Transient and Dynamic Modeling of the New Langlois VFT Asynchronous Tie and Validation with Commissioning Tests

D. Mc Nabb, D. Nadeau, A. Nantel, E. Pratico, E. Larsen, G.Sybille, Van Que Do, D. Paré

Abstract-The Variable Frequency Transformer (VFT) developed by GE is a new AC technology to transfer power between two asynchronous networks. The first installation of this new technology is located at the Langlois substation, interconnecting the New York (USA) and the Hydro-Québec (Canada) systems through the Cedar Rapid Transmission lines as indicated in figure 1. This new installation was commissioned in the fall of 2003 and is now in commercial operation. The technology is based on a rotary transformer (continuously variable phase-shifting transformer) with three-phase windings on both rotor and stator. A drive system adjusts the VFT rotor position in order to control the phase shift between the two networks through the action of a fast power controller. The VFT controls power transfer up to 100 MW in both directions. Transient and dynamic models for Hypersim and PSS/e were developed for this new technology. Basic control functions are shown. Simulation results for the transient and dynamic performance are compared with recordings obtained during commissioning tests and during a lightning fault that occurred close to the Langlois substation.

Keywords: Variable Frequency Transformer, Asynchronous Interconnection, FACTS, Controlled Power Flow, Transient and Dynamic Behavior, PSS/e model, HYPERSIM model

I. Introduction

The world first application of a variable frequency transformer (VFT) was put in service in the fall of 2003 and is now commercially operated by Hydro-Québec TransÉnergie. This new technology is used to interconnect two asynchronous networks and is located at the Langlois substation (fig 1). A 100 MW VFT was added on the 120 kV circuit between Langlois substation and the Les Cèdres substation where the CRT line is connected. This will increase, by 100 MW, the simultaneous export capability to the New York and Ontario systems and add a new 100 MW importing capability from New York.

Models to simulate the behavior of this new technology were developed for the PSS/e stability software and for the Hypersim real time transient simulation software. This paper will focus on the dynamic behavior of the VFT, system requirements for the project, and modeling considerations for this new technology. Validation with tests that were performed during the commissioning and subsequent real grid events such as faults near the Langlois substation will be presented.

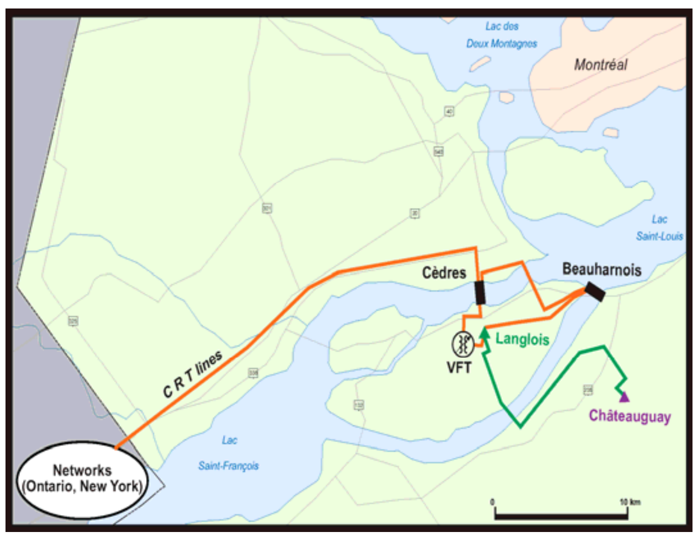

Figure 1-Location of the new VFT installation

II. Variable frequency transformer technology

The variable frequency transformer (VFT) is essentially a continuously variable phase shifting transformer that can operate at an adjustable phase angle [1], [2], [3]. The core technology of the VFT is a rotary transformer with three-phase windings on both rotor and stator. The collector system conducts current between the three-phase rotor winding and its stationary bus work. One power grid is connected to the rotor side of the VFT and another power grid is connected to the stator side of the VFT.

Power flow is proportional to the electrical angle of the rotary transformer, as with any other AC power circuit. The impedances of the rotary transformer and AC grid determine the magnitude of phase shift required for a given power transfer.

