Delayed Current Zero Crossing Issue in Static VAR Compensator SF_6 Circuit Breakers

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***Abstract*-- The paper examines the failure risk for SF_6 circuit breakers switching static VAR compensators (SVC) trying to interrupt higher than their capacity transient currents with a high DC component and delayed zero crossings. Various system parameters were studied to establish the worst case scenario and determine the suitable solutions to be implemented for each SVC.**

***Keywords*: Static VAR compensator (SVC), SF_6 circuit breakers, delayed zero crossing, transient currents, EMTP**

I. INTRODUCTION

Most of Hydro-Québec's (HQ) 735 kV network was built in the 1970s and the majority of the substations' equipment has now reached its end of life. Among others, more than 300 air-blast circuit breakers are currently being replaced by SF_6 insulated circuit breakers (CB). Although this technology is known to be safer (especially with composite bushings), it has lesser current chopping capacity compared to the air-blast circuit breakers. This may pose an issue in cases of CB dedicated to series or shunt-compensated lines, where the current to be interrupted has delayed zero crossings, as reported in [1], [2] and [3]. HQ has studied [4] in details the problem for shunt-compensated lines, but further analysis was required to validate whether this could also occur with SVCs.

This paper focuses on the phenomenon of delayed current zero crossings that can appear as a result of a fault in the vicinity of an SVC. Background information about SVC design, phenomenon theory and circuit breaker operation is given. Then, modelling approaches of SVC controls and key system parameters are explained. The last sections present results and solutions that can be implemented in each of HQ's 19 SVCs listed in Table I and displayed in Fig. 1.

TABLE I : CHARACTERISTICS OF HYDRO-QUÉBEC'S SVCS

Substation (qty)	Un (kV)	Mvar range	SVC configuration
La Vérendrye (2)	735	-105 to +300	1 TCR, 3 TSC
Chamouchouane (2)	735	-300 to +300	3 TCR, 3 TSC
Nemiscau (2)	735	-105 to +300	2 TCR, 2 TSC, 2 filters
Albanel (2)	735	-105 to +300	2 TCR, 2 TSC, 2 filters
Chibougamau (2)	735	-105 to +300	1 TCR, 3 TSC
Chénier (2)	735	-300 to +300	2 TCR, 1 TSC, 3 filters
Bout-de-l'Île (2)	735	-300 to +300	2 TCR, 1 TSC, 1 filter
Lévis (1)	315	-115 to +225	1 TCR, 1TSC, 3 filters
Laurentides (1)	735	-115 to +350	1 TCT, 1 filter
Châteauguay (2)	120	-99 to +166	2 TCR, 2 TSC
Figuery (1)	315	-100 to +300	1 TCR, 1 TSC, 4 filters

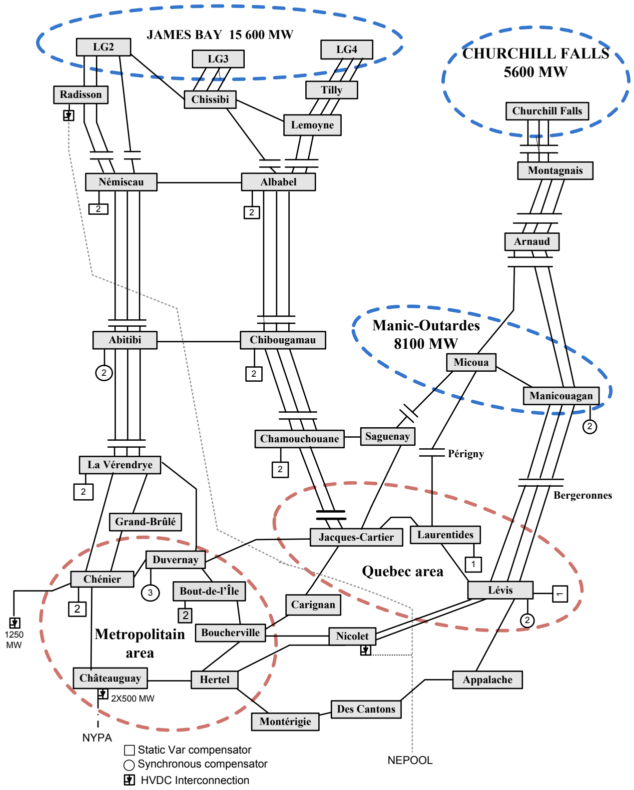

Fig. 1. Hydro-Québec's 735 kV transmission network

II. SVC DESIGN AND OPERATION

A static VAR compensator is a shunt equipment with the capacity to absorb or generate reactive power (Mvar). It reacts to electric network transients and temporary disturbances or system configuration changes. It typically includes a coupling transformer, one or more inductive branches called thyristor-controlled reactors (TCR), one or more capacitive branches also known as thyristor-switched capacitors (TSC) and, in most cases, filters. The right side elements of Fig. 2 illustrate a typical SVC layout with 2 TCR, 1 TSC, filters, a circuit breaker and a load connected to the secondary busbar.

