A Solution to Sensitivity Challenges for the Protection of Large Fuseless Capacitor Banks

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Abstract

Hydro-Québec's transmission network includes several large wye-connected fuseless capacitor banks operated at 120, 161, 230 and 315 kV that range from 108 to 384 MVARs. These banks are protected by short circuit protection, system overvoltage protection and element failure overvoltage protection in the form of voltage differential or neutral overcurrent methods, depending on the bank's grounding design.

This paper will focus on the voltage differential method mentioned above and will address protection sensitivity which is the main challenge of large fuseless capacitor bank voltage differential protection. It will discuss voltage differential protection industry standards versus Hydro-Québec's multi-zone approach which has proved to be a reliable solution to sensitivity problems in wye-grounded large capacitor banks.

Introduction

Hydro-Québec is a government owned utility in the province of Québec, Canada. Hydro-Québec generates, transmits and distributes electricity that is generated mainly in large hydro-electric plants as well as wind farms and biomass plants. It also carries out construction projects and conducts R&D in energy-related fields, including energy efficiency.

Hydro-Québec TransÉnergie, a division of Hydro-Québec, operates the most extensive transmission network in North America, comprising 530 substations and over 34,187 km (21,243 miles) of transmission lines (see Table 1). Fifteen (15) interconnections with neighboring provinces and states (Ontario, New-Brunswick and the U.S. Northeast) allow for 6,025 MW import capacity and 7,974 MW export capacity. This division also markets system capacity, manages power flow across Québec and acts as the reliability coordinator for transmission systems in Québec.

Voltage	Substations (number)	Lines (km)
765 kV and 735 kV	39	11,683[a]
±450 kV DC	2	1,218
315 kV	70	5,438
230 kV	54	3,230[b]
161 kV	43	2,125
120 kV	218	6,938
> 69 kV or less	104[d]	3,555[c]
Total	**530**	**33,613**

a) Including 261 km of 735 kV lines operated at 315 kV.
b) Including 33 km of 230 kV lines operated at 120 kV.
c) 3,283 km of lines operated by Hydro-Québec TransÉnergie and 272 km by Hydro-Québec Distribution (the distribution division of Hydro-Québec).
d) 93 substations operated by Hydro-Québec TransÉnergie and 11 by Hydro-Québec Distribution (the distribution division of Hydro-Québec).

December 31, 2014

Table 1 – Overview of Hydro-Québec TransÉnergie's transmission network

Neighboring system	Quantity	Import mode (MW)	Export mode (MW)
New York	2	1,100	1,999
Ontario	8	1,970	2,705
New England	3	2,170	2,275
New-Brunswick	3	785	1,029
Total	**15***	**6,025**	**7,974****

* An interconnection common to New York and Ontario is only counted once in the total.
** 325 MW maximum for simultaneous delivery (export) for the interconnection common to New York and Ontario (not 359 MW).

Table 2 – Overview of Hydro-Québec TransÉnergie's interconnections

Several capacitor banks supply reactive power to Hydro-Québec TransÉnergie's network in order to control system voltage, ensure 735kV network stability as well as safe and efficient energy transfer (see Table 3). These banks have various designs including wye or split-wye, fused or fuseless depending on the year of manufacture of the bank and use (200 kVARs externally fused cans, 600 kVARs internally fused cans or 500 kVARs fuseless cans). Since these banks offer the most cost effective network management solution, they are frequently operated during the harsh winter peak periods 1 to 3 times a day making availability a critical design feature.

Voltage	Number of in-service banks			Planned additions
	Externally fused / MVARs	Internally Fused / MVARs	Fuseless / MVARs	Fuseless / MVARs
315 kV	N/A	3 / 1,123.2	9 / 3,024	N/A
230 kV	14 / 1,968	N/A	5 / 1,224	1 / 216
161 kV	4 / 34.5	N/A	2 / 360	2 / 360
120 kV	52 / 3,912.8	13 / 1,100.2	21 / 1,683	9 / 702
Total	**70 / 5,915.3**	**16 / 2,223.4**	**37 / 6,291**	**12 / 1,278**
Total reactive power of 15,707.7 MVARs				

Table 3 – Number of capacitor banks on Hydro-Québec TransÉnergie's transmission network

The first fuseless capacitor banks were added to the network in 2004 and two (2) different protection schemes were used for unbalance protection: neutral current unbalance for ungrounded wye-wye banks and voltage differential for single-wye grounded banks. Traditional voltage differential protection could not be applied because of sensitivity issues and further studies showed that dividing the bank into smaller wye connected zones allowed for better sensitivity as well as easier maintenance.

This solution was implemented in the field and gave satisfying results. In 2012, a new fuseless capacitor bank design was standardised (see Figure 1). All new capacitor banks going forward will follow this design and will be protected by a voltage differential scheme.

