GMD Impacts on Hydro-Québec system

Luc Gérin-Lajoie, Louis Gibson

***Abstract*--Geomagnetic disturbances (GMD) affect power systems by causing transformer saturation. The primary impacts of transformer saturation are increased harmonic current injections and var losses, which may lead to damage of high-voltage transformers and/or voltage collapse. The investigation of GMD risks and mitigation strategies requires accurate modeling of a GMD.**

This paper firstly presents the requirements in terms of modeling components to correctly simulate GMD in EMTP, and secondly the impacts of GMD on Hydro-Québec transmission system, which is fully represented in EMTP, a GMD-EMT simulation world premiere.

***Keywords*: AVR, GMD, GIC, Power System**

I. INTRODUCTION

Geomagnetic disturbances (GMDs) or geomagnetically induced current (GIC) have received considerable research attention lately due to their impact on pipelines, telecommunication grid, and power transmission grids [1]-[4]. In electrical systems, for simulation purposes, a GMD can be represented by an induced DC voltage source in transmission lines. There are two main risks associated with a GMD: the first is the possible damage to high-voltage transformers caused by overheating and the second is the increased Mvar consumption of saturated transformers causing voltage collapse [5][6].

Hydro-Québec's EMT studies department has developed and maintained an EMTP model of its complete transmission system from power plants down to loads since 2009 [7]. This model includes 11 000-1ph buses, 330 transmission lines and 100 power plants. Since 2013 up to today, Hydro-Québec has worked to implement GMD on EMTP to analyse the impact on the system [8]. The modeling techniques described below were applied on HQ's Transmission system. This is the first-time theses results are published.

II. TPL007 - TRANSMISSION SYSTEM PLANNED PERFORMANCE FOR GEOMAGNETIC DISTURBANCE EVENTS (GMD)

NERC developed TPL-007 with many utilities. Four versions of the TPL-007 were introduced. These standards mandate utilities to assess the impact of GMD events on their system and dictates the parameters of the study according to different inputs such as system topology and latitude. Briefly: TPL-007-1 imposed a 4V/km benchmark event with correcting factor according to the latitude and the earth resistivity models, TPL-007-2 added localized 12V/km supplemental events with the same correcting factors, TPL-007-3 is a regional Canadian version where Canadian utilities can adapt their GMD scenario based on their research and experience, and the TPL-007-4 added corrective action plans for the localized supplemental events

For TPL-007-3 studies, HQ adopted an approach based on geological studies and statistical extreme values analysis for an occurrence of 1 in a 100-year event provided by Natural Resources Canada (NRCAN) and shown in Fig. 1.

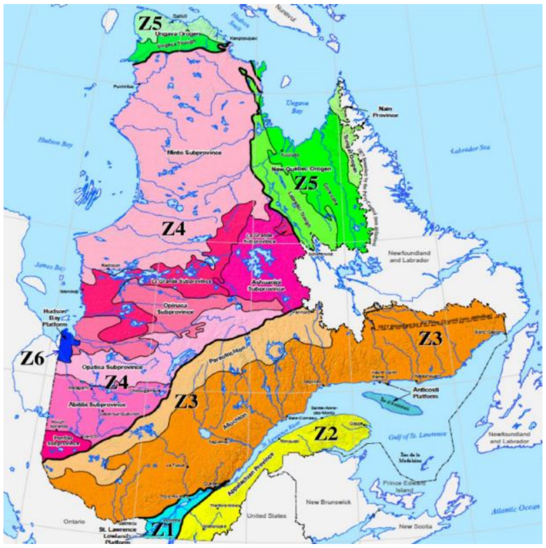

Fig. 1 Québec Geological Areas for GMD Studies. Source NRCAN.

III. TECHNICAL ASPECTS FOR SIMULATED GMD WITH EMTP

Some essential modifications to EMTP model parameters are required to perform GMD studies. Modifications described in III.A and III.B are required for all simulations. Modifications described in III.C and III.D are required for voltage regulation study. Modification described in III.E is required for steady state calculations.