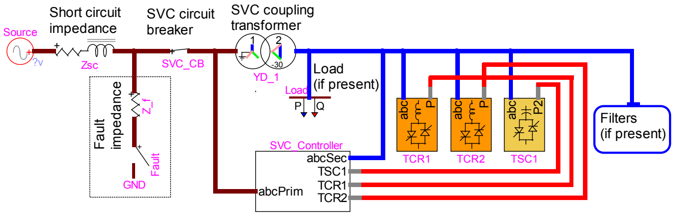

Fig. 2. Single-line diagram of the circuit used for simulations

A 6-pulse SVC design means that there is only one secondary winding used for reactive power. A coupling power transformer with Yg-Δ connection is normally used for this design (as in Fig. 2). A 12-pulse SVC has two secondary

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windings with a 30° phase shift (Yg-y-Δ). The TCR branches of each winding equally share the inductive output to ensure cancellation of specific harmonics (5th, 7th, 17th, 19th, etc.). The Laurentides SVC is a particular prototype design using a high impedance thyristor-controlled transformer (TCT).

III. Phenomenon Theory and Explanation

By definition, a reactor (TCR branch of an SVC) opposes to current variations. As presented in equation (1), when the voltage drops to zero, the current theoretically remains at the value it was prior to the fault was initiated. In reality, the current slowly decreases with a time constant which depends on the circuit's quality factor as shown in Fig. 9.

$$i_L(t) = \frac{1}{L}\int_{t_0}^{t} v\,dt + i(t_0) \qquad (1)$$

If a 3-ϕ fault would occur anywhere inside the SVC zone (i.e. to the right of the CB in Fig. 2), the circuit breaker would only see the network's fault current contribution waveform that would cross zero rapidly, even for asymmetrical faults. For the circuit breaker to see an exponentially decreasing current waveform, the fault must be located outside of the SVC zone, i.e. to the left of the CB in Fig. 2. This last configuration was considered for our study.

In steady-state operation, the SVC current comprises contributions from up to three types of elements: TCR, TSC and filters. Following the voltage drop caused by a fault, the SVC typically becomes capacitive to support the voltage, which means that the controller gives the order to turn off (block) the inductive branches (TCR) and turn on the capacitive ones (TSC). However, if the voltage is too low to allow any thyristor firing (< 0.3 p.u.), the SVC orders the blocking of TCR and TSC. The TSC is able to block since it has a small reactor which creates an oscillation at the tuning frequency (typically around n=4.5). Unfortunately, the TCR branch cannot be blocked since its current does not cross zero. Therefore, the current seen by the SVC breaker is composed of the contributions from the TCR and the filters (if any).

IV. Circuit breaker opening operation

All circuit breakers can be exposed to currents with delayed zero-crossings, for example during an asymmetrical fault. However, in circumstances defined above, the current takes too much time to reach zero or to a value low enough for the current to be chopped by the CB.

Fig. 3 shows the opening operation timing when a CB clears a fault [5], [6]. If the current is still above the current chopping capacity of the CB throughout the arcing time (see Fig. 3 and Fig. 4), during which the gas blast and arc quenching normally occurs, the probability that the fault cannot be cleared is high. The current remaining in the open CB can damage the contacts and interrupting chambers resulting in long-term unavailability of strategic equipment and power transit restrictions.

This issue is of greater concern with SF_6 CB, since their current chopping capacity is lesser compared to an air-blast CB (which can be a few hundred amperes depending on the type and model). In fact, according to [7] and [8], the maximum inductive current chopping capacity of SF_6 circuit breakers is between 15 A and 20 A. Thus, as a conservative approach, a value of 10 A was chosen for our study.

