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Control of Over-voltages on Hydro-Québec 735-kV Series-Compensated System During a Major Electro-mechanical Transient Disturbance.

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Abstract - **Hydro-Québec 735-kV transmission system is made up of two 1000-km branches linking isolated generating centres to the North and the load area to the South. Following a system separation, severe temporary over-voltages (TOV) due to Ferranti effect appear on long unloaded lines that are still connected to generators. A protection system, called SPSR, which consists of switched metal-oxide surge arresters (SMOSA) and an unloaded-line switching scheme, has been implemented during the 1980s. In the beginning of the 1990s, Hydro-Québec has undertaken a major program to upgrade the reliability of its transmission system. This program has included the installation of 32 series-capacitor banks adding up to 11200 Mvar, the upgrading of transmission line protections and the addition of various controlled switching schemes. These additions provide a new network configuration for the operation of the actual SPSR. Therefore, electromagnetic transient studies including the presentation of system dynamics have been conducted to verify the efficiency of SPSR to control temporary over-voltages following a separation of the newly series-compensated system. The results of these studies are summarised in this report. All the required modifications to the actual SPSR for enhancement of its operation in the series-compensated system are also described in this paper.**

Keywords: Series-Compensated Systems, Temporary Over-voltages (TOV), Switched Metal-Oxide Surge Arresters (SMOSA), Transient Recovery Voltages (TRV), Power System Dynamics, Modelling Techniques.

I. INTRODUCTION

The Hydro-Québec 735-kV transmission system, as illustrated in Fig. 1, is a long radial network. Three of its four main production sites, The James Bay Complex (15600 MW), The Manic-Outardes Complex (8100 MW) and The Churchill Falls Complex (5600 MW), are located in the North. The main load centres Québec City and Montréal, are concentrated in the South. The length of the two major transmission branches, running from Churchill Falls to Québec City and from James Bay generating stations to Montréal, is approximately 1000 km. In the early phases of its developments, shunt reactors, synchronous condensers and static var compensators have been installed in this transmission system. Moreover, all primary protections of 735-kV lines were made up of distance relays. On such a system, a severe fault could result in out-of-phase condition between distant generating centres and, subsequently the separation of the two major transmission branches caused by simultaneous tripping of all lines where virtual faults (or near-zero voltages) take place. Following a system separation, severe TOV due to

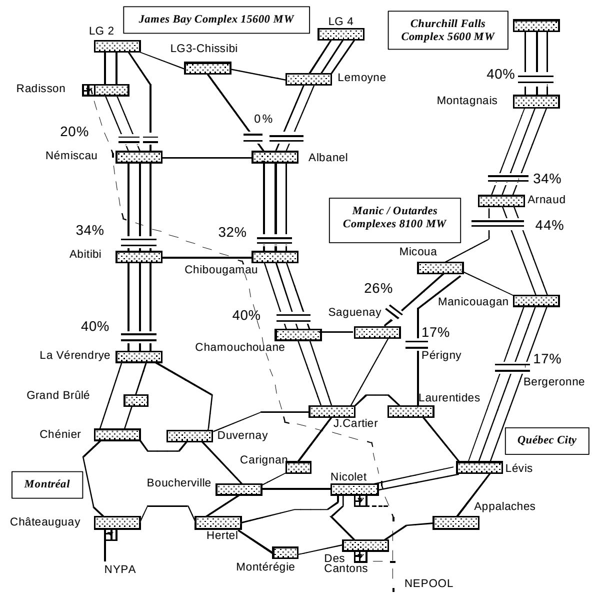

Fig. 1. Hydro-Québec 735-kV series-compensated transmission system.

Ferranti effect appear on long unloaded lines which are still connected to generators. Extensive studies conducted during the 1980s have identified that the separation of shunt-compensated system could take place anywhere in the 735-kV network from the South of Abitibi/ Chibougamau up to Churchill Falls Complex [1]. The scenario of the system separation to the South of La Vérendrye and Chamouchouane would result in the worst TOV condition because of longer lines involved. For the comprehension of study results, the p.u. value in the paper is defined as 600 kV-peak (=735 kV rms phase-to-phase x $\sqrt{2}/\sqrt{3}$).

