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Upgrade to HVDC AC Filters Protections – Using Impedance Calculation

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SUMMARY

Hydro-Québec (HQ) is a public utility operating 100 individual alternating current (AC) shunt filters and shunt capacitor banks in order to exchange close to 5,000 MW with neighbouring utilities through its four line-commutated converter high-voltage direct current (LCC-HVDC) links. These filters have not suffered any major failures since they were built, mostly in the 1980s.

In 2017-2018, however, severe faults occurred on shunt filters and capacitor banks. Some were bad luck (e.g., lightning strike on one filter bank) and others were due to normal aging of filter components. Most of these faults were detected late, resulting in extra damage to filters and thus in long outage time for the filters. Hence, there was a higher risk of getting a forced HVDC outage.

Three of the main cases occurred at different substations. At Chateauguay, an air-core reactor part of the resonant branch of a C-type filter had turn-to-turn failure, leading to a complete short-circuit of the parallel branch resistance after several seconds. At Outaouais, a bird started an avalanche effect in a capacitor bank arranged in an H-bridge configuration, resulting in a complete bank short-circuit after a few seconds, a fault that went unnoticed by the unbalance protection. At Radisson, the re-tunable filters suffered resistance and low-voltage capacitor failures that went undetected for many days before being discovered through a visual inspection, forcing an HVDC outage.

These events were reproduced in simulations to determine the exact sequence of events. This analysis indicated that one key improvement applicable to all AC shunt filters and capacitor banks is protection based on impedance. To our knowledge, this type of protection is not typically used in HVDC systems. In a pilot project, new impedance protection was developed in the programmable protection system and commissioned at Chateauguay on a shunt capacitor bank and a C-type filter. Using the same base design, 5th harmonic impedance protection was developed for Radisson's re-tunable filter. High-sensitivity protection was achieved through proper filtering of calculated impedance imbalance among the three phases, which constitutes a distinctive feature. A suitable time delay and steady-state operating voltage range allow immunity to non-tripping conditions.

This paper presents a brief analysis of the fault cases, demonstrating the need to upgrade the AC filter state-of-the-art protection scheme. It goes on to describe the impedance protection commissioned in Chateauguay, including the test results. The paper highlights the fact that impedance-based protection could have helped reduce the adverse effects of the faults.

KEYWORDS

AC shunt filters, shunt capacitors banks, HVDC protection, impedance protection, distance protection, C-type filter, re-tunable filter, turn-to-turn failure, short-circuit fault, H-bridge, unbalance protection

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INTRODUCTION

Due to its intrinsic design, LCC-HVDC generates significant harmonics and consumes higher reactive power as power transmission increases. Consequently, AC shunt filters are required in the five HQ substations with LCC-HVDC converters to maintain acceptable power quality and supply sufficient reactive power to maintain a unity power factor. In almost all substations, all filter-types are redundant for harmonic purpose, including one redundant filter per converter for reactive power compensation purpose.

With the exception of Outaouais, commissioned in 2009, all of HQ's HVDC substations, including shunt filters, were commissioned in the 1980s. Due to the lower life expectancy of their controls and protection systems, these systems were refurbished at substation half-life, between 2010 and 2015. As no major issues were found during the first half-life, the AC filter protection philosophy and settings were transposed to the new systems using standard protections from the supplier.

In 2017-2018, five major failure events occurred on AC shunt filters and capacitor banks in different substations. Overall, the faults affected a huge number of capacitor units (58), one reactor and many resistance units (40). Long outage times, up to more than a year, were needed to put the filters back into service, mainly due to the high number of broken elements, combined with aging and a lack of spare parts. Two failure cases affected power flow directly: one converter was tripped following the breakdown of the only available filter of its type and two separate failure events on two identical filters led to a short HVDC outage.

All the cases were reproduced in simulation to perform an in-depth analysis of protection actions and identify possible improvements. The common conclusion for all events was that the trip delays were too long, resulting in extra damage to the filter. Flaws, lack of coverage and primary protection failure, including inadequate settings, were discovered, most of which could not be attributed to the refurbishments. These events also demonstrated that even when a state-of-the-art HVDC AC filter protection scheme [2, 3] is used, backup protection cannot be relied on to prevent major damage.

The latter issue can be attributed to the ground overcurrent protection associated with unbalance protection schemes [1] to this day. Because this protection is prone to false trips caused by external faults, however, trip time delays have been extended to many seconds over the years and the trip level has been raised very high [3]. As there is no other type of backup protection commonly used for unbalance faults, as validated from the literature state-of-the-art protection scheme [2, 3], the end result is massive damage if the primary protection fails.

One of the key recommendations arising from the events analysis was therefore to add effective backup protection that uses different principles and independent measurements. Given the age of the installations and the high use factor, the protection had to be cost-effective and low computer-load. Thus, no measurement devices could be added, and the protection had to fit with the current programmable protection platforms for all filters.

Over the years, the distance relay, as an example of impedance-based protection, has become a very sophisticated tool for detecting line faults. It is also marginally recognized as possible protection for detecting faults within shunt capacitor banks [2]. However, to our knowledge, it is not used in HVDC projects to protect shunt filter banks. As the latter use presents very different challenges from lines protection, we believe a specific impedance scheme, covering primary protection weaknesses, is best suited to protecting a shunt bank.