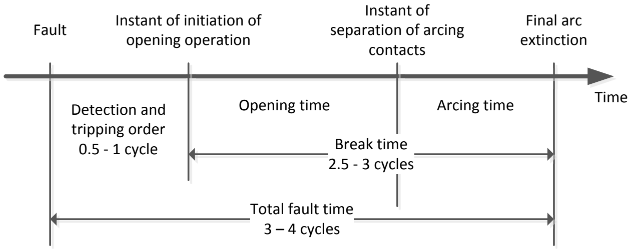

Fig. 3. Circuit breaker timing for opening operation

As shown in Fig. 4, if the current has no zero-crossing and is still above the inductive current chopping threshold of 10 A four cycles (67 ms at 60 Hz) after the fault has occurred, the interruption of a SF_6 circuit breaker cannot be guaranteed.

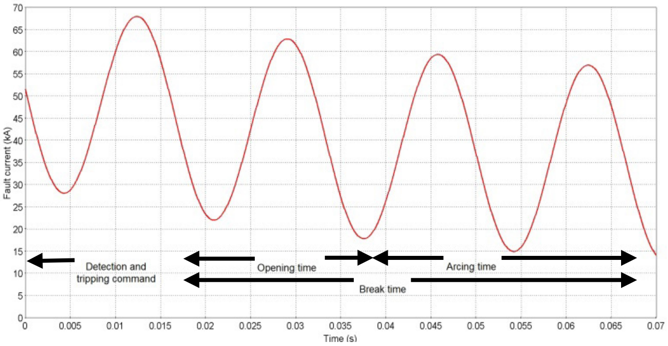

Fig. 4. Circuit breaker timing for an asymmetrical fault

V. Modeling of SVC Controls

A. Detailed Model vs. Passive Elements

Detailed EMTP SVC models provided by the manufacturers (including control strategies) are only available for SVCs installed in the last decade. For older installation, generic models with passive elements were used to reproduce the SVC behavior. Benchmark tests were performed in order to validate whether the usage of passive elements was accurate enough for our study.

Fig. 5 compares the CB current in the 3 phases with both modeling approaches (in red: real controls; in blue: passive elements). The main difference lies in the control, which slightly limits the maximum TCR current via the firing angle, α, (i.e. α = 95° vs. full conduction: α = 90°). Hence, when detailed models were not available, using passive elements to mimic the action of TCR and TSC was deemed acceptable due to the minimal difference observed in the results.

B. Validation with Hypersim and control replicas

Further validation steps were performed using control replicas and Hypersim software, in order to confirm that the behavior was truly representative of what the circuit breaker would subjected to and of how the SVC would react. Results from benchmark tests conducted with control replicas from recently commissioned SVCs at Chénier, Châteauguay and Figuery substations confirmed that the phenomenon and SVC behavior was represented adequately in EMTP.

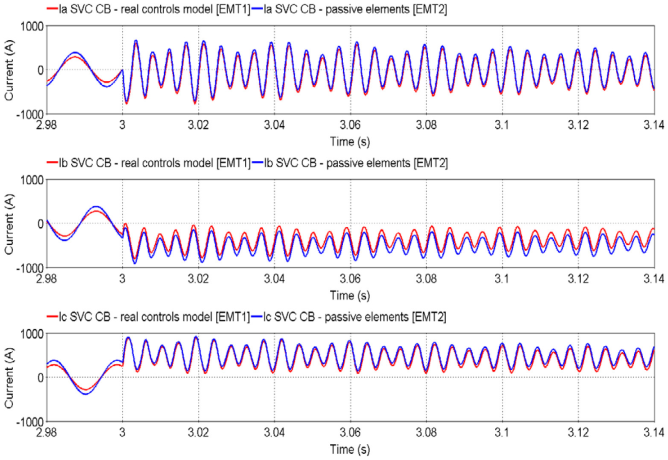

Fig. 5. Figuery SVC with detailed model (red) vs. passive elements (blue)

VI. KEY FACTORS OF INFLUENCE

A deterministic approach was used for the study to find the parameters that maximize the time for the current reach the 10 A chopping threshold. Table II lists the key factors that influence this delay and the retained hypotheses for the study. Detailed explanations are provided in the next subsections.

