Simplified Approach for Synthesizing Frequency Dependent Network Equivalents Including Dynamic Behaviors of Large Power Transmission Systems

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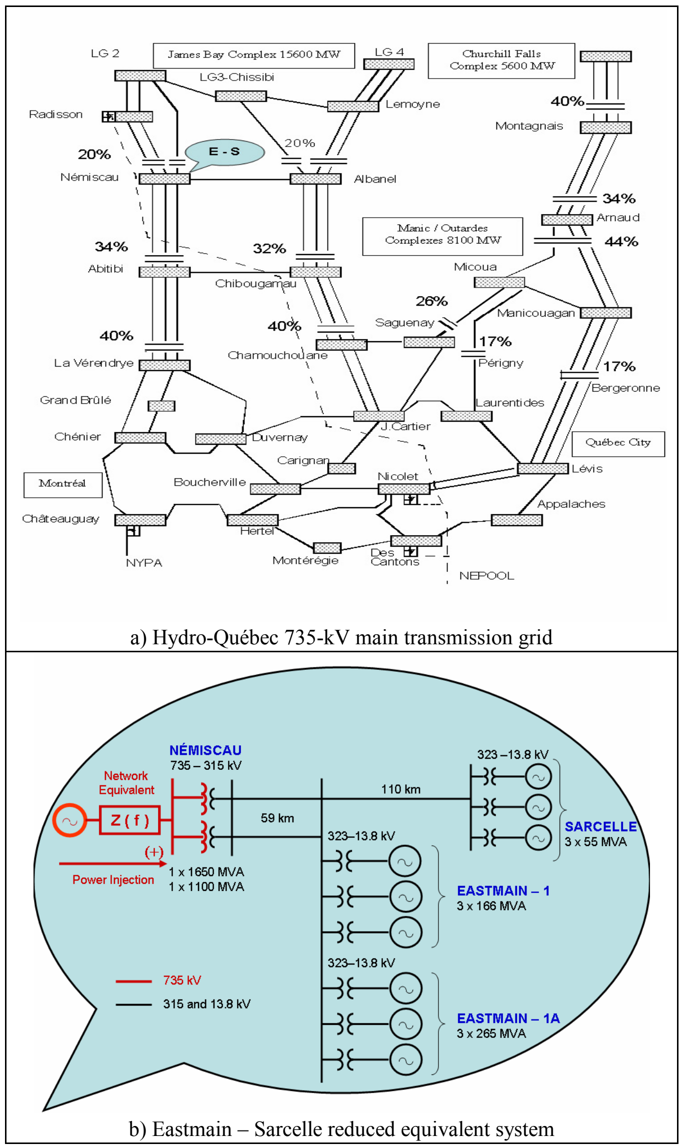
Abstract **– The extent of Hydro-Québec power transmission system has substantially increased the complexity of transient simulation studies for the integration of new power production and transmission facilities, even if these studies were performed using the powerful simulation tool such as EMTP-RV nowadays available. Furthermore, the specifications of turn-key projects for static VAr compensators and HVDC interconnections often require precise transmission system data which have to be provided in a simplified manner. In order to reduce the size of power systems for transient simulation studies and to be able to provide transmission system data in a compact format, a simplified method for the synthesis of equivalents for large power transmission systems was developed. As an application, the transient simulation studies for the integration of Eastmain-Sarcelle (E-S) hydropower plants at the Némiscau 735-315 kV substation were performed using this network synthesis approach. The steady states of the complex network are preserved by controlling the voltage and the power injection at the equivalent bus bar (Némiscau 735 kV) in the reduced system. Furthermore, the frequency dependent network impedances of positive and zero sequences as well as the system dynamic behaviors during an electromechanical transient disturbance are included in this network synthesis.**

Keywords **– Network Equivalent, Data Simplification, Power System Dynamic, Harmonic, Modeling Technique**

I. Introduction

The Eastmain-Sarcelle (E-S) hydroelectric power development, as illustrated in Fig. 1, consists of three generating stations: Eastmain-1 with 3 units of 166 MVA, Eastmain-1A with 3 units of 265 MVA and Sarcelle with 3 units of 55 MVA. The total power generated by these generating stations will be carried via a 59-km, 315-kV double-circuit line and injected into Hydro-Québec main transmission grid from the Némiscau 735-315-kV substation. The Eastmain and Sarcelle generating stations are interconnected by a 110-km, 315-kV single-circuit line. System studies have to be conducted to assess the transient performances of HV/EHV equipment, protection and control systems that will be implemented for the integration of this project. However, the extent of Hydro-Québec power transmission system has substantially increased the complexity of transient simulation studies, even if they were performed using the powerful simulation tool such as EMTP-RV nowadays available. Therefore, a simplified method for the synthesis of equivalents for large power transmission systems was developed. This paper summarizes the methodology of this network synthesis approach as well as the results of its application in transient simulation studies for the integration of the E-S hydropower project.