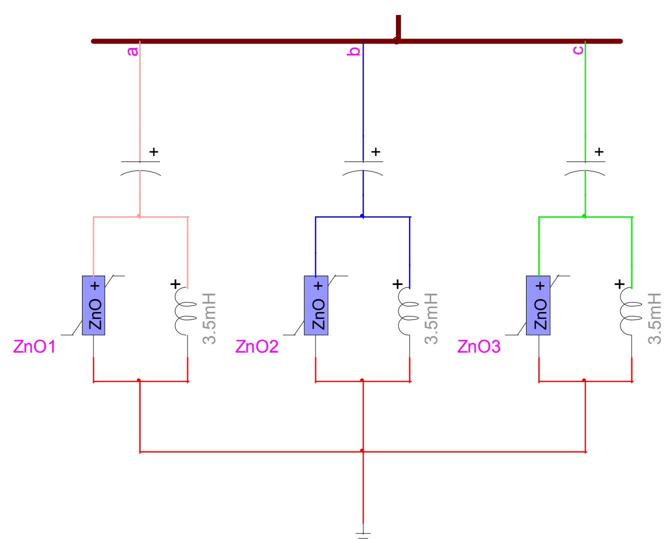


Figure 1 – Wye grounded fuseless capacitor bank design with an inductance on the low voltage side

The sensitivity challenge for fuseless capacitor banks

Sensitivity of protection involves the ability of a protection system to reliably distinguish an internal fault from other system anomalies, including environmental variations, external faults, loading and noise. In the case of voltage differential protection applied to wye-grounded capacitor banks, the principal protection signal is the difference voltage (V_{dif}) calculated by subtracting a portion of the capacitor voltage (V_{tap}) from the bus voltage (Equation 1). This difference voltage is compensated for the static variations in capacitance of healthy cans and for phase imbalances present in the bus voltage by allowing for per-phase “K” factors. The actual capacitance of individual elements will vary dynamically based on element temperature which causes dynamic difference voltages, especially if the various cans in the bank are exposed to different ambient conditions (typical on physically large banks when some cans are in the sun and some are in the shade or when some cans are in the wind and some are sheltered). Dynamic difference voltages are also generated by drift in capacitance caused by ageing.

$$V_{dif} = V_{bus} - K\,V_{tap} \qquad \text{(Equation 1)}$$

Difference voltage may also be generated by harmonics and noise measured by or induced on the voltage inputs of the relay. On modern digital relays, the difference voltage is based on fundamentally filtered input signals. While this filtering removes much of the effects of noise and harmonics, dynamic difference voltages can be generated if the noise/harmonics are rapidly changing.

On externally fused banks, the difference voltage makes a significant step change when a fuse blows, allowing for alarm and trip settings which are significantly larger than the difference voltage generated by dynamic capacitance changes and noise/harmonics. This has typically allowed for adequate reliability and sensitivity of voltage differential protection when applied to externally fused capacitor banks.

For fuseless banks, the difference voltage makes small step changes as individual elements short within the cans. Often, the alarm and trip settings required for adequate sensitivity are in the same range as the difference voltage generated by dynamic capacitance changes and noise/harmonics. In fact, the required primary differential voltages are often so low as to be outside the reliable accuracy range of the voltage transformers used to measure them. These challenges increase as the size of the bank increases.

The industry utilizes various design approaches to increase the sensitivity of the differential voltage protection for fuseless banks, including using larger KVAR rated cans, higher individual can and bank voltage ratings and bank reconfigurations including split-wye designs and breaking larger banks into multiple smaller banks. When properly applied, these designs can increase the magnitude of the difference voltages enough to provide security and sensitivity. However, they may not be adequate when the owner specifies very large banks.

In Hydro- Québec’s case, the banks are standardized. Changing the size of the bank is not an option. Since typical industry standard solutions could not be applied, the only avenue was to find an alternative protection method that would allow for secure and sensitive alarm and trip settings.

Studied cases

A 180 MVARS, 161 kV capacitor bank was modeled in specialized transient simulation software. This bank has 120 fuseless capacitors per phase arranged in 15 strings of eight (8) series capacitors. Each capacitor can is rated at 12 kV, 500 kVARs and has seven (7) elements in series by three (3) in parallel (see Figure 2). One by one each of the seven (7) series elements of a capacitor were short-circuited and the voltage increase was measured across the remaining healthy elements for three (3) different voltage differential cases.

In the first case, one voltage differential protection covers the entire bank. In the second, the bank is split in two, in a split-wye arrangement (industry standard approach) covered by two independent voltage differentials. In the third, the bank is split in smaller wye-connected zones -- each one monitored by an independent voltage differential protection.

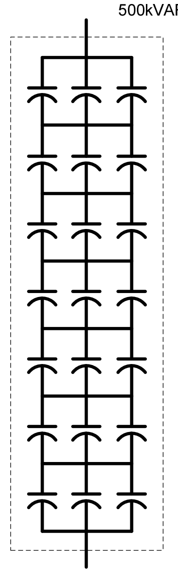


Figure 2 – Internal configuration of individual 500 kVAR, 12kV cans

The Bus VT has a ratio of 1400:1 V.

A step-down circuit or protection module (PM) was used in all three cases to measure the tap voltage. This circuit consisted of one or more 167 kVARs, 825 V monitoring capacitors, a 1250:250 V (5:1 ratio) VT and a 100 Ω, 100 W resistance. Generally, one monitoring capacitor was installed per 100 A flowing through the circuit.

An alarm was set to occur immediately before the failure of the element that would cause an overvoltage of 5% or more on the remaining healthy capacitors. Tripping was set to occur before the failure of the element that would cause an overvoltage of 10% or more on the remaining healthy capacitors.

Case 1 – Voltage differential protection covering the entire bank

Figure 3 shows the arrangement for this test case, where only one voltage differential protection covers the entire bank. The current flowing through the PM is equal to 623 A; therefore seven (7) monitoring capacitors are set in parallel.