II. DESCRIPTION OF THE ACTUAL SPSR

In order to control the magnitude and the duration of TOV following a system separation, a protection system, called SPSR, has been implemented in the Hydro-Québec 735-kV transmission network. This protection system consists of two schemes: the first one has been installed in the James Bay system and the second has been implemented in the Churchill Falls system.

2.1) In the James Bay system, SMOSA having a rated voltage of 484 kV rms, were installed to the North-side line terminals of Abitibi, Chibougamau, La Vérendrye, Chamouchouane and Saguenay substations. These surge arresters limit the magnitude of TOV in case of system separation to approximately 1.60 p.u. Since their rated voltage is too low to be permanently connected to the system, they must therefore be switched in for short periods of time (≈ 15 s) during system disturbances by local power swing detection, by remote detection of over-frequency, or by open-corridor condition. The two corridors of the James Bay system are independently protected by SPSR. The West corridor is delimited by LG-2, Radisson, Némiscau, Abitibi, La Vérendrye, Grand Brûlé, Chénier and Duvernay substations. The East corridor includes Lemoyne, Albanel, Chibougamau, Chamouchouane, Saguenay and Jacques Cartier substations. As illustrated in Fig. 2, the following features have been implemented in these two corridors:

- *Instantaneous 1.4-p.u. over-voltage protections installed in all line terminals in each substation* – For the security of their operation, these over-voltage protections are not active during normal system condition.
- *Over-frequency detection at Radisson substation for the West corridor, and that at Lemoyne substation for the East corridor* – When over-frequency reaches a threshold value of 63 Hz, instability signals are sent to all substations in the same corridor to activate all instantaneous 1.4-p.u. over-voltage protections and to switch in all SMOSA.
- *Open-corridor detection at each substation of the two corridors* – Upon the detection of open-corridor condition, instability signals are transmitted to all substations in the same corridor to activate all instantaneous 1.4-p.u. over-voltage protections and to switch in all SMOSA.

All these features will ensure that, should a system separation occur, all unloaded lines will be removed rapidly by 1.4-p.u. over-voltage protections and the magnitude of TOV in the James Bay system will be controlled by the presence of SMOSA.

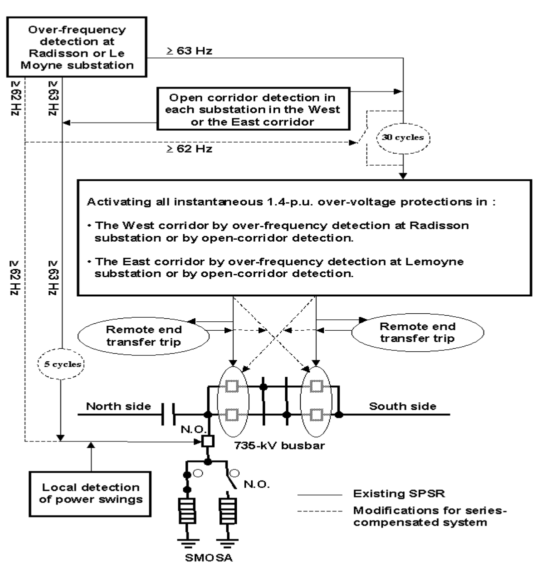

Fig. 2. Functional diagram of SPSR in the James Bay system.