A. *Lines: R0 and DC voltage sources*

Firstly, the value of R0 in Constant Parameter (CP) [15] and PI lines components needs to be adapted. It was decided to use CP and PI instead Frequency Dependent (FD) line models to avoid months of work in 200-300 lines; it was judged CP and PI are precise enough for 0-400Hz bandwidth. PI models are

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L. Gérin-Lajoie is with Hydro-Québec, Montréal, Québec.
(email: gerin-lajoie.luc@hydroquebec.com)
Louis Gibson is with Hydro-Québec, Montréal, Québec. (email: gibson.louis@hydroquebec.com)

Paper submitted to the International Conference on Power Systems Transients (IPST2023) in Thessaloniki, Greece, June 12-15, 2023.

used for lines less than 20 km. The parameters R1, L1, C1, R0, L0, C0 are defined or calculated at the system frequency (60Hz). However, the DC voltage source in series with lines that represents the quasi-DC voltage between the substation ground at both ends of a line [9] is a DC zero-sequence source. Consequently, to achieve the correct DC current value, R0 must be equal to R_{dc} of the conductor. In practice, we use $R0=R1_{60Hz}$ because $R1_{60Hz}\approx R_{dc}$ [15].

In the simulated EMTP HQ-network, the 735, 315, 230 and 120 kV lines have a 3ph-DC voltage source in series for a total of 193 DC voltage sources. The DC source devices are individual controlled (see Fig. 2) with an external input giving the calculation functions described below to determine the DC voltage magnitude.

The inputs to the model are Ex (northward electric field in V/km) and Ey (eastward electric field in V/km). Four parameters are required: latitude and longitude of nodes i and j. Vdc(t) is calculated based on [1] and where Θ_L and Θ_{GEF} are the north-south angles of the line and the Geoelectric Field:

$$V_{\mathrm{dc}}(t) = \ell\sqrt{E_x^2 + E_y^2}\cos(\theta(t)) \qquad (1)$$

$$\theta(t) = \theta_L - \theta_{\mathrm{GEF}}(t) \qquad (2)$$

$$\ell = \sqrt{\ell_x^2 + \ell_y^2} \qquad (3)$$

$$\ell_x = 111.2(\mathrm{Lat}_i - \mathrm{Lat}_j) \qquad (4)$$

$$\ell_y = 111.2(\mathrm{Long}_i - \mathrm{Long}_j)\sin(90^\circ - 0.5(\mathrm{Lat}_i + \mathrm{Lat}_j)) \quad (5)$$

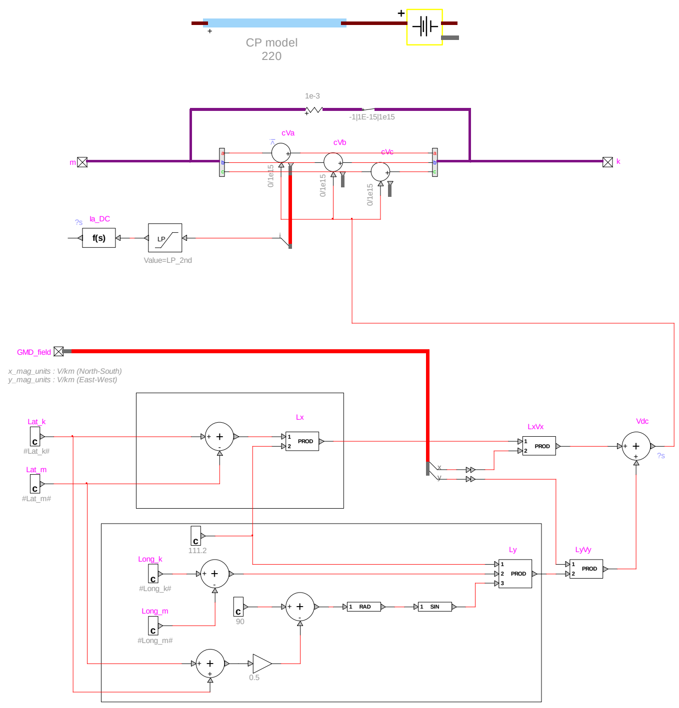


Fig. 2 Implementation of Eq. 1 to 5 for Vdc(t) in EMTP.