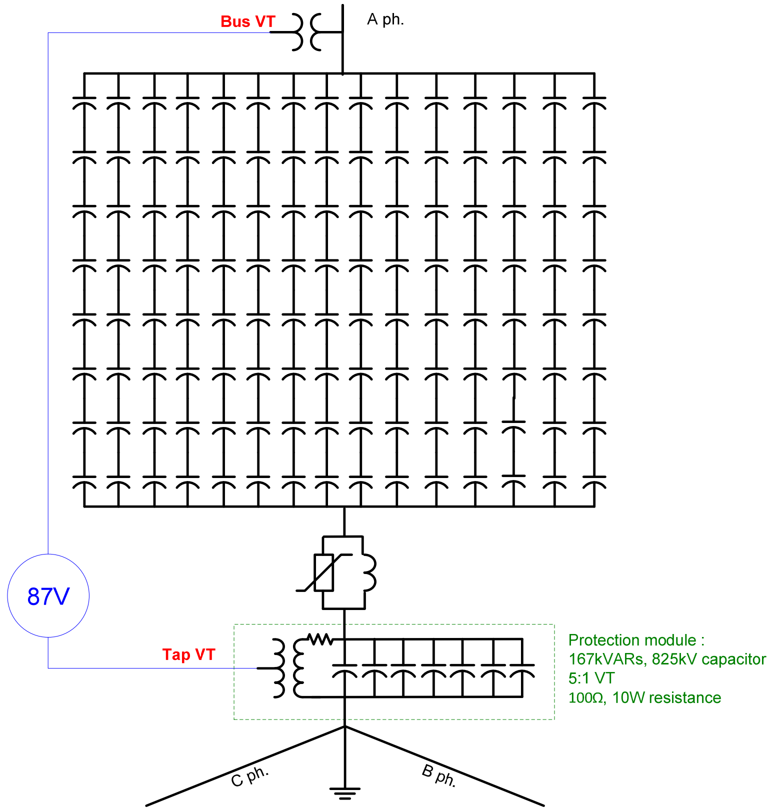


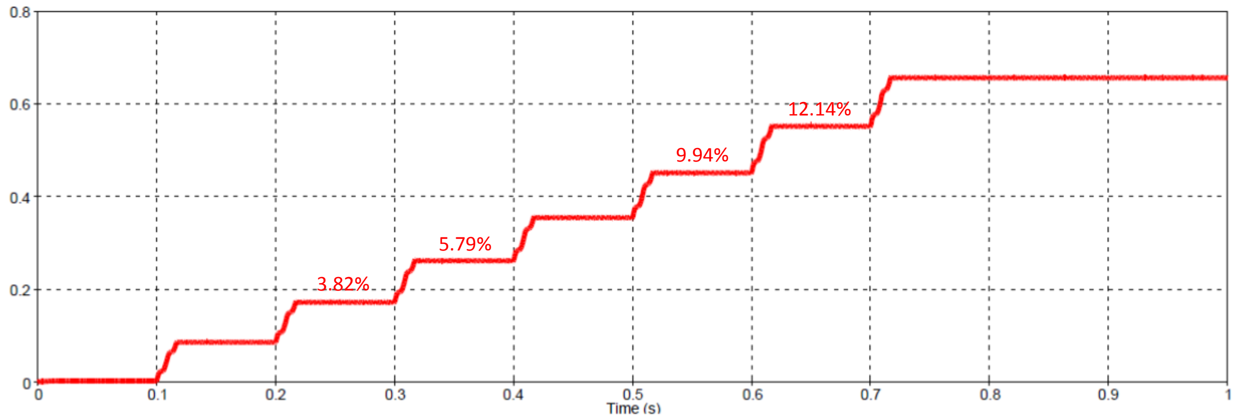
Figure 3 – Single voltage differential protection on a 180MVARs, 161kV capacitor bank

Simulation results are illustrated in Figure 4. Figure 4 b) shows the secondary difference voltage calculated from Equation 1:

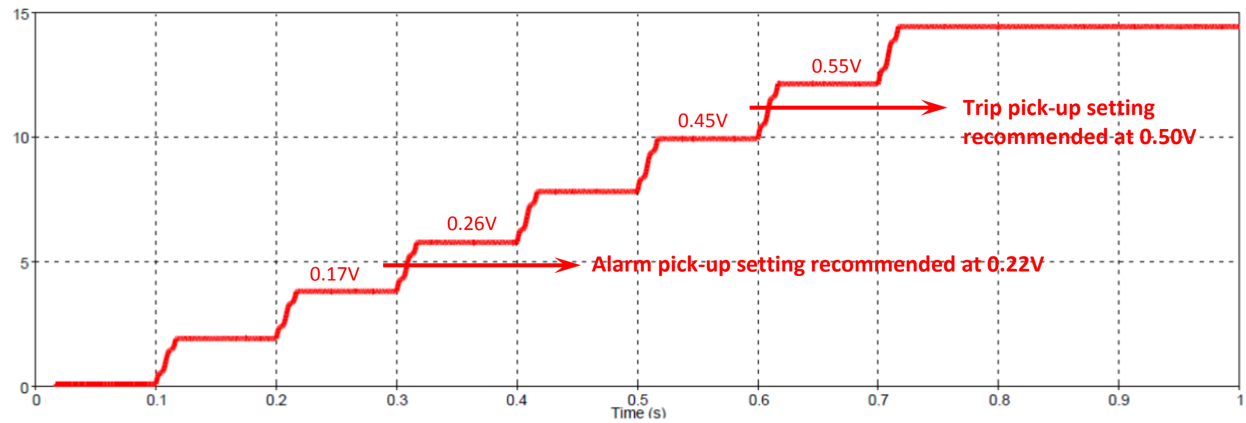
$$V_{dif} = V_{bus} - K\,V_{tap} \qquad \text{(Equation 1)}$$

where K is the compensation factor $\left(K = \dfrac{V_{bus}}{V_{tap}} \right)$.