D. Mc Nabb, D. Nadeau, A. Nantel are with Hydro-Québec – TransÉnergie, Planification des Actifs et Affaires réglementaires – 150 rue Ste-Catherine, 2 Complexe Desjardins, tour est, 10e étage, Montréal (Québec), Canada, H5B 1H7. Corresponding author's E-Mail is Mcnabb.Danielle@hydro.qc.ca

E. Pratico, E. Larsen are with GE Energy, 1 River Road, Schenectady, NY 12345, USA.

G.Sybille, Van Que Do and D. Paré are with Power System Simulation Laboratory, IREQ, 1800 Boul. Lionel Boulet, Varennes (Québec), Canada, J3X 1S1.

Presented at the International Conference on Power Systems Transients (IPST'05) in Montreal, Canada on June 19-23, 2005
Paper No. IPST05-075

Regulating torque applied on the rotor, through a motor drive system, controls power transfer through the VFT. In steady-state, power flow is proportional to the magnitude and direction of the torque applied. Regardless of power flow, the rotor inherently orients itself to follow the phase angle difference imposed by the two asynchronous systems, and will rotate continuously if the grids are at different frequencies.

III. Power System Design Requirements

The VFT was designed to supply 100 MW of transfer capability in both directions with a power factor of 0,9. As power transfer increases, the VFT is required to supply enough reactive power to compensate its own reactive power consumption, which is approximately 50 Mvar at full load. For the Langlois substation, three 25 Mvar banks were implemented on the Cèdres side. Individual capacitor banks were limited to 25 Mvar to limit voltage variations during switching operations. The additional reactive supply -vs- consumption is useful for supporting the transmission grid on the Cèdres side.

Power systems are subject to various disturbances resulting in frequency and voltage deviations. To keep a constant power transfer through the installation, the VFT control system must constantly take action and compensate for any frequency variations across the two asynchronous networks to maintain the relative position of the rotor with respect to the stator. To insure proper behaviour for normal system operation and sufficient robustness during system events, the new VFT station was designed for a large range of system conditions.

Normal operating conditions - Normal operating conditions are defined for a voltage range between 0,9 and 1,1 pu and small deviations in frequency that do not exceed 0,5 Hz. Within this range, the VFT must maintain a constant power transfer within 2% of set value for small voltage and frequency deviations varying from 0 to 0,05 pu/s for voltage and from 0 to 0,25 Hz/s for frequency.

Normal disturbances – Equipment switching, sudden variations in load or distant faults may cause rapid variations in voltage angle even though the variations are still within normal operating conditions. For these conditions, larger accelerations exceeding 0,25 Hz/s could be observed. Control actions will bring power transfer back within 2% of set value within 200 ms.

Severe disturbances – Severe events could lead to large frequency deviations and voltage variations. Undervoltage caused by faults close to the installation will inhibit power transfer. Faults should normally be cleared within 100 ms. However, under backup conditions faults creating a drop of up to 60% in voltage could take up to 600 ms to be cleared. After fault clearing, the control system will react and stabilize power oscillations. At the Langlois substation, these power oscillations will range between 0,5 and 1,5 Hz.

For larger frequency deviations and accelerations due to the loss of large production units or large amounts of load, it is required that the VFT remains in service (must not trip) for frequency deviations up to ±3 Hz. Maximum acceleration or deceleration for such events is defined in the following table:

TABLE 1
Maximum acceleration or deceleration

Total maximum deviation of ±3 Hz	Maximum acceleration or deceleration	Duration
Initially	3 Hz/s	0,3 s
Followed by	2 Hz/s	0,6 s
Followed by	1 Hz/s	1,0 s

During severe system events, voltage profiles could drop below the normal operating voltage for some period of time. These low voltages must not cause the VFT to trip. The VFT drive system and auxiliary services must ride through voltage profiles that could drop to zero for up to 300 ms (breaker failure), rise back to 0,75 p.u. during a few seconds (power swings), up to 0,85 p.u. during five minutes and finally come back to the minimum operating voltage of 0,9 p.u.

IV. System Configurations

The VFT normal system operation configuration is presented in figure 2. The Hydro-Québec (HQ) system at Langlois is connected to the stator side of the VFT and the New York (NY) system is connected on the rotor side. This is completely arbitrary. As a convention, positive transit (plus sign) was established as flowing from HQ to NY connected at Cèdres substation.