This paper uses real-life examples to show the need to upgrade AC filter protection schemes and how that can be done using impedance protection. Tips will also be provided for other improvements, including in settings. The second part of the paper presents the new impedance-based protection developed to protect a capacitor bank, a C-type filter and a double-tuned re-tunable filter. An upgraded protection scheme ensuring effective primary and backup coverage against component failures will be presented.

1. CASE STUDIES

All events were reproduced in simulation with a simplified network but with a detailed one-phase filter model. The most probable sequence of events was identified despite sometimes missing information and recording on the beginning of faults. Action or non-action by protection systems was carefully evaluated for all cases, and improvements were identified in every case.

1.1 C-type 2nd harmonic filter at Chateauguay

Second harmonic filters were added at Chateauguay in 1990 to dampen transient harmonic overvoltage [4]. In this C-type filter (Fig. 1), the inductance (L) and capacitor (C2) form a 60 Hz-tuned branch, meaning that almost no 60 Hz current flows to the resistance branch (R). The fault started when L experienced turn-to-turn failure of undetermined origin, resulting in detuning of the branch. The detuning led to excessive 60 Hz current flowing in R, rated 24 A steady-state (42A/60s; 70A/10s). With no protection acting fast enough, R short-circuited and caught fire. The resistance overcurrent protection (ROP: 110A/1s in CT4) finally isolated the filter when 650 A was circulating in the resistance branch. L and R were complete losses.

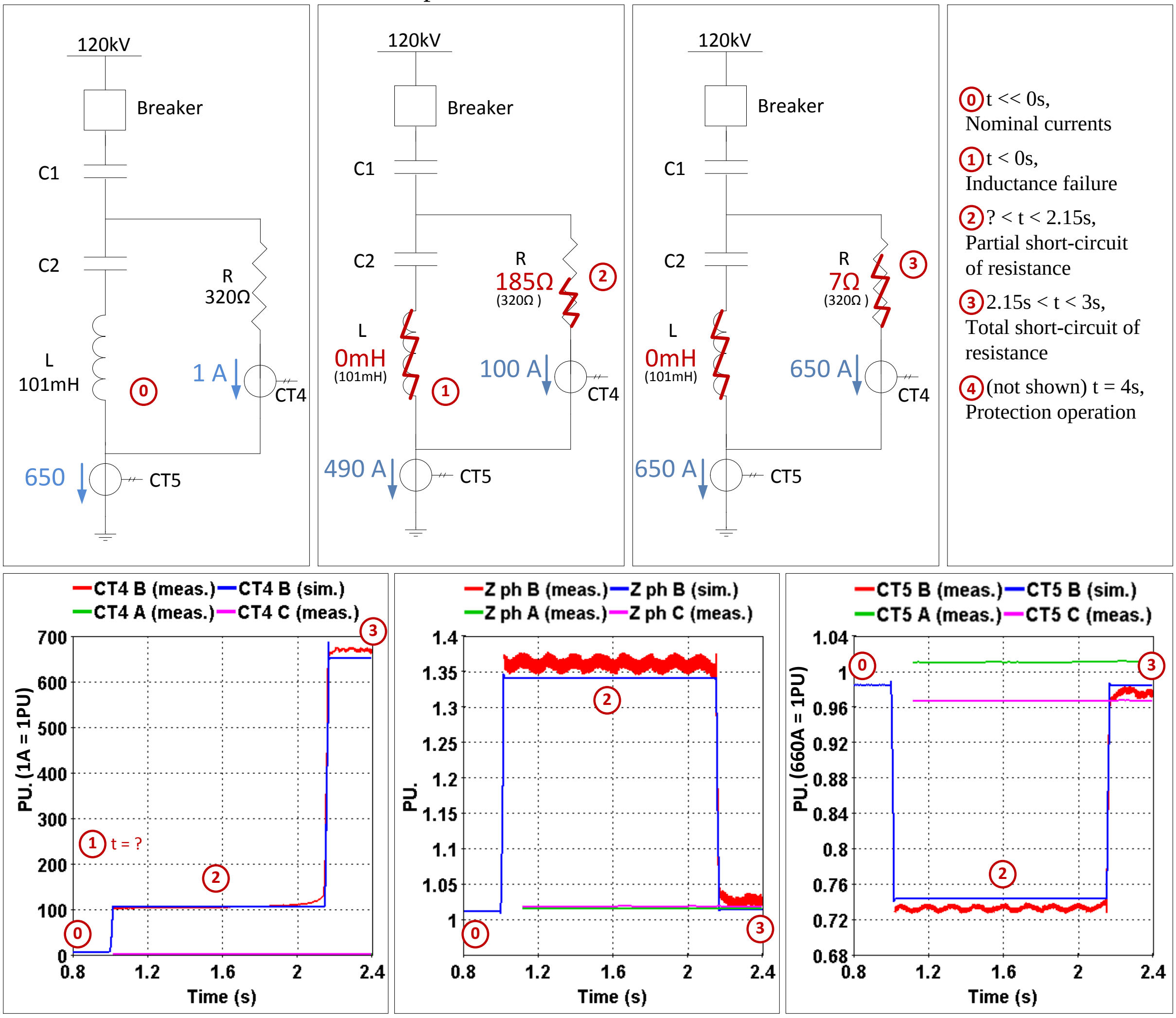

Figure 1: Event on a 2nd harmonic filter at Chateauguay

The ROP setting was set up to cover major failure in the resistance but not for this detuning situation. The first corrective action was to add more stages to this protection to respect the resistance current capability. Resistance overload protection using the inverse curve characteristic only considers harmonics current and thus does not address this issue.

