Large Wind Power Plants Modeling Techniques for Power System Simulation Studies

C. Larose, R. Gagnon, G. Turmel, P. Giroux, J. Brochu, D. McNabb, D. Lefebvre

***Abstract*—This paper presents efficient modeling techniques for the simulation of large wind power plants in the EMT domain using a parallel supercomputer. Using these techniques, large wind power plants can be simulated in detail, with each wind turbine individually represented, as well as the collector and receiving network. The simulation speed of the resulting models is fast enough to perform both EMT and transient stability studies.**

The techniques are applied to develop an EMT detailed model of a generic wind power plant consisting of 73 x 1.5-MW doubly-fed induction generator (DFIG) wind turbine. Validation of the modeling techniques is presented using a comparison with a Matlab/SimPowerSystems simulation.

To demonstrate the simulation capabilities using these modeling techniques, simulations involving a 120-bus receiving network with two generic wind power plants (146 wind turbines) are performed. The complete system is modeled using the Hypersim simulator and Matlab/SimPowerSystems. The simulations are performed on a 32-processor supercomputer using an EMTP-like solution with a time step of 18.4 µs. The simulation performance is 10 times slower than in real-time, which is a huge gain in performance compared to traditional tools. The simulation is designed to run in real-time so it never stops, resulting in a capability to perform thousand of tests via automatic testing tools.

***Index Terms*—Modeling techniques, power system simulation, real-time, wind farms, wind power plants.**

I. INTRODUCTION

FOR the next seven years, Hydro-Québec will be completing the integration of 4000 MW of wind power into its power system network. This new reality brings with it a wide range of new simulation needs, especially when dealing with an already complex network that includes HVDC lines, asynchronous interconnections, SVCs and series-compensated lines. As a result, many power system studies, in the time frames of both EMT and transient stability, must be conducted to properly integrate this new form of power generation.

Unfortunately, the traditional tools used to conduct these power system studies are now reaching their performance limits dealing with large wind power plants. For one thing, traditional EMT simulation offers precise results but the simulation time becomes extremely long as the network size and number of wind turbines increase. Even if wind power plants are modeled as one equivalent wind turbine, the large number of wind power plants in the power system leads to the same performance limitations. Furthermore, although traditional transient stability programs are capable of dealing with large networks and large number of turbines, the natural electrical modes of the network are not represented. Consequently, studies such as interaction between series compensation and wind power plants cannot be addressed.

The ideal situation would be to perform fast EMT simulations of the complete network in detail, including wind power plants. The use of full EMT simulation models eliminates all uncertainties and simplification assumptions associated with traditional transient stability models. Development done in the past 25 years in real-time simulator is a key pointing in this direction.

Recent supercomputers and real-time simulators now fully exploit the advantage of massive parallel processing. Simulation of large networks can now be performed in real-time or close to real-time using EMT models. Moreover, since the simulation is built to be running in real-time, it never stops, and thousands of tests can be performed quickly using automatic testing tools.

This paper presents the modeling techniques used to develop detailed models of wind power plants in the EMT domain using a parallel supercomputer. The resulting models allow simulation needs to be fulfilled in the time frame of EMT and transient-stability studies. Using these techniques, large wind power plants can be simulated in detail, with each wind turbine individually represented, together with its collector and receiving networks.

The modeling techniques presented are: 1- average and switching-functions modeling of power electronic converters; 2- integration of wind turbine models into the wind power plant collector network, 3- the decoupling of collector network equations using transmission lines with the contribution of underground cable capacitances and wind turbine transformer leakage inductances.

These techniques are validated using a detailed Matlab/SimPowerSystems (SPS) simulation. To demonstrate the performance of the simulation using these modeling techniques, simulations involving a 120-bus receiving network with two large wind power plants are performed on a 32-processor supercomputer. Simulations are performed 10 times slower than in real-time, which represents a huge gain in performance compared to traditional tools.

