Transient Analysis of Capacitor Bank Installation at Distribution Stations with PSCAD/EMTDC

P. Wang, D. Muthumuni, Z. Zhou, J. C. Alonso, P. Wilson, R. Wachal

J. Waddell

Abstract--Capacitive compensation has been widely used in power system at different voltage levels. Manitoba Hydro (MH) is planning to return to service 41 units of 2.4MVAr 12.47kV distribution level Pad Mount Capacitor (PMC) banks located at 17 substations to provide the needed power factor correction and VAR support. To ensure safe and successful operations of the PMC banks, unfavorable transient issues associated with capacitor switching and potential nearby faults must be thoroughly evaluated. The heavily interconnected MH distribution system presents a challenge to analyze the impact due to addition of those capacitor banks.

This paper presents details of various PSCAD/EMTDC models of the MH distribution system to determine required inductance for limiting both inrush and out-rush transient currents, frequency scans for network compliance, arrester energy duty during transient over-voltage (i.e. re-strikes and fault clearing), and breaker TRV ratings. Based on the transient analysis, several recommendations were suggested to modify the installation.

Keywords: capacitor switching, distribution system, transient analysis, PSCAD/EMTDC, E-TRAN.

I. INTRODUCTION

Shunt capacitor banks are common devices used in power systems for reactive power compensation, voltage regulation and power factor correction [1]. Manitoba Hydro is planning to place back in service 41 units of 2.4MVAr 12.47kV distribution level PMC banks located at 17 stations throughout the city of Winnipeg. The pad mount capacitor banks were first deployed in the early 1990's, but encountered some operational problems. Re-energization of the PMC bank was recently requested in order to provide needed power factor correction and VAR support.

Operation of the PMC bank will raise various concerns regarding protection of the banks as well as other substation equipment. These are mainly related to high frequency, high magnitude inrush and out-rush currents, and over-voltages generated during capacitor switching and potential nearby faults. At distribution levels, these associated transients during capacitor switching are generally studied with analytical approach and/or monitored with the field measurement [2-5]. However, the MH distribution system is heavily interconnected with the required 17 installations of PMC banks located in the close range. Therefore, the simulation method was mainly used in this study to investigate potential unfavorable transient issues and to ensure safe and successful operations of the PMC bank.

In this paper, several simulation models developed with PSCAD/EMTDC and E-TRAN were used to perform the related transient analysis. The findings covering limiting inductance required for both inrush and out-rush currents, and frequency scans for network compliance under various system configurations are presented. In addition, this paper deals with network transient performance for switching surges, arrester sizing and breaker TRV.

II. MODEL DEVELOPMEENT AND VERIFICATION

The PMC bank is configured as a solidly grounded shunt system in three 800kVAr legs for a total reactive compensation of 2.4MVar as shown in Fig. 1[6]. Each leg consists of current limiting fuse and a vacuum type circuit switcher capable of switching the PMC bank. All three legs are connected to the 12.47 kV feeders via a cable dip and 3 single phase cut-outs. The Ohio Brass MOV surge arresters were installed on line sides of the main fuse to provide protection during lightning and switching surges.

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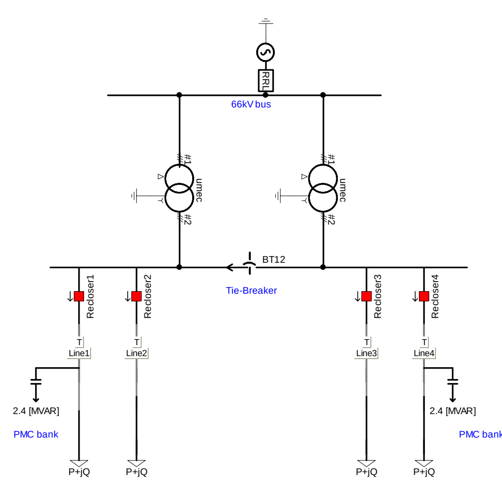

Fig. 1 Typical 12.47 kV, 2.4MVAr PMC bank installation

* P. Wang, D. Muthumuni, Z. Zhou, J. C. Alonso, P. Wilson, R. Wachal are with Manitoba HVDC Research Centre, Winnipeg, MB, Canada (e-mail of correspondence: peiw@hvdc.ca)

** J. Waddell is with Manitoba Hydro distribution engineering group, Winnipeg, MB, Canada (e-mail: jwaddell@hydro.mb.ca)

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In the present configuration, the PMC banks are located outside of the substations. There are no limiting reactors installed; instead, the impedance of distribution transmission line or/and underground cable connections are used to limit high transient currents during back-to-back switching and under fault conditions. At each station, the number of installed PMC units ranges from 1 to 5. When there are multiple units of PMC banks installed at one station, individual PMC banks are connected to separate 12kV feeders.