a) Hydro-Québec 735-kV main transmission grid

b) Eastmain – Sarcelle reduced equivalent system

Fig. 1. Integration of Eastmain-Sarcelle hydropower plants in Hydro Québec 735-kV transmission system

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II. Objectives of Network Synthesis

The main objectives for synthesizing a large power transmission system are to reduce its size in order to facilitate transient simulation studies as well as to be able to provide transmission system data in a simplified manner for turn-key power projects such as static VAr compensators, HVDC interconnections, etc. Furthermore, in order to maintain sufficient degree of accuracy for transient simulation studies using the reduced synthesized system, the following performance criteria should be fulfilled:

- The steady-state conditions as well as the short circuit levels in the integrated network should be preserved in the reduced equivalent system.
- The frequency responses of the integrated network should be synthesized for a wide band of frequencies covering all the electromagnetic transient phenomena under study.
- Finally, the dynamic behaviors of the integrated network could be reproduced by using the reduced synthesized system.

III. Steady-State Conditions and Short-Circuit Levels in the Integrated Network

The simplest equivalent of a large power system is the steady state Thévenin equivalent at the power frequency of 60 Hz (or 50 Hz). For a balanced three-phase power system, in which positive and negative sequence impedances are supposed equal, the Thévenin impedances can be represented by the positive and zero sequence short-circuit impedances seen at the equivalent bus bar, as illustrated in Fig. 2a. Furthermore, to preserve the steady-state conditions according to the load-flow in the integrated network, the internal equivalent voltage, $V_i \angle \delta_i$, is calculated from the steady state terminal voltage, $V_T \angle \delta_T$, and the power injection, $P+jQ$, at the equivalent bus bar using the following equations (Fig. 2b):

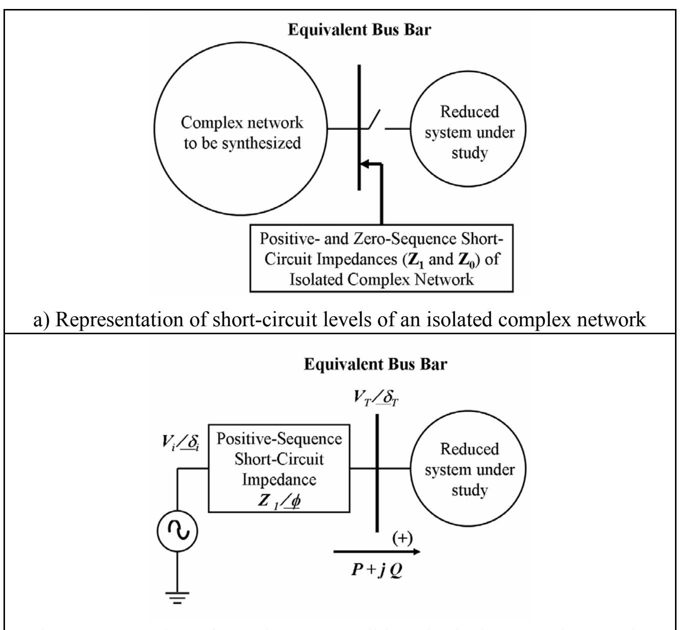


Fig. 2. Steady state equivalent at power frequency of a large power system

$$\delta = \phi - \arctan\left(\frac{P + \frac{V_T^2}{Z_1}\cos(\phi)}{Q + \frac{V_T^2}{Z_1}\sin(\phi)} \right) \qquad (1)$$

$$V_i = \left(Q + \frac{V_T^2}{Z_1}\sin(\phi) \right) \frac{Z_1}{V_T \sin(\phi - \delta)} \qquad (2)$$

$$\delta_i = \delta_T + \delta \qquad (3)$$

Where:

$Z_1 \angle \phi$	Positive-sequence impedance at the system frequency of 60 Hz (or 50 Hz), as seen at the equivalent bus bar, of the isolated network to be synthesized
$V_T \angle \delta_T$	Steady-state voltage at the equivalent bus bar according to the load-flow in the integrated system
$P + j\,Q$	Power injection into the equivalent bus bar according to the load-flow in the integrated system
$V_i \angle \delta_i$	Calculated internal equivalent voltage

Table I shows the steady state terminal voltage, $V_T \angle \delta_T$, the power injection, $P+jQ$, as well as the short circuit levels at Némiscau 735 kV obtained by EMTP simulations using the integrated network and the E-S reduced system with the calculated internal equivalent voltage, $V_i \angle \delta_i$.