TABLE II SUMMARY OF RETAINED HYPOTHESES

Factor of influence	**Retained hypothesis**
SVC operating point	Fully inductive for SVCs with filters and at least one TCR at full output for other SVCs
Type of fault	3-ϕ to ground outside SVC zone
Fault timing	Voltage zero on HV side which corresponds to a current peak.
Quality factor (X/R)	Exact value if available. Typical TCR X/R value of 500 when not known
Auxiliary load	Maximum value currently installed
Fault impedance	Low impedance fault (1 mΩ)

A. SVC Operating Point

A conducting TCR is required to have delayed current zero crossing. A validation was made to verify whether it only occurs when the SVC is fully inductive, with no TSC branch in conduction. Fig. 6 shows a 3-ϕ fault case (at t = 3 s) for the Figuery SVC with two operating points:

1. -100 Mvar (full inductive output)
2. +100 Mvar (TSC almost fully offset by TCR + filters)

Both currents in phases B and C take more than 4 cycles to cross the zero axis. The TSC branch blocks its current, which means that the CB sees the sum of the currents coming from the TCR (exponentially decreasing) and the filters discharging. Following these results, it was decided to set the SVC to maximum inductive output for installations including filters and have at least one TCR at full output for the others.

B. Types of Fault

As mentioned earlier, only faults in the zone outside of the SVC CB can cause problems. Phase-to-ground faults are not an issue, because the TCR branch voltages are not zero. This is due to the fact that they are delta connected to allow cancellation of triplen harmonics. The example of Nemiscau SVC seen in Fig. 7 shows that two and three phase faults can be problematic with the circuit breaker interruption. It was decided to proceed with the simulation of a 3-ϕ fault, since it generates the longest delay before the current reaches 10 A.

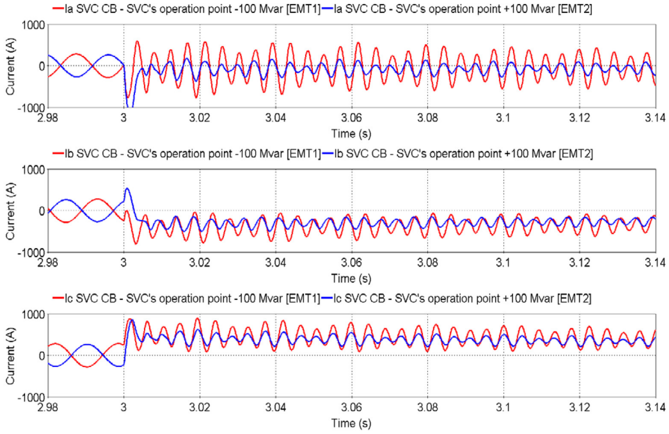

Fig. 6. Effect of operating point on the transient current for Figuery SVC - Q = -100 Mvar (red) vs. Q = +100 Mvar (blue)

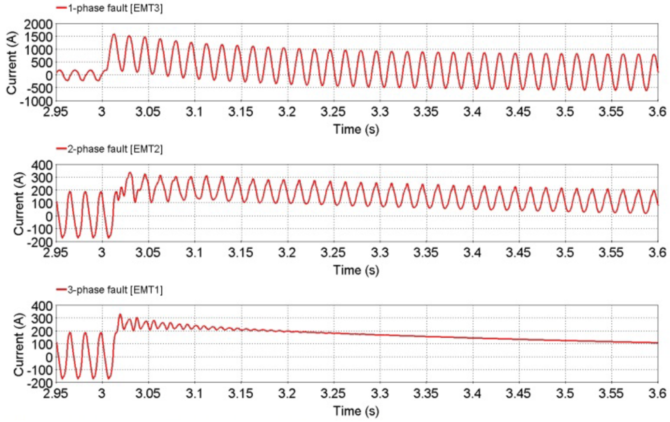

Fig. 7. Nemiscau SVC circuit breaker current for different types of fault

C. Fault Timing

Fig. 8 demonstrates the effect on the initial current seen by the CB when a fault appears for an SVC without filters (only the TCR current). Fault timing was varied on phase C voltage between 90° (voltage peak) and 180° (voltage zero). All cases, except 90°, can hinder current interruption, but the voltage zero (180°) was chosen to cover the worst case scenario.

