Fundamental frequency coupling between HVAC and HVDC lines in the Quebec-New England multiterminal system - Comparison between field measurements and EMTDC simulations

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Abstract: Fundamental frequency coupling between HVAC and HVDC lines has been investigated through actual field measurements in the Quebec-New England multiterminal HVDC system. These are the first field measurements, which clearly exhibit the fundamental frequency coupling. The measurements covered the sections of interaction located along the Radisson-Des Cantons part (approximately 1120 km long) of the HVDC transmission line. In these sections, the distances between the AC and DC lines do not exceed 1,5 km. During the field measurements, the recorded fundamental frequency currents in the DC line ranged between 1,05 and 1,20 A rms. An EMTDC computer model of the coupling phenomenon has been developed and validated based on these measurements. This article presents the computer model and the results of the validation.

I. INTRODUCTION

An HVDC line running in parallel with an HVAC line will be exposed to a fundamental frequency coupling. The coupling effects, if strong enough, have been recognized as an important subject concerning the performance and the design of an HVDC system [1]. Equipment both on the AC and DC sides of the converter station can be affected by this phenomenon. Induced fundamental frequency current can lead to saturation of the converter transformer core due to unsymmetrical magnetization. Saturation leads to an increased noise level and increased heating in the transformer. The commutation in the converter and the saturation of the transformer may also generate higher order harmonic currents in the AC and DC networks, which will influence the filter design.

The superimposed AC current on an HVDC transmission line is based on two effects:
- The coupling between AC and DC lines
- The dynamic characteristic of the HVDC converter with its terminating impedance, responding to the fundamental frequency current on the DC line.

These two effects must be added, thus complicating the calculation and evaluation of the actual coupling to the DC line. The analysis must therefore be performed both with and without the converters in operation.

In 1990 Hydro-Quebec carried out a series of field measurements of the coupling effects on the Radisson-Des Cantons part of the Quebec-New England HVDC transmission line [4]. The converters were not in operation during the field measurements and the DC transmission line was directly exposed to electromagnetic coupling from neighboring AC transmission systems.

To our knowledge, this is the first set of field measurements of its kind, which clearly exhibits the fundamental frequency coupling between AC and DC lines. Since field measurements are expensive and time consuming, it is of interest to develop and validate a computer model that represents correctly the coupling effects. The model should be able to accurately represent detailed geometrical configurations including transpositions, different ground resistivities and the terminating impedances of the lines.

In the future, there will be an increased pressure for various reasons, e.g. economical and ecological, to locate the DC lines along the same right-of-way as the AC lines. Therefore, reliable analyses of more complex configurations, with HVDC converters included, are necessary. Some interesting simulator studies have already been made for AC-DC hybrid transmission systems [2], [3], where the AC and DC lines are located on the same tower. However, the results presented are not yet confirmed by field measurements.

II. DESCRIPTION OF FIELD MEASUREMENTS

The field measurements were carried out on the northern part of the Quebec-New England Phase II multiterminal HVDC system, see Fig.1. This part of the system is a bipolar 450 kV overhead transmission line. It is spanning from the Radisson converter station (2,250 MW), in the James Bay area, to the Des Cantons converter station (690 MW) near the US border. The length is 1120 km. A third converter station, Nicolet (2,138 MW), is located between the two previously mentioned stations, 90 km north of Des Cantons. At the time of the field measurements, all converter terminals and their associated equipment were disconnected. Hence, the transmission line was passive and measurements were not amplified by resonances with the line terminating impedances.

Three sections of the HVDC line were exposed to AC line couplings, as shown in Fig. 1 and detailed in Table 1.
• Section **I**: Radisson - Némiscau
• Section **II**: Trenche/La Tuque - Trois Rivières/Des Hêtres
• Section **III**: Bécancour- Nicolet

In the first section, starting at about 25 km south of Radisson station, the DC line runs close to two 735 kV lines (L7062 and L7063) for about 31.5 km. The second section is about 94 km long and starts at 800 km south of Radisson: the coupling comes mainly from two 230 kV lines (L2370 and L2380). In the last section, immediately north of Nicolet station, the DC line is exposed for 22.5 km to two 230 kV lines (L2381 and L2382).

