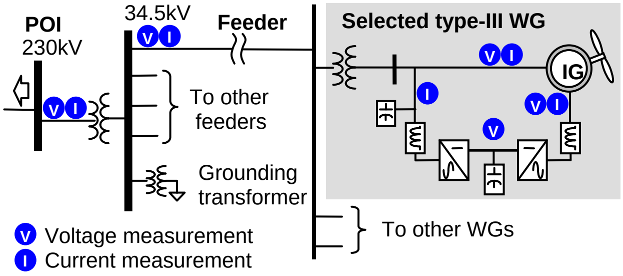


Fig. 8. Measurement points of a wind power plant

The model validation process used is based on playback techniques, where the model is fed with recorded voltages from the actual WG, and validation is confirmed when the model produces the same current as those recorded during the disturbance. Following the same approach of waveform playback, the entire WPP model has also been validated, using recorded voltages and currents at the POI level. The WFMS was also modeled and validated in the mean time.

Fig. 9 shows a comparison between simulation results and field measurements for a remote fault. It can be seen that the conformity of the model with the field measurements is very good for this particular event. Such good correspondence of the model for a number of different operating conditions and recorded disturbances has greatly contributed to increase the confidence in the validity of the model. Fine-tuning the model is a process relatively straight-forward for small disturbance, but it becomes more complex with large and/or unbalanced disturbance due to various non-linearities. Regardless of the disturbance severity, this approach requires a good understanding of internal dynamics and control strategies of the WG to model.

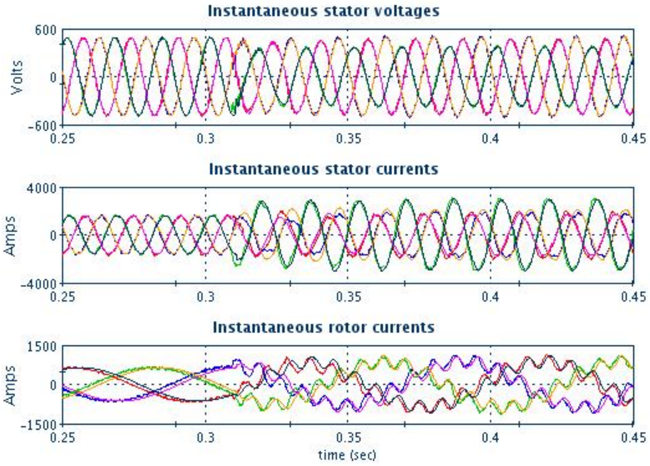


Fig 9. Comparison of recorded and simulated waveforms at the type-III WG level during a fault on the transmission network

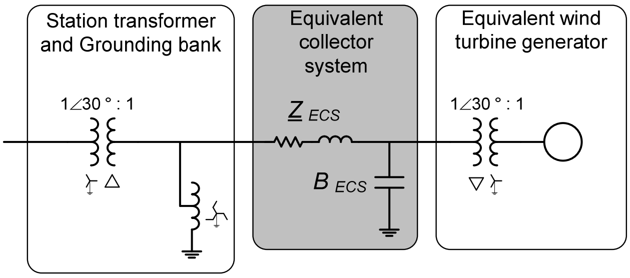
B. Validation of aggregation techniques for WPP modeling

Use of the WPP aggregate models is required for power system studies. However, until recently, precision and validity of such models remained to be evaluated.

In order to validate the precision of aggregate models for EMT simulation, a detailed model of an actual 109.5-MW WPP was developed. Its 73 WGs of 1.5 MW are connected to a 34.5-kV collector system comprising 17 km of overhead lines and 62 km of cables. The detailed EMT model was developed using the modeling techniques presented in section IV.

With the availability of the fast-simulating detailed model of this WPP, an exhaustive simulation study [5] was performed for validating the adequacy of the National Renewable Energy Laboratory (NREL) equivalencing method [6]-[7] for modeling WPPs. This method, promoted by the Wind Generation Modeling Group (WGMG) of the Western Electricity Coordinating Council is illustrated in Fig. 10. Aggregated WGs of a WPP are represented by an equivalent WPP comprised of only one equivalent WG, one equivalent collector system (ECS) and actual station step-up and grounding transformers.