C. Larose, R. Gagnon , G. Turmel, P. Giroux and J. Brochu are with IREQ Hydro-Québec Research Institute, Varennes, QC Canada J3X 1S1 (email: larose.christian@ireq.ca) (email: gagnon.richard@ireq.ca)

D. McNabb and D. Lefebvre are with Hydro-Québec TransEnergie, Montréal QC Canada H5B 1H7.

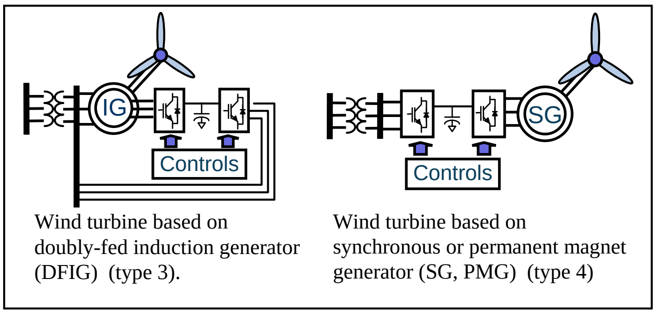
II. MODELING TECHNIQUES FOR LARGE WIND POWER PLANTS

The development of accurate and fast-simulating models of large wind power plants for detailed EMT studies poses various technical challenges. First, all the turbines must be represented in order to study phenomena that can occur on the collector network of the wind farm. Second, most modern wind turbines comprise power electronic converters, which require a small simulation time step and involve time-consuming matrix computations. Third, wind farm collector networks use very short underground (U/G) cables and overhead (O/H) lines that limit the capability to decouple the set of equations to be solved.

To overcome these technical challenges and achieve fast simulation of large wind power plants, three modeling techniques have been developed and validated.

A. Modeling of power electronics in a wind turbine

Most modern wind turbines use either induction generators in a doubly-fed configuration (DFIG) or synchronous or permanent-magnet generators with a full-scale converter. These configurations are identified as types 3 and 4 by [1], and are shown in Figure 1. The proposed techniques presented in this paper are applied to type 3 wind turbines but can also be used for any type of wind turbine architecture.



Wind turbine based on doubly-fed induction generator (DFIG) (type 3).

Wind turbine based on synchronous or permanent magnet generator (SG, PMG) (type 4)

Fig. 1. Architecture of recent wind turbine.

At the present time, wind turbines using PWM converters in the 1-5-kHz range are common. The simulation of PWM switching is very demanding for EMT simulation, since each switching implies matrix manipulation that is very costly in computation time.

Consequently, instead of using a detailed switch model, two different approaches were implemented. These are identified as the average model and the switching-functions model.

The first approach, the average model, which was used by [2], allows the entire back-to-back converter to be represented by two 3-phase controlled voltage sources. These sources are driven by the control voltages of the PWM converters. Consequently, the simulation of converters implies no switching and no change in network topology. To consider the capacitor voltage (V_{dc}), the AC power (P_{ac}) flowing in each converter must be equal to the DC power (P_{dc}), so the following equation is applied for both converters:

$$I_{dc} = P_{ac} / V_{dc} = (V_{ab} I_a - V_{bc} I_c) / V_{dc} \qquad (1)$$

Having the total amount of DC current flowing in or out of the capacitor, this current can be integrated in order to obtain the instantaneous capacitor voltage. The next figure shows the implementation of the average model to represent the back-to-back PWM converter of a DFIG wind turbine.

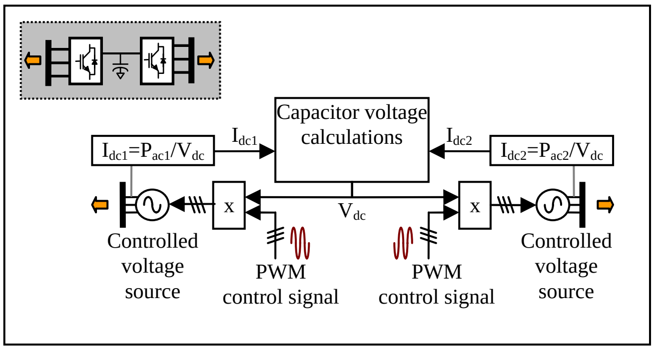


Fig. 2. Average modeling of a back-to-back PWM converter.

As a result, the average model allows quite a large simulation time step (around 20 to 50 µs) and offers very fast simulation speed. Even though harmonics are not represented, this efficient modeling of converters can be used to conduct various power system studies in EMT and transient stability time frame.

The second approach, the switching-functions model, has been demonstrated and used by [3]. This model also represents the entire back-to-back converter by two 3-phase controlled voltage sources, but includes harmonics generated by PWM. To do so, the voltage sources inject switched output voltages derived from the PWM control signals and PWM generators. Capacitor voltage variation is also considered, as in the previous case. Again, the simulation of converters implies no switching and no change in network topology. Figure 3 depicts the implementation of the switching-functions model.