B. Transformers: Grounding impedances

A resistor Rgrounding connected between the grounding terminal of each transformer and the ground was added in each substation to represent the following elements:

- Impedance of the substation grounding grid Rgrid which is set to 1.5Ω, a typical value based on HQ experience.
- In parallel with the lines grounding, typically 2Ω (shield wires and counterpoise of each line) divided by the number of lines connected to the substation.
- Typically, Rgrounding is set between 0.2 and 1.0Ω.

C. Synchronous machines. Regulators

In HQ's EMTP network, each synchronous machine (SM) has its own AVR, Governor and excitation system. The effect of Over Excitation Limiter (OEL1B and MAXEX2 models) is important in this kind of study, so OEL models have been implemented in 13 major power plants and synchronous condensers (SC), as shown in Fig. 3.

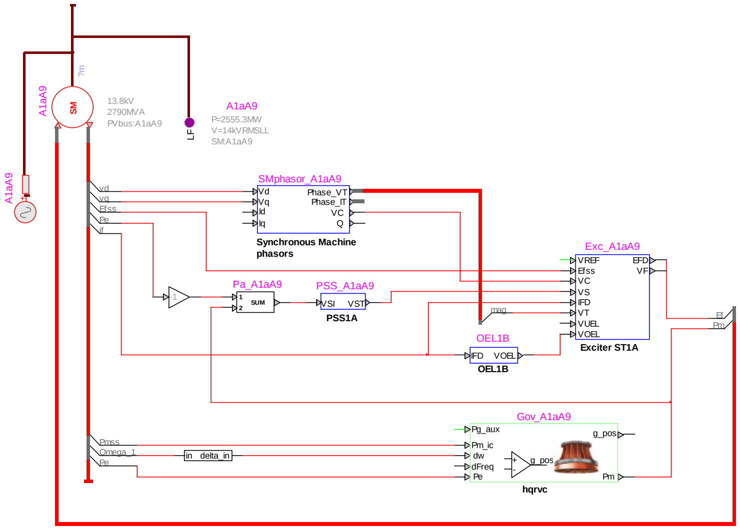


Fig. 3 Example of AVR-GOV implementation at LaGrande-4 power plant.

D. Automatic controls

Three major automatic controls are implemented to achieve correct long term voltage simulation:

- 98 transformer on-line tap changers (OLTC): By default, OLTCs have -8/0/+8 steps for ±10% voltage range and are set at initial condition, in central position.
- 21 automatically removable shunt reactors (165/330MVAR): Undervoltage trip setting is typically 0.97 pu over 5s to 15s.
- One special undervoltage load shedding scheme in Montreal: Three settings in magnitude and time for 500-300-650MW of load.

These automatic controls represent in a simplified manner a major part of the voltage control schemes that are implemented in HQ's system. They are necessary for the voltage stability section of this paper.

E. V with impedance

Two types of GMD studies were performed with the EMTP network, both for 300s duration time:

- GMD dynamic impacts on voltage stability with

SM.

- GMD steady-state analysis. In this case all SM are replaced by a constant voltage source behind a regular RL impedance generally calculated from the synchronous reactance of the machine (Xd). This approach gives the *natural* I_{DC_GMD} without interaction between GMD, SM controls and other special control schemes.

IV. 1989. REPRODUCTION OF THE EVENTS

One of the first uses with this GMD modeling technique was to reproduce the 1989 blackout. From the 2020 network topology, a retrofit on the topology of March 13 1989 was done by removing additions to the network since today to 1989:

- Generation and loads,
- 735kV lines and all series compensation,
- HVDC links and Static Var Compensator (SVC) installations.

By chance, harmonic and DC current measurement equipment was installed in many substations in 1989 for tests *in situ*. These measurements are the only ones HQ had related to the storm. We tried to reproduce those measures with our study.