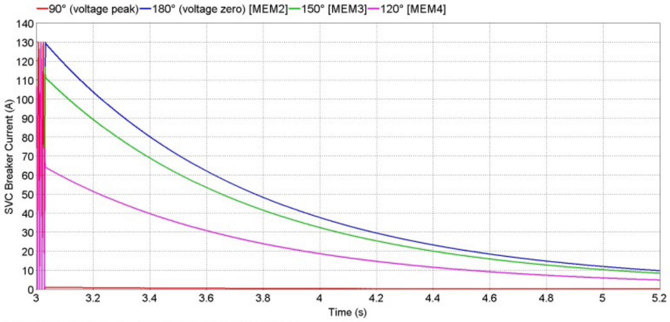

Fig. 8. Effect of the fault timing on the zero-crossing delay (blue: 180°, zero voltage, green: 150°, pink: 120°, red: 90°, peak voltage)

D. Quality Factor

As seen in Fig. 9, the Chamouchouane SVC circuit breaker current decreases according to the circuit's time constant, which is mainly influenced by the X/R ratio of the coupling transformer and the TCR reactors. The transformer data was readily available, so values from nameplates or test reports were used. Unlike for older SVCs, for recent SVCs, TCR reactors X/R values were also available. In Fig. 9, the minimum and maximum X/R value taken from the four most recent SVC projects were simulated. Since an X/R of 735 only slightly increases the delay to reach 10 A, it was judged that an average value taken from the last four SVC projects of 500 was adequate for substations where this data is unknown.

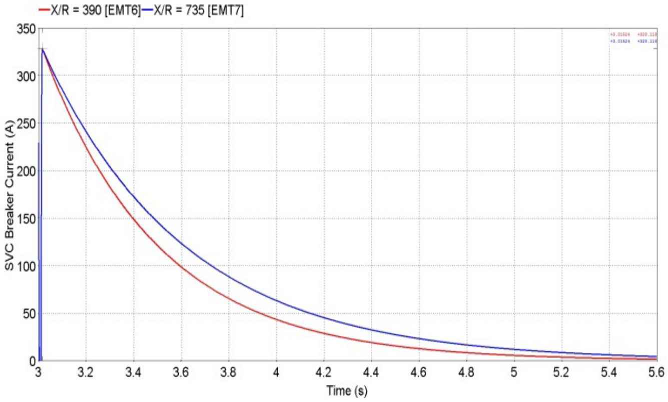

Fig. 9. Effect of TCR quality factor on zero-crossing delay for the Chamouchouane SVC (blue: X/R = 735, red: X/R = 390)

E. Auxiliary Load

In certain substations, SVCs are used to feed auxiliary and/or local loads from their secondary or tertiary winding. As shown in Fig. 10, when we consider the maximum 30 MVA load (69 kV sub-network) that the Nemiscau SVCs are expected to feed in the near future, it increases the pre-fault current and the time to reach the 10 A threshold. Therefore, it was decided to consider the maximum load fed by each SVC in the simulations.

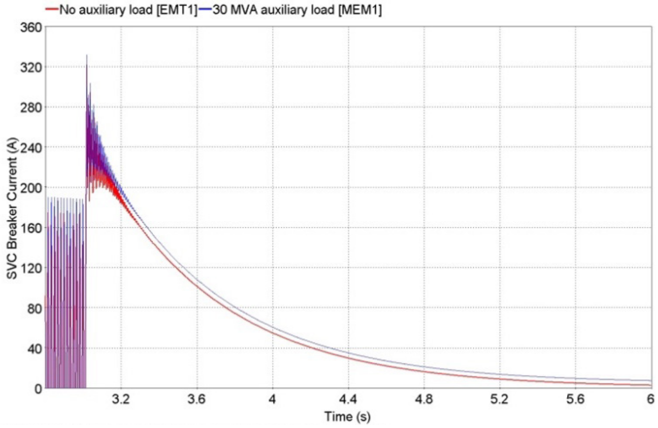

Fig. 10. Effect of load fed by the Nemiscau SVC (blue: 30 MVA, red: no load)

F. Fault Impedance

In Fig. 11, the current in phase C of the SVC circuit breaker is depicted with three different values of fault impedance (1 mΩ, 1 Ω and 10 Ω) for a 3-ϕ fault at the Figuery substation. Higher impedance faults (i.e. ≥ 1 Ω) add more damping in the circuit which rapidly forces the current to zero, while very low impedance faults (around 1 mΩ), such as forgotten temporary grounds, are the most problematic for the circuit breaker interruption. The value of 1 mΩ was chosen in our study to find the longest delays.