The simulation study demonstrates that the method proposed by NREL appears to offer precise results for various types of disturbances and operating conditions, for both EMT and stability studies. Fig. 11 shows the performance of the NREL method for WPP modeling. In this figure, a 2-phase fault is applied to 4 different models of WPP: the detailed 73-WG model, and three different aggregate WPPs consisting of 1, 2 and 4 equivalent WGs.



Equivalent WTG = Actual WTG in pu

Fig. 10. Single-machine equivalent WPP promoted by the WGMG.

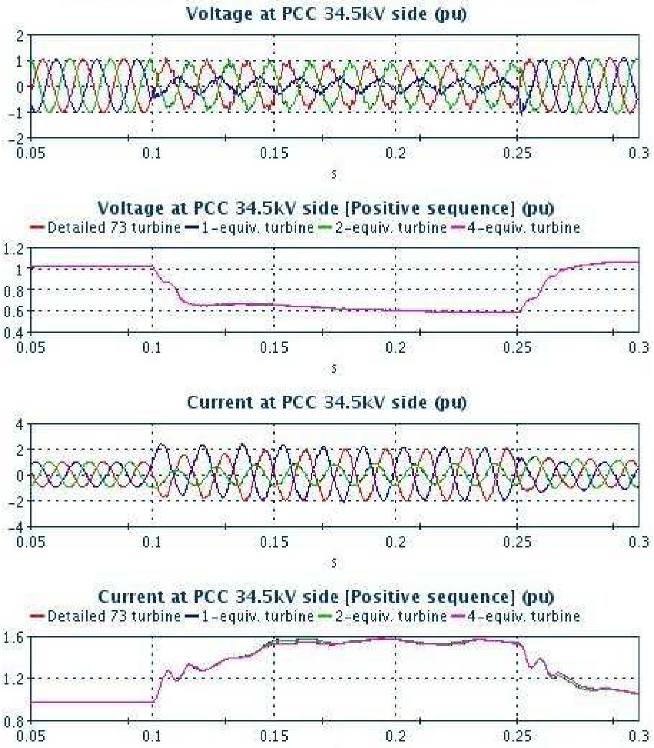


Fig. 11. Comparison of a detailed WPP model with a 1-, 2- and 4-WG equivalent WPP models. More than one equivalent WG is not necessary for modeling a WPP when all WGs are exposed to the same wind speed.

C. Generic equivalent collector system parameters for large WPPs

The equivalent collector systems of 17 WPPs rated between 50 and 300 MW were analyzed. Using this sample, a set of generic equivalent collector system parameters were calculated to be used for prospective studies of WPPs for which little or no information is available yet. An exhaustive sensitivity study based on EMT simulations has confirmed the adequacy of the generic equivalent collector system parameters [8].

VI. LARGE-SCALE REAL-TIME SIMULATION OF WPPS

The objective of this section is to integrate the modeling techniques explained in the previous sections in order to simulate in real-time WPPs connected to the Hypersim model of the series-compensated Hydro-Québec power system.

A. Description of the Hypersim model of Hydro-Québec power system

The Hypersim model of the main part of Hydro-Québec power system is illustrated in Fig. 12. The eastern part of this power system, connected at Lévis substation, is illustrated in Fig. 13. In these figures the location of WPPs, including WFMS, is shown by wind turbine pictures. For the main part of the power system, all 735-kV buses are represented, the main 315-kV and 230-kV buses and some 161- and 120-kV buses are also represented. As for the eastern part of the power system, all 315- 230- 161- and 120-kV and some 69-kV buses are represented. The major part of the lower voltage transmission and distribution system, including the loads and generation, are represented by reduced equivalents. The hydroelectric generators models include turbine, automatic voltage regulator (AVR) and stabilizer. The line series compensation is also represented [9]. The simulated power system includes the following main components:

- 643 three phase buses
- 34 hydroelectric generators (turbine, AVR, stabilizer)
- 1 steam turbine generator
- 25 WPPs
- 7 static VAR compensators
- 6 synchronous condensers
- 167 three-phase lines
- More than 150 transformers including magnetic saturation

The total production is 35000 MW including 2700 MW of wind power. 1800 MW of wind power are produced by 16 WPPs in the eastern power system. The 9 WPPs connected to the main power system produce the remaining 900 MW.