A. *The sequence of events (GMT+0)*

- 00h00 - beginning of the GMD
- 07h44m:17s @ 19s - loss of two SVCs at Chibougamau
- 07h44m:33s @ 46s - loss of four SVCs at Albanel and Nemiscau
- 07h45m:16s - loss of the SVC at La Vérendrye
- 07h45m:24.7s - loss of the line 7025 (during the voltage collapse)

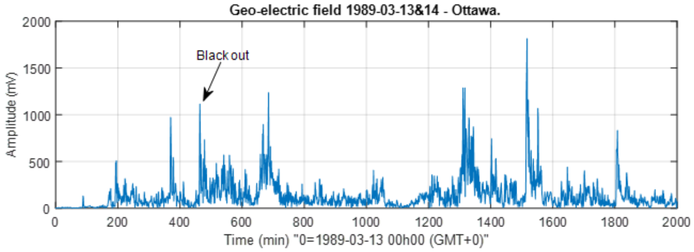


Fig. 4 Geo-electric field *estimated* from magnetometer [10].

A. *Methodology. Estimation of the storm*

Measurements obtained from magnetometers installed in Ottawa allowed NRCAN estimate the peak GEF during the event to around 1,200 mV/km (see Fig. 4). Based on that information, simulations were performed as follows:

- Variation of a constant uniform electric field from 0.5 to 2.5 V/km
- Try to match the 1989 measurements: Voltage droop, asymmetry and the DC flow. Asymmetry was replaced in 2000's by harmonic measurement.

$$Asym = (V+ - V-)/ (V+ + V-) \qquad (6)$$

- Recreate the network voltage collapse

B. *Results – Voltage droop, asymmetry, and DC flow*

Table 1 compares 14-ΔU field measurements in red with GMD simulation in green. As can be observed, the best matches were with GMD close to 1.5V/km and with some local peaks at 2V/km.

TABLE I

STEADY-STATE VOLTAGES - MEASUREMENT VS SIMULATION

				GMD(V/km)				
	Measurment (kV)			0.5	1.0	1.5	2.0	2.5
Poste	Before	During	ΔU	ΔU				
LG2	742	735	7	3	5	7	10	13
Némiscau	735	726	9	5	9	13	18	24
Abitibi	737	725	12	6	11	17	24	32
La Vérendrye	734	718	16	6	13	19	28	40
Chénier	734	714	20	9	18	27	38	51
Tilly	737	735	2	3	7	10	14	17
Albanel	734	727	7	5	9	13	18	24
Chibougamau	747	725	22	6	11	17	24	32
Chamouchouane	740	718	22	6	12	18	25	33
Bouchervillle	729	718	11	8	17	26	36	48
Laurentides	739	722	17	5	10	15	21	29
Micoua	736	711	25	4	8	13	18	23
Jacques-Cartier	736	714	22	6	12	18	24	33
Levis	739	719	20	5	11	16	22	30
ΔQ (MVAR)				600	1260	2000	2540	3160

For asymmetry (table II) and DC flows (Table III), it can be noted the best matches were with GMD close to 2.0 V/km and with some local peaks at 3V/km.

TABLE II

ASYMMETRY ON 735KV BUS - MEASUREMENT VS SIMULATION

	Asymetry (%)			
	Field	GMD (V/km)		
Albanel		1.0	2.0	3.0
Arnaud	<4	2.5	3.0	2.5
Boucherville	<10	4.8	6.0	3.6
Chateauguay	<2.5	1.2	2.6	3.8
Chibougamau	<5	0.8	2.2	4.3
La Vérendrye	<1	1.5	2.7	4.9
LG2	1.5-3.2	3.6	6.0	6.6

TABLE III

NEUTRAL CURRENT TRANSFORMER - MEASUREMENT VS SIMULATION

	IDC neutral (A)				
	Field	GMD (V/km)			
		1.0	2.0	3.0	4.0
Saguenay T1	55.3	-27	-47	-71	-95
Radisson T3	-100	-60	-120	-180	-230
Des Cantons T2	85	27	53	80	106

C. *Results – Voltage collapse.*

Many HQ reports confirmed that the outage on March 13, 1989, was caused by a voltage collapse. Previous studies represented the event by switching shunt reactors in positive sequence dynamic software. Here, for the first time, the voltage collapse was observed without forcing any shunt reactor switching and was caused *only* by the GMD DC voltage injection. HQ had only the two dynamic curves shown in Fig. 5 relating of the blackout, here digitalized from original paper disturbance recorder.