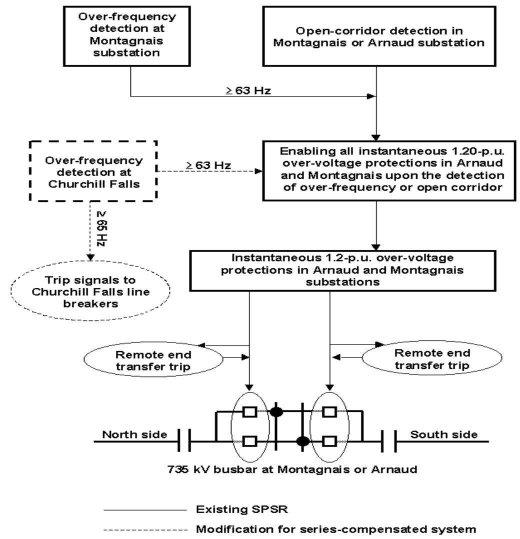

Fig. 3. Functional diagram of SPSR in the Churchill Falls system

2.2) In the Churchill Falls system, SPSR was applied in the North-Shore corridor which includes Churchill Falls, Montagnais, Arnaud, Micoua and Manicouagan substations. This protection scheme is similar to the one installed in the James Bay system, except that there is no SMOSA because of less severe TOV observed in the Churchill Falls system. As illustrated in Fig. 3, the following features have been implemented :

- *Instantaneous 1.2-p.u. over-voltage protections installed in all line terminals in Montagnais and Arnaud substations* – Again, for the security of their operation, these over-voltage protections are not active during normal system condition.
- *Over-frequency detection at Montagnais substation* – When over-frequency reaches 63 Hz, instability signals are emitted to enable all instantaneous 1.2-p.u. over-voltage protections in Montagnais and Arnaud substations.
- *Open-corridor detection at Montagnais and Arnaud substations* – Upon the detection of open-corridor condition, instability signals are then emitted to enable all instantaneous 1.2-p.u. over-voltage protections in Montagnais and Arnaud substations.

All these features will ensure that, should a system separation occur, instantaneous 1.2-p.u. over-voltage protections will remove rapidly all unloaded lines in this corridor and, therefore reduce the TOV duration.

III. CONTEXT OF SERIES-COMPENSATED TRANSMISSION SYSTEM

In the beginning of the 1990s, Hydro-Québec has undertaken a major program to upgrade the reliability of its transmission system. This program has included:

- The implementation of 32 series-capacitor banks adding up to 11200 Mvar to increase the system robustness.

- The upgrading of 735-kV line protections to enhance the security and the reliability of their operation. Majority of 735-kV lines was upgraded with two new protections. A primary protection, made up of series-compensated line protective relays, is insensitive to virtual faults. However, telecommunication is needed for the operation of this protection. A back-up protection with time delay, realised with distance relays, covers the loss of telecommunication.
- The addition of various automatic switching schemes to preserve the system stability during extreme contingencies. These automatic switching schemes, which are described in detail in [2] and [3], include the automatic generation rejection and remote load shedding scheme called RPTC, and the shunt reactor automatic switching system named MAIS.

These additions provide a new network configuration for the operation of the actual SPSR. Therefore, system studies have been conducted to verify its efficiency to control TOV following a separation of the newly series-compensated system.

IV. SEPARATION OF 735-kV SERIES-COMPENSATED SYSTEM

Stability study results have shown that the series-compensated system could be unstable under extremely severe disturbances and led to a system separation. The following scenarios have been observed:

- Voltage oscillations in the North-Shore corridor.
- Voltage oscillations in the James Bay system.
- System separation caused by virtual faults.
- Steady increase in generator frequency.

These scenarios are beyond the system design criteria regarding stability performance. However, equipment should be protected against excessive TOV following system separation. To analyse the efficiency of SPSR in the newly series-compensated system, these scenarios have been simulated by using detailed electromagnetic transient models including power system dynamics, transformer saturation and metal-oxide surge arresters.

4.1) Modelling of system dynamics. To represent the system dynamic behaviour, all generating stations and Thévenin equivalents were simulated by dynamic voltage source models using the Transient Analysis of Control Systems (TACS) in DCG-EMTP, as illustrated in Fig. 4.