Results show that an overvoltage of more than 5% occurred on the healthy elements after the loss of three (3) elements in one capacitor and corresponded to a secondary difference voltage of 0.26 V. The alarm should therefore be set after the loss of the second element, at 0.22V. An overvoltage of more than 10% occurred on the healthy elements after the loss of six (6) elements in one capacitor and corresponded to a secondary difference voltage of 0.55V. Tripping should therefore be set after the loss of the fifth element, at 0.50V.



a) Overvoltages on healthy capacitor banks (%)



b) Secondary difference voltage on healthy capacitor banks (dV)

Figure 4 – Overvoltages and secondary difference voltage for a single voltage differential on a 180MVARs, 161kV capacitor bank

Case 2 – Split-wye arrangement (industry standard approach)

The industry standard approach would be to split the bank in two, in a split-wye arrangement (see Figure 5). The first wye would count eight (8) strings of eight (8) series capacitors, while the second would count the other seven (7) strings. The current flowing through the PM of the first leg is equal to 323 A; therefore four (4) monitoring capacitors are set in parallel. In the second leg, current is 282 A and three (3) monitoring capacitors are set in parallel.

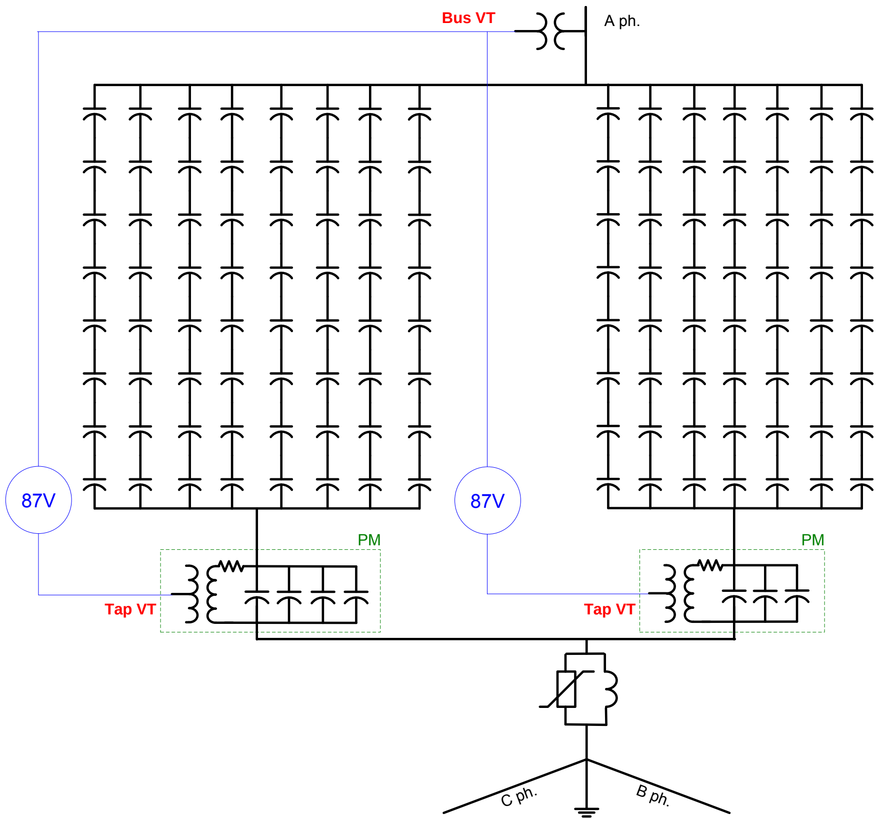
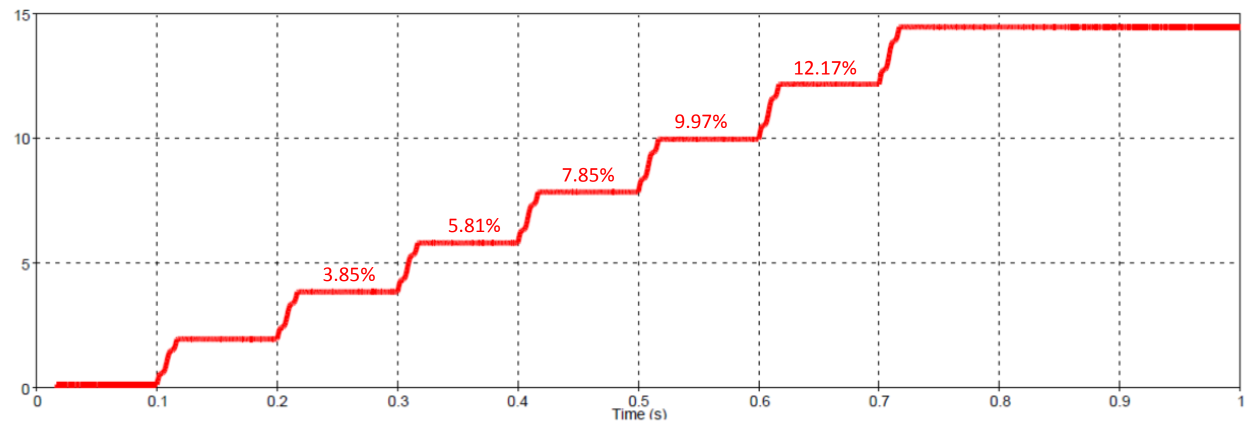