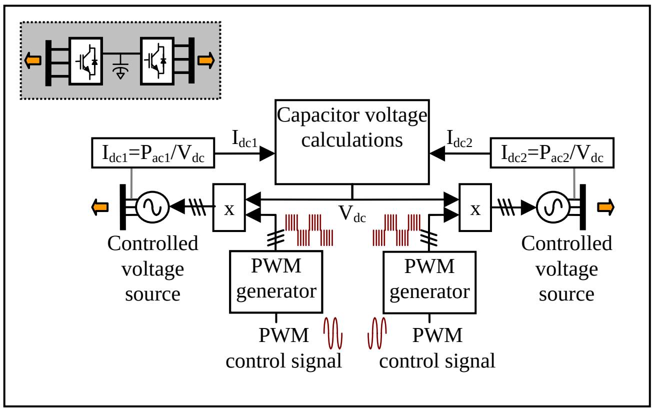


Fig. 3. Switching-functions modeling of a back-to-back PWM converter.

The time step used for this model is around 1 to 5 µs. This technique keeps the representation of harmonics and capacitor voltage variation. It offers precise results, as demonstrated by [3], and a fast simulation performance. This efficient modeling of power converters will satisfy most large-scale power system studies, including EMT and harmonics.

B. Integration of wind turbine models into the wind power plant collector network

Typically, a Hypersim [5] simulation is performed by processing two computation steps. First, network equations are solved (V=ZI) to calculate the voltage at each node based on the current injection. Second, power system models, like machines, are solved to obtain the new current injection at specific nodes. Thus, power system models are integrated into the network as current sources, and specific concerns about algebraic loops and numerical delays at the interface must be addressed.

In actual implementation, these two computation steps are implemented in two different simulation solvers. First, the collector network is implemented and solved using the Hypersim [5] real-time solver. This EMTP-like [6] simulator uses a supercomputer to simulate the network in parallel on many processors. Second, SimPowerSystems (SPS) from The MathWorks Inc. [7] is used to establish the wind turbine model itself. The C-code of this model is generated by Matlab/RealTimeWorkshop and is exported and simulated in Hypersim. Both solvers use discrete-time modeling with a fixed time step. As a result, the SPS set of equations is directly controlling current sources back to the Hypersim solver. With this approach, a joint closed-loop simulation is obtained, benefiting from the advantage offered by both environments. Validation has been done to demonstrate the accuracy of this technique.

C. Decoupling of power system equations

Real-time digital simulators, based on multi-processor system, have been relying on power system equation decoupling for more than a decade [4]. Using this technique, 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.

Since the total propagation time must be longer than the simulation time step, transmission lines must be long enough to be able to use this technique. Unfortunately, wind farm collector networks use short lines, so the technique cannot be applied directly.

Therefore, in order to use equation decoupling with wind power plants, the propagation delay of some selected lines needs to be artificially increased without affecting the precision of the simulation results. The propagation delay (t_{propag}) of a transmission line involves its length (l) and its propagation speed (v), where:

$$v = \frac{1}{\sqrt{LC}} \tag{2}$$

$$t_{propag} = {}^{l}\!/_{v} \tag{3}$$

To increase the propagation time (t_{propag}) of a line, two cases are presented based on the same approach. The general idea is to reduce the propagation speed by increasing the L or C of the line. This artificial increase is done by virtually moving an L or a C from the surrounding power system components with negligible effect on simulation results.

The first case where this technique is applicable is to decouple the collector network from a specific U/G cable. To achieve this, capacitances (C) of the surrounding U/G cables are grouped at the selected decoupling cable in order to obtain a propagation delay that is greater than the time step. Doing this, the global capacitance of the system is not modified, only nearby capacitances are grouped to a punctual location. Figure 4 depicts this technique.

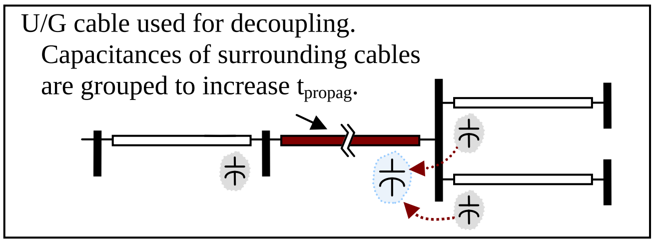


Fig 4. Decoupling the wind power plant collector network at selected U/G cable.

This technique is applied to U/G cables but could also be applied to O/H lines. U/G cables were selected for practical reasons since the C value is larger. To minimize the impact on the simulation results, the virtual displacement of capacitances should be done in order to preserve the same total capacitance for each positive, negative and zero-sequence. Using this technique, the collector network can be decoupled in numerous sub-networks, using frequency constant distributed parameter lines (FCDP) and PI-section lines.