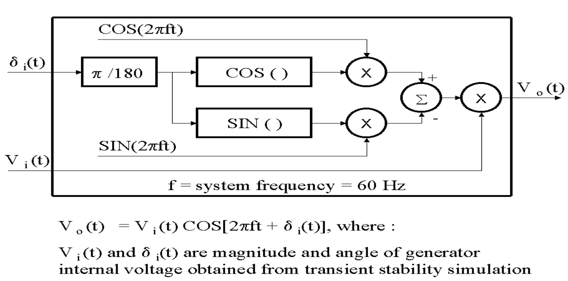

Fig. 4. Dynamic source model in DCG-EMTP.

The dynamic output voltage, V_o (t), was applied behind the generator (or Thévenin) equivalent impedance. All necessary input signals, V_i (t) and δ_i (t), have been collected or calculated from the results of stability study.

4.2) Voltage oscillations in the North-Shore corridor were observed following a three-phase-to-ground fault with delayed clearing time due one-phase stuck breaker:

- At t = 0, the series-compensated system is under steady state peak-load condition.
- At t = 100 ms, a three-phase-to-ground fault is initiated on one of the three lines between Churchill Falls and Montagnais.
- At t = 167 ms, two phases of the faulty line are opened at Churchill Falls line end.
- At t = 183 ms, three phases of the faulty line are opened at Montagnais line end.
- At t = 317 ms, the third phase of the faulty line is cleared at Churchill Falls line end.

It can be seen in Fig. 5 that after fault clearing, the system becomes unstable. The frequency of generators in Churchill Falls Complex increases rapidly. Pronounced voltage oscillations as well as virtual faults are observed at Montagnais. However, these virtual faults have not caused system separation because of insensitivity of series-compensated line protections. Moreover, during this disturbance 63-Hz over-frequency at Montagnais could be detected by the actual SPSR and the North-Shore corridor could be split at Montagnais (MTG7) or Arnaud (ARN7) by 1.2-p.u. over-voltage protections in these substations. Following a system separation, all unloaded lines would be rapidly removed up to Churchill Falls and Micoua/Manicouagan by 1.2-p.u. over-voltage protections and by remote-end transfer-trip features in the actual SPSR.

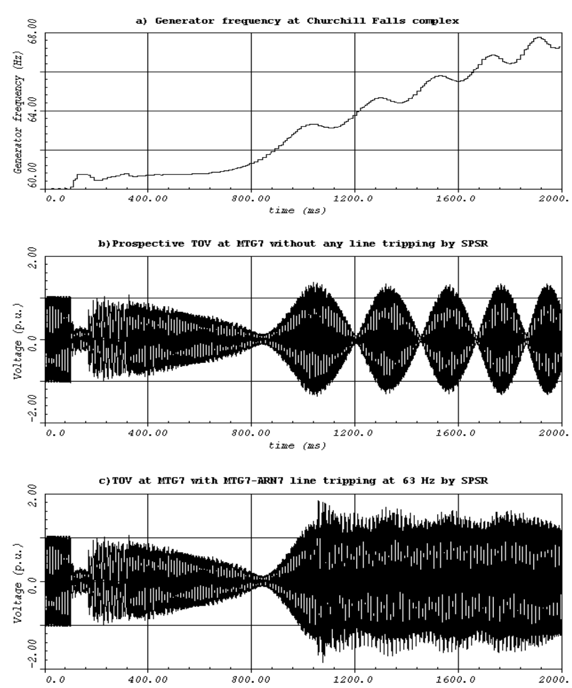

Fig. 5. Voltage oscillations in the North-Shore corridor.

It should be mentioned that the reliability of SPSR to protect the North-Shore corridor is relied on the detection of the over-frequency at Montagnais. This over-frequency detection could be jeopardised by the presence of virtual faults closed to this substation. Therefore, it was recommended to implement an additional over-frequency detection at Churchill Falls, as indicated in Fig. 3, in order to improve the performance of the actual SPSR. This new over-frequency detection will have two settings: at 63 Hz, instability signals will be emitted to activate all 1.2 p.u. over-voltage protections in Montagnais and Arnaud and at 65 Hz, trip signals will be sent to Churchill Falls 735-kV line breakers.