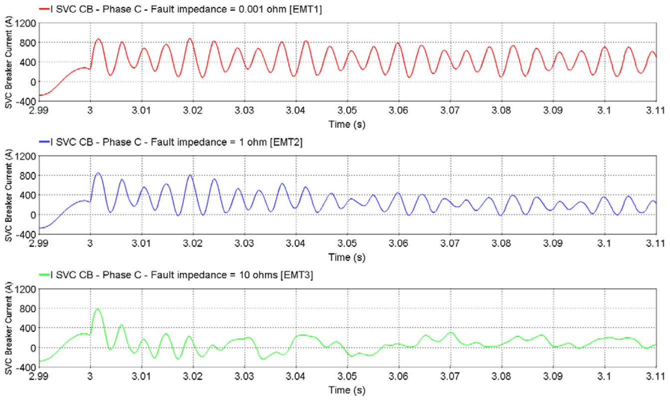

Fig. 11. Effect of fault impedance (red: 1 mΩ, blue: 1 Ω, green: 10 Ω)

VII. RESULTS

Three examples of results with different SVC topologies are described in the next subsections.

A. 6-pulse SVC with Filters

The Figuery SVC, commissioned in 2015, is a 6-pulse design with a secondary voltage of 23.8 kV, 1 TCR, 1 TSC and four filters (3rd, 5th, 7th and high-pass). This setup provides a reactive power output from 100 Mvar inductive to 300 Mvar capacitive. Table III gives the details about the case settings. As seen in Fig. 12, the worst case current exhibits both high frequency and DC contents and eventually reaches 10 A threshold, 2.3 seconds after the fault appeared (not shown in the figure). This may cause damages to circuit breaker contacts since it will be unable to interrupt the current.

TABLE III CASE SETTINGS FOR FIGUERY SVC

Parameter	Setting
Pre-fault voltage	333.9 kV (1.06 p.u.)
Load	none
Pre-fault operating point	-115 Mvar

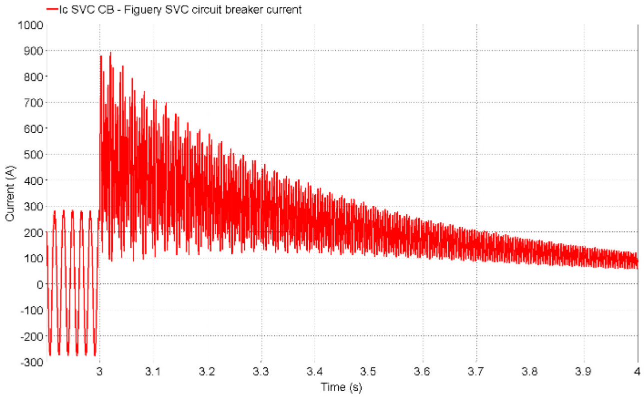

Fig. 12. Figuery SVC circuit breaker current

B. 6-pulse SVC without Filters

The two SVCs at La Vérendrye substation were installed in 1984. A Yg-Δ-Δ transformer is required for this 6-pulse design with 16 kV as the secondary voltage and a tertiary winding at 26.4 kV feeding the local load of 12 MVA. Since power quality requirements were not as stringent in earlier times, there are no filters installed and the reactive power output is provided solely by 3 TSC and 1 TCR. Table IV provides details on the case settings, while Fig. 13 shows the worst case current that reaches 10 A nearly 2.2 s after the fault. Once again, the circuit breaker can be damaged since it does not have sufficient current-chopping capability.

TABLE IV CASE SETTINGS FOR LA VÉRENDRYE SVC

Parameter	Setting
Pre-fault voltage	781 kV (1.063 p.u.)
Load on tertiary winding	12 MVA (p.f. = 0.9)
Pre-fault operating point	-23 Mvar

