EHV SINGLE-POLE SWITCHING: IT IS NOT ONLY A MATTER OF SECONDARY ARC EXTINCTION

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Abstract-- This paper reports the results of an in-dept transient system study related to the application of single-pole switching on the three sections of a 240 km double-circuit 330 kV transmission line collecting some 1500 MW of Hydro power in northern Québec. While the paper discusses secondary arc extinction time from laboratory test results, EMTP modeling of secondary arc and related transient studies, the main focus is on findings related to the creation of severe harmonic over-voltages during both the dead-time and upon the circuit-breaker reclosing. These findings were important enough to prevent the application of single-pole switching on these lines. To the author's knowledge, no such a restriction has ever been previously mentioned in the literature on the application of single-poleswitching.

Keywords: Single-pole-switching - Secondary arc, Harmonic over-voltages, EMTP-RV.

I. INTRODUCTION

TYDRO-QUÉBEC bulk transmission system is composed Lof eleven 735 kV very long lines (over 1000 km each) bringing about 30,000 MW of hydro-electric power to its customers in the south (Montreal and Québec city). The application of Single-Pole Switching (SPS) on these lines was not judged to be justifiable firstly because of its marginal benefit on the transient stability of a system with many parallel lines and secondly because of the necessity to install reactors at the neutral point of shunt inductances (costs). SPS has however been applied since the mid 70's at the subtransmission voltage level of 330 kV where relatively long double-circuit transmission lines (up to 160 km) connect the main system to remote consumption sites containing some small local generations. In these cases, the main role of SPS is to maintain the transient stability of remote local generations and to assure good continuity of service for remote customers.

This paper covers Hydro-Québec's SPS experiences at 330 kV. It describes first the secondary arc extinction time estimations obtained from laboratory tests and presents a realistic secondary arc model in EMTP-RV. In the second chapter, system studies related to the application of SPS on the three sections of a 240 km double-circuit 330 kV transmission line are described. Findings related to the latter are the main

purpose of this paper.

II. 330 KV SINGLE-POLE RECLOSING AT HYDRO-QUEBEC

Single-pole reclosing advantages and practice have been described in the literature as early as 1942 in the US at 138 kV [1] and later at 275 kV [2]. In early 70's, 500 kV field tests were described for the first time in [3]. A good article on various key factors determining the secondary arc extinction times is presented in [4].

A. Laboratory tests

At Hydro-Québec, single-pole reclosing times of 0.75 and 1 second have been applied systematically on 330 kV single and double-circuit transmission lines respectively. In the early 80's, analysis of about 10 years of operation data showed some unsuccessful reclosing due to the secondary arc non-extinction on a 151 km compact 330 kV double-circuit transmission line. As EMTP-based results of secondary arc parameters showed in Table I indicated a higher than normal Vr/*l* parameter (17.4 kV/m vs. 13 kV/m), extensive laboratory tests were performed at IREQ in 1986 [5]. During these outdoor tests, secondary arc currents were varied from 10 to 40 A, recovery voltages from 7 to 18 kV/m, primary arc currents from 5 to 30 kA and line compensation degrees from 0 to 50 and 75%.

TABLE I SECONDARY ARC PARAMETERS OF HYDRO-QUÉBEC 330 kV TRANSMISSION LINES (*l* = 2.3 m)

330 kV line	Single circuit		Double-circuit (compact)	
	Transp.	Untransp.	Transp.	Untransp.
Is (A/km)	0.11	0.13	0.16	0.19
Vr (kV)	29.0	31.8	36.5	40
Vr/l (kV/m)	12.6	13.8	15.9	17.4

Is: Secondary arc current

Vr: Secondary arc recovery voltage

l: Insulator strings length

Figure 1 shows the test-deduced reclosing times on Hydro-Québec's 330 kV compact double-circuit lines. Depending on the line length, the minimum short-circuit current and the degree of compensation, single-pole reclosing times are determined. For the 151 km transmission line in question, reclosing time was elongated from 1 to 1.3 s and satisfactory results were obtained.

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Figure 1. SPS reclosing times on 330 kV double-circuit compact lines

B. EMTP-RV Model

The 'Examples' library in EMTP-RV contains a secondary arc model developed by the author which is based on the pioneering work described in [6]. The user has only to input the instant of fault creation, the initial arc length and its variation with time. Figure 2 shows that an adequate arc length variation with time is the key to reproduce precisely the field recordings of secondary arc current and voltage. Such a fast variation in the first 200 ms or so is typical and is mainly dependant to the speed of the wind (around 10 km/h in the test) and the amplitude of the primary arc current (around 5 kA rms). The so-called secondary arc 'instantaneous extinction mode' [4] in this time frame is rarely seen in practice since a high fault current and a low secondary arc current should coexist. Consequently, the model focuses mainly on the 'progressive extinction mode' [4] of the secondary arc which is really of interest in practice. In this region, secondary arc length variation of 5 pu/s has been reported (see Fig. 3).



Figure 2. EMTP-RV secondary arc model in comparison with a field test



Figure 3. Arc elongation for a 150 A secondary arc (from [7])

At this rate, EMTP-RV simulations of SPS on the previously-mentioned 151 km 330 kV double-circuit line predict a secondary arc extinction time of 0.91 s (Fig. 4) thus confirming the adequate choice of a reclosing time equal to 1.3 s.



Figure 4. Secondary arc extinction time at 330 kV predicted by EMTP-RV

III. SPS APPLICATION ON THE BRISAY - TILLY 330 KV TRANSMISSION NETWORK

The Brisay-Laforge2-Laforge1 hydro-electric complex in northern Québec generates about 1500 MW and was developed in mid 1990's. This power is injected to the main 735 kV transmission system via a 240 km 330 kV doublecircuit transmission line (Fig. 5). Single-pole switching was initially planned but never applied mainly because of a very low lightning activity in the region (2-3 days per year) and the fear of severe harmonic over-voltage creation.