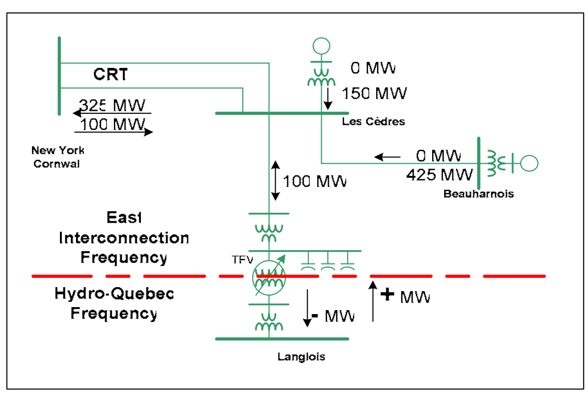

Fig. 2. Normal Operating System Configuration for Power Transfers Between HQ and NY

For testing purposes, in order not to disturb the neighboring network, the VFT was initially setup in a round power configuration as indicated in figure 3. This configuration was used for the commissioning tests. In that case, the load at Dorion was fed by another bus. An islanded configuration was also used. In that case, a parallel line linking the Cèdres and Langlois buses was opened.

This configuration was also used for some time after commissioning to confirm proper operation under normal system operating conditions.

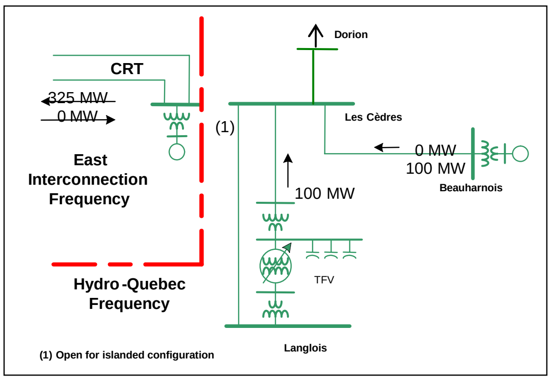

Fig. 3. Special Configuration for VFT operation with Power Transfer on HQ system only.

V. Control of Power Transfer Between Networks

The control system must maintain constant power transfer from one network to the other at a level equal to the operator order and accommodate any changes in operating conditions. This is achieved through a fast acting closed-loop power regulator. Any deviation in frequency will result in a variation in rotor speed and possibly rotational direction. Power regulation is the normal mode of operation. The power order may be modified by other control functions, including governor, power-swing damping, and power runbacks. These are described below:

Governor – The governor adjusts VFT power flow on a droop characteristic when frequency on either side exceeds a dead band. This function is designed to assist one of the interconnected power grids during a major disturbance involving significant generation/load imbalance. If frequency falls below the dead band threshold, the VFT will increase power import (or reduce export) to assist in returning grid frequency to the normal range. The VFT is designed to operate with one side isolated. If the local grid on one side of the Langlois VFT becomes isolated from the rest of the network, the VFT will continue to operate regardless of whether the isolated system has local generation or not. If there is no local generation, the VFT will automatically feed all the necessary power up to its full rating. If there is local generation, the VFT will make up the difference between local generation and local load, and share frequency governing with the local generator. The VFT also has an isochronous governor that will regulate the frequency of the isolated network to 60 Hz, when engaged by the operator.

Power Swing Damping Control – This function adds damping to inter-area electromechanical oscillations, normally in the range of 0,5 Hz to 1,5 Hz. This function is installed but disengaged at Langlois at this time.

Power runback – This function quickly steps VFT power to a preset level. It is externally triggered following major network events. The CRT system is subject to thermal overload after the loss of one of the two circuits. There are also stability limits that apply under the N-1 configuration. To maintain the integrity of the interconnection, the Cèdres substation is equipped with an automatic power rejection scheme that reduces power transfer following the loss of one circuit by rejecting machines either at the Cèdres or the Beauharnois power plants. Because the VFT can run at any power level between + and – 100 MW, a large amount of power rejection can be provided by ordering the VFT to apply a runback function at a preset power level. This power level is now set at - 65 MW (65 MW feeding from Cèdres to Langlois).

The Reactive Power Control function automatically switches shunt capacitor banks to compensate var consumption as the power transfer increases or with changes in 17 kV voltage. For the Langlois application, three 25 Mvar capacitor banks were implemented at the 17,5 kV rotor bus.