4.3) Voltage oscillations in the James Bay system were observed following a three-phase-to-ground fault and the loss of three lines:

- At t = 0, the series-compensated system is under steady state peak-load condition.
- At t = 100 ms, a three-phase-to-ground fault is initiated at Chibougamau 735-kV bus bar.
- At t = 200 ms, the three-phase-to-ground fault at Chibougamau is cleared and the loss of 3 lines between Chibougamau and Chamouchouane (loss of the East corridor) and the tie line Chibougamau – Abitibi.
- At t = 450 ms, RPTC orders the total generation rejection at LG-4.
- At t = 533 ms, the remote shedding of 2500 MW of loads and 1510 Mvar of capacitor banks in Montréal and Québec City is completed by RPTC.

The system becomes unstable following these disturbances as illustrated in Fig. 6. The frequency of the generators in the James Bay Complex increases rapidly and reaches 63 Hz within the first second following these disturbances. Meanwhile, voltage oscillations, having magnitudes greater than 1.4 p.u., were observed at La Vérendrye, Abitibi, Némiscau, Radisson, LG-2, Lemoyne, Albanel and Chibougamau. Upon the detection of 63-Hz over-frequency at Radisson, the system separation could be initiated by 1.4-p.u. over-voltage protections on the West corridor from La Vérendrye up to LG-2. Following the system separation, the magnitude and duration of TOV will be controlled by SMOSA and 1.4-p.u. over-voltage protections which are already switched in and activated on the West and the East corridors by the detection of 63-Hz, open-corridor or power-swing condition.

It can also be seen in Fig. 6 that the frequency of the James Bay system reaches 63 Hz almost at the same time as the apparition of 1.4-p.u. over-voltages that could initiate a system separation before the switching in of SMOSA. Therefore, it was recommended to implement a new over-frequency threshold of 62 Hz at Radisson and Lemoyne, as illustrated in Fig. 2, in order to ensure that all SMOSA will be switched in before system separation takes place.

The results of this scenario have also indicated that following a disturbance implying the loss of the East corridor, the separation of the James Bay system could take place anywhere on the West corridor from La Vérendrye (LVD7) up to LG-2. Similarly, this system could also be separated by 1.4-p.u. over-voltage protections on the East corridor from Chamouchouane up to Lemoyne following a disturbance implying the loss of the West corridor. For both of these scenarios, the magnitude and duration of TOV following a system separation will be controlled by SMOSA and 1.4-p.u. over-voltage protections.

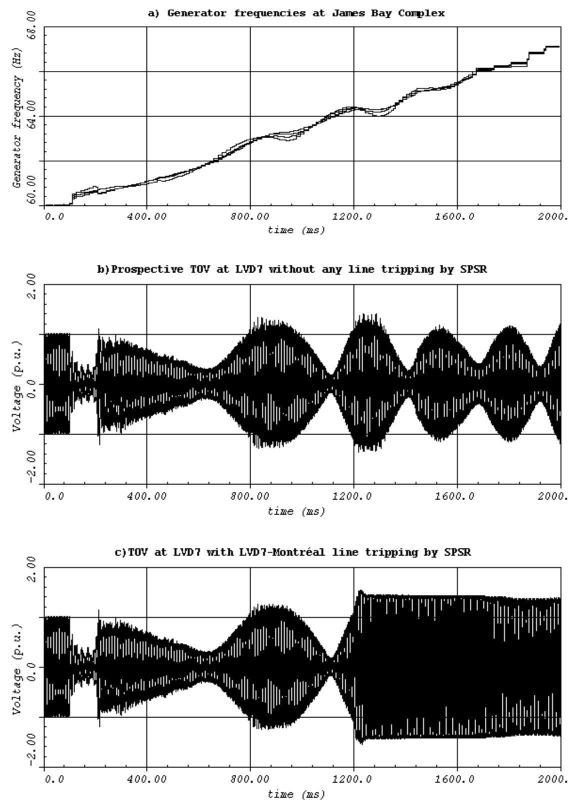

Fig. 6. Voltage oscillations in the James Bay system.