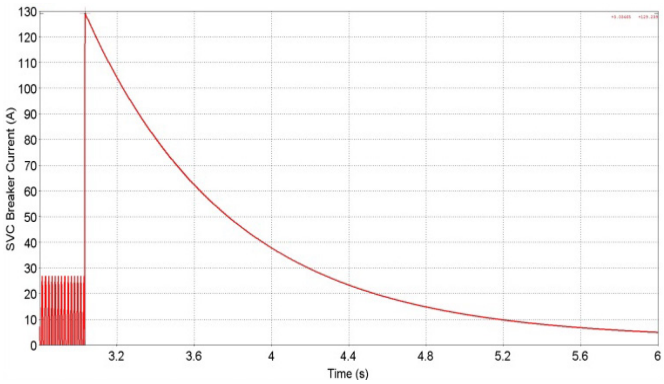

Fig. 13. La Vérendrye SVC circuit breaker current

C. *12-pulse SVC with Filters*

The two 735 kV 12-pulse SVC located at the Nemiscau substation were recently overhauled in 2013 and 2014. The original coupling transformers (Yg-y-Δ) with two secondary 22 kV windings were kept. The reactive power range of -100 to +300 Mvar for each SVC is provided by 2 TCR, 2 TSC and two filters (2nd and 3rd). Although not currently used, there are short-term plans to use the Y-winding to feed a 30 MVA local load. Table V provides details on the case settings and Fig. 14 shows the worst case current for a 3-ϕ fault seen by its CB which reaches 10 A 2.2 seconds after the fault has occurred. Based on these results, the Nemiscau SVC circuit breaker may encounter the same problems as the two previous examples.

TABLE V CASE SETTINGS FOR NEMISCAU SVC

Parameter	Setting
Pre-fault voltage	779 kV (1.06 p.u.)
Load on y-winding	30 MVA (p.f. = 0.95)
Pre-fault operating point	-172 Mvar

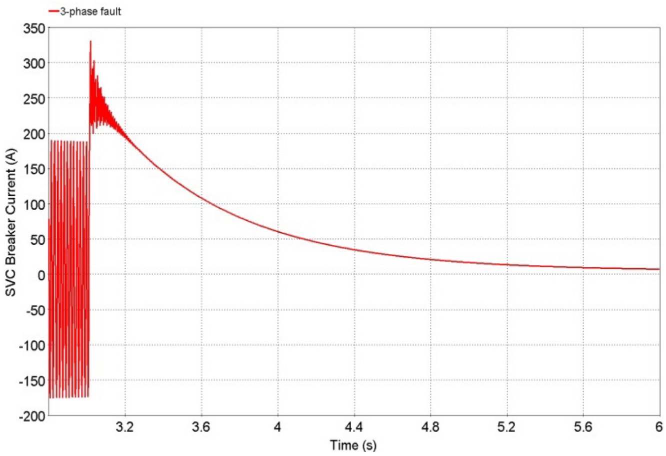

Fig. 14. Nemiscau SVC circuit breaker current

VIII. RESULTS SUMMARY

As seen in the previous section, the problematic can occur no matter the type of SVC topology. TABLE VI shows, for each installation, the longest time required for the current to reach 10 A, following a three phase fault outside of the SVC zone. Even the shortest time delay of 0.2 s obtained at the Laurentides substation can cause damage to CBs, since it is longer than the 4 cycles maximum total fault time (see Fig. 3).

TABLE VI : TIME TO REACH THE 10 A THRESHOLD

Substation	Time (s)
La Vérendrye	2.2
Chamouchouane	4.8
Nemiscau	2.2
Albanel	2.2
Chibougamau	2
Chénier	1.8
Bout-de-l'Île	3.3
Lévis	3.7
Laurentides	0.2
Châteauguay	1.7
Figuery	2.3

Since all of Hydro-Québec's SVC CBs will be of SF_6 technology by 2020, this delayed current zero crossing phenomenon has to be addressed in the short-term.

IX. SOLUTIONS

The probability to have a three (or even a two) phase fault outside of the SVC zone is extremely low. Still, this could lead to severe damage to the SF_6 CB, meaning losing an SVC and reducing the power transit on the network for a significant period of time. In order to protect its SVC circuit breakers from a fault outside of the SVC zone, Hydro-Québec intends to deploy the following solutions.

A. *SVCs Integrated with One CB*

As shown in Fig. 15, there is no impact to delay the opening of the SVC CB. As the fault is quickly cleared by the three circuit breakers to the left of the fault (CB 1, 2 and 3), the SVC CB can open after a delay without any consequence for network stability.

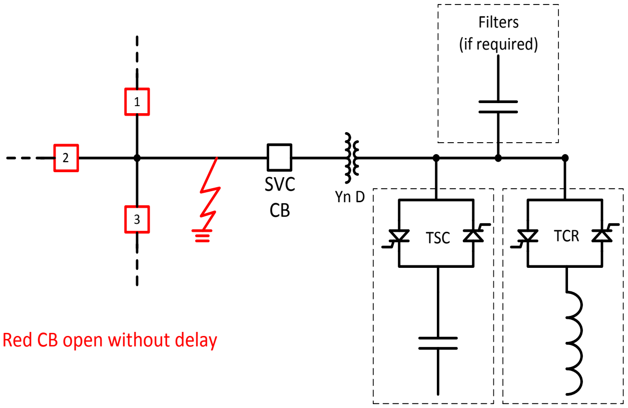

Fig. 15. Example of a fault outside of the SVC zone for a SVC integrated with only one CB