The inherent capability of the VFT to supply a radial load is well illustrated in figure 4. It shows field measurements for a system event where a local load at the Dorion substation was fed through the VFT after a line linking the Dorion substation to the Hydro-Québec network tripped, as shown in figure 3. The line was reclosed by operator after synchronisation and full transit through the VFT was resumed. The VFT automatically readjusted power transfer to supply the load while maintaining island frequency according to the governor characteristic programmed in the controls.

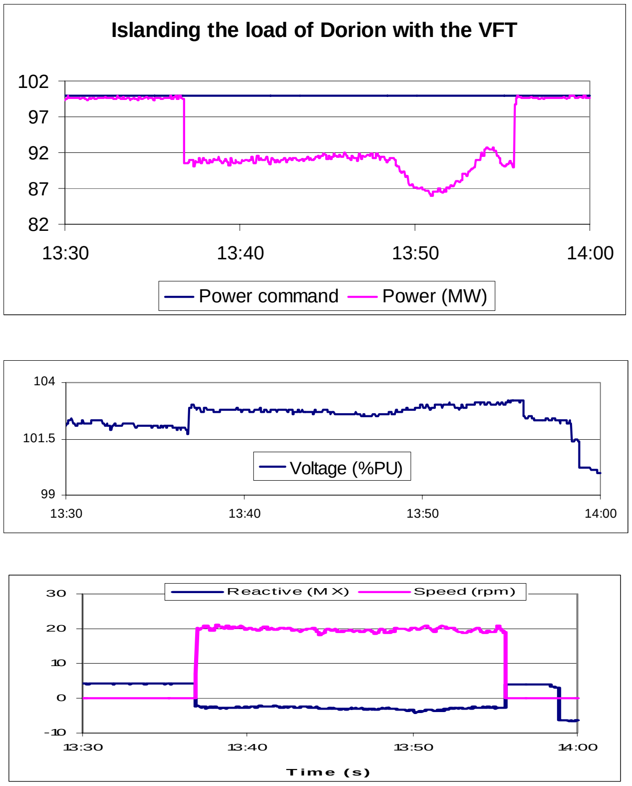

Figure 4-Local load at Dorion substation fed radially through the new Langlois VFT installation

VI. VFT REPRESENTATION FOR SYSTEM STUDIES

A. Model for Load flow and Stability System Simulations

Figure 5 gives the representation of the VFT for system studies. For the Langlois application, area 1 is located on the Hydro-Québec (HQ) network and area 2 is located on the New York (NY) side.

The VFT was modeled in the PSS/e load flow and stability software package. It is modeled as a phase shifter transformer with step-up transformers on both sides. The phase shifter was implemented in a way that it can apply phase angle shifts continually from plus to minus 180 degrees.

The VFT control system measures ac system variables on both sides, plus rotor speed, and applies drive torque to regulate power transfer in a stable manner. The VFT control functions were implemented through the user model facility in the software package.

The basic parameters for the VFT are indicated in table 2. The inherently large inertia of the rotary transformer helps stabilize during system events.

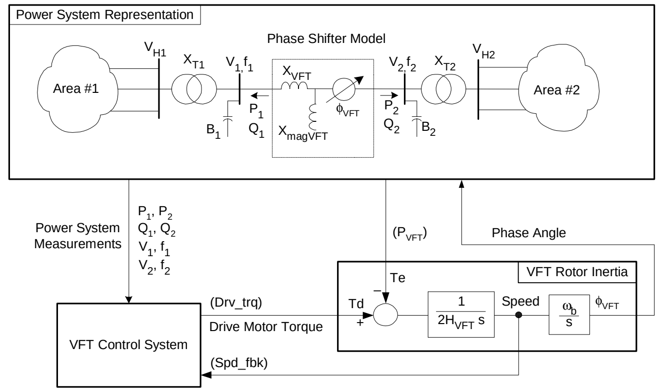

Fig 5: VFT Representation for Load Flow and Stability System Simulation

TABLE 2
LANGLOIS VFT BASIC PARAMETRS

PARAMETERS	VALUES
MVA_{base}	100 MVA
Stator kV $_{base}$	17 kV
Rotor kV $_{base}$	17.5 kV
X_{VFT}	12 %
X_{magVFT}	5.6 pu (i.e., I_{mag}=18%)
X_{T1}	10%
System 1 kV_{base}	120 kV
X_{T2}	10%
System 2 kV_{base}	120 kV
H	26 pu-sec