A. PSCAD Models

Based on the objectives of simulation work and to facilitate its process, three different types of PSCAD models were developed: the simple station-based model to examine inrush and out-rush transient currents, a detailed distribution network model for the TOV and frequency scan analysis, and the detailed station model for TRV investigation.

For evaluation of inrush and out-rush currents, the simple PSCAD model based on individual station can be implemented. This model includes PMC capacitors, transmission lines from the bus to the PMC location, and equivalent sources. A basic single line diagram of the PSCAD model is shown in Fig. 2, which consists of a station with two PMC banks in service. To calculate transient currents at individual stations, only simple modifications of the basic model are necessary.

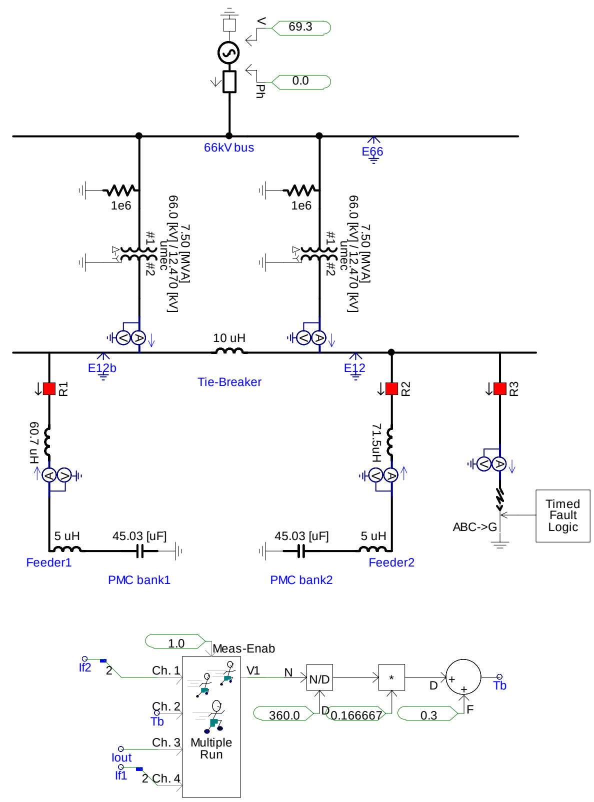

Fig. 2 PSCAD model for inrush and out-rush evaluation

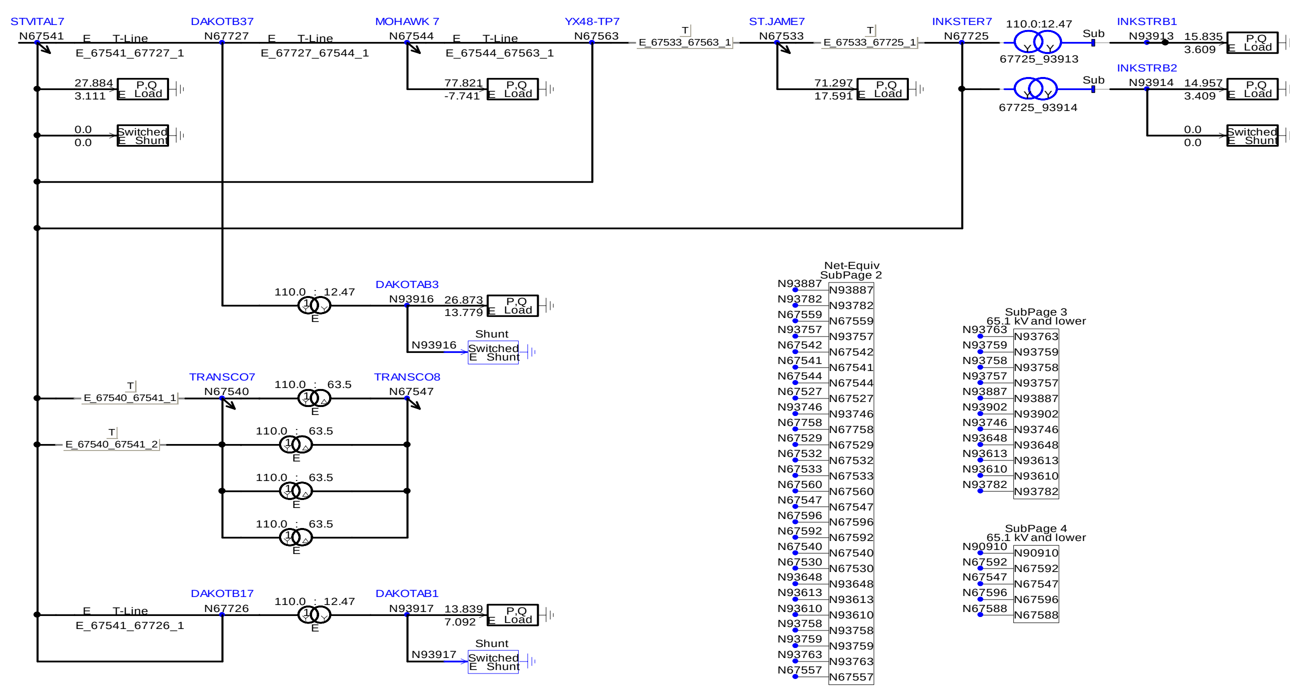

Fig. 3 Section of the detailed distribution network model in PSCAD

The detailed distribution network model was created for frequency scan and TOV studies. This is due to the fact that the studied distribution system is heavily interconnected and all 17 stations are in the close ranges. The software E-TRAN was adopted to automatically generate the preliminary system model in PSCAD/EMTDC from original PSS/E data files. In addition, network equivalences were created by E-TRAN in order to represent remaining sections of the network. The resultant simulation model includes parts of MH 230 kV and 115kV transmission networks, and the 66 kV and 12.47 kV distribution networks covering all 17 stations and their vicinities. A sample section of single line diagram of the generated simulation model is shown in Fig. 3. Detailed information for transient analysis such as transformer saturation, arrester V-I curve, zero sequence of network equivalences and etc were inputs in addition to those captured from the PSS/E files.