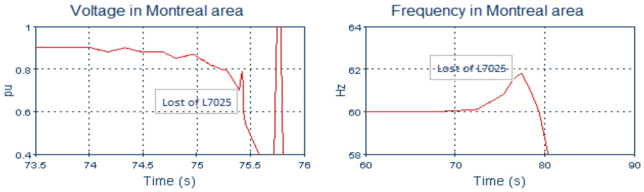


Fig. 5 Voltage and frequency measurements in 1989.

Fig. 6 shows the result of the EMTP simulation of the 1989 event. According with B section above, note the GMD magnitude (top left) the best magnitude to reproduce the event. The concordance between the simulation and the measurements is not perfect, as can be observed on the voltage collapse graph (top-right) and the network frequency graph (bottom-right), but quite similar. Considering that many data used in the simulation are hypothesis, this simulation confirms that the GMD simulation method is reasonably accurate and can be used to estimate the impact of other GMD scenarios in system studies.

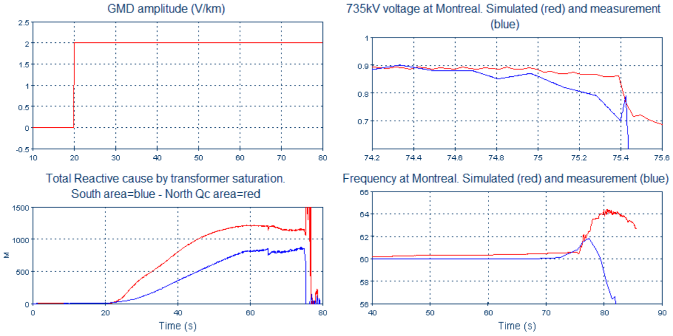


Fig. 6 Reproduction of the 1989 HQ Voltage collapse in EMTP.

V. USAGE ON 2022 HQ SYSTEM – A CASE STUDY

The HQ network had a lot of new equipment added since 1989: series compensation in 27 substations, 735 kV lines, strategic automatic controls schemes to keep the network in operation during GMD and other major events. The method discussed above was used to simulate geomagnetic events and assess their impact on HQ's system as would be required by TPL-007-3. This section is not the official position of HQ about the TPL-007-3: results are preliminary, but they illustrate the powerful approach of EMTP for GMD studies to help HQ quantify the impact of GMD on its network (see Fig. 1).

A. *Transformers: Ieffective, VAR Consumption*

The thermal limit in the TPL-007 was defined with Ieffective. For a classic 2 or 3 windings transformer,

$$Ieff = Ineutral/3 \qquad (7)$$

For an autotransformer, NERC[14] and IEEE[13] give the same results.

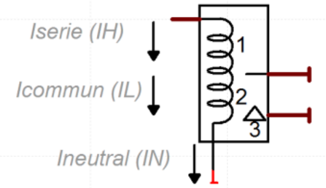
$$Ieffect = IH + (IN/3 - IH) \times VX/VH \qquad \text{(NERC)} \quad (8)$$

$$Ieffect = IH + (IL \times VX/VH) \qquad \text{(IEEE)} \quad (9)$$

Where

VX= Vcom, VH= Vcom+Vserie

IL= Icom, IH=Iserie



Simulations of an event were performed in EMTP with the complete transmission system and the results are presented below.

For 100 of the 270 transformers, the dynamic of Ieffective is illustrated in Fig. 7. Note some take more than 2 minutes to reach steady-state values, but the large majority take less than 60s. Most transformer models represent 2, 3 or 4 units; the individual unit results are not showed. This approach will be used to estimate which transformers could have Ieff≥75A or 85A as is required by TPL-007 for thermal evaluation.