Figure 5 – Voltage differential protection for an 188MVARs, 161kV capacitor bank in split-why arrangement

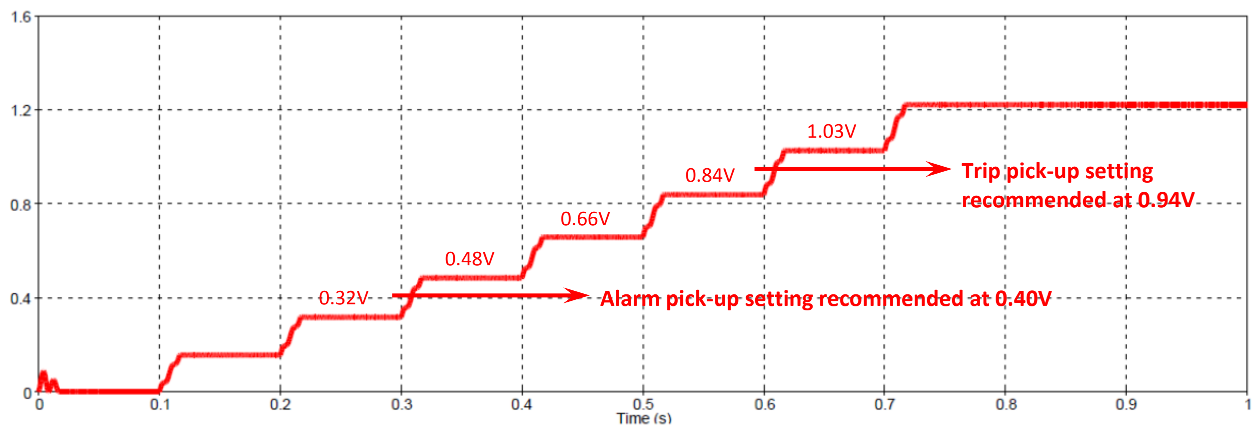
Simulation results are illustrated in Figure 6 for the first leg of the split-wye arrangement (8 series x 8 parallel). Results show that an overvoltage of more than 5% occurred on the healthy elements after the loss of three (3) elements in one capacitor and corresponded to a secondary difference voltage of 0.48 V. The alarm should therefore be set after the loss of the second element, at 0.40V. An overvoltage of more than 10% occurred on the healthy elements after the loss of six (6) elements in one capacitor and corresponded to a secondary difference voltage of 1.03V. Tripping should therefore be set after the loss of the fifth element, at 0.94V.

For the second wye (8 series x 7 parallel), results show that an overvoltage of more than 5% occurred on the healthy elements after the loss of three (3) elements in one capacitor and corresponded to a secondary difference voltage of 0.55V (see Figure 7). The alarm should therefore be set after the loss of the second element, at 0.46V. An overvoltage of more than 10% occurred on the healthy elements after the loss of five (5) elements in one capacitor and corresponded to a secondary difference voltage of 0.96V. Tripping should therefore be set after the loss of the forth element, at 0.86V.

Note that the alarm and trip settings are smaller in the first wye than in the second wye. This illustrates the fundamental issue that sensitivity is worse as the size of the bank increases.

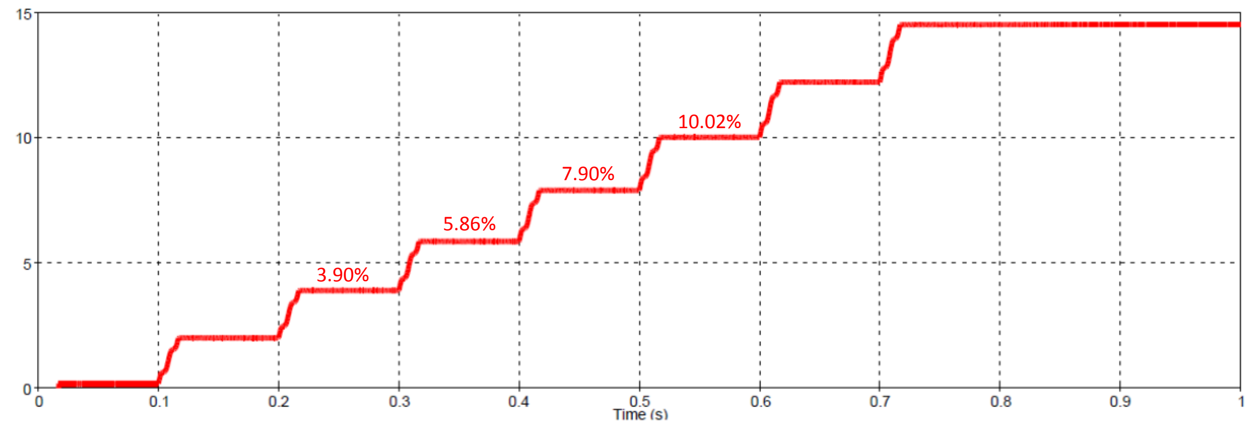


a) Overvoltages on healthy capacitor banks (%)