Two more efficient approaches were studied and commissioned. Impedance protection protects mainly C1 but can also catch detuning of the resonant branch (C2+L) as backup protection. Fundamental wave protection, presented briefly in [3], offered even better protection coverage for the resonant branch. It is based on the fact that low current is expected in the resonant branch as the components do not have ideal values and an infinite quality factor. This current can be estimated using online measured total filter current and offline measured component values, as the two parallel branches form a current divider circuit.

The impedance of the components varies, however, due to temperature and frequency drift. These aspects can be effectively compensated for using three-phase comparison compensation in a similar fashion as described in section 2. The result is sensitive protection that can act as a valuable backup for the C2 H-bridge unbalance protection and primary protection for a turn-to-turn fault inside L.

1.2 High-pass 12th harmonic filter at Outaouais

A fault initiated by a bird occurred on a high-pass filter branch arranged in an H-bridge configuration (Fig. 2). The fault consisted of short-circuiting of capacitor groups through arcing in the structure lasting more than 1.7 second (initiation time is unknown). The entire bank eventually short-circuited, leading to a differential protection trip. The final short-circuit caused the explosion of a capacitor and burning of the entire bank. The bank had to be rebuilt, meaning that it would be unavailable for over a year.

Only one fault scenario matches the recorded measurements at every step of the fault almost perfectly. It proves that high current should have been measured by the unbalance current transformer (CT-U: rated 1.5 A). The most likely hypothesis for this failure involves H-bridge unbalance protection weaknesses, as follows:

- A high initial current fault can lead to bypass of the unbalance current through passive spark gap protection without a trip if not properly handled, or to destructive damage to the measurement device prior to the trip if passive protection devices fail to function properly.
- As there is very low current in the H-bridge in normal operation, any misconnection or unsupervised failure of the measurement device can remain undiscovered for a long time.
- Equivalent failures in two opposed quadrants of the H-bridge cannot be detected [6].

In this specific case, the CT-U transducer was found to be damaged, possibly by the initial fault. The root cause will be corrected, if possible (the investigation is ongoing); however, this case proves the necessity of adding a backup scheme that is not susceptible to H-bridge vulnerabilities.