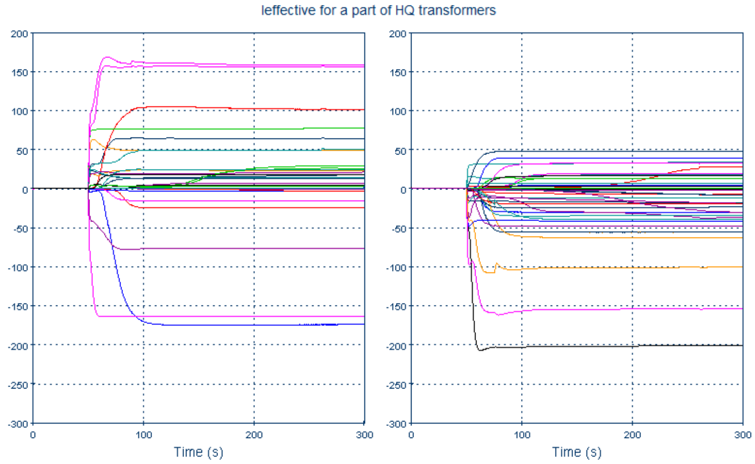


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Fig. 7 Ieffective for 2-3 windings transformers.

The Mvar consumption of a transformer is estimated with the equation given by [11]-Eq (10), by multiplying the 60Hz-FFT of Uac and Iac of phase A of the magnetization branch of the transformer.

$$Q_{GIC} = FFT_{60Hz}(Uac\_a) * FFT_{60Hz}(Iac\_a) * 3 \qquad (10)$$

Fig. 8 shows the individual Mvar consumption of all transformers. The total consumption is around 5500 Mvar, as shown in Fig. 9.

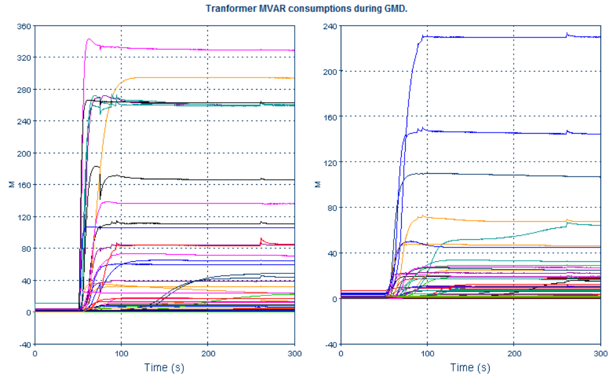

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Fig. 8 The individual Mvar consumption of transformers

Fig. 9 shows the dynamic behavior of the total Mvar consumption of the system (Addition of the 270 transformers individual Mvar consumption). It is possible to estimate:

- Rising time at 67% ≈ 15s
- Rising time at 90% ≈ 50s

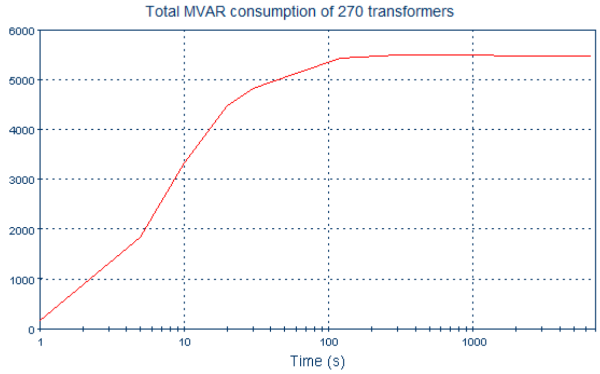

Fig. 9 The total MVARS consumption.

B. *System voltage regulation behavior*

The addition of more than 5500 Mvar of reactive power consumption has a huge impact on the network voltage. The following figures show how the network is reacting. Fig. 10 shows the 735kV voltage (top-left), the automatically switched reactors (bottom-left), the automatic load shedding (top-right), SVC and SC production. All these automatic controls are strategic. GMD start at 50s.

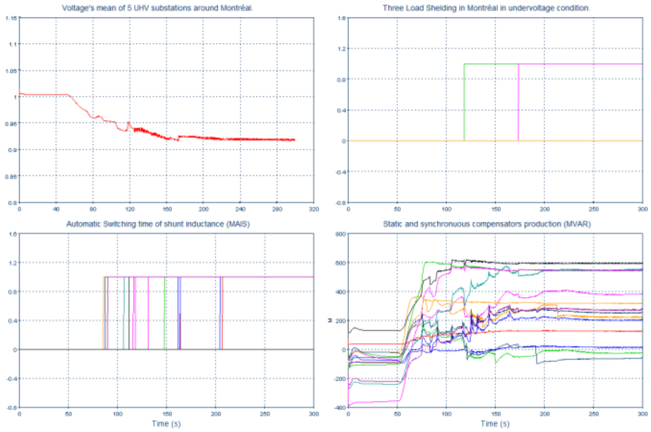

Fig. 10 Summary of 735 kV system behavior

Automatic switching of reactors (MAIS) and the automatic load shedding plays an important role to maintain the 735 kV voltage above 0.9pu where voltage collapse is more likely to happen. To illustrate this, the same simulation was performed without theses controls. Fig. 11 shows the result. It can be observed that even if all SVCs and SCs become fully capacitive, values above 0,9pu cannot be met.