The second case where this technique is used is to decouple the wind turbine from the collector network equations. This decoupling is done at the U/G cable that interconnects the turbine transformer to the collector network. Again, to artificially increase the propagation delay of this U/G cable, the capacitances of surrounding U/G cables are grouped, and part of the leakage inductance of the transformer is included in the decoupling cable. Figure 5 depicts this technique.

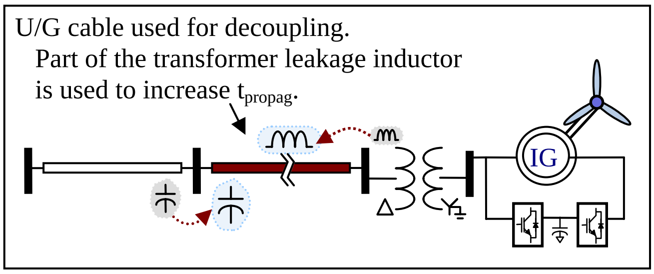


Fig 5. Decoupling each wind turbine at the transformer U/G cable.

This technique, where part of the leakage inductance of a transformer is moved to the local U/G cable, is applied to a grid-side transformer connection. Since this is a delta connection, the zero-sequence impedance of the system is not affected.

III. VALIDATION OF THE MODELING TECHNIQUES

For validation purposes, a generic wind power plant model has been established. It represents typical large wind power plant from 50 to 200 MW. It is composed of 73 wind turbines distributed into four feeders, as shown in Figure 6. The collector network comprises mainly U/G cables and some O/H lines rated 34.5 kV. The power plant is interconnected to the power system network, at the point of common coupling (PCC), via a 34.5/230-kV transformer. Each wind turbine uses a doubly-fed induction generator (DFIG) at 575 V and 1.5-MW rating.

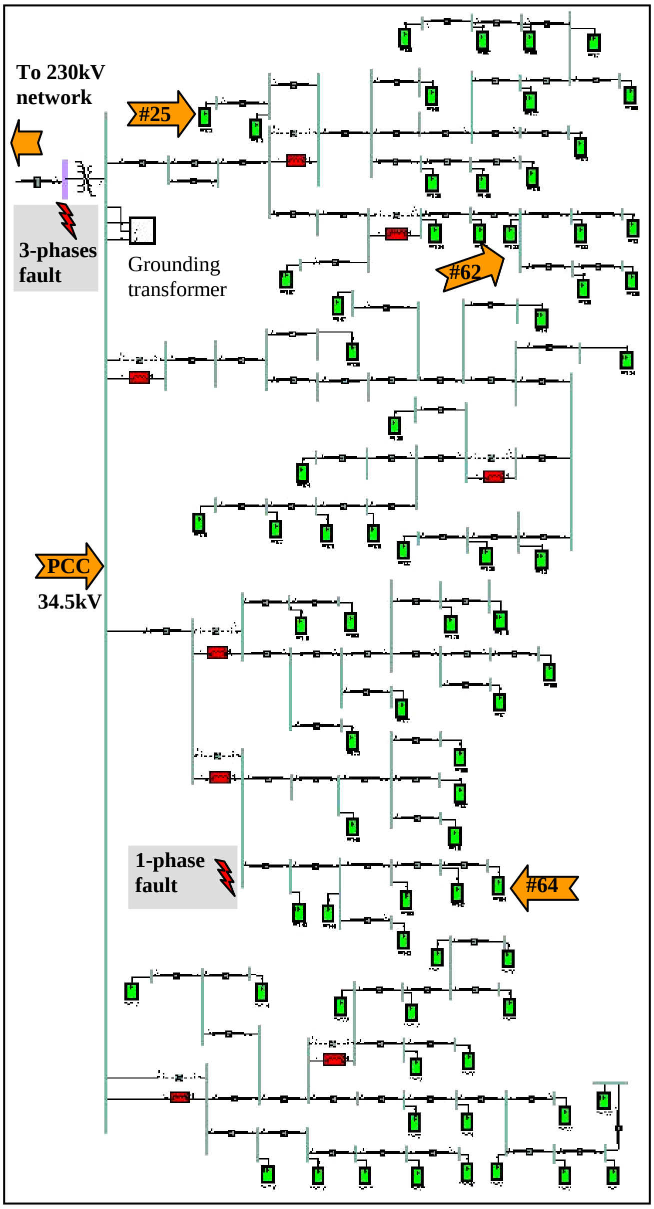


Fig. 6. The 73-turbine generic wind power plant model, based on a 1.5-MW DFIG wind turbine and a 34.5-kV collector network.