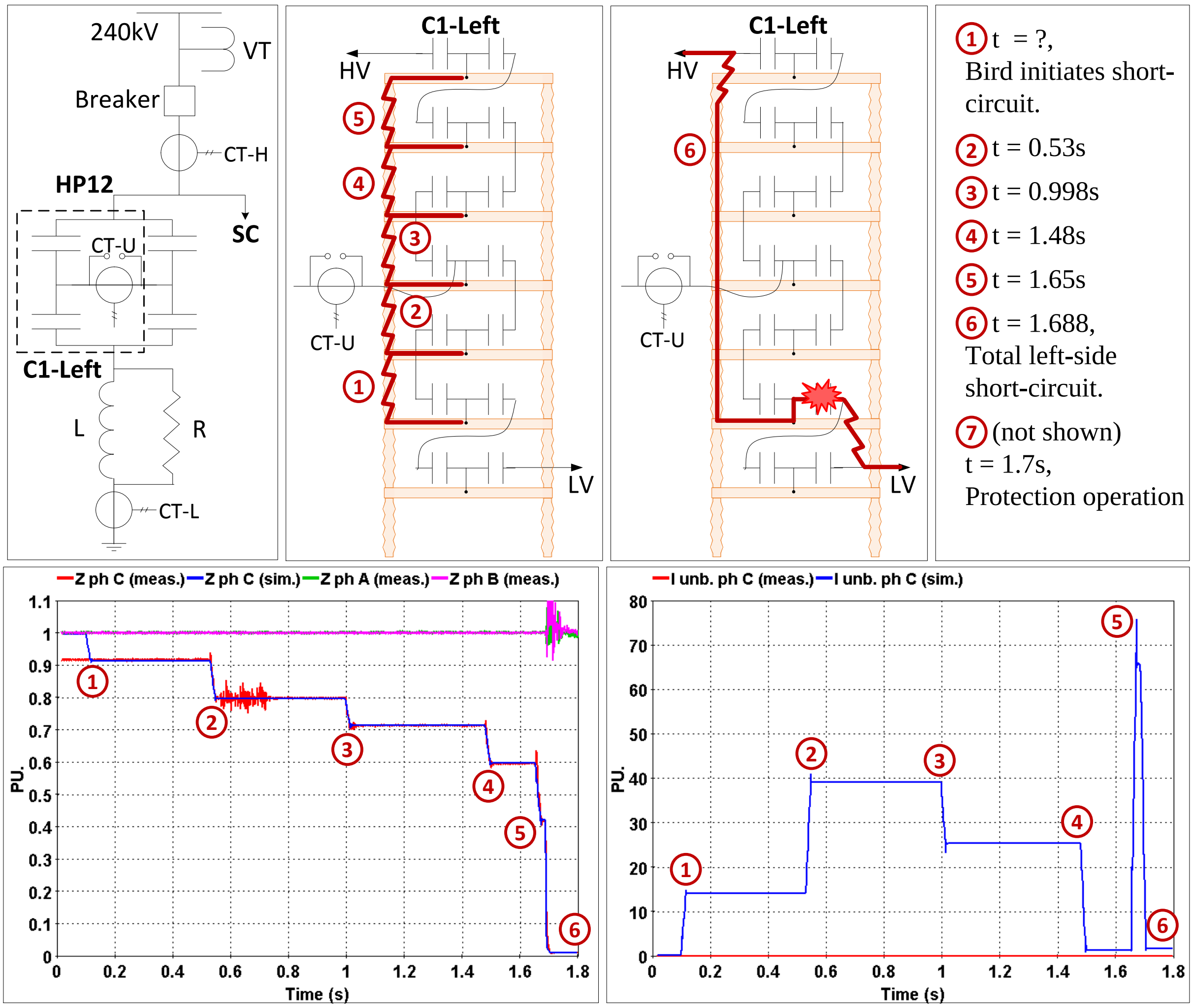

Figure 2: Event on a high-pass 12th harmonic filter at Outaouais

1.3 Double-tuned/re-tunable 36th/48th/5th harmonics filter at Radisson

This filter (Fig. 3) is normally tuned to the 36th/48th harmonics but will be automatically re-tuned to the 5th harmonic by opening the bypass breaker if there is an excess of 5th/7th harmonics on the AC grid [5]. In recent years, the breaker was almost never in a 5th harmonic configuration. However, in May 2018, a rare activation of the 5th harmonic reconfiguration went unnoticed. After one week, unusual noises led to the discovery that 20 of the 80 resistors units composing R3 were burned. As spare parts for this resistor were lacking, the filter could not be put back online. Two days later, the other filter of the same type was found with one of its two parallel capacitor units forming C2 to be faulty. Power flow had to be suspended for a short time until the capacitor could be replaced.

This case is distinct from those presented above because the fault affected mainly the harmonic impedance of the filter and not the fundamental impedance. This makes it more difficult to identify a failure with protection, given the lower precision of the measurement device at higher frequencies. Detuning supervision was added to detect imbalance in the three-phase 35th to 37th harmonics current (CT-M) of the parallel resonant branch (C2+L2+R2). Impedance protection at these frequencies cannot be achieved due to low harmonic voltage. In addition, 5th harmonic impedance protection was added to detect failure in R3 or L3. Impedance protection looks to the fundamental impedance in normal operating mode as backup protection for C1.