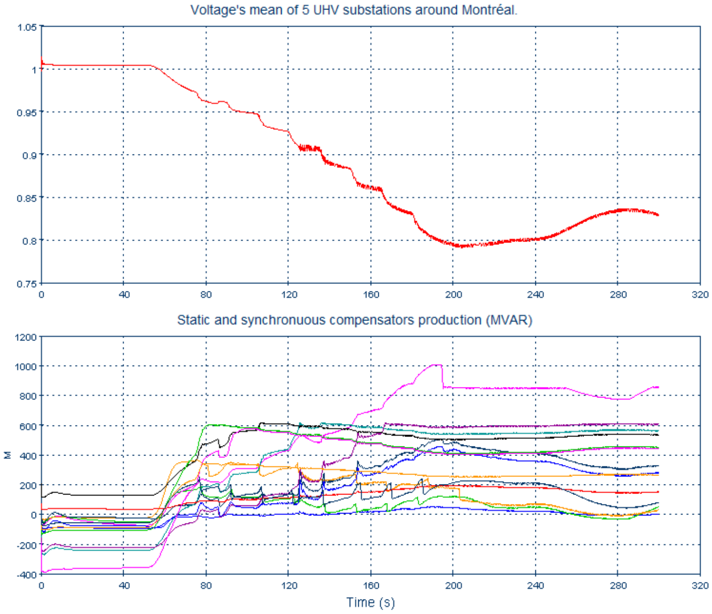

Fig. 11 735 kV system behavior without MAIS and load shedding

Fig. 12 below shows the OLTC actions during the GMD. The action of these is unhelpful from 735kV voltage regulation point of view.

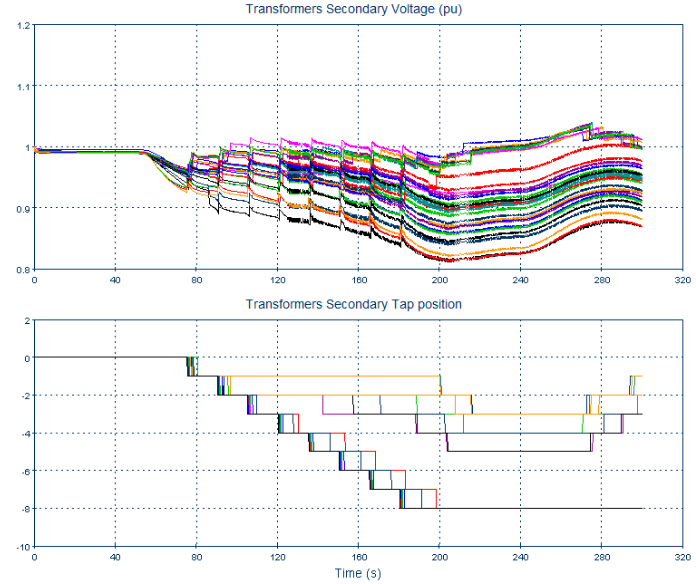

Fig. 12 Behavior of some OLTC.

C. *Harmonics*

Harmonics are maybe the most difficult value to estimate in GMD events. EMTP gives an opportunity to estimate the potential harmonic content. 35 harmonic meters are connected in different locations. They indicate how the Power Quality of the AC voltage may be affected by a high level of GMD amplitude. Up to 10% total harmonic distortion has been measured in the worst case, which is very high. How the load could be affected needs to be investigated further.