The 25 WPPs are each modeled as single-machine equivalents using the validated NREL method with generic equivalent collector system parameters presented in section V. Although various WG technologies could have been used, all WPPs simulated here use the type-III model presented in section III. In order to achieve real-time simulation performance the modeling techniques presented in section IV are used for decoupling WPP equations. The average model is used to simulate the power electronic converters of WGs.

B. Illustrative example of real-time simulation

The power system of Fig. 12 and 13 is simulated in real-time using a SGI Altix 4700 supercomputer using 72 processors, at a 50 µs time step.

In steady-state each WPP is producing its nominal power and zero reactive power. The speed of each WPP is 1.2 pu (synchronous speed is 1 pu).

Simulation results shown in Fig. 14 illustrate the system response to a 6-cycle single-line-to-ground fault. The fault is applied at t = 0.1s at 315-kV Lévis bus and it is eliminated at t = 0.2s.

The first column of Fig. 14 illustrates the three-phase voltage at 315-kV Lévis bus and the positive-sequence voltages at 735-kV Boucherville bus close to Montréal and 230-kV Matane bus in the eastern system. The terminal voltage, the speed and the active and reactive powers of the synchronous generator at Manic 5 are illustrated in the second column of this figure. Finally, the two last columns illustrate the active and reactive powers, the DC bus voltages and the speeds of WPP7 and WPP9. WPP7 is located in the far eastern part of the power system and WPP9 is located in the south of Montréal. Speeds and voltages of all synchronous generators and WPPs recover after fault clearing. This particular power system configuration is therefore stable for this particular WPPs location.

VII. CONCLUSION

The WPP modeling project conducted at IREQ has delivered the following models and methods: 1) a type-III WG model, 2) validation of an aggregation method for modeling WPPs and 3) validation of the WG and WPP models of an actual WPP connected to the Hydro-Québec power system. Field measurements have been used for model validation.

The modeling techniques developed in this project for simulating WPPs on a supercomputer allow rapid EMT simulations of WPPs on large-scale power systems. Real-time simulation has been achieved to simulate 25 WPPs on the Hydro-Québec power system.

It is now feasible to study possible interactions between series-compensated power system, real HVDC controls, and massive wind power generation.

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IX. BIOGRAPHIES

Richard Gagnon 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). From 1996 to 2001, he was professor of electrical engineering at Université du Québec à Rimouski. Since 2001, he has been a research engineer at IREQ (Hydro-Québec’s research institute). His professional interests include modeling and simulation of power system devices and wind generators.

Gilbert Turmel obtained is DEC in 1980 in Longueuil, Canada. He joined the Institut de recherche d'Hydro-Québec (IREQ) in 1980. He is working in the power system simulation group since 1991. He is a senior operator of the real-time simulator. His work involved the specification, validation and operation of the Hypersim real-time simulator for power system studies and also in giving training session on the use of the Hypersim simulator.

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

Jacques Brochu obtained his B.A.Sc. and M.A.Sc. degrees in electrical engineering from Université Laval in Québec City in 1981 and 1986 respectively and his Ph.D. degree from École Polytechnique de Montréal in 1997. From 1981 to 1983, he was production engineer for Canadian General Electric. He is currently a research engineer at IREQ (Hydro-Québec’s research institute) where he has worked since 1985. His main areas of interest include power electronics and power flow control devices for power systems. He has been involved in the development of the Interphase Power Controller (IPC) technology and is the author of a reference book on the subject.

Gilbert Sybille received the B.S. degree in electrical engineering from ESEO, Angers, France, in 1970 and M.Sc. degree from Laval University, Quebec City, QC, Canada, in 1978. In 1978 he joined Hydro-Québec Power System Simulation Department, 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 software programs for the IREQ’s real-time simulator. He is the technical leader and one the key developers of the MATLAB SimPowerSystems simulation software.