Using the proposed techniques, the wind power plant model has been simulated in parallel on a 32-processor supercomputer. Each wind turbine was decoupled from the collector network, and the collector network itself was decoupled into nine subsystems. U/G cables used for decoupling are shown in red on Figure 6.

In order to validate the precision of the modeling techniques, the same wind power plant is also modeled in SPS for comparison. Simulation results of a 3-phase fault, applied at the PCC of the wind power plant, are compared in Figure 7. Results of the simulations performed using Hypersim with 32 processors are compared to those on SPS using one processor without decoupling. The first two graphs in this figure compare the voltage and current of phase A at the PCC. The last graph compares the DC bus voltage at wind turbine #62.

From this comparison, the effect capacitances and inductances grouping is not perceptible, demonstrating the good performance of the decoupling technique. The simulation is performed at 20 μs in Hypersim, while using 50 μs in SPS for feasibility reasons.

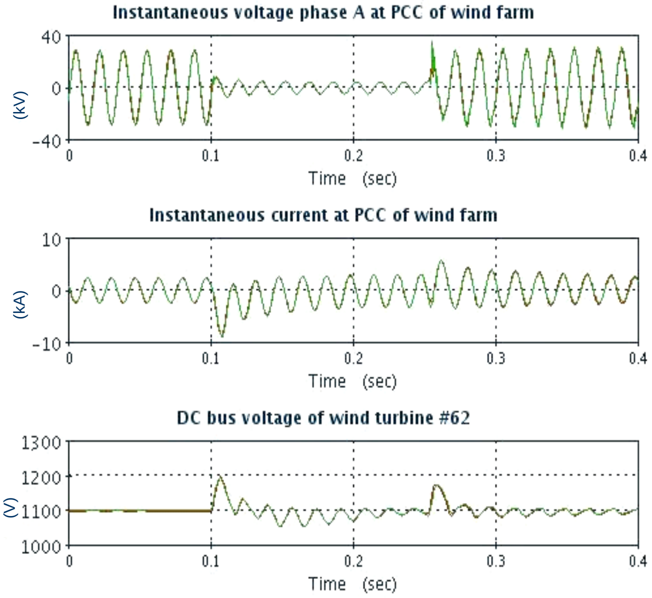


Fig. 7. Comparison of simulation results during a 3-phase fault at the PCC of a wind farm. A decoupled Hypersim simulation using 32 processors vs a single-processor SPS simulation.

IV. SIMULATION IN THE EMT DOMAIN OF A120-BUS SYSTEM NETWORK WITH TWO LARGE WIND POWER PLANTS.

To demonstrate the performance of the proposed techniques, a detailed EMT simulation of a 120-bus power system network with two wind power plants (146 DFIG wind turbines) was performed. The receiving network was a model of the Hydro-Québec network in the Matapédia region, as presented in Figure 8. It is composed of 120 buses, 20 transformers and 85 transmission lines. An equivalent 3000-MW synchronous machine feeds this power system network. Both wind power plants use the configuration presented in Figure 6 and are interconnected to this network separated by 30 km. The simulation is performed on a 32-processor supercomputer using a time step of 18.4 μs. The simulation performance is 10 times slower than real-time, quite fast enough for EMT and stability studies.

Figure 9 shows the results of a 9-cycle 3-phase fault applied at the PCC (230-kV side) of the first wind farm. In the first two graphs, the instantaneous voltage and current of the first wind farm, at the PCC (34.5-kV side), are shown.

The last two graphs show the superposition of active power and DC bus voltage of two selected wind turbines. Turbines #25 and #64 were selected for their geographic location, as turbine #25 is close to PCC while #64 is about 8 km away.

To demonstrate that the proposed modeling can be used to study phenomena occurring in the wind farm, simulation results of a single-phase-to-ground fault on the collector network of the first wind farm are also presented. Figure 10 shows the results of this unbalanced fault for six cycles. Again, the first two graphs show the instantaneous voltage and current of the first wind farm at the PCC, and last two, the superposition of active power and DC bus voltage of wind turbines #25 and #64.