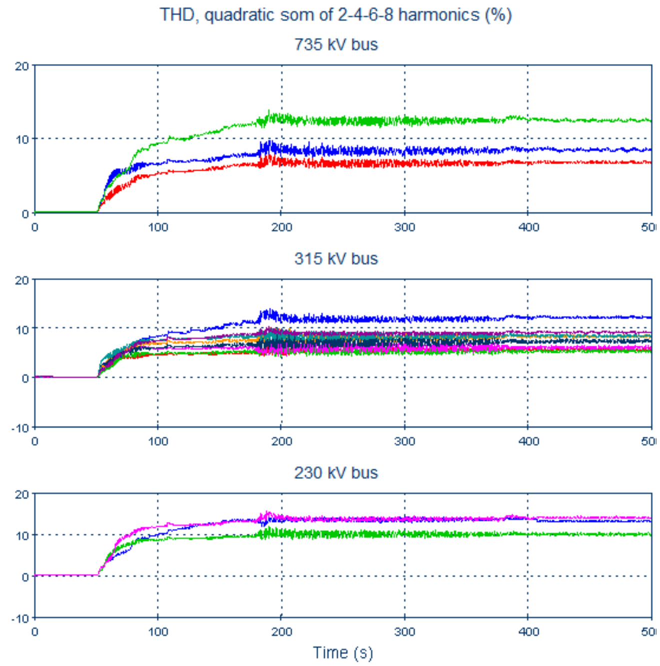

Fig. 13 THD on different bus levels.

Hydro-Québec has many shunt capacitors at 230 and 315kV levels for a total of more than 2000Mvar. Fig. 14 shows the U_{THD} increase (left), and U1 decrease and I_{RMS} increase (right), during the GMD event. This demonstrates that shunt capacitors may also be affected by GMD events. Their overload protections will be closely studied.

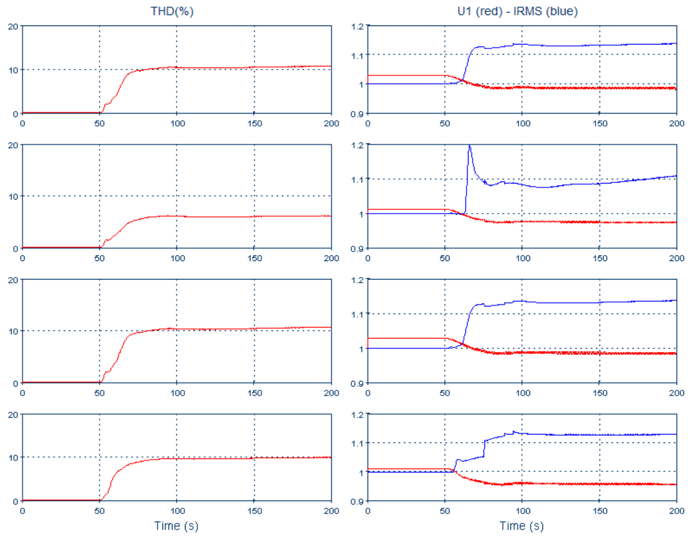

Fig. 14 THD, voltage and current of 4 shunt capacitors at 230 and 315 kV

VI. SOLUTIONS TO MINIMIZE GMD IMPACT

For the next years, Hydro-Québec will continue studies on:

- Shunt capacitor protections,
- Thermal model for transformers which have Ieffective above thresholds.
- If required, the effect of adding low impedance 2.5S series compensation in middle of lines [12].

VII. CONCLUSIONS

This paper presented GMD study of the HQ networks on EMTP. The simulations done to reproduce the 1989 GMD storm conclude the level was close to 2V/km. The TPL-007 level benchmark scenario corresponds about 3 times “1989”.

This approach opens many opportunities to study complete overall GMD on transmission system, from DC-LF to full transient simulation and to consider the overall dynamic system with voltage regulation, excitation limiters, tap changers and harmonics levels estimations. After years of R&D effort by authors, the technique is mature. The method was applied for the first time to perform a GMD analysis in time-domain with EMTP.

VIII. ACKNOWLEDGMENT

Sincere acknowledgements also to Omar Saad and Jean Mahseredjian for their contributions on EMTP scripting and engine.

The authors also want to thank Sébastien Guillon for 1989 measures and Gilbert Sybille for auto-transformer modeling information.

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