Martin Fecteau, ing. received a B.SC.A in electrical engineering in 2001 from Laval University in Québec city. Since 2002 he has worked for Hydro-Québec TransÉnergie in the system studies group of the transmission system planning department where he has been involved in several studies concerning wind farm integration, grid code issues, protection and EMTP modelling. Mr. Fecteau is a member of the IEEE Power Engineering Society and is a registered professional engineer in the province of Québec.

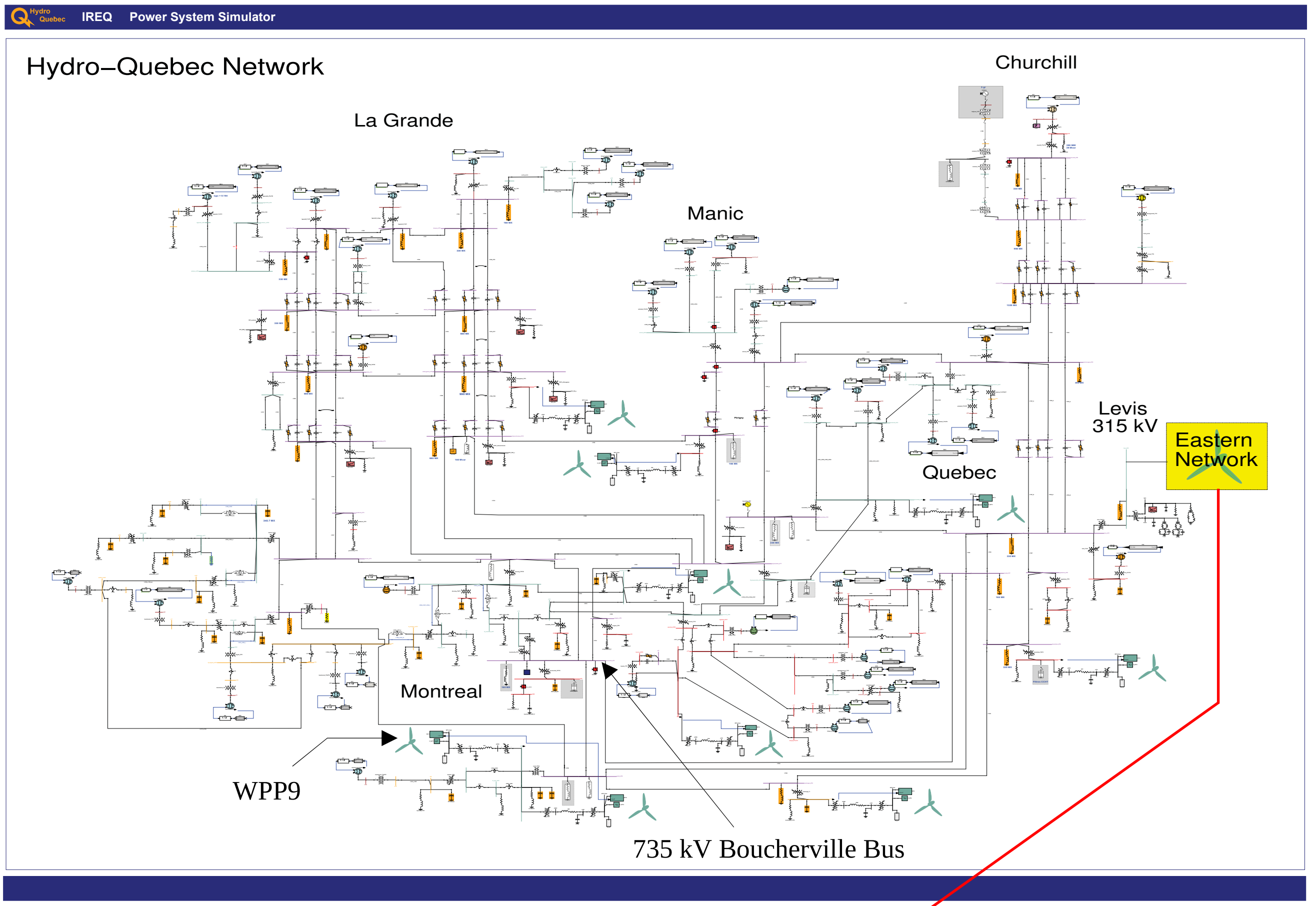