B. Modeling for Electromagnetic real time representation

Dynamic performance testing of the VFT controls was performed by GE on a real time simulator. A three phase model of the rotary transformer, with both electrical and mechanical rotor dynamics, drive motor and converters, switched capacitors and synchronizing breaker were implemented on the simulator. The power systems on both sides including Cèdres and Beauharnois machine dynamics were also represented. Real drive controls were tested for a large range of system conditions and events prior to site commissioning tests. The layout for the Dynamic performance study is presented in figure 6.

The simulator was used by GE for both control development and final performance confirmation as described in [2]. Initially the simulator was interfaced with the prototype Unit VFT Control (UVC) for development and later it was connected to the production UVC cabinet for factory testing before shipment to the site.

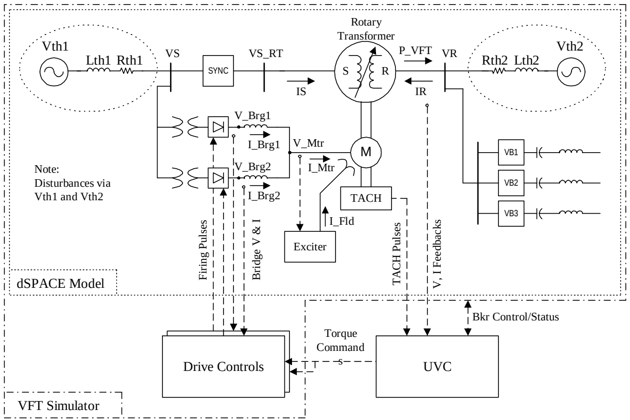

Fig 6. Overview of VFT Simulator Control Interfaces

For Hydro-Québec TransÉnergie internal validation studies, a simplified version of a three phase real time VFT model with a numerical version of the VFT control system was also implemented in the HYPERSIM simulator.

VII. Validation with Field Measurements during Commissioning Tests

Commissioning tests were performed to validate behavior of this new technology. Two Beauharnois machines were synchronized to the Cèdres substation in the islanded configuration presented in figure 3 (Cèdres-Langlois line opened and Dorion load fed from another bus). The total production of the two machines in the island was set at 45 MW (35 and 10 MW respectively). Figure 7 shows the Power command and Measured Power through the VFT compared to system simulation. Results agree very well.

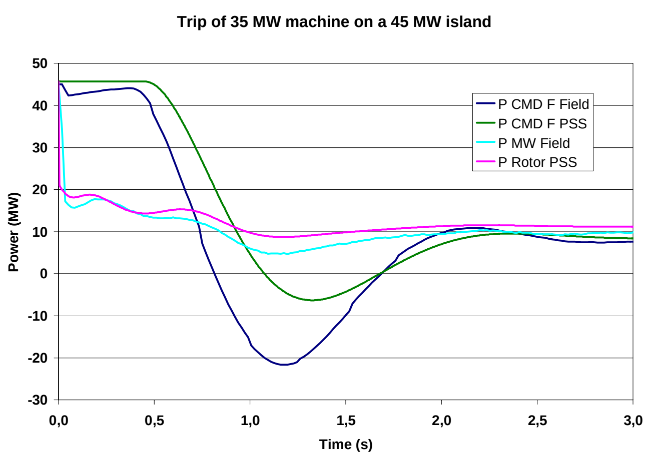

Fig. 7. Dynamic Behavior of the VFT after the trip of a 35 MW machine on a 45 MW island.

Figure 8 shows variations in the applied torque. Comparison with simulation results also indicates very good agreement between both curves.