4.4) System separation South of La Vérendrye and Chamouchouane caused by virtual faults. For the provision of future series compensation, all 735-kV lines connected to the South of La Vérendrye and Chamouchouane substations have been upgraded with two new line protections as described earlier. These lines could be tripped by their time-delayed back-up protections made of distance relays if RPTC unsuccessfully sheds loads following a three-phase-to-ground fault and the loss of three lines:

- At t = 0, the series-compensated system is under steady state peak-load condition.
- At t = 100 ms, a three-phase-to-ground fault is initiated at Chamouchouane 735-kV bus bar.
- At t = 200 ms, the three-phase-to-ground fault at Chamouchouane is cleared implying the loss of 3 lines South of Chamouchouane (loss of the East corridor)
- At t = 450 ms, RPTC successfully orders the total generation rejection at LG-4 but unsuccessfully shed loads in Montréal and Québec City.
- At t = 916 ms, due to the presence of virtual faults, the three lines South of La Vérendrye are tripped by their time-delayed back-up protections making the system separation.

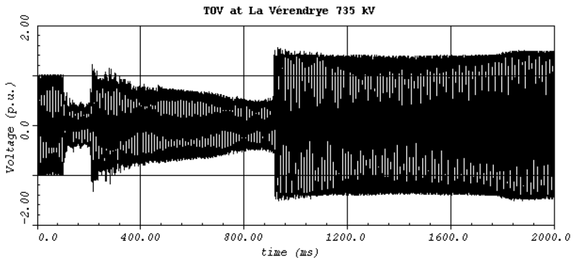

Fig. 7. TOV during the system separation South of La Vérendrye and Chamouchouane caused by virtual faults.

As illustrated in Fig. 7, the magnitude of TOV following the system separation is limited to 1.5 – 1.6 p.u. by SMOSA which have been switched in upon the detection of 63-Hz, open-corridor or power-swing condition. Fast removals of all unloaded lines upstream of La Vérendrye and Chamouchouane by actions of 1.4-p.u over-voltage protections will then reduce the TOV duration.

4.5) System separation South of Micoua and Manicouagan caused by virtual faults. Since the series-compensation of the three lines Manicouagan – Lévis and that of Micoua – Laurentides are installed in the middle of these lines, distance relays have been used for their primary and back-up protections. The system separation to the South of Micoua and Manicouagan takes place following a three-phase-to-ground fault and the loss of three lines:

- At t = 0, the series-compensated system is under steady state peak-load condition.
- At t = 100 ms, a three-phase-to-ground fault is initiated at Micoua 735-kV bus bar.
- At t = 200 ms, the three-phase-to-ground fault Micoua is cleared and the loss of 3 lines connected to the South of Micoua: Micoua – Manicouagan, Micoua – Saguenay and Micoua – Laurentides.
- At t = 1550 ms, due to the presence of virtual faults, the three lines Manicouagan – Lévis are tripped by their primary protections making the system separation.

Following the system separation, TOV of 1.3 – 1.4 p.u. appear on the North-Shore corridor as illustrated in Fig. 8. The fast removals of this unloaded corridor by 1.2-p.u. over-voltage protections, which have already activated in Montagnais and Arnaud substations upon the detection of 63 Hz, will then limit the duration of TOV in the Churchill Falls system.