Table I
Validation of Steady-State Thévenin Equivalent

Results	With the integrated network	With the E-S reduced system
Calculated internal equivalent voltage (phase-to-grd. peak), $V_i \angle \delta_i$, using (1), (2) and (3)	Not applicable	617.01 kV$\angle$ 64.5°
Steady-state terminal voltage at Némiscau 735 kV (phase-to-grd. peak): $V_T \angle \delta_T$	617.33 kV$\angle$ 67.5°	617.36 kV$\angle$67.5°
Power injection $(P + j\,Q)$ to Némiscau 735 kV	(-1363.0 +j 250.4) MVA	(-1363.0 +j 256.7) MVA
Three-phase short-circuit current at Némiscau 735 kV	20.0 kA	20.2 kA
Phase-to-ground short-circuit current at Némiscau 735 kV	17.2 kA	17.5 kA

It can be noticed that there is a good agreement between the results obtained with the E-S reduced system and those with the integrated network.

IV. Simplified Approach for the Synthesis of Network Frequency Responses

The previous steady state equivalent is not adequate for analyzing electromagnetic transient phenomena which include high frequency spectrum such as temporary/switching overvoltages, inrush transients, harmonic phenomena, etc. Therefore, the frequency responses of the integrated network should be represented in the reduced equivalent system.

A. Frequency responses of the isolated Hydro-Québec 735-kV main grid

In order to represent the frequency behaviors of the integrated network, the frequency scans were first performed for the frequency dependent impedances in zero and positive sequences, Z_0 (f) and Z_1 (f), seen at Némiscau 735 kV in the isolated Hydro-Québec main transmission grid. Fig. 3 shows the magnitudes and the imaginary parts of Z_0 (f) and Z_1 (f).

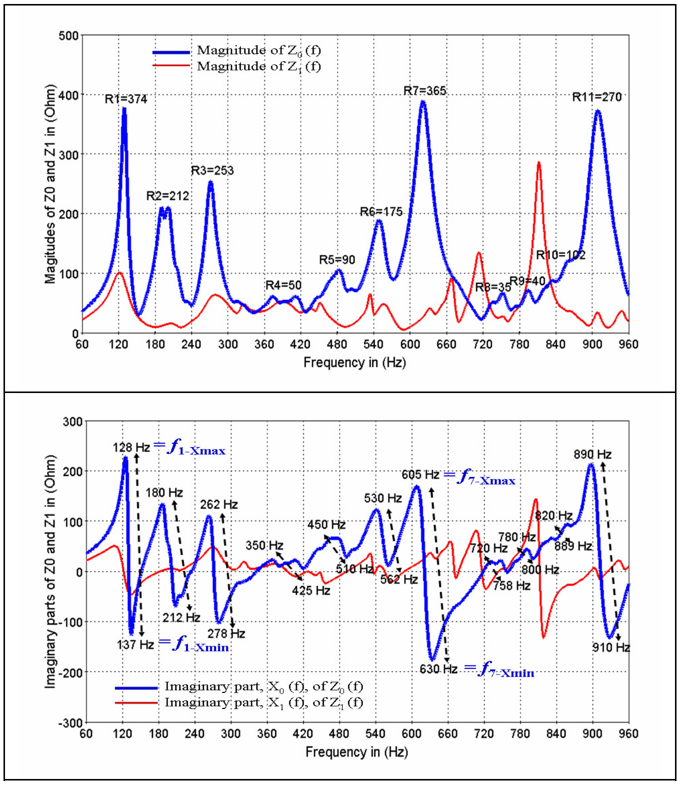


Fig.3. Magnitudes (top) and imaginary parts (bottom) of Z_0 (f) and Z_1 (f) seen at Némiscau 735-kV in the isolated Hydro-Québec 735-kV main grid

On these frequency responses, the following parameters can be identified for the nth pole of Z_0 (f) or Z_1 (f):

- R_n is the magnitude of the nth pole of Z_0 (f) or Z_1 (f).
- $f_{n\text{-}X\ max}$ is the frequency at which the imaginary part, X_0 (or X_1), of Z_0 (or Z_1) is maximum.
- $f_{n\text{-}X\ min}$ is the frequency at which the imaginary part, X_0 (or X_1), of Z_0 (or Z_1) is minimum.

These parameters together with the properties of parallel R-L-C circuits allow synthesizing the frequency dependent impedances, Z_0 (f) and Z_1 (f), which have n identifiable poles, using the Foster equivalent circuit as illustrated in Fig. 4 [1].