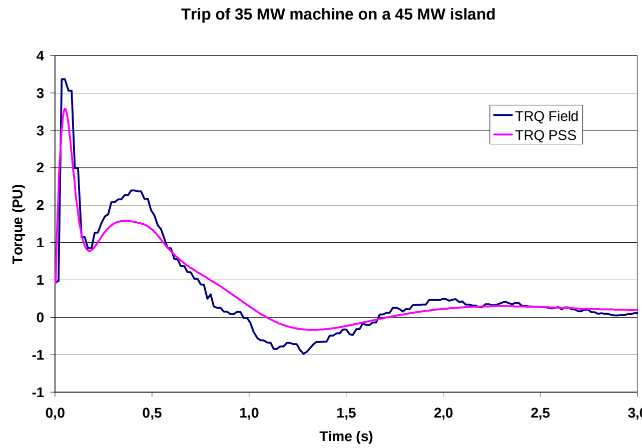

Fig. 8. Variation in Applied Torque on the VFT after Generator Trip- Comparison between Field Measurements and PSS/e Simulation.

VIII. Validation with Field Measurements during System Events

As previously mentioned, the VFT was operated in the special round power configuration shown in figure 3 for some time after commissioning. During this period, a single line to ground phase fault occurred at the Dorion substation. This event was simulated and results were compared with field measurements. Figure 9 shows variations in Power command and transferred power through the VFT during this system event. Results show very good agreement.

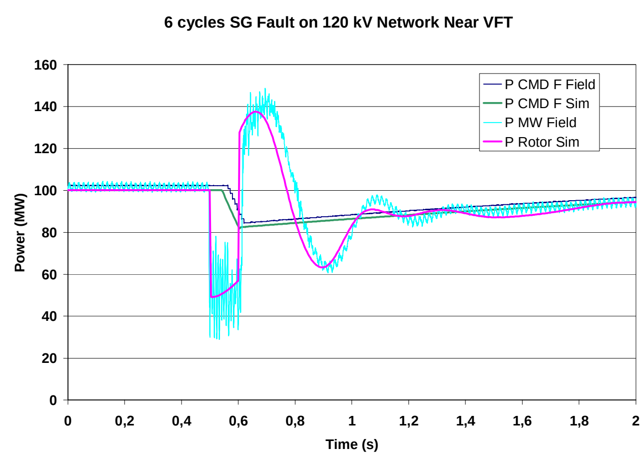

Fig. 9. Power Transfer Through the VFT During a Single Line to Ground Fault - Comparison Between Field Measurements and PSS/e Simulation.

Figure 10 shows variations in torque applied to the VFT during the event. Here also, there is very good agreement between field measurement and simulation results.

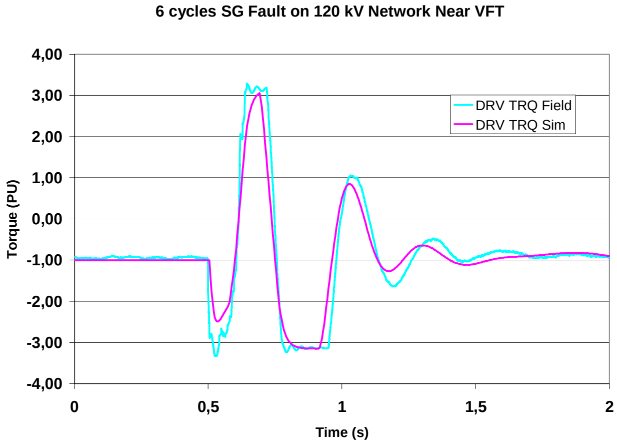

Fig. 10. VFT Torque During a Single Line to Ground Fault - Comparison Between Field measurements and PSS/e simulation

These results show dynamic behavior of the VFT when it is subjected to a fault on the network for the round power configuration. As a comparison, three phase faults were simulated both on the real time simulator setup by GE for Dynamic performance study (DPS) of the VFT control system and on the Hydro-Québec digital power system simulator Hypersim. Figure 11 shows results obtained during DPS simulations for a fault at Langlois on the HQ side with the normal asynchronous system configuration.