4.6) Steady increase in generator frequency. All generators in the peak-load series-compensated system would be accelerated in the same fashion following the loss of Abitibi 735-kV substation:

- At t = 0, the series-compensated system is under steady state peak-load condition.
- At t = 100 ms, loss of Abitibi 735-kV substation.
- At t = 350 ms, RPTC orders the total generation rejection at LG-2.
- At t = 533 ms, RPTC successfully sheds 2500 MW of loads in Montréal and Québec City.

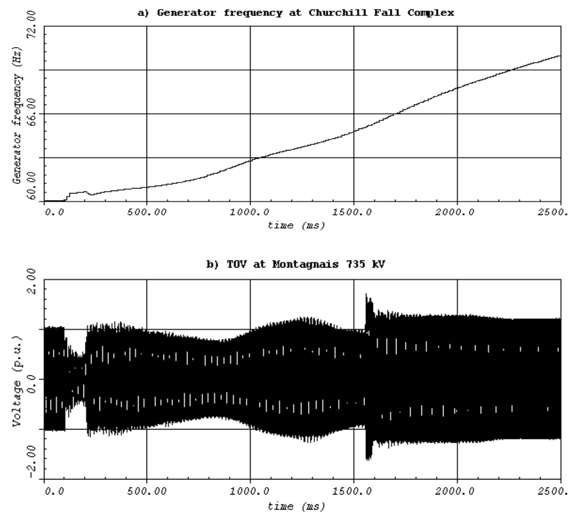

Fig. 8. TOV during the system separation South of Micoua and Manicouagan caused by virtual faults

As shown in Fig. 9, the frequency of all generators at James Bay, Manic-Outardes and Churchill Falls increases steadily after these disturbances. At t = 4500 ms, the over-frequency reaches 63-Hz threshold that will activate all 1.4-p.u. and 1.2-p.u. over-voltage protections in the James Bay and the Churchill Falls systems. All SMOSA in the James Bay system would also be switched in upon the detection of this over-frequency. Since TOV are less than 1.4 p.u. in the James Bay system and less than 1.2 p.u. in the Churchill Falls system, the system separation did not occur. At t = 6830 ms, the bipolar HVDC Radisson-Nicolet is tripped by its protection.

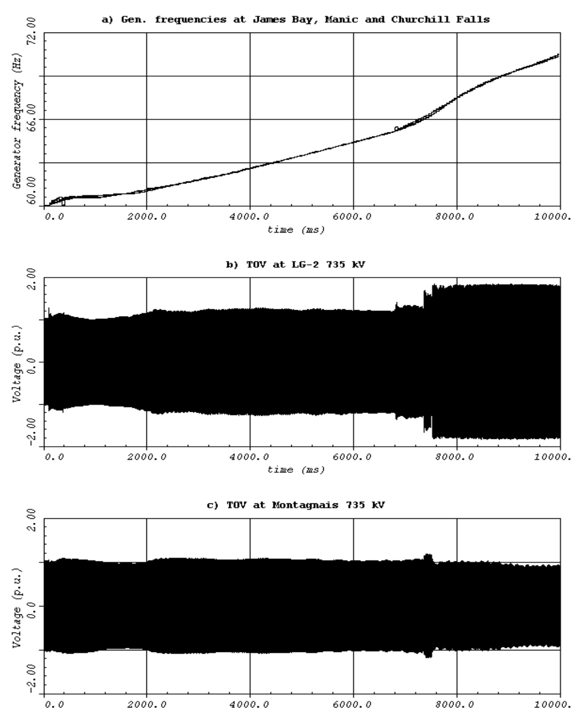

Fig. 9. Scenario of steady increase in generator frequency.

Furthermore, during the period from 7330 ms to 7500 ms, remaining generators in the James Bay system are tripped out by their 66-Hz over-frequency protections. Once all generators are tripped out, TOV higher than 1.4-p.u. were observed from Némiscau/Albanel up to the James Bay Complex. Then, the presence of SMOSA and the actions of 1.4 p.u. over-voltage protections will limit the magnitude and duration of TOV in the James Bay system.