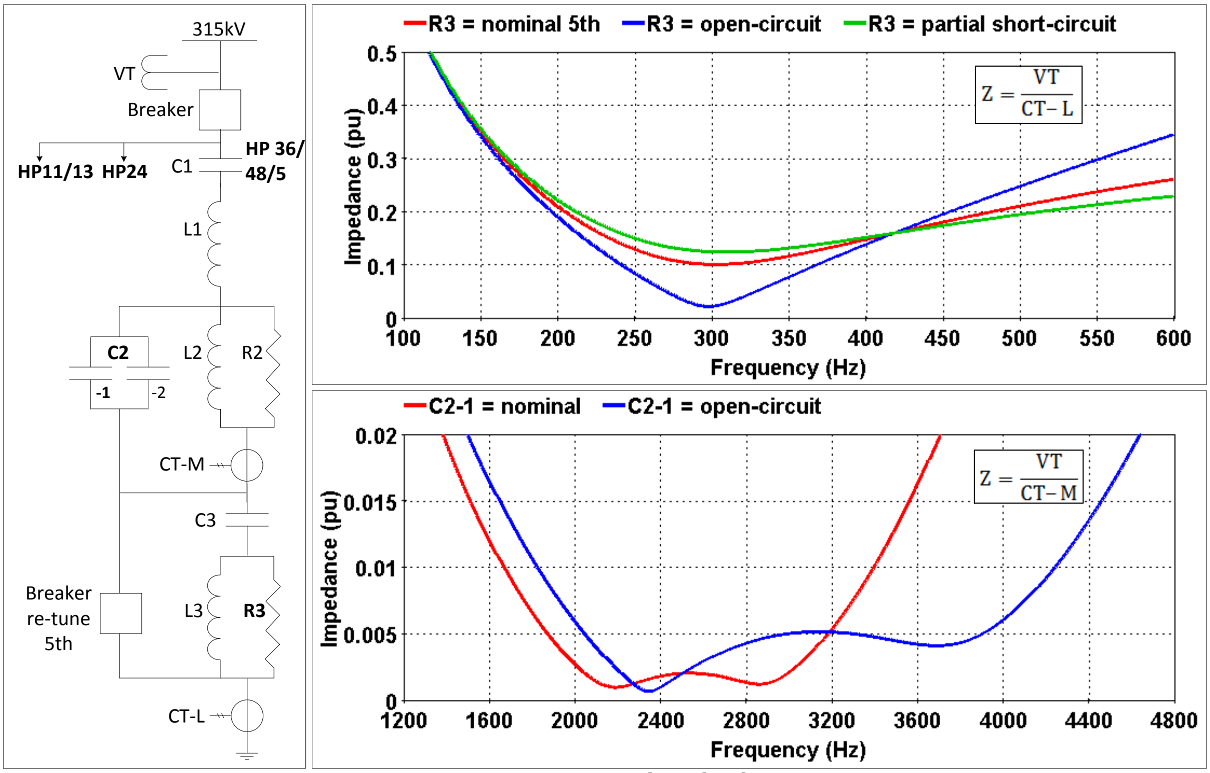

Figure 3: Events on the double-tuned/re-tunable 36th/48th/5th harmonics filters at Radisson

1.4 Double wye externally fused shunt capacitor bank at Chateauguay

Dielectric failure led to the explosion of one unit capacitor of this externally fused capacitor bank without an H-bridge connection (Fig. 4). As a result, the fuse could not operate and a short-circuit of its row was initiated. Up to five groups of series capacitors were short-circuited alternately through arcing in the structure or in the capacitor units. Many fuses operated, as the fault went on for 22 seconds before the ground overcurrent protection isolated the faulty bank. New capacitor units had to be bought, and the bank was unavailable for almost a full year.

The primary protection is a current comparison scheme with another filter branch. Protection was deactivated as the compared filter branch was not in operation at that time. The new impedance protection described in section 2 has been developed in part to act as the new primary protection for this shunt capacitor bank. The protection is sensitive enough to display an alarm on one open-circuit capacitor event. It can also react promptly to the short-circuit of one capacitor group.

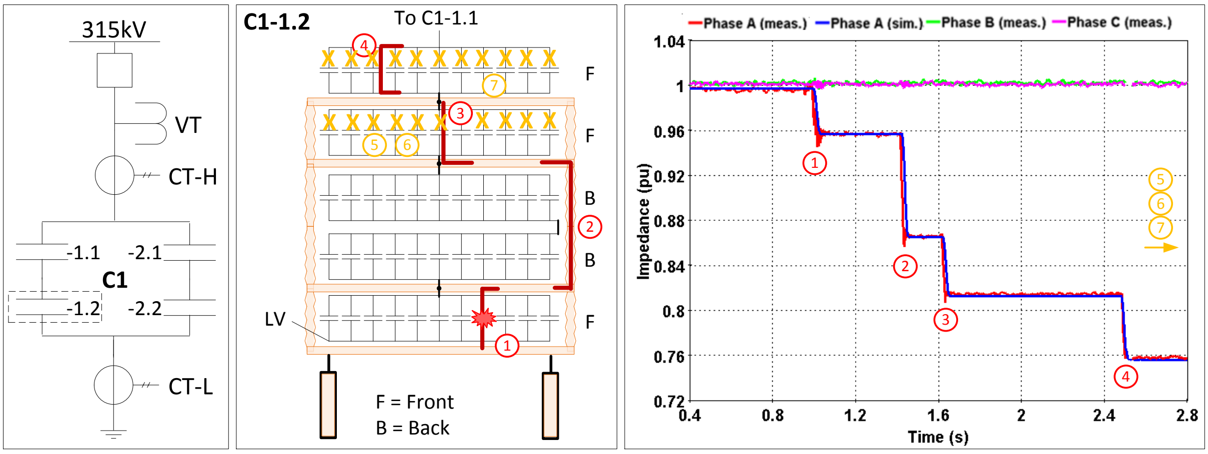

Figure 4: Event on a double wye externally fused shunt capacitor bank at Chateauguay

1.5 Single-tuned 13th harmonic filter at Chateauguay

A lightning bolt hit one of the towers of the capacitor bank directly (Fig. 5). The strike caused secondary arcing to ground at the bottom of the tower. As a result, five groups of series capacitors in the C1-1 tower and L were bypassed by the fault to ground. After 2 seconds, the fault evolved into a bus-to-ground fault, exploding two capacitors in the process. The differential protection finally operated, isolating the bank.

The differential protection did not operate before the final short-circuit due to the slope of the restraint current, set at 53%. This restraint current (0.53*CT-H) kept increasing above the ground fault current (CT_H-CT_L), as it bypassed up to 7 of the 13 capacitor groups, demonstrating the need for a slope of 20% to 30%, as stated in [3]. This erroneous setting could have been discovered by simulating ground faults during factory system testing, as proposed in [8]. The unbalance protection, using current branch comparison, deactivated itself when the current went low in the branch current measurement (CT-L) due to the ground fault. This flaw was corrected by ensuring that the three phases go low before deactivating. Impedance protection would have prevented most of the damage.