Finally, to demonstrate that the proposed techniques can also be used for stability studies, Figure 11 presents the simulation results of a 400-MW load switch-on on this power system network. This disturbance creates a large frequency swing on the synchronous machine. Again, the simulation is done in the EMT instantaneous domain, but on-line processing of simulation results is performed to extract fundamental positive-sequence measurements. Grabbing results live from an ongoing simulation allows the sampling of each signal to be reduced, thereby accelerating access to understandable results. The first graph in this figure shows the network frequency, resulting from the speed of the synchronous machine. The second graph shows the rms voltage at the PCC of the wind farm, while the last two graphs show the active and reactive power, also at the PCC 34.5kV.

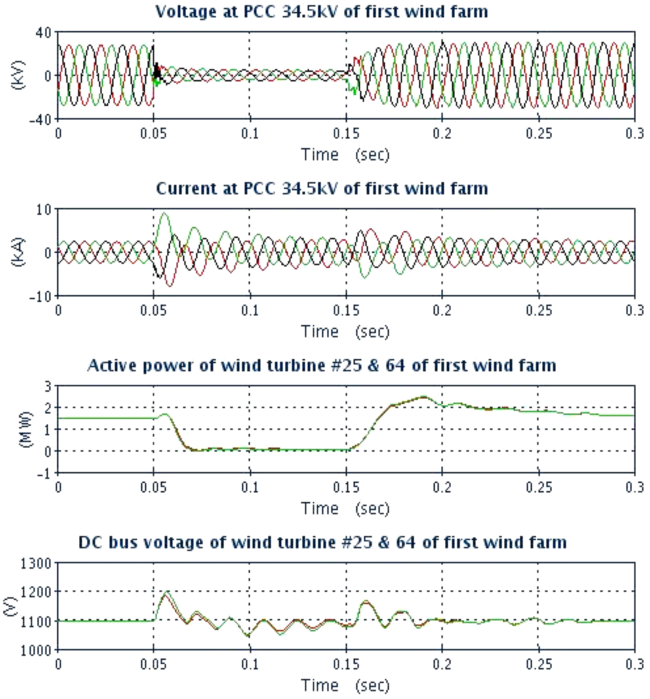
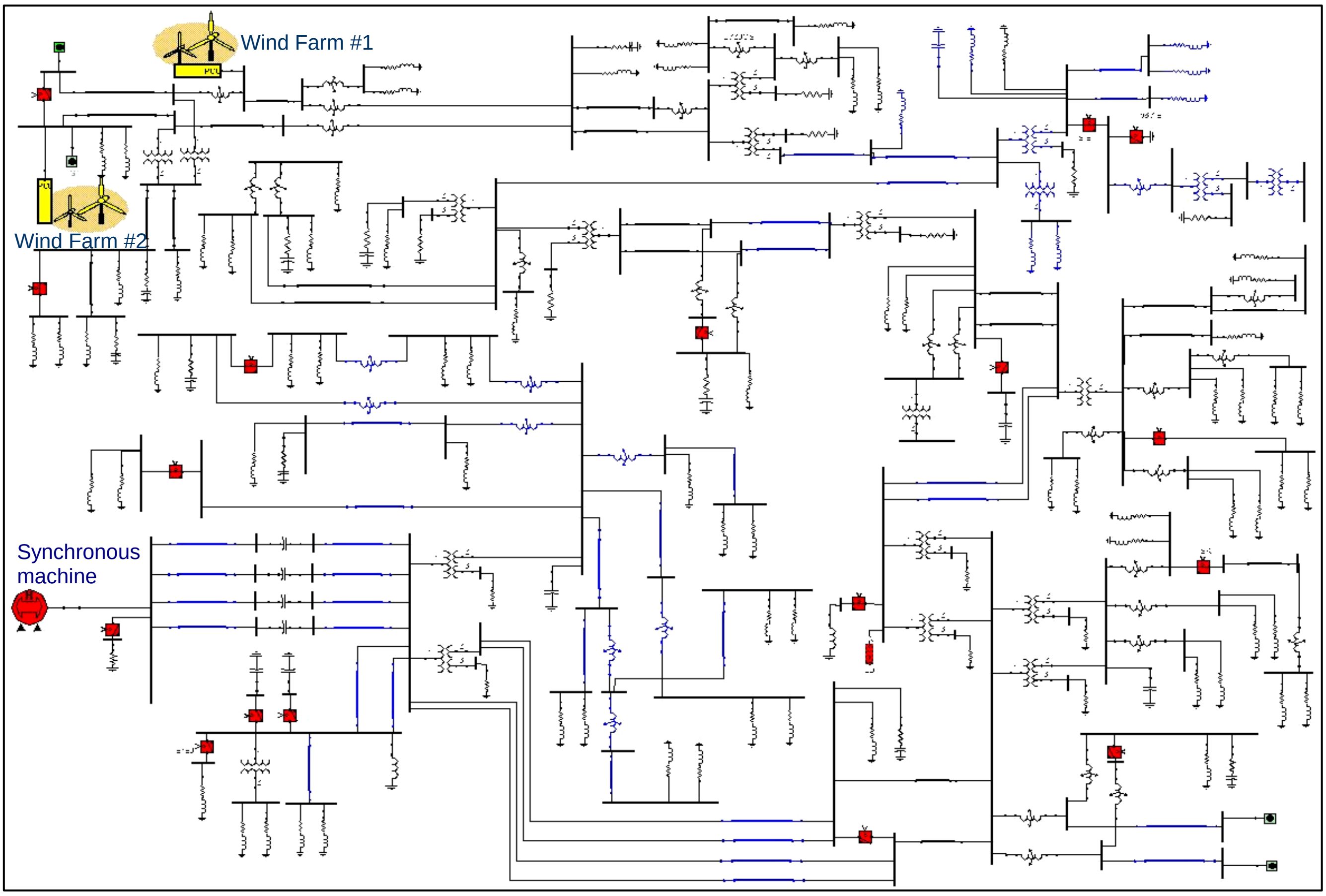