The break TRV is mostly a localized phenomenon, so proper representation of stray capacitances and inductance of station equipment is very important in the simulation modeling. In the investigation of the breaker TRV, the detailed distribution network model was used as the simulation base case to represent system interconnection. In addition, a detailed page component which takes into account capacitance and inductance of station equipment was created to replace the station equivalence converted from PSS/E files. When the parameters of equipment reactance were not available, recommended values from published standards were adopted. The sample single line diagram of a station page component used in TRV study is shown in Fig. 4.

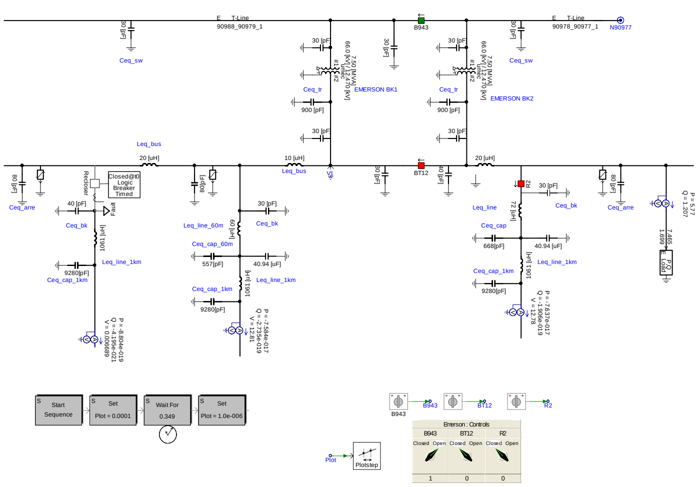

Fig. 4 Detailed PSCAD station model for breaker TRV investigation

B. Model Verifications

The detailed distribution network model in PSCAD was validated in two steps. First, simulations were run in order to check compliance with the original PSS/E power flows. It was found that the load flows obtained in both PSS/E and PSCAD were in good agreement, and the maximum difference is less than 2.0%.

Secondly, the positive and zero sequence impedances were calculated in PSCAD for the 17 stations, and compared to Manitoba Hydro Station Short Circuit Data. The impedance values are generally comparable, but with noticeable differences existing in zero sequence at certain substations as shown in Table 1. The difference lies mainly in the fact that the referred MH Short Circuit Data were based on the system configuration of full generation, loadings and fully inter-networked scheme, while the PSCAD cases were created with typical loadings and interconnection schemes for the system winter and summer peaks.