1) *Recommended solution for new SVCs*

The detection of a fault outside of the SVC zone should be signaled to the SVC control system (without a CB trip order). The SVC control system should open the circuit breaker only if it is risk-free. One of the two following strategies should be applied by the control system:

1. Wait 5 seconds before tripping the SVC CB (this delay is sufficient to cover all cases)
2. Trip the SVC CB as soon as there are zero crossings for all three phases (e.g. by monitoring the current or simply by tripping the CB as soon as all of the TCR valves are blocked, meaning that there is no more DC offset in the current).

A minor advantage of the second strategy is that if the fault does not include delayed current zero crossings, there will be no unnecessary waiting time before opening the SVC CB. With the collaboration of SVC manufacturers, these solutions can be easily implemented for new SVCs.

2) *Recommended solution for existing SVCs*

For existing SVCs, the first thing to do is to disable the tripping order of the SVC CB initiated by the protections that detect an external fault, no matter what kind of fault it is. As there are no impacts on delaying the CB opening, the simplest solution is to avoid opening, even for a single phase fault.

Afterwards, the software should be modified to initiate the opening of the CB after a 5 s delay, following the reception of a trip signal from the protections that have detected an external fault. As discussed before, this delay is sufficient to cover all our cases (see Table VI). Using a unique delay for all of our SVCs also avoids complexity and mistakes.

B. *Particular case - SVCs Integrated with Two CBs*

Hydro-Québec has one particular arrangement in Albanel substation where each SVC is integrated with 2 CBs. As shown in Fig. 16, when a 3-phase fault occurs, SVC CB1 will also see the network's sinusoidal contribution going through the SVC CB2, which means that there is no interruption issue. Therefore, it must be opened without delay to avoid transient stability problems due to the prolonged fault duration.

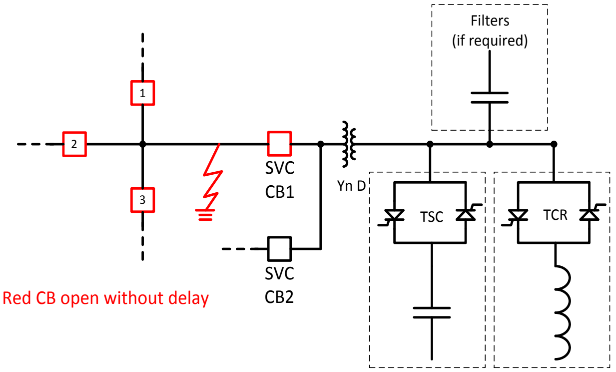

Fig. 16. Example of a fault outside of the SVC zone for a SVC integrated with two CB

Unfortunately, this strategy is not applicable when one CB is out of service for maintenance purposes or other reasons because it brings the SVC breaker back into a potential problematic situation. In order to cover all situations, the control system would need to consider the CB's state (open or closed) which is not easily achievable for the existing Albanel SVCs, but could be implemented for future installations.

Since the normal operating mode for the Albanel SVCs is with both CBs closed, our recommendation is to manage the risk. The network operator is informed about the risk to operate with only one SVC CB at this substation and will minimize the time spent in this configuration.

X. CONCLUSIONS

A massive replacement program of 300 air-blast circuit breakers by SF_6 technology was initiated in the last years at Hydro-Québec. Those SF_6 CBs do not have the same current chopping capacity as their predecessors, when the current exhibits high DC content and the zero crossings are delayed.

System studies related to the phenomenon of delayed current zero crossing in SVC CB were conducted in EMTP, taking into consideration different hypothesis such as the SVC operating point, the type of faults, the fault timing and impedance, the quality factor and the auxiliary load.

Except for Albanel SVCs, the proposed solution is to protect the SVC circuit breakers for faults outside the SVC zone in order to avoid SVC unavailability due to a breaker failure and possible major impacts on power transfer capability. This can be achieved either by delaying the trip order 5 seconds or by opening the circuit breaker when the current exhibits zero crossings or is sufficiently low that its interruption is possible.

For Albanel SVCs, it was decided to manage the risk since the normal operating mode is with both circuit breakers. This means that the probability of having an SVC operating with only one CB and high TCR current simultaneously with a two or three phase fault at a specific location in the substation is extremely low.

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