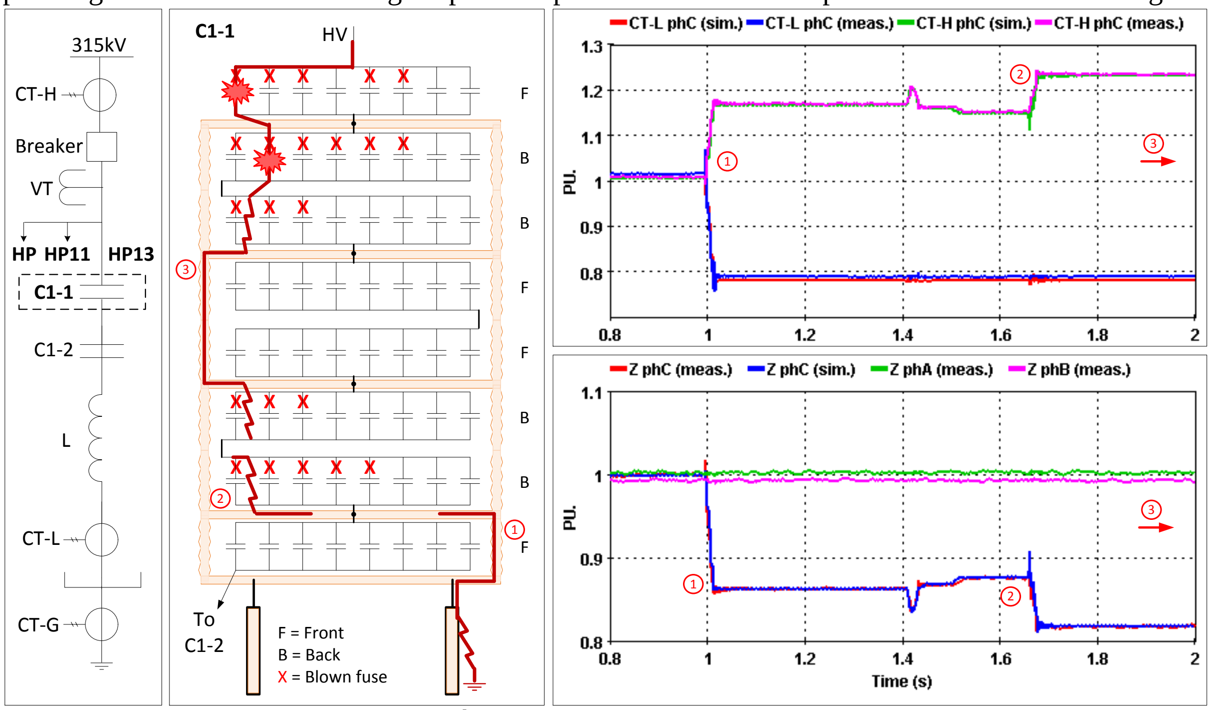

Figure 5: Event on a single-tuned 13th harmonic filter at Châteauguay

2. IMPEDANCE BASED PROTECTION

This impedance protection scheme is based on Ohm's law, which says that the filter impedance of any phase is equal to the voltage across it divided by the current flowing through it.

$$Z_{ph}=\frac{V_{ph}-V_N}{I_{ph}} \tag{1}$$

where V_{ph} is the phase-to-ground voltage, I_{ph} and Z_{ph} are the phase current and impedance, respectively, and V_N is the neutral-to-ground voltage.

When the filter is solidly grounded, the neutral does not have to be measured and is considered to be zero. For ungrounded filters, if the neutral voltage measure is not available or unreliable, the line-to-line voltage and current have to be used instead to calculate the line-to-line impedance.

Any filter fundamental impedance is dominated by the high voltage capacitor impedance.

$$|Z_{filter}| \approx |Z_{Capacitor}| = \left|\frac{-j}{2\pi f \cdot C(T)}\right| \tag{2}$$

where C(T) is the capacitor value depending on temperature and f is the grid frequency.

The filter impedance will vary constantly according to frequency and temperature, and these variations must be taken into account in the settings or compensated by measurements. Without compensation, this protection scheme achieves high sensitivity by calculating the differential impedance between the phases of the filter, such as:

$$\Delta Z_{ab} = |Z_a| - |Z_b| \qquad \Delta Z_{bc} = |Z_b| - |Z_c| \qquad \Delta Z_{ca} = |Z_c| - |Z_a| \tag{3}$$

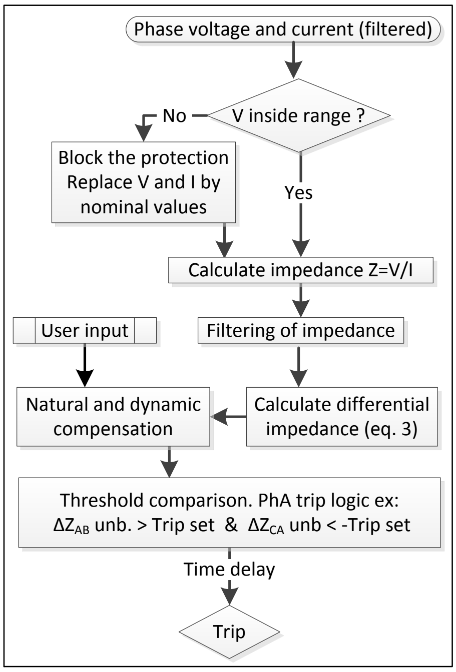

Figure 6 : Flow chart of the differential impedance protection

Applying equation (3) eliminates the zero-sequence impedance, thus only the imbalances between the three-phase impedances remain. This is equivalent to obtaining the sum of positive and negative sequence impedance without explicitly calculating the symmetrical components. The natural imbalances between the three-phase impedances should be compensated for in the protection system when it returns online after performing modifications to the filter. The trip decision will be taken if the differential impedance is above or below a threshold corresponding to abnormal conditions, such as an open-circuit or short-circuit. A choice can be made whether the differential impedance of one phase-to-phase (e.g., ΔZ_{ab}) must be different from those of the other two or only from one of them.