Fig. 9. Results of an EMT simulation of a 120-bus power system network with 2 x 73-turbine wind farms. A 3-phase fault is applied at the PCC 230-kV of the first wind farm.

V. CONCLUSION

Using the proposed modeling techniques combined with the latest developments in supercomputer and real-time simulators, it is now possible to simulate, in EMT and transient stability, numerous wind farms on large power system networks.

Fig. 8. The 120-bus receiving network, which is a model of the actual Hydro-Québec network in the Matapédia region, including two wind farms.



Also, the proposed modeling techniques have contributed to the development of a generic model of wind farm in the EMT domain. This generic model has been used as a benchmark for other research in this area, such as the development of reduced or aggregated models of a wind farm. The next development on the agenda will be validation of the wind farm model with actual field measurements.

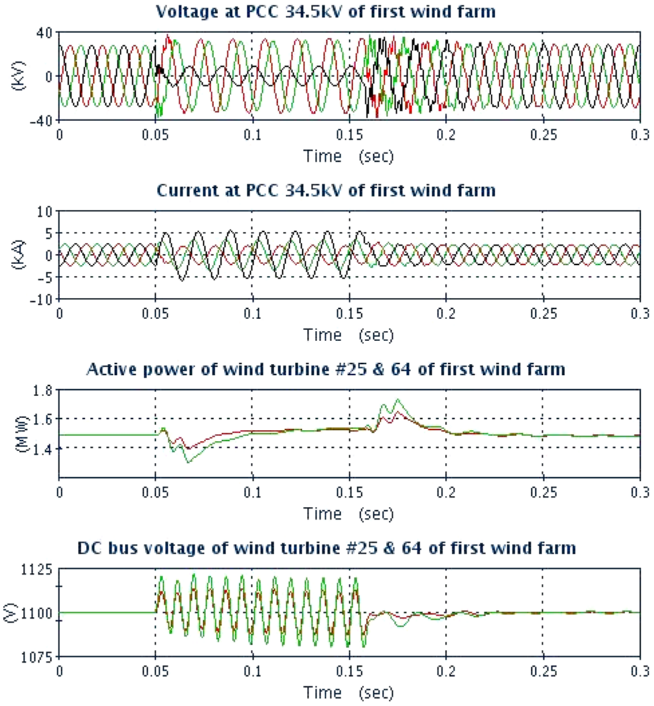


Fig. 10. Results of an EMT simulation of a 120-bus power system network with 2x 73 turbines wind farms. A single-phase fault is applied to the collector network of the first wind farm.