The measurements were carried out for two configurations of the DC line:

a) Configuration 1: both poles of the DC line were grounded at the southern end (Des Cantons) but left open-circuited at Radisson where the pole voltages were measured.

b) Configuration 2: both poles of the DC line were grounded at both ends and the pole currents were measured at Radisson.

A nine-cycle acquisition of the DC line voltages or currents was taken every minute via a digital oscilloscope and the data was processed to obtain the first ten harmonics. While the above DC line measurements were ongoing, voltage and currents of 735 kV line L7063 and of 230 kV lines L2370 and L2380 were being monitored continuously via power analysers to also obtain the first ten harmonics about every seven minutes. 735 kV line L7062 was not monitored as it was not in service during that time period and was open-circuited at both ends. Also, since the third coupling section is relatively short, 230 kV lines L2381 and L2382 were not specially monitored and the data came from the hourly records of the system control center.
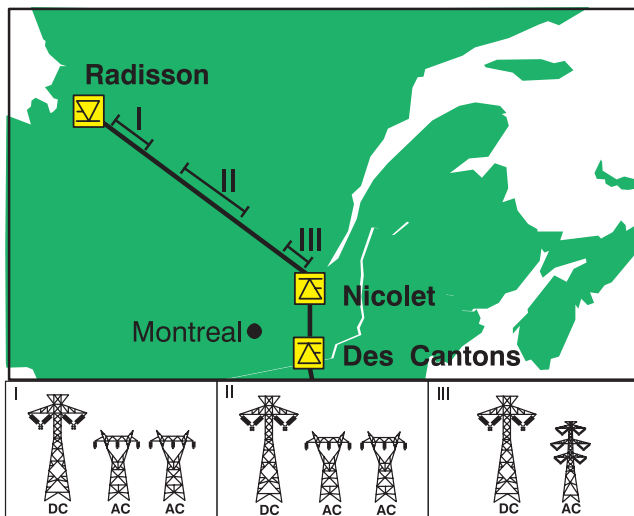
III. RESULTS OF THE FIELD MEASUREMENTS

A. Configuration 1

On the DC line, the recordings lasted for about 24 hours and indicate that about 1 kV was induced on each pole. A strong correlation was noticed between these induced voltages and the positive sequence current on line L2380. This is the AC line running closest to the DC line and for the longest coupling section.

B. Configuration 2

The measurements for DC line configuration 2 lasted only 90 minutes and showed fundamental frequency currents of 1.05 and 1.20 A rms for pole 1 and pole 2, respectively.

The coupling factor in configuration 2, where the DC lines are short-circuited to ground in Radisson, is different from configuration 1. The inductive coupling is dominating and gives a higher value for the current of pole 2, due to its closer location to the AC lines. The tower geometry of the bipolar transmission line and the location of the neighboring AC lines are shown in Fig. 1. Considering also the coupling lengths and the relative position of the lines given in Table 2, it can be confirmed that pole 2 is exposed to a stronger inductive coupling compared to pole 1.

The voltage and currents of 735 kV line L7063 and 230 kV lines L2370 and L2380 are presented in Table 1. The table lists the average magnitudes of the positive-, negative- and zero-sequence components, calculated from the continuously monitored ones in configuration 2.

From the hourly records, the average value of the positive sequence magnitudes for 230 kV lines L2381 and L2382 are calculated. The negative and zero sequences for these lines have not been monitored.

Fig. 1. The 1120 km Radisson - Nicolet-Des Cantons ± 450 kV HVDC system.