With this proposed scheme (Fig. 6), balance three-phases perturbations will not affect the algorithm. In a conventional scheme, slow drifting ambient temperature can be compensated for dynamically online by distinguishing fast from slow impedance drift; however, it is difficult to detect a fault when the filter is put back online after being offline with changing ambient temperature. This scheme does not have this issue, as only a small time delay is needed when energizing the filter to reach steady state impedance unaffected by a three-phase common condition. Nevertheless, if the physical orientation of the capacitor bank is not ideal, uneven sun exposure conditions for the three phases can be dynamically compensated for.

One rare ambiguous situation for this scheme occurs when two or three phases slowly build up equivalent failures, such as the same number of fuses blowing in an internally fused capacitor bank. For this reason, having another fast stage supervising the individual phase impedance, but with large enough settings to account for normal impedance variations, is recommended. As a backup protection, however, this scheme has strong complementarity with H-bridge unbalance protection, as the latter has blind spots and weaknesses related to faults within the same phase [6], not within the three phases. The reliability of this primary and backup protection scheme is further enhanced by the use of different principles and measurement devices.

This protection scheme (Fig. 7) is steady-state protection looking exclusively at one frequency component. Two protection stages were necessary to sense a single element failure in a large bank (e.g., one open fuse) and take fast action for a large fault (e.g., short-circuit). Impedance calculated from rectified voltage and current values was less noisy than one-cycle Direct Fourier Transform (DFT), and higher sensitivity was achieved. However, DFT allowed faster trip action on a larger fault.

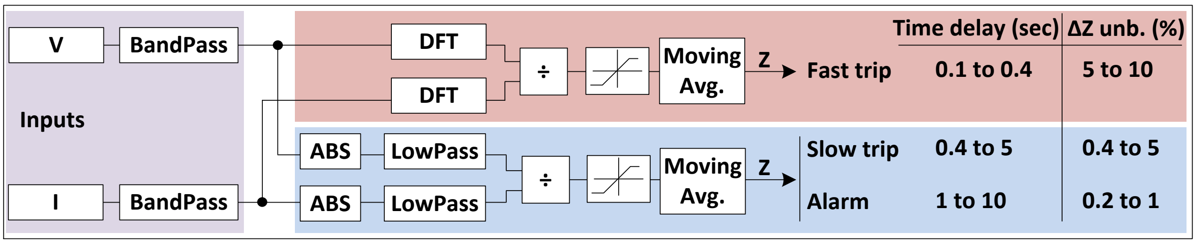

Figure 7 : Diagram of two parallel filtering stages of the impedance protection

In contrast to distance protection of lines, AC shunt filter impedance protection can be deactivated during faults on the AC network. The voltage drop caused by an internal fault is very low due to the high impedance of one capacitor group compared to the grid impedance. Totally shorted capacitor banks should be tripped by differential and overcurrent protection, hence a steady-state voltage range per phase (e.g., 0.8 to 1.2 pu) activates the protection to maintain high sensitivity and security.

The biggest drawback of this scheme is the use of a voltage measurement from a voltage transformer that has a generally higher failure rate than the current transformer. In particular, a capacitor voltage transformer (CVT) can have a faulty capacitor unit that causes erroneous voltage-dependant protection decisions [7]. This failure should mainly be detected if only one voltage measurement is used for many shunt filters. This scheme proposes to restrain the protection action on high zero-sequence voltage not matched by equivalent initially compensated zero-sequence current (Fig. 8), a strategy that adds security to the scheme.

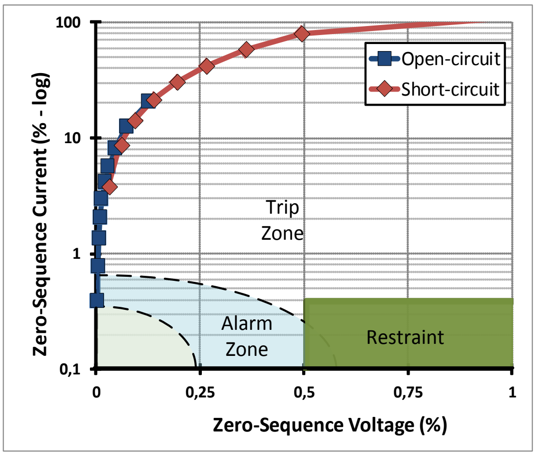

Figure 8 : Restraint of V0-voltage for an externally fused capacitor bank

Like any new protection, this scheme has been extensively tested, using a real-time hardware-in-the-loop setup. A large range of unbalance faults on the bus and nearby filters were simulated. Depending on the expected trip delay of the protection, appropriate CVT and CT models should be used in the simulation. Also key is the ability to replay past events with the new protection in place. Hence, both internal faults and major external events (Fig. 9) on the grid were replayed successfully. This process enhanced confidence in the scheme. A one-year observation period is also scheduled, with continuous monitoring of the measured impedance and alarms.

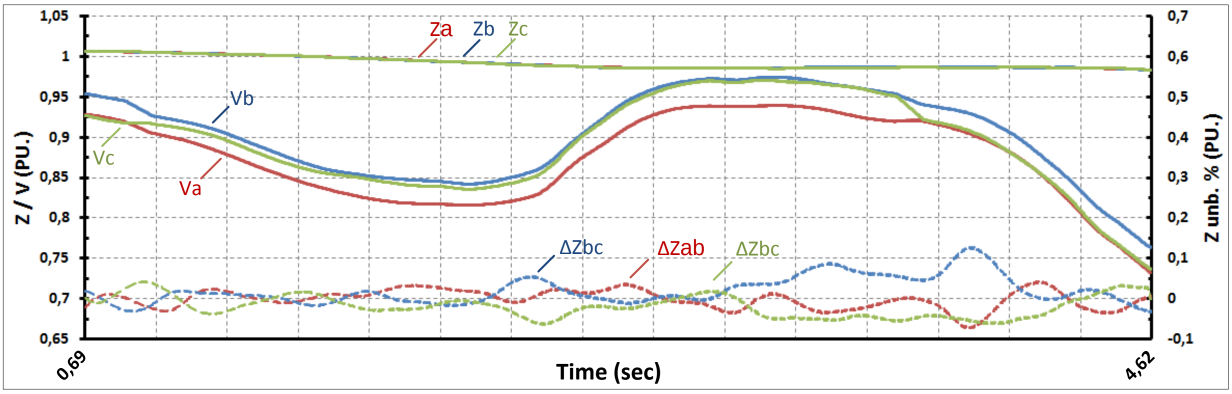

Figure 9: Real event affecting voltage and frequency playback to the impedance protection

3. PROPOSED UPGRADED PROTECTION SCHEME

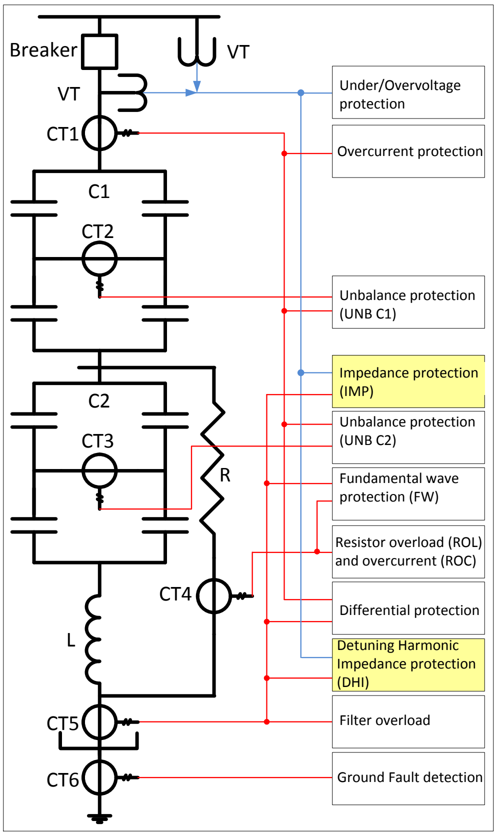

Figure 10: Example of an upgraded protection scheme for a C-type filter

As the events presented demonstrate, effective backup unbalance protection is much needed to prevent major damage to filter components. One suggestion of an upgraded scheme is presented in Figure 10. It includes impedance protection as global backup protection. All components have effective primary and backup protection. Based on this protection scheme, an example from Chateauguay of the protection coverage that could be expected is presented in Table 1. The cost of this upgraded scheme is low, especially if programmable relays or a programmable protection system are used, as no additional measurement devices are needed.

Detuning harmonic protection is proposed, as it could help in detecting faulty components that have a low impact on 60 Hz impedance but a much higher impact on the tuned harmonic. If the voltage transformer has sufficient precision, harmonic impedance could be calculated to enhance the detection of a fault and possibly add tripping condition for major faults.

Table 1: Example of protection coverage based on a C-type filter at Chateauguay

Effective protection coverage for internal fault at nominal voltage						
Element	Primary protection			Backup protection		
	Prot.	Coverage	Time delay	Prot.	Coverage	Time delay
C1	UNB C1	98%	0,1 sec	IMP	98%	0,3 sec
C2	UNB C2	99%	0,1 sec	FW	96%	0,1 sec
R	FW	50%	0,1 sec	DHI	75%	1 sec
L	FW	96%	0,1 sec	IMP	95%	0,3 sec

CONCLUSION

This paper uses explicit examples to show the need – in the case of heavily used filters – to upgrade state-of-the-art AC shunt filter protection scheme in order to significantly reduce damage and thus the duration of outages resulting from internal failures. Impedance protection, using simple but efficient strategies, is one of the solutions put forward in this paper. This flexible, low-cost, low-computer-load solution can be applied to multiple-filter branches with appropriate settings and interlocking conditions to ensure maximum security of the scheme.

Turn-to-turn failures of the filter reactors remain a challenge, and may require harmonic impedance protection with enhanced measurement devices.

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