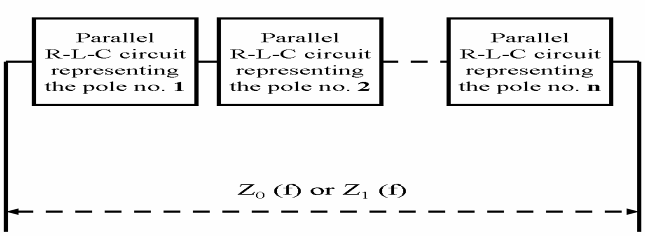


Fig. 4. Foster equivalent circuit synthesizing Z_0 (f) or Z_1 (f) having n identifiable poles

B. Properties of parallel R-L-C circuits

- Parallel R-L circuit:
  - Impedance of the parallel R-L circuit

$$Z(f) = \frac{R\ j2\pi\ f}{j2\pi\ f + (R/L)} \tag{4}$$

As an example, the magnitudes of *Z (f)*, for *R*=10 Ω and L varying between 2 mH and 10 mH, are illustrated in Fig. 5.

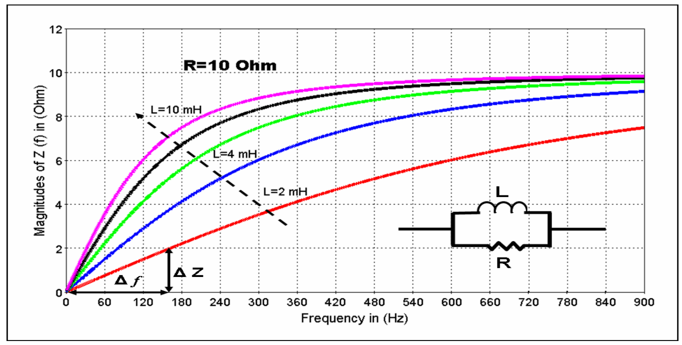


Fig. 5. Magnitudes of *Z (f)* for *R*=10Ω and L varying between 2mH and 10 mH

- Synthesizing properties [1].

$$R = \lim \left| Z(f) \right|\ f \to \infty \tag{5}$$

$$L = \frac{\Delta Z}{2\pi\ \Delta f}\ \ (\text{linear slope of } |Z(f)|\ |\ f \to 0\ ) \tag{6}$$

- Parallel R-C circuit:
  - Impedance of the parallel R-C circuit

$$Z(f) = \frac{1/C}{j2\pi\ f + (1/RC)} \tag{7}$$

Fig. 6 shows an example of the magnitudes and imaginary parts of *Z (f)* for *R*=10 Ω and *C* varying between 1 μF and 100 μF.

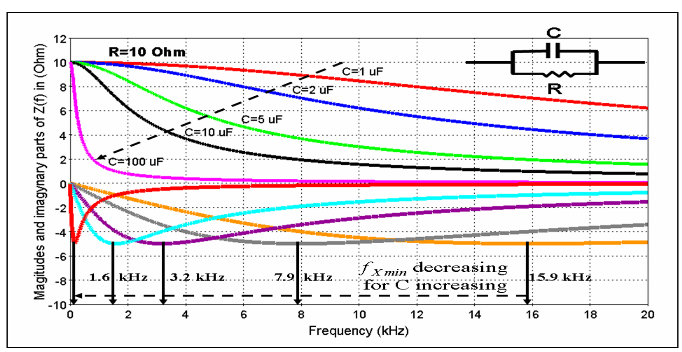


Fig. 6. Magnitudes (top) and imaginary parts (bottom) of *Z (f)* for *R*=10 Ω and *C* varying between 1 μF and 100 μF

- Synthesizing properties [1].

$$R = Z(f) \big|\ f = 0 \tag{8}$$

$$C = \frac{1}{2\pi\ R\ f_{X-\min}}. \tag{9}$$

Where $f_{X\text{-min}}$ is the frequency at which the imaginary part of Z is minimum.

- Parallel R-L-C circuit:

  – Impedance of the parallel R-L-C circuit

$$Z_n(f) = \frac{(1/C_n)(j2\pi f)}{(j2\pi f)^2 + (1/R_n C_n)(j2\pi f) + (1/L_n C_n)} \qquad (10)$$

Fig. 7 depicts an example of the magnitudes and imaginary parts of Z_n *(f)* for L_n = 33.1 mH, C_n = 54.3 µF and R_n varying between 50 Ω and 250 Ω.