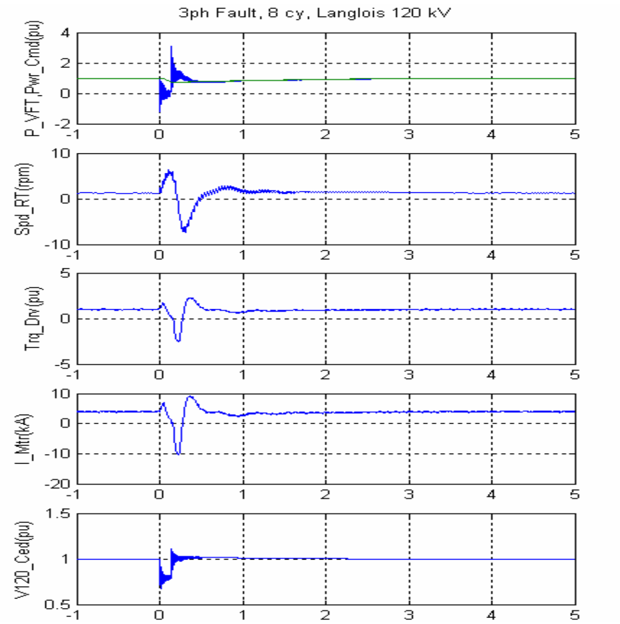

Fig. 11. Results from dynamic performance study for 3 phase fault at Langlois 120 kV on HQ side

Figure 12 shows results of Langlois VFT behavior for the same event as simulated on the Hypersim real time simulator. Results show good agreement (compare respectively P_VFT, Spd_RT, Trq_ Drv of Fig.11 with P1, dw_VFT, Te_VFT of Fig. 12).

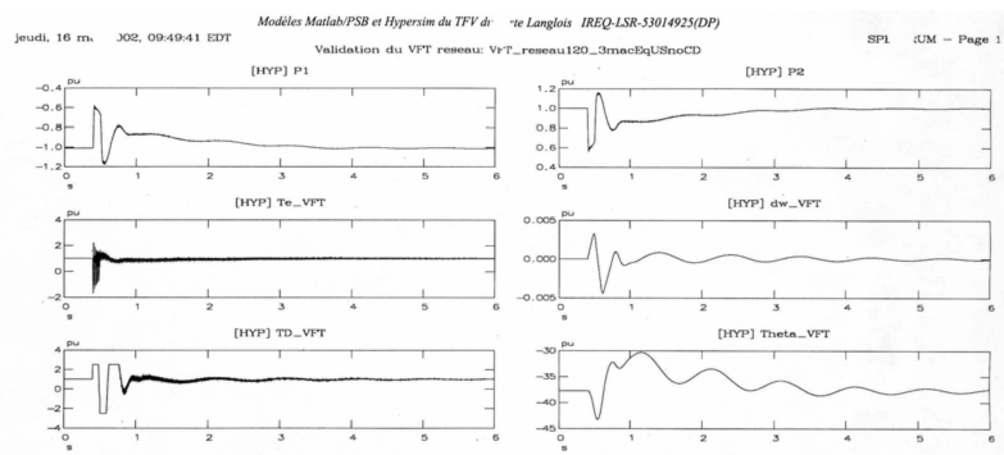

Fig 12 – Hypersim simulation results for VFT behavior after a 3 phase fault at Langlois 120 kV (HQ side)

IX. Conclusions

The new VFT asynchronous interconnection was commissioned in 2003. The transient and dynamic behavior of this new technology was verified with extensive real time simulations and field tests. Stability and real time simulation models were developed and implemented. Modeling of the VFT was validated through comparisons with field measurements. Results indicated that this new technology behaves well. Dynamic performance showed very good agreement with predicted behavior.

X. References

[1] E.Larsen, R.Piwko, D.McLaren, D.McNabb, M.Granger, M.Dusseault, L-P.Rollin, J.Primeau, "Variable-Frequency Transformer – A New Alternative for Asynchronous Power Transfer", presented at Canada Power, Toronto, Ontario, CANADA, September 28-30, 2004.

[2] P.Doyon, D.McLaren, M.White, Y.Li, P.Truman, E.Larsen, C.Wegner, E.Pratico, R.Piwko, "Development of a 100 MW Variable Frequency Transformer", presented at Canada Power, Toronto, Ontario, CANADA, September 28-30, 2004.

[3] J.M.Gagnon, D.Galibois, M.Granger, D.McNabb, D.Nadeau, J.Primeau, S.Fiset, E.Larsen, G.Drobniak, I.McIntyre, E.Pratico, C.Wegner, "First VFT Application and Commissioning" presented at Canada Power, Toronto, Ontario, CANADA, September 28-30, 2004.