Figure 5. Brisay - Tilly 330 kV transmission network

Table II shows lightning-caused fault statistics on the 83 km line section between Laforge1 and Tilly. Between 1995

and 2011, a total of 15 fugitive faults have occurred on this section. Out of these 15 cases, 9 faults have resulted in the system separation and loss of generations of the whole three generating stations. The amount of the total power loss varied from 260 up to 900 MW. Out of these 9 cases, 7 could have been prevented by the application of SPS. Consequently, Hydro-Québec Operation Department asked for a more through SPS study with the aim to put the SPS in service, at least in the most crucial section of Tilly-Laforge1. Precise EMTP-RV simulations were therefore performed by using frequency-dependant line and saturable transformer models. Generation units were represented with synchronous machine models along with their excitation and governor replica built by using the control library elements of the Software. SPS simulations were performed on many of the possible configurations observed during the year 2011.

TABLE II FAULT STATISTICS ON THE 83 km DOUBLE-CIRCUIT LINE BETWEEN TH LY AND LAFORGEL SUBSTATIONS

Date	Faulted phases	Date	Faulted phases
(D-M-Y)	C#1 C#2	(D-M-Y)	C#1 C#2
30-06-95	a a	18-08-02	c
30-06-95	a	01-08-05	a - c a - c
14-09-97	-b	16-07-06	a b -
21-06-99	c	30-08-07	ab-ab-
22-08-99	cc	13-07-08	- b
21-07-01	cc	10-08-08	a a
21-07-01	- b b -	03-07-11	- b b -
04-08-01	a		

Figure 6 corresponds to EMTP-RV simulation of the weakest possible operation scenario for this network (129 hours of operation during 2011). This scenario corresponds to:

- One generating unit of 235 MVA at Brisay
- One generating unit of 147 MVA at Laforge1
- One 55 km circuit between Brisay and Laforge2
- Two 107 km circuits between Laforge2 and Laforge1
- One 83 km circuit between Laforge1 and Tilly.

SPS was applied on the Tilly-Laforge1 circuit following a single-line-to-ground fault at Tilly. Simulation results of figure 7 indicate the creation of severe harmonic over-voltages at the three substations during the SPS dead-time. Frequency scan applied at Laforge2 shows indeed a near-third harmonic resonance at this bus-bar when phase B is opened (Fig. 8). These over-voltages are therefore created by the interaction of the magnetizing currents of the power transformers at Tilly (saturation following fault removal) with the high impedance peak of third harmonic resonance. The fact that these over-voltages vanish gradually after several cycles is most probably due to the de-tuning of the network third harmonic resonance by the time domain variation of the machine impedances (from X''d to X'd to Xd) following the fault removal.

Another configuration which was studied in detail is shown in figure 9. This is the most frequent configuration which corresponds to more than 1200 hours of operation during 2011. This scenario corresponds to:

- Two generating units of 235 MVA at Brisay
- Four generating units of 147 MVA at Laforge1
- Two 55 km circuits between Brisay and Laforge2
- Two 107 km circuits between Laforge2 and Laforge1
- Two 83 km circuits between Laforge1 and Tilly.



Figure 6. EMTP-RV design of the weakest configuration





In this scenario, a single-line-to-ground fault is applied on phase A of both the circuits at Laforge1. Simulation results of figure 10 show creation of fifth harmonic over-voltages at the three substations (mostly on phase A), not during the SPS dead-time but upon the circuit-breakers successful reclosing. To understand the difference with the previous case, frequency scans were again performed. Figure 11 shows that a fifth-

harmonic resonance exist normally at Brisay 330 kV

substation in this configuration. During the SPS dead-time, this resonance is detuned due to the opened phase A on each circuit. Upon circuit-breakers reclosing, saturation currents of the machine transformers at Laforge1 and Brisay (following fault removal) interact with the re-appearance of the firth harmonic resonance, thus producing up to 1.8 pu of temporary over-voltages for a couple of seconds. These over-voltages were again judged to be harmful and consequently SPS was prohibited permanently on the Brisay-Laforge2-Laforge1 network.

To the author's knowledge, no such a restriction has been ever reported in the literature. It is also the author's opinion that the reported cases of harmful temporary over-voltage generations are not specific to the Hydro-Québec described system. As SPS finds its most useful applications at EHV and UHV (1100 kV in China for example), where one or two very long transmission lines connect two systems through large power transformers at each end, the same SPS restriction may apply. Therefore, SPS application on such systems should include extensive EMTP simulations both in time domain and in the frequency scan mode.



Figure 9. EMTP-RV design of the most frequent configuration



Figure 10. Harmonic over-voltages at 330 kV substations after SPS reclosing

IV. CONCLUSION

Beside secondary arc extinction, an important aspect of SPS that needs to be studied in-dept is the potential of harmonic over-voltage creation during both the dead-time period and/or after successful circuit-breakers reclosing. During the dead-time period, single-phase fault removal may saturate power transformers at one of the two ends of the line. The harmonic contents of these saturation currents may interact with low order low-loss harmonic impedance (second or third) of the network weakened by single-phase opening to create severe temporary over-voltages. In stronger systems where resonant conditions exist normally (mostly 4th, 5th and 7th), harmonic over-voltages may be created upon circuitbreakers reclosing.



Figure 11. Frequency scan result at Brisay substation for the most frequent configuration

V. ACKNOWLEDGMENT

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