V. TRANSIENT RECOVERY VOLTAGES (TRV) ACROSS 735-kV LINE BREAKERS

As shown earlier, under extremely severe disturbances, the Hydro-Québec 735-kV series-compensated system could be split by 1.2 p.u. over-voltage protections in the North-Shore corridor, 1.4 p.u. over-voltage protections in the James Bay system or virtual faults to the South of La Vérendrye, Chamouchouane, Micoua and Manicouagan substations.

During the 1980s, many 735-kV line breakers located from the South of Abitibi/Chibougamau substations up to Churchill Falls Complex have been reinforced to withstand TRV stresses during the separation of shunt-compensated system caused by virtual faults. These line breakers remain adequate for TRV stresses during the separation of the series-compensated system.

However, as summarised in the Table-I, many other existing 735 kV line breakers located from the North side of Abitibi/Chibougamau substations up to the James Bay Complex have not been reinforced and might not be adequate to withstand TRV stresses during the separation of series-compensated system that are initiated by 1.4-p.u. over-voltage protections. Therefore, the following remedy measures have been recommended:

- To remove existing 1.4-p.u. over-voltage protections on the two tie lines: Némiscau – Albanel and Abitibi – Chibougamau in order to avoid TRV stresses on these line breakers during system separation;
- To modify the remaining 1.4-p.u. over-voltage protections in the Abitibi, Némiscau, Albanel and Chibougamau substations in such a way that each pair of North/South line sections in series will be simultaneously tripped by 1.4-p.u. over-voltage protections on the North-side and on the South-side line terminals, as illustrated in Fig. 2. This simultaneous tripping should also be applied to the receiving signals from the remote-end transfer-trip features. This measure ensures that during system separation and during fast removal of unloaded lines, TRV stresses will be shared between the line breakers in series.
- To add a time delay of 5 cycles to the 1.4-p.u. over-voltage protections in the Radisson, LG-2 and Lemoyne substations in order reduce TRV stresses during unloaded line interruption. However, this time delay should not be applied to the emitting signals from the remote-end transfer-trip features.

Table-I: Maximum TRV stresses during system separation and unloaded-line interruption.

735-kV substations	***System separation***		***Unloaded line interruption***	
	Maximum TRV Stress (p.u.) (*)	Circuit breaker withstand (p.u.)	Maximum TRV stress (p.u.) (*)	Circuit breaker withstand (p.u.)
Abitibi	2.62	2.35	3.45	3.00
Chibougamau	2.62	2.35	3.45	3.00
Némiscau	2.68	2.35	3.22	3.00
Albanel	2.68	2.35	3.36	3.00
Radisson	2.90	2.35-2.75	3.20	3.00
LG-2	2.90	2.35	3.00	3.00
Lemoyne	2.90	2.35	3.30	3.00

(*) Maximum TRV stress on individual 735-kV line breaker.

All these measures allow to reduce TRV stresses on the existing 735-kV line breakers and therefore minimise the risks of breaker failure during the separation of the series-compensated system caused by 1.4-p.u. over-voltage protections.

VI. CONCLUSIONS

Extensive electromagnetic transient studies have been conducted to verify the efficiency of SPSR to control temporary over-voltages following a separation of Hydro-Québec 735-kV series-compensated system. In light of these study results, the following conclusions could be drawn:

- Under extremely severe disturbances, the Hydro-Québec 735-kV series-compensated system could be separated by 1.2/1.4-p.u. over-voltage protections of the actual SPSR or by the presence of virtual faults to the South of La Vérendrye, Chamouchouane, Micoua and Manicouagan.
- The presence of SMOSA and the actions of 1.2/1.4-p.u. over-voltage protections allow to control the magnitude and duration of TOV following a system separation.
- All the modifications to the actual SPSR, as recommended earlier in the paper, will ensure the improvement of its performance in the series-compensated system and allow to reduce TRV stresses on the existing 735-kV line breakers during system separation.

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