TABLE 1. SEQUENCE VOLTAGES AND CURRENTS. AVERAGE VALUES OF THE FIELD MEASUREMENTS FROM CONFIGURATION 2 OF THE REPORT. DATE: JULY 22, 1990. TIME: 13:38 - 15:04 [4].

Section	Line	Voltage & Current*	Positive sequence	Negative sequence	Zero sequence
			Mag	Mag	Mag
I	L7063	I_1 [A]	760	17	3
		U_{1g} [kV]	430	3,6	1,5
II	L2380	I_1 [A]	440	10	8
		U_{1g} [kV]	132	0,3	0,3
	L2370	I_1 [A]	280	9	7
		U_{1g} [kV]	132	0,7	0,7
III	L2381	I_1 [A]	187	-	-
		U_{1g} [kV]	132	-	-
	L2382	I_1 [A]	273	-	-
		U_{1g} [kV]	132	-	-

* I_1 - phase current, rms value.
   U_{1g} - phase to ground voltage, rms value.

IV. EMTDC COMPUTER MODEL

A. Modeling of the coupling sections

The coupling effects are modeled and simulated using the electromagnetic transients simulation program EMTDC [6], [7]. The selected multi-transmission line model is a Bergeron, single frequency model, tuned to 60 Hz.

Three AC line sections are considered to have an impact on the fundamental frequency coupling, as shown in Fig. 1.

The EMTDC model, as an approximation, includes these three most dominant sections and neglects the coupling from all other AC lines. Table 2 lists the parameters of the three sections, as presented by Hydro-Quebec in the technical specifications of the project [5]. Furthermore, the model includes both AC and DC transpositions, as well as the position (East or West) of the DC line with respect to the AC lines. Outside the coupling sections, the DC line is extended to its full length, 1,120 km, as a bipolar transmission line. On the other hand, the AC lines are terminated at the end of each coupling section by equivalent impedances representing the AC network. These impedances vary in time depending of the actual load flow and the simulation has to use the appropriate values.

TABLE 2. CONFIGURATION PARAMETERS FOR THE THREE COUPLING SECTIONS.

Section	Length (km)	Dist. to AC line (m)	DC line position	DC pole 1 position	Earth resistivity (Ohm.m)	AC line transposition	3-phase AC lines (number)
	9,6	800	W	W	1250	yes	L7063
I	19,3	1500	W	W	1250	no	L7063
	2,6	80	W	W	1250	no	L7063
	35,2	50	W	*	3000	no	L2380
II	48,5	50/90	W	*	3000	no	L2380/L2370
	9,7	50/90	E	W	3000	no	L2380/L2370
	7,6	45	W	W	850	no	L2381/L2382
III	15,2	45	E	W	850	no	L2381/L2382

Note 1: the position of the DC line relative to the AC lines is given by W (west) or E (east).
Note 2: the position of DC pole 1 relative to the center of the tower is given by W (west) or E (east).
* DC line transposition.

B. Modeling of driving sources

The driving sources for the coupling on the DC line are made of the voltages and currents of the AC lines. These three-phase variables can be represented by the corresponding positive-, negative- and zero-sequence components. Out of these components (three for voltage and three for current), only three are modeled: positive-sequence voltage and current and zero-sequence current. Positive-sequence components are important because of their magnitudes which are close to one per-unit. The negative-sequence voltage and current are neglected since they are quite small compared to positive-sequence, while obeying the same coupling mechanisms. The zero-sequence voltage is also small and cannot couple much current on the DC line. Even if the zero-sequence currents are small, their coupling contribution cannot be neglected: as these currents must return through ground or via overhead ground wires.

B.1 Simulation for the *worst coupling*

For each coupling AC line, the simulation is performed in two steps. The first one covers the coupling from the positive-sequence voltage and current, see Fig. 2. A three-phase voltage source is connected at each end of the coupling section and the angle between these two sources is adjusted to obtain the proper positive-sequence current. Therefore, both the capacitive and the inductive couplings related to the positive sequence are represented simultaneously.