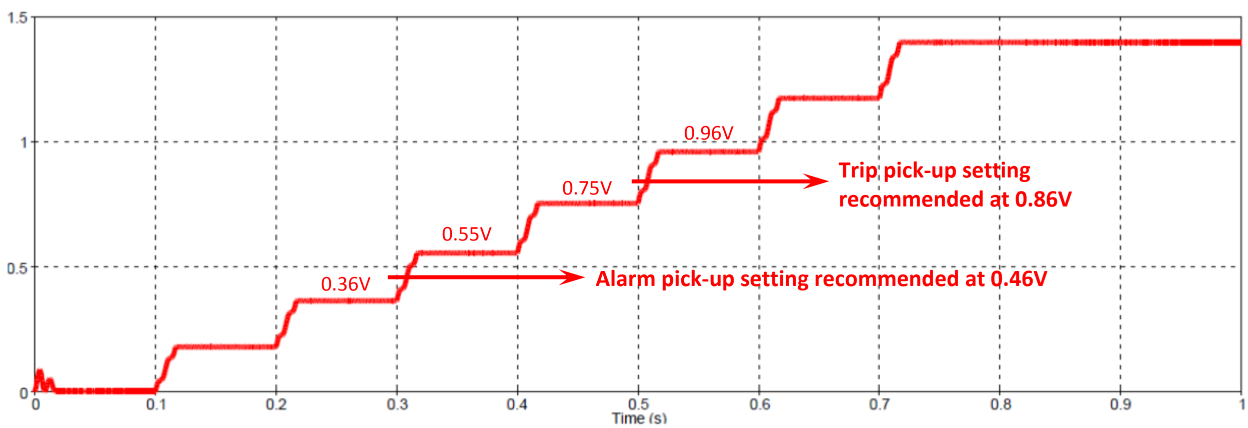


b) Secondary difference voltage on healthy capacitor banks (dV)

Figure 6 – Overvoltages and secondary difference voltage for the first leg (8 series x 8 parallel) of the split-wye arrangement on a 180MVARs, 161kV capacitor bank



a) Overvoltages on healthy capacitor banks (%)



b) Secondary difference voltage on healthy capacitor banks (dV)

Figure 7 – Overvoltages and secondary difference voltage for the second leg (8 series x 7 parallel) of the split-wye arrangement on a 180MVARs, 161kV capacitor bank

Case 3 – Smaller wye-connected zones (Hydro-Quebec's solution)

Another approach is to split the bank into smaller wye-connected zones and protect each one with an independent 87V element. Figure 8 shows the bank divided in five (5) zones. Each zone has three (3) strings of eight (8) series capacitors, for a total of five (5) wye-connected zones per phase. Each zone counts 24 capacitors. The current flowing through the PM is equal to 121 A; therefore two (2) monitoring capacitors are set in parallel.