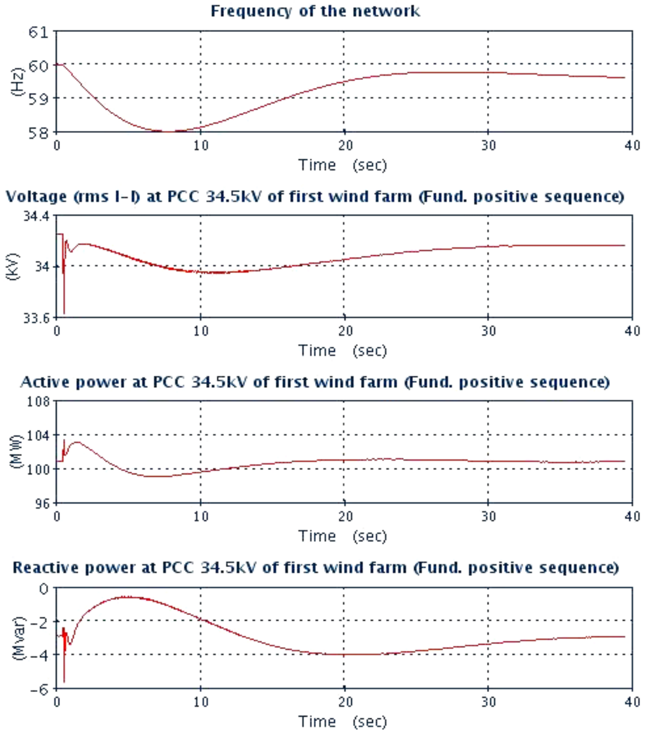


Fig. 11. Results of an EMT simulation of a 120-bus power system network with 2 x 73-turbine wind farms. A load switch-on creates a 2-Hz frequency swing.

VI. REFERENCES

[1] Wind Generator Modeling Group, “Standard Wind Turbine-Generator Models,” UWIG Modeling and Interconnection User Group Meeting, Oklahoma City, October 2006.

[2] R. Gagnon, G. Sybille, S.Bernard, "Modeling and real-time simulation of a doubly-fed induction generator driver by a wind turbine," in *Proceedings of the International Conference on Power Systems Transient* IPST05, Montreal, June 2005, paper No. IPST05-162

[3] H. Le-Huy, G. Sybille, R. Gagnon, V.Q. Do, "Real-time simulation of PWM power converters in a doubly-fed induction generator using switching-function-based models," IEEE Industrial Electronics Conference 2005, pp.1878-1883

[4] H. LeHuy, J.-C. Soumagne, "Digital real-time simulation of transmission lines using parallel processors," IMACS-TC1 93, Montréal, July 1993, pp. 29-32.

[5] D. Pare, G. Turmel, J.-C. Soumagne, "Validation of the Hypersim digital real-time simulator with a large AC-DC network," in *Proceedings of the International Conference on Power Systems Transients* IPST03, New Orleans, Sept 2003, paper No. IPST03-13-5

[6] H.W. Dommel, "Digital computer solution of electromagnetic transients in single and multiphase networks," IEEE Transactions on Power Apparatus and Systems, vol. PAS-88, No. 4, April 1969, pp. 388-399.

[7] *SimPowerSystems User’s Guide*, The Mathworks Inc., 2005.

[8] A.M. Gole, A. Keri, C. Kwankpa, "Guidelines for modeling power electronics in electric power engineering applications," IEEE Transactions on Power Delivery, vol. 12, No. 1, January 1977, pp. 505-514.

VII. BIOGRAPHIES

Christian Larose 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.

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

Gilbert Turmel obtained his 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 Laboratory 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 study and also in giving training session on the use of the Hypersim simulator.

Pierre Giroux obtained his BSSE degree in 1976 from the Université de Montréal (École Polytechnique). He joined the Institut de recherche d’Hydro-Québec in 1988 as a research engineer. His work includes design, real-time simulation and testing of controllers for FACTS and Power Quality Devices. He is a registered engineer with the Ordre des ingénieurs du Québec.

Jacques Brochu (M’86-SM’06) 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. From 1990 to 2002 he was seconded to the Centre d’Innovation sur le Transport d’Énergie du Québec (CITEQ) in Varennes, Qc. 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.

Danielle McNabb received her B.Sc.A. in engineering physics in 1973, her M.Ing. in nuclear engineering in 1980 and her M.Ing. in Electrical Engineering in 1986, all from École Polytechnique, Université de Montréal, Canada. She joined Hydro-Québec in 1980 where she has been involved with control modelling and simulation for the commissioning of Gentilly 2 nuclear power plant and, since 1986, in control modeling and protection studies for the Hydro-Québec Planning Department. She represents Hydro-Québec TransÉnergie on the CEATI power system planning and operations interest group and is a registered professional engineer in the province of Québec, Canada.

Daniel Lefebvre received his B.Eng. degree in Electrical Engineering from Ecole Polytechnique, Montreal, in 1990. Since then, he has been with Hydro-Quebec, TransEnergie Division where he is involved in operations planning for the Main Network. He is now a team leader in this group. He is a registered professional engineer.