Then, in the second step, the zero-sequence current effects are modeled for each coupling AC line by using a zero-sequence current source. While the simulation is performed for one AC line, the sources are short-circuited in all the other AC lines to allow the circulation of secondary currents.

In the steps above, the sources are adjusted to the average values recorded during the field measurements for configuration 2, where the DC line was short-circuited at both ends and the induced currents on pole 1 and pole 2 were measured. This configuration is considered more interesting than configuration 1 because induction issues (presented in the introduction of this paper) are more often described in terms of induced currents. As only the positive-sequence values are available for L2381 and L2382, their zero-sequence currents were assumed to be 1% (typically used value) of the positive-sequence currents.
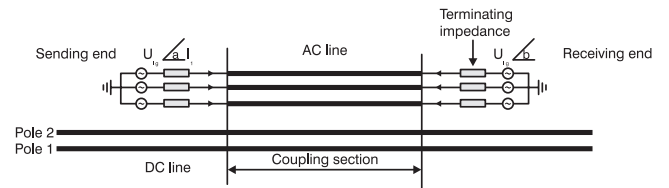

Fig. 2. Modeling of the positive-sequence voltage and current driving sources.

These two steps of simulation per AC line will produce 10 values of induced current (2 steps x 5 lines) for each pole of the DC line. The *worst coupling* can be evaluated by two calculation methods:

a) <u>arithmetic sum</u>: the resulting pole current is obtained by an arithmetic sum of the 10 values of induced currents;

b) <u>root-sum-squares (RSS)</u>: the resulting pole current is obtained by the square root of the sum of the 10 squared values of induced currents.

The RSS calculation is usually recommended for telephone interference studies, while the arithmetic sum is used for control and protection studies [1].

B.2 Simulation of *simultaneous coupling*

A final simulation is performed considering the fact that the driving sources are phasors. It simultaneously represents the effects of all the positive-sequence voltage and current of all the AC lines. Their magnitudes are adjusted. The angles between the local voltages and currents are adjusted to the values recorded during the field measurements. However the phase angle between the voltage sources of the various coupling sections are obtained from a load flow, corresponding to the light load conditions prevailing during the summer of 1990. This load flow indicated that the Radisson (section I) 735 kV bus voltage is ahead by 40 degrees of the Nicolet

(section III) 230 kV bus voltage, while there is no phase difference between Nicolet and Des Hêtres (section II).

V. SIMULATION RESULTS

A. Worst coupling, comparison with field measurements

The results of the EMTDC simulation, according to the *worst coupling* method, are shown in Table 3. The dominating contribution of fundamental frequency coupling corresponds to positive sequence values in coupling section II. It implies that the distance between AC and DC lines and the line length of paralleling are dominating factors. Besides, the higher resistivity of earth may result in a stronger capacitive coupling.

Section II will also contribute most to the coupling from the zero sequence driving sources. It can be seen that the corresponding magnitudes for this section will even be higher than the positive sequence magnitudes of sections I and III.

The zero sequence current was typically assumed to be 1 % for lines L2381 and L2382. Even if a higher value was assumed for this current, such as 2-3 %, it would not affect significantly the final result.

TABLE 3. AMPLITUDE OF INDUCED CURRENTS IN THE DC LINE AT THE RADISSON TERMINAL (A rms). EMTDC SIMULATION, WORST COUPLING.

Section	Line	Current induced by positive sequence voltage and current (A)		Current induced by zero sequence currents (A)	
		P1	P2	P1	P2
I	L7063	0,07	0,12	0,02	0,02
II	L2380	0,59	0,85	0,30	0,30
	L2370	0,65	0,77	0,16	0,15
III	L2381	0,12	0,05	0,04	0,03
	L2382	0,07	0,14	0,02	0,03

In Table 4, the sum of the effects from the positive sequence and the zero sequence driving sources are calculated (arithmetically and RSS) and compared with the field measurements.