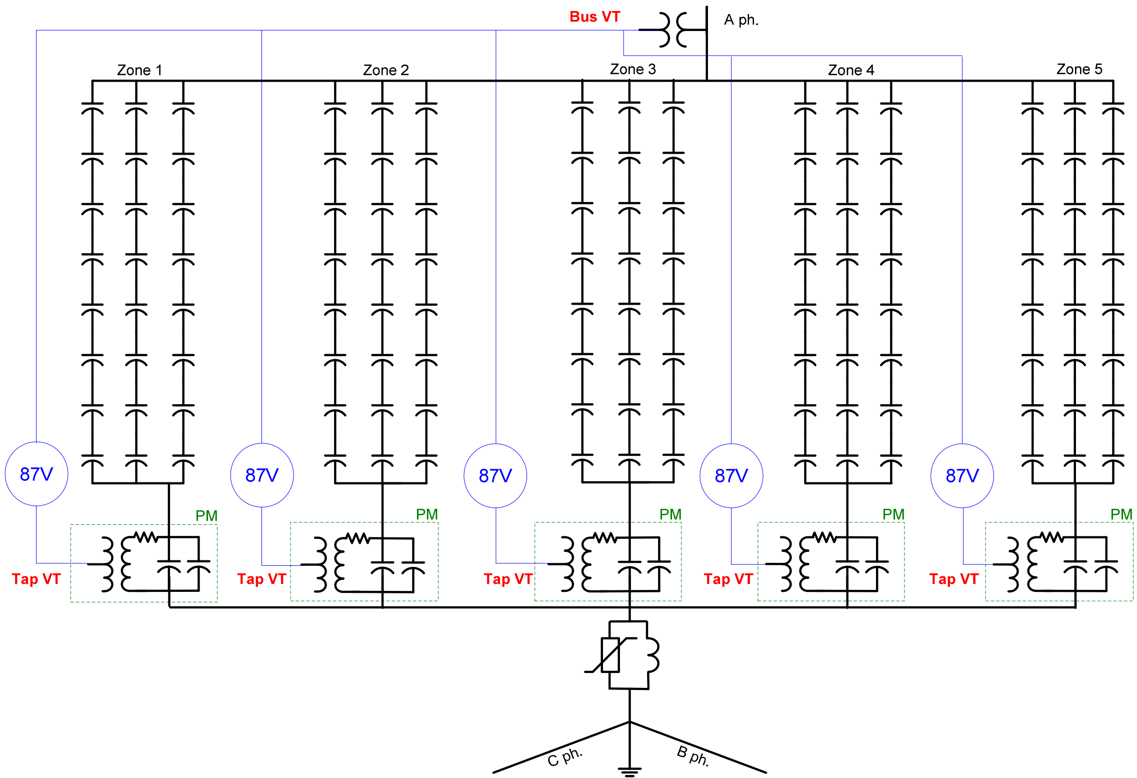
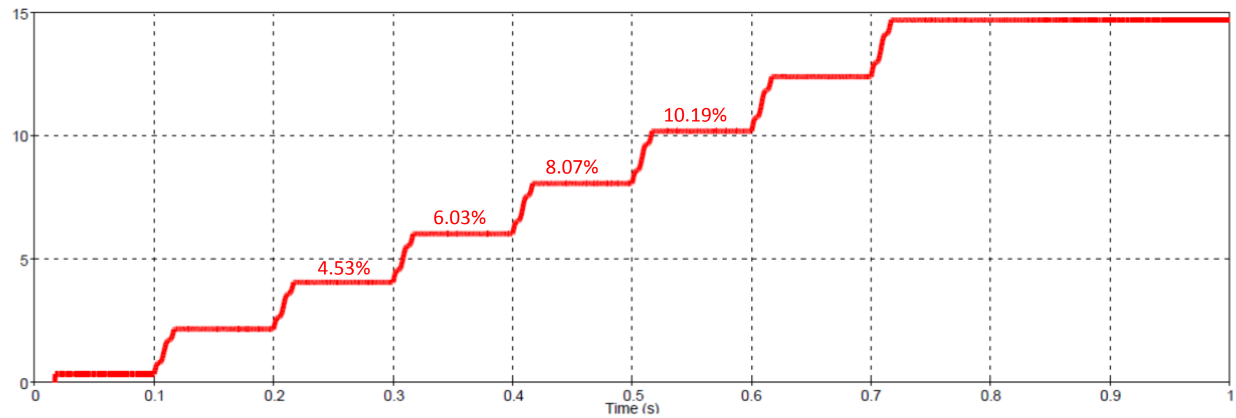
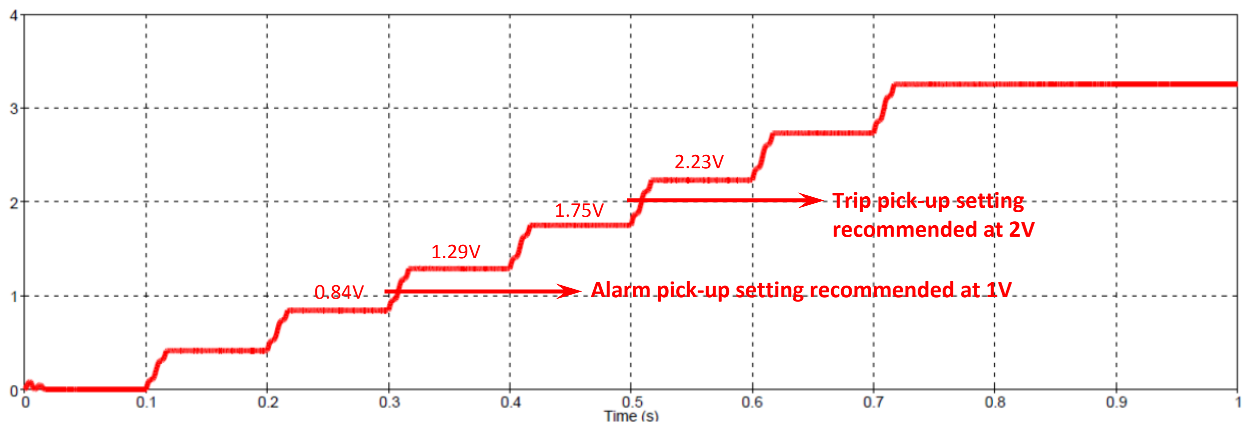


Figure 8 – Multiple voltage differential protections on a 180MVARs, 161kV capacitor bank

As shown in Figure 9, an overvoltage of more than 5% occurred on the healthy elements after the loss of three (3) elements in one capacitor and corresponded to a secondary difference voltage of 1.29V. The alarm should therefore be set after the loss of the second element, at 1V. An overvoltage of more than 10% occurred on the healthy elements after the loss of five (5) elements in one capacitor and corresponded to a secondary difference voltage of 2.23V. Tripping should therefore be set after the loss of the forth element, at 2V.



a) Overvoltages on healthy capacitor banks (%)



b) Secondary difference voltage on healthy capacitor banks (dV)

Figure 9 – Overvoltages and secondary difference voltage for multiple voltage differentials on a 180MVARs, 161kV capacitor bank

Results analysis and comparison

Comparison of results shows that in the third scenario, alarm and trip pick-ups could be set approximately five (5) times higher than in the first scenario and twice higher than in the second, thus increasing reliability and sensitivity of protection. This was possible because the number of capacitors protected in one zone was considerably reduced, making it such that the over-voltages monitored on the healthy capacitors following element failure were much higher than in the first case. It is also evident that fault location is improved since each zone has its own alarm and trip targets.