TABLE 1 COMPARISON OF SHORT CIRCUIT DATA

	Voltage [kV]	Z base [ohms]	MH data Positive seq [pu] R	MH data Positive seq [pu] X	MH data Z pu [ohms]	PSCAD measuremnts SUMMER Pos. seq. [ohms]	PSCAD measuremnts WINTER Pos. seq. [ohms]
Station A	66	43.56	0.0254	0.0914	4.131	4.019	4.008
Station B	66	43.56	0.0201	0.0878	3.923	4.022	4.012
Station C	66	43.56	0.0038	0.0400	1.752	2.091	1.800
Station D	66	43.56	0.0164	0.0767	3.417	3.456	3.446
Station E	66	43.56	0.0044	0.0345	1.513	1.619	1.606
Station F	115	132.25	0.0045	0.0227	3.059	3.422	3.089

	Voltage [kV]	Z base [ohms]	MH data Zero seq. [pu] R	MH data Zero seq. [pu] X	MH data Z pu [ohms]	PSCAD measuremnts SUMMER Zero seq. [ohms]	PSCAD measuremnts WINTER Zero seq. [ohms]
Station A	66	43.56	0.0458	0.2169	9.655	8.653	8.691
Station B	66	43.56	0.0550	0.3262	14.409	11.015	11.091
Station C	66	43.56	0.0241	0.2030	8.904	6.784	8.622
Station D	66	43.56	0.0444	0.2670	11.789	10.879	10.954
Station E	66	43.56	0.0082	0.1045	4.567	6.314	6.347
Station F	115	132.25	0.0060	0.0297	4.006	1.594	1.353

III. Simulation Results

A. Inrush and out-rush Currents

Both vacuum type circuit switcher of PMC bank and the distribution re-closers were evaluated against transient currents. The PMC bank inrush currents were examined for the situations of an isolated bank and back-to-back switching, while out-rush currents were obtained for a breaker closing into a nearby fault. In the analysis, both theoretical calculation and PSCAD simulation were carried out.

First, limiting inductance required was calculated by hand using various well defined engineering techniques and standards [7-9] with the following assumptions:

- Rated 12.47kV L-L with 5% over-voltage deviation
- +/-10% positive tolerance for the capacitance.
- 10% safety factor for load harmonic content.
- 10uH bus-bar inductance between capacitor banks
- 5uF capacitor bank stray inductance

Then, the similar PSCAD model shown in Fig. 2 was adopted in the transient currents simulation on a point-on-wave switching approach. The typical values of transient currents obtained with hand calculation and PSCAD simulation are shown in Table 2, while there are two PMC banks in service in this case. In the analysis, the calculated inrush currents occurred during back-to-back switching while the out-rush currents consists of discharges from two energized banks to the fault on nearby feeder. It can be seen that the results are in a good agreement, and insufficient limiting reactance in out-rush situation was identified in both hand calculation and PSCAD simulation.

TABLE 2 COMPARISON OF INRUSH AND OUTRUSH CURRENTS AT STATION B

		Peak Current (A)	Frequency (Hz)	f*I (A. Hz.1e7)
Inrush	**Design limit**	6000	4240	2
	Calculated	4293	2581	1.11
	PSCAD	4748	2694	1.28
Outrush	**Design limit**	12000	4240	2
	Calculated	16600	2744	4.56
	PSCAD	16770	2782	4.67

B. *TOV and Arrester Energy Duty*

Switching events may impose high energy duty stresses on MOV arresters connected near the PMC capacitors, especially during breaker re-strikes. The MOV energy duty evaluation is recommended even if the breakers are commercialized as “re-strike free” [7].

The MOV arresters currently installed are rated at 7.65MCOV with an energy level of 3.4kJ/kV. For the purpose of the arrester energy duty evaluation, the detailed network model described in section A was used, while the arrester V-I curves were based on the manufacture data. The re-closers were assumed to be single pole operated, and only the first re-strike was considered. In addition, the recommended limiting reactors calculated in the inrush and out-rush study were not considered, while the loads were disconnected for worst case scenarios. In the case of observation of MOV high energy absorption requirements, a loading sensitivity study was then performed to study the load damping effect.

The MOV arrester energy duty was evaluated by applying faults at various point-on-wave intervals, and switching of capacitor banks under various network and capacitor bank configurations. The results for all 17 stations indicated a maximum TOV level up to 2.15 pu, and typical waveforms of energy duty, over-voltage and currents at station F are shown in Fig. 5. Table 3 lists typical MOV energy duties for different capacitor configurations. It was observed that there are no energy duty stresses at most stations, and the highest energy absorption requirement occurs at station F during breaker re-strike. The further loading sensitivity performed shows that this MOV energy duty stress can be mitigated by adding only 10% of typical loads as shown in Table 4.