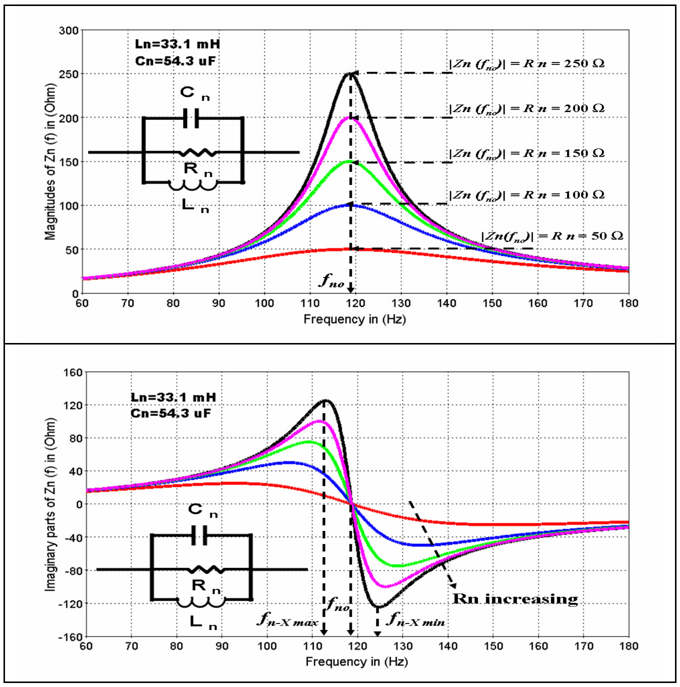


Fig. 7. Magnitudes (top) and imaginary parts (bottom) of Z_n *(f)* for *Ln*=33.1 mH, *Cn*=54.3 µF and *Rn* varying between 50 Ω and 250 Ω

  – Synthesizing properties [2], [3].

$$R_n = |Z_n(f_{no})| \qquad (11)$$

$$L_n = \frac{R_n \times (f_{n-X\min} - f_{n-X\max})}{2\pi \times (f_{n-X\min} \times f_{n-X\max})} \qquad (12)$$

$$k_n = 4\pi^2 \times (f_{n-X\min} \times f_{n-X\max}) \qquad (13)$$

$$C_n = \frac{1}{k_n \times L_n} \qquad (14)$$

Where:

f_{no} $= 1/(2\pi\sqrt{L_n C_n})$ = resonance frequency

R_n Magnitude of Z_n at resonance frequency f_{no}

$f_{n\text{-}X\,max}$ Frequency at which the imaginary part of Z_n is maximum

$f_{n\text{-}X\,min}$ Frequency at which the imaginary part of Z_n is minimum

C. *Synthesized circuits for Z_0 (f) and Z_1 (f) seen at Némiscau 735 kV*

Table II summarizes the parameters of synthesized parallel R-L-C circuits, which were calculated for Z_0 (f) and Z_1 (f), using (11), (12), (13) and (14) as well as the data for R_n, $f_{n\text{-X max}}$, $f_{n\text{-X min}}$, of identifiable poles on Fig. 3.

TABLE II
PARAMETERS OF SYNTHESIZED CIRCUITS FOR Z_0 (f) AND Z_1 (f)

POLE NO.	Parameters of the synthesized parallel R-L-C circuits for Z_0 (f) seen at Némiscau 735 kV			Parameters of the synthesized parallel R-L-C circuits for Z_1 (f) seen at Némiscau 735kV		
	R_n (Ω)	L_n (m H)	C_n (µF)	R_n (Ω)	L_n (m H)	C_n (µF)
1	374	30.54	47.28	101	33.13	54.33
2	212	28.29	23.46	55	3.85	82.68
3	253	8.84	39.32	50	5.92	31.83
4	50	4.01	42.44	59	0.37	245.23
5	90	3.74	29.47	40	0.25	331.57
6	175	2.99	28.42	35	0.17	378.94
7	365	3.81	17.44	85	0.43	133.74
8	35	0.38	119.66	125	0.94	53.05
9	40	0.20	198.94	280	1.09	35.53
10	102	1.54	22.61	--	--	--
11	270	1.06	29.47	--	--	--

Although the synthesis results were not presented in Table II, few other poles of Z_0 (f) and Z_1 (f) at sub-synchronous frequencies were also included in the final synthesized circuits in order to represent the effects of series compensation at Némiscau 735 kV. Moreover, ideal transformers were used in the three-phase connections of the synthesized circuits to decouple the zero-sequence impedance, Z_0 (f), from the positive sequence impedance, Z_1 (f), as illustrated in Fig. 8 [4]. Furthermore, to represent the steady state conditions in the integrated network, the magnitude and the phase angle of the three-phase internal voltages were set at the value of internal equivalent voltage, $V_i \angle \delta_i$, previously calculated in Table I.

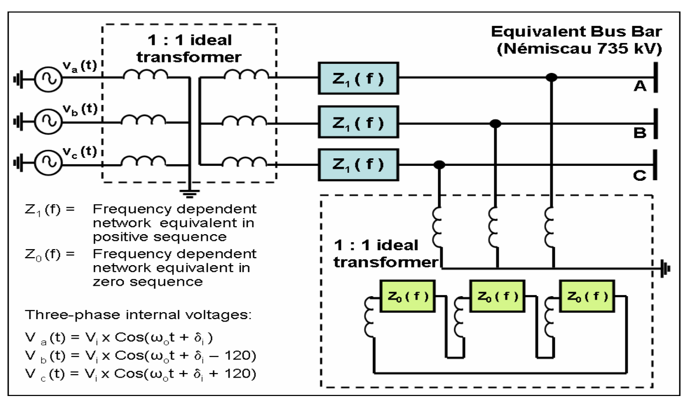


Fig. 8. Three-phase connections of synthesized circuits for Z_0 (f) and Z_1 (f) seen at Némiscau 735 kV

V. VALIDATION OF FREQUENCY DEPENDENT NETWORK EQUIVALENT (FDNE) AT NÉMISCAU 735 KV

A. *Validation in frequency domain*

The frequency dependent impedances in zero and positive sequences that are seen at the equivalent bus bar of the three-phase synthesized circuit in Fig. 8, were compared to the frequency responses, Z_0 (f) and Z_1 (f), previously obtained with the isolated Hydro-Québec 735-kV main grid. Simulation results, as illustrated in Fig. 9, indicated that there is a good agreement between the synthesized and the complex networks.

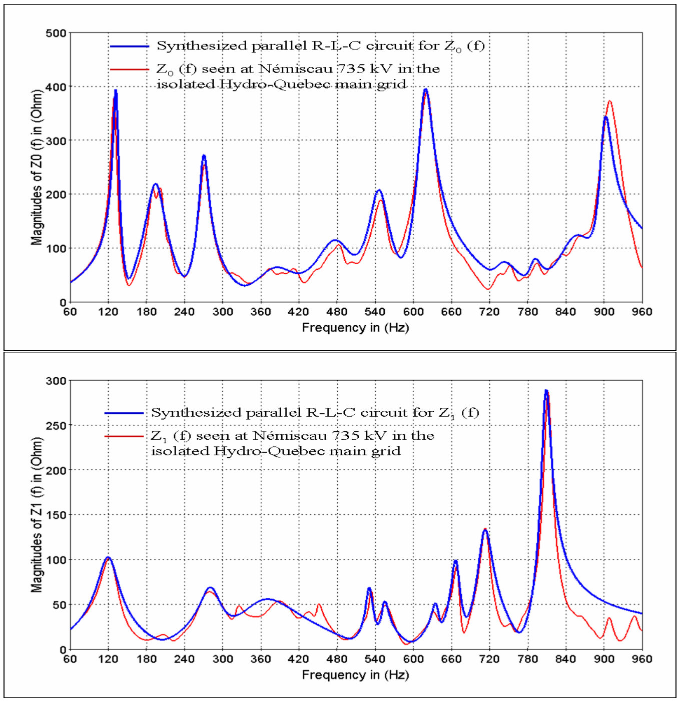


Fig. 9. Validation in frequency domain of the synthesized circuits for Z_0 (f) (top) and Z_1 (f) (bottom) seen at Némiscau 735 kV

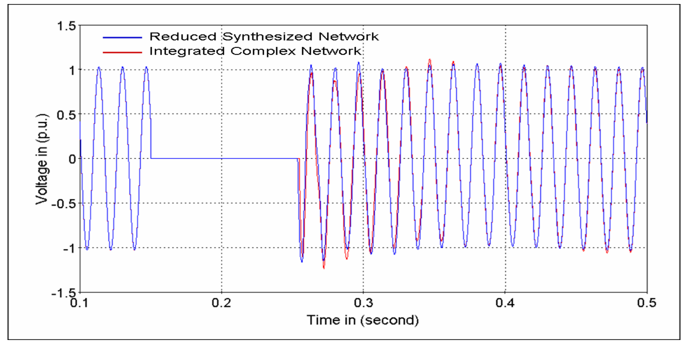
In this figure, one can also observe a perfect matching between the positive and zero sequence impedances at 60 Hz seen at Némiscau 735 kV in the isolated Hydro-Québec main grid and those obtained with the synthesized parallel R-L-C circuits. Therefore, for this case, it is not necessary to make additional adjustments to the synthesized circuit to preserve short-circuit levels in the integrated system. For general application, in case of mismatch between impedances at 60 Hz (or 50 Hz), additional parallel R-L or R-C circuits can be used to adjust short-circuit levels in the reduced synthesized system.

B. Validation in time domain

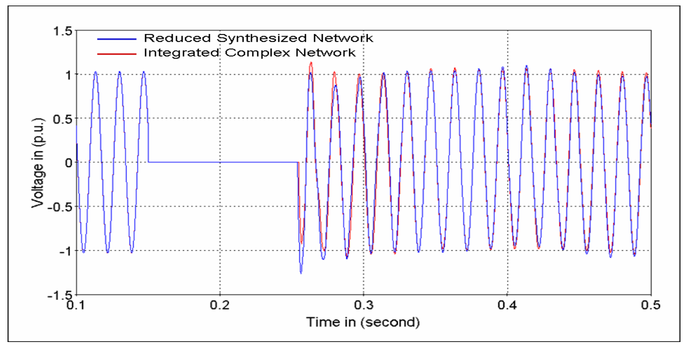
The simulations in time domain of three-phase-to-ground and line-to-ground faults at Némiscau 735 kV were performed with the E-S reduced synthesized network as well as with the integrated complex network. Again, it can be observed in Fig. 10a and 10b that there is a good agreement between the results obtained with the reduced synthesized network and those with the integrated complex network.

VI. Modeling Complex System Dynamic Behaviors

The previous FDNE at Némiscau 735 kV with constant three-phase internal voltages does not allow studying the dynamic behaviors of Hydro-Québec integrated complex network. Therefore, in order to reproduce these dynamic behaviors using EMTP and the E-S reduced system, all the generating stations Eastmain-1, Eastmain-1A and Sarcelle as well as the FDNE at Némiscau 735 kV, were simulated with internal dynamic voltage models, as illustrated in Fig. 11 [5], [6].



a) Three-phase-to-ground fault at Némiscau 735 kV



b) Line-to-ground fault at Némiscau 735 kV

Fig. 10. Voltages at Némiscau 735 kV during three-phase-to-ground (a) and line-to-ground (b) faults at Némiscau 735 kV

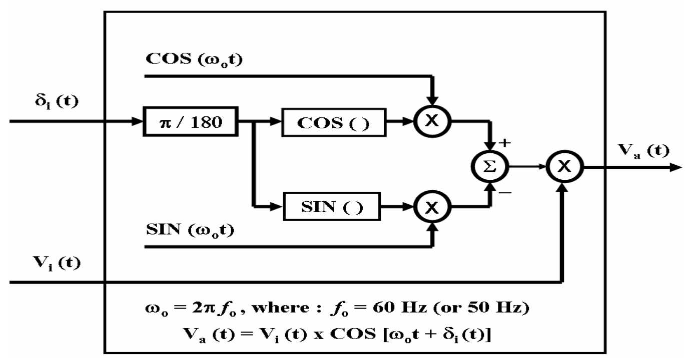
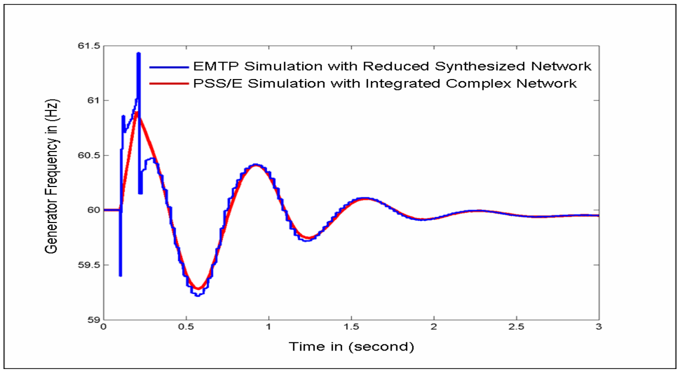
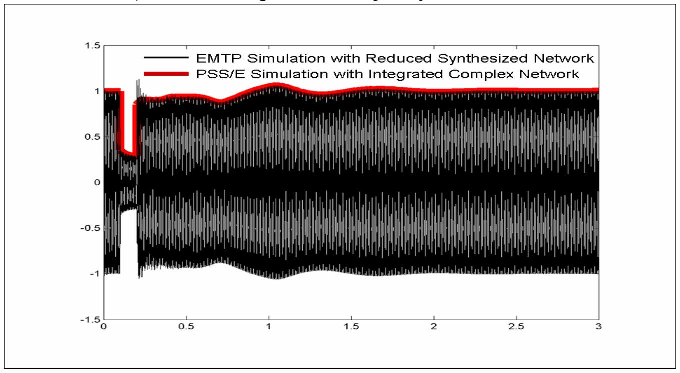


Fig. 11. Internal dynamic voltage model

For each generating station (or FDNE), the internal dynamic voltage, V_a (t), was applied to the phase A behind the generating station equivalent (or the FDNE). The input signals, V_i *(t)* and δ_i *(t)*, were calculated from the positive sequence equivalent impedance, $Z_1 \angle \phi$, at power frequency and from the results of system stability simulation, *P (t)+jQ (t)* and $V_T(t) \angle \delta_T(t)$, using (1), (2) and (3). For the phases B and C, the internal dynamic voltages, V_b (t) and V_c (t), have the same magnitude as V_a (t), but their phase angles were respectively displaced -120° and +120° with respect to the phase A. This modeling technique was used to simulate the dynamic behavior of Eastmain – Sarcelle generating stations during a three-phase fault at Eastmain-1 315 kV implying the loss of one 315-kV circuit between Eastmain-1 and Némiscau. EMTP results were then compared to those obtained by system stability simulation using PSS/E and Hydro-Québec integrated complex network. Although there are some discrepancies inherent to the two simulation techniques (PSS/E vs. EMTP), it can be observed in Fig. 12a and 12b that the overall dynamic behavior of Hydro-Québec integrated complex network was accurately reproduced using the E-S reduced synthesized system.



a) Variation of generator frequency at Eastmain-1



b) Three-phase voltages at Eastmain-1 13.8 kV

Fig. 12. Variation of generator frequency at Eastmain-1 (a) and three-phase voltages at Eastmain-1 13.8 kV (b) during a three-phase fault at Eastmain-1 315 kV implying the loss of one 315-kV circuit Eastmain-1 – Némiscau.

VII. Conclusions

A simplified approach using the properties of parallel R-L-C circuits for synthesizing Hydro-Québec 735-kV main transmission grid has been developed and described in this paper. The results of its application for the transient simulation studies using the E-S reduced synthesized system lead to the following conclusions:

- The short-circuit levels in a complex integrated transmission grid could be maintained in the reduced equivalent system by using the zero and positive sequence short-circuit impedances at power frequency as seen at the equivalent bus bar.
- The steady state conditions in the complex integrated transmission grid could be preserved by controlling the terminal voltage and the power injection at the equivalent bus bar.
- The frequency responses in zero and positive sequences, Z_0 (f) and Z_1 (f), of a complex transmission grid with n identifiable poles could be accurately synthesized by a combination of parallel R-L-C circuits.
- The dynamic behaviors of a complex integrated transmission grid could be well reproduced using internal dynamic voltage models in the reduced synthesized system.
- Finally, this simplified synthesis approach allows providing large transmission system data in a simplified manner for turn-key power projects such as: static VAr compensators, HVDC interconnections, etc.

VIII. Acknowledgment

The authors gratefully acknowledge the contribution of Mr. Bruno Picard for the PSS/E simulation results used to validate the synthesized model.

IX. References

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X. Biographies

Que Bui-Van has received B. A. Sc. in Electrical Engineering from École Polytechnique de Montréal in 1975. He has been with the System Studies and Equipment Performance Criteria group of Hydro-Québec TransÉnergie since his graduation. Mr. Bui-Van has been working on HV/EHV equipment specifications, lightning performance of transmission lines, insulation coordination of HV/EHV AC/DC power cables and GIS. He was responsible of electrical performance specifications for power cables from 25 kV to 345 kV used in Hydro-Québec power system. Mr. Bui-Van has been involved in several system studies for the implementation of special surge protective devices, static VAr compensators, series compensation and HVDC interconnections in Hydro-Québec 735-kV transmission system. During the 1990s, he has also been involved in several system studies for international power system projects especially: the Vietnamese (EVN), the Libyan (GECOL), the Saudi Arabian (SCECO Central), the Iranian (Water & Power Resource Development Co.), the Peruvian (Consorcio TransMantaro S. A.) and the Chilean (Transelec) power systems. Mr. Bui-Van is the Chairman of the Canadian Subcommittee on IEC's TC28: Insulation Coordination, an active member of the CIGRÉ WG A3-13: Changing Network Conditions and System Requirements as well as a Registered Professional Engineer in the Province of Québec.

Francis Beauchemin has graduated from "Institut en Génie de l'Énergie Électrique – École Polytechnique de Montréal" in 2003. During this year, he has joined the System Studies and Equipment Performance Criteria group of Hydro-Québec TransÉnergie for a short training period. Since 2004, Mr. Beauchemin has been with "Conception - Appareillage électrique et commande, Ingénierie de production, Hydro-Québec Équipement" where he has been involving in the Péribonka 385-MW hydroelectric power development as well as in several refurbishment projects of existing hydroelectric generating stations.