When the arithmetical summing method is used, the simulation gives magnitudes of induced currents that are twice the ones observed during the field measurements. This method will always lead to the biggest overestimation because it does not allow for any cancellation effects. The overestimation will generally increase with the number of coupling sections.

The RSS calculation corresponds very well with the field measurements. This can be a quite appropriate method specially when there are many coupling sections, but one has to remember that it could in some occasions lead to underestimations.

TABLE 4. 60 HZ CURRENTS RECORDED IN FIELD MEASUREMENTS VERSUS OBTAINED IN EMTDC SIMULATIONS.

	Pole 1 (A rms)	Pole 2 (A rms)
Worst coupling, Arithmetical sum	2,0	2,5
Worst coupling, RSS sum	1,0	1,2
Simultaneous coupling	1,4	1,6
Field measurement	1,05	1,20

B. Simultaneous coupling, comparison with field measurements

The simultaneous coupling, with a specific load flow condition, seems to give a good approximation of the reality even if it does not include the zero sequence coupling. It seems that conservative results are obtained with only the positive sequence generated in the driving sources. A further investigation taking into account zero sequence has not been done.

Depending on the phase displacement between the sequences, inclusion of the zero sequence effects, could help in bringing the simulation results closer to the field measurements. Typically, zero sequence effects tend to add to the positive sequence effects, the zero sequence being affected by such factors as ground resistivity and line configuration.

C. Simultaneous coupling, comparison with worst coupling

Taking into account the phase displacement of the various positive sequences reduces the induced current from 1.5 - 1.9 A rms, see Table 3, to 1.4 - 1.6 A rms, see Table 4.

VI. CONCLUSIONS

Fundamental frequency coupling between HVAC and HVDC lines has been investigated through actual field measurements, for the Quebec-New England multiterminal HVDC system. An EMTDC model of the coupling phenomenon has been developed and validated based on these measurements. The following conclusions can be made:

The superimposed 60 Hz currents in the DC lines have magnitudes ranging from 1.05 to 1.20 A rms, according to the field measurements. In EMTDC simulations, the coupling currents vary between 1.0 A to 2.5 A rms, depending on the calculation method.

The method that arithmetically adds the contribution from each AC line section, in most cases, results in an overestimation of the magnitude of superimposed fundamental frequency current (1,0 A compared to 2,5 A), but can give the upper limit of the estimated *worst coupling* current.

The RSS method will, in the case of multiple coupling sections, generate a closer approximation to reality compared to the arithmetical value. It sets the lower limit of the *worst coupling* current.

Conservative results and close matching with field results (1.4 A and 1.6 A), can be obtained by using the *simultaneous coupling* method based on the appropriate load flow condition of the AC system. The load flow will determine the phase relationships between the driving sources. It is recommended

to assume peak load conditions in the neighboring AC system in order to obtain the worst condition possible.

The arithmetic and RSS calculation methods can be used to identify the range of the worst coupling current for multiple driving sections. The concept of simultaneous coupling gives conservative results and is recommended for analysis of more complex configurations. The drawback of this method is the special concern regarding the terminating impedances and the loadflow conditions of the neighboring AC lines, which can be difficult to assess in some studies.

The coupling effects between the HVDC and the AC lines being adequately represented, the EMTDC model can be confidently expanded to include the dynamic characteristics of the HVDC converters.

VII. REFERENCES

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VIII. BIOGRAPHIES

Johan Ulleryd graduated from Chalmers University of Technology, Gothenburg, Sweden, in 1993 with an M. Sc. degree in E.E. In 1994 he joined ABB Ludvika, Sweden, as a trainee engineer, which included a half year stay at Manitoba HVDC Research Centre, Winnipeg, Canada. From 1995 he is working as a system engineer at ABB Power Systems AB, HVDC division. He is non-member of IEEE.

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