Fig. 12. Hypersim model of the main part of Hydro-Québec power system

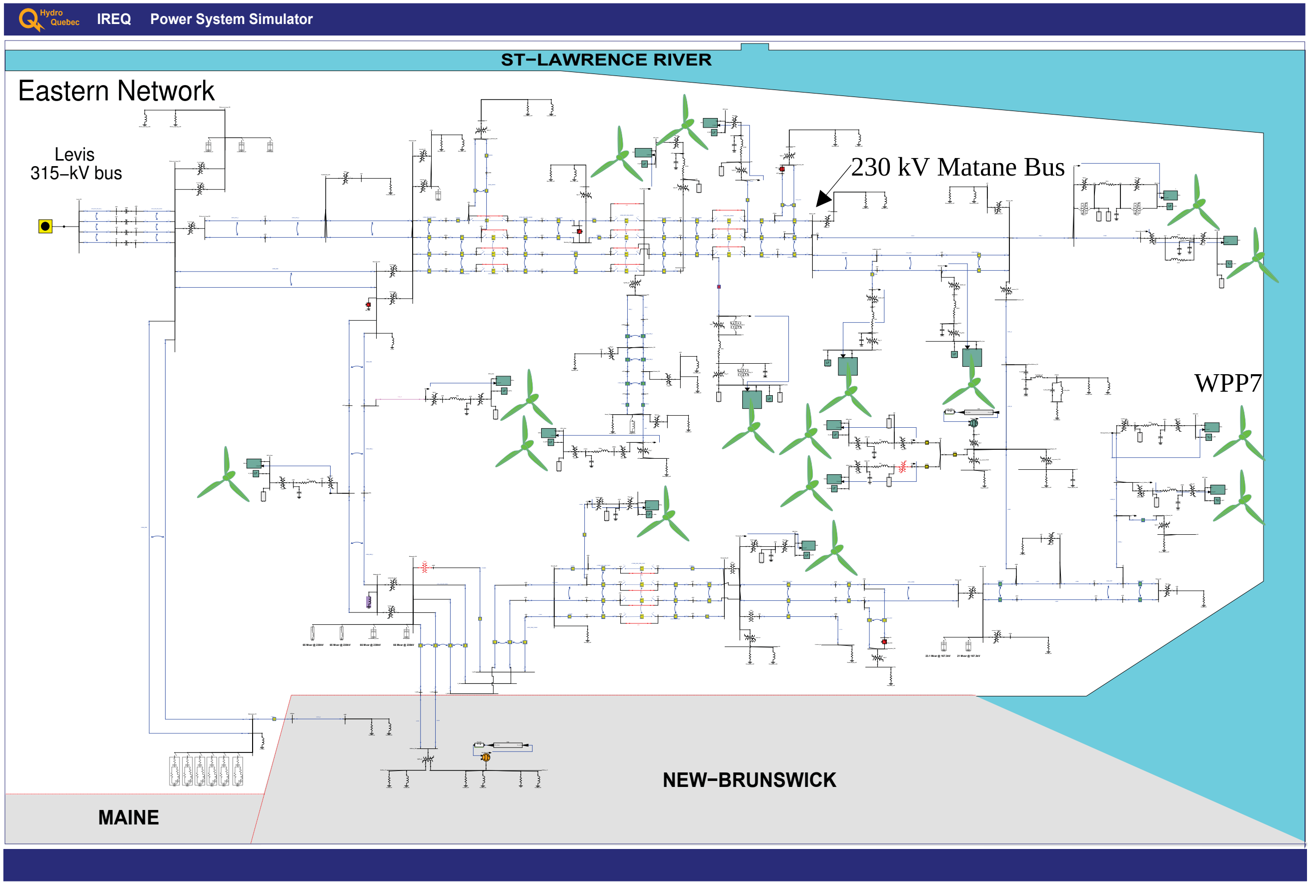

Fig. 13. The eastern part of Hydro-Québec power system

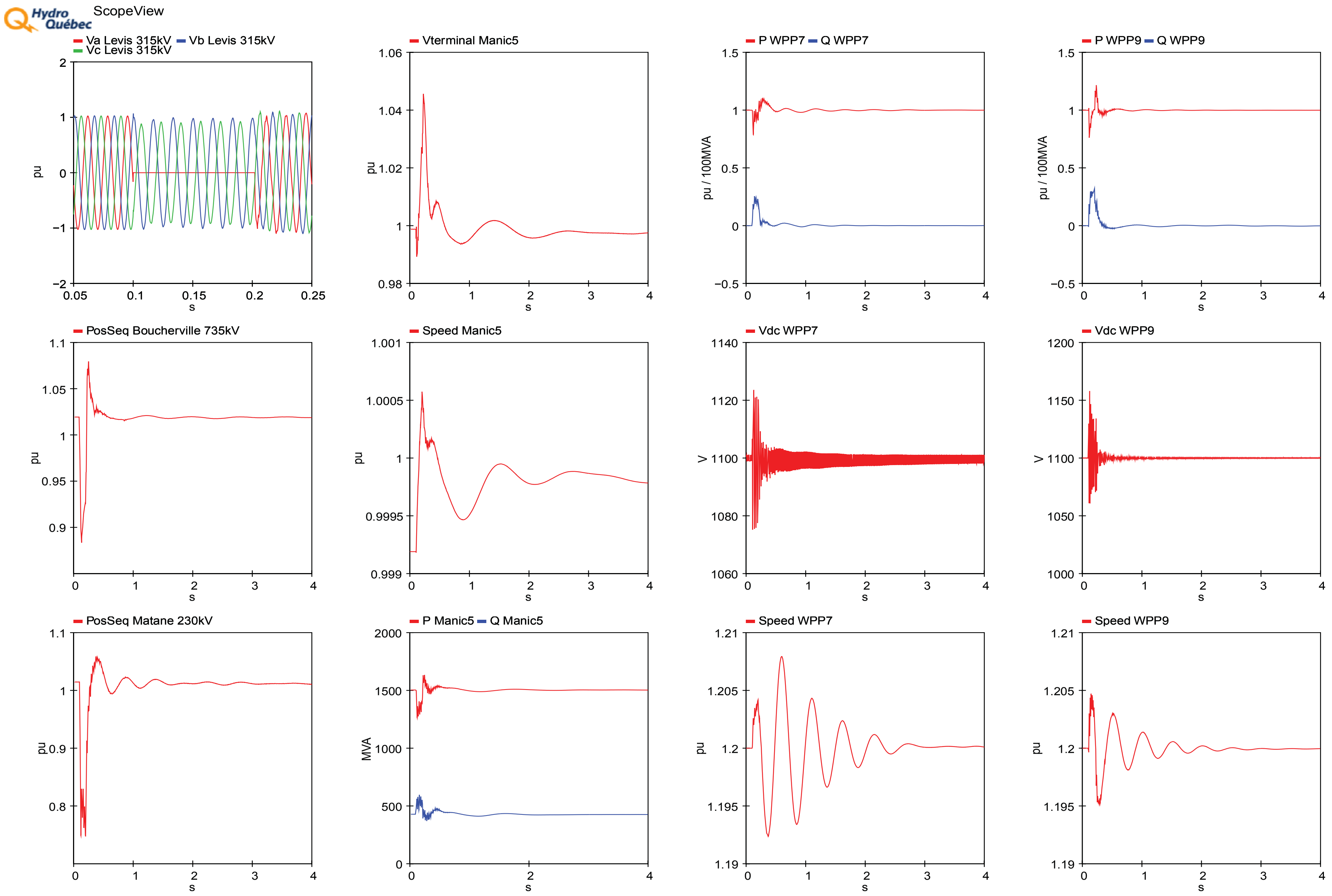

Fig. 14. System response to a 6-cycle single-line-to-ground fault