In-service field experience at Hydro-Québec has shown that a minimum threshold of 1V is required for alarm signal in order to avoid false alarm due to the dynamic difference voltages caused by dynamic capacitance variations, noise/harmonics and voltage transformer accuracies. Likewise, a minimum threshold of 2V is suitable for tripping. Splitting this specific bank into zones of three (3) strings is sufficient to meet the minimum alarm and trip settings, although, for even larger banks, it may be required to further reduce the number of protected capacitors in each zone to reach desired sensitivity.

Relay implementation

Relay implementation for the Hydro-Québec design is challenging due to the large number of three-phase voltage inputs and 87V functions required. Many relays have only one 87V function, requiring 6 relays to protect a 384 MVARs, 315 kV bank. To reduce the number of required relays (and the associated cost) it was essential that the selected relay could handle as many zones as possible. Therefore, a modular and customizable relay is desirable to meet this requirement. The chosen relay has one (1) three-phase current input (including A, B, C and Ground) and five (5) three-phase voltage inputs (including A, B, C and auxiliary) and includes three voltage differential zones.

Standardization of the solution

The following four (4) capacitor banks were also modeled and divided into smaller wye-connected zones of various sizes in order to determine the number of strings per zone that would provide sufficient reliability and sensitivity:

- 108 MVARs, 120 kV with a rated voltage of 124.7 kV and a total of 216 capacitors (6 series x 12 parallel);
- 216 MVARs, 230 kV with a rated voltage of 249 kV and a total of 432 capacitors (12 series x 12 parallel);
- 288 MVARs, 230 kV with a rated voltage of 249 kV and a total of 576 capacitors (12 series x 16 parallel);
- 384 MVARs, 315 kV with a rated voltage of 333 kV and a total of 768 capacitors (16 series x 16 parallel).

Results are shown in Table 4. For zones with four strings, the alarm and trip pickups were too low for the 161, 230 and 315 kV banks but not for 120 kV banks. For zones with two (2) or three (3) strings, the alarm and trip pick-ups can be set above the minimums discussed above. However, dividing the larger 230 kV and 315 kV banks into two (2) string zones requires an extra relay (chosen relay can handle three zones). Consequently, it was decided to split the 120 kV banks into zones of four (4) strings and use one relay and to divide the other banks into a combination of zones of two (2) and three (3) strings and use a maximum of two (2) relays (see Table 5).

	4 strings per zone				3 strings per zone				2 strings per zone			
	Alarm (V)	Trip (V)	No. of zones	No. of relays	Alarm (V)	Trip (V)	No. of zones	No. of relays	Alarm (V)	Trip (V)	No. of zones	No. of relays
124.7kV, 108MVARs (6x12)	1.1	2.1	3	1	1.5	2.9	4	2				
166.3kV, 180MVARs (8x15)	0.8	1.9	4	2	1.1	2	5	2				
249kV, 216MVARs (12x12)	1	1.5	3	1	1	2	4	2	2	3	6	2
249kV, 288MVARs (12x16)	0.8	1.5	4	2	1	2	6	2	1.5	3	8	3
330kV, 384MVARs (16x16)	0.9	1.1	4	2	1.3	1.5	6	2	1.9	2.25	8	3

Table 4 – Simulation results for different capacitor bank sizes

	4 strings per zone			3 strings per zone			2 strings per zone			**No. of relays needed**
	Alarm (V)	Trip (V)	No. of zones	Alarm (V)	Trip (V)	No. of zones	Alarm (V)	Trip (V)	No. of zones	
124.7kV, 108MVARs (6x12)	1	2	3	N/A			N/A			1
166.3kV, 180MVARs (8x15)	N/A			1	2	5	N/A			2
249kV, 216MVARs (12x12)	N/A			1	2	4	N/A			2
249kV, 288MVARs (12x16)	N/A			1	2	4	1.5	3	2	2
330kV, 384MVARs (16x16)	N/A			1	1.5	4	1.5	2.25	2	2

Table 5 – Alarm and trip pick-up setting and number of relays needed

Conclusions

Hydro-Québec needed a solution to sensitivity problems on large fuseless shunt capacitor banks because industry standard solutions were not adequate. A multi-zone approach was chosen and implemented in the field. With careful relay selection, this solution doesn't necessarily require more relays than the traditional voltage differential method yet offers higher protection sensitivity as well as improved fault location.

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Biographies

Fatima Cristina Radics is a protection engineer for Hydro-Québec TransÉnergie, a division of Hydro-Québec. She is part of the Automation and Control team since 2010 and specialises in real-time simulation and testing for certification and standardisation. Fatima graduated as an electrical engineer from École Polytechnique de Montréal in 2009 and is a member of the Ordre des ingénieurs du Québec (OIQ).

Tom Ernst is a P&C Technical Application Engineer for the North American Commercial team. He has been with GE since 2011 supporting the Grid Automation Protection and Control Portfolio. Prior to joining GE, Tom has been with Minnesota Power as a Supervising Engineer, Delta Engineering International as a Manager of Electrical Engineering, HDR Engineering as a Manager of Electrical Engineering and Northern States Power as a Supervising Engineer. He received his Bachelor of Science in Electrical Engineering from the University of Minnesota in 1978 and his Master of Science in Power Systems from Michigan Technological University in 2008. He is a registered Professional Engineer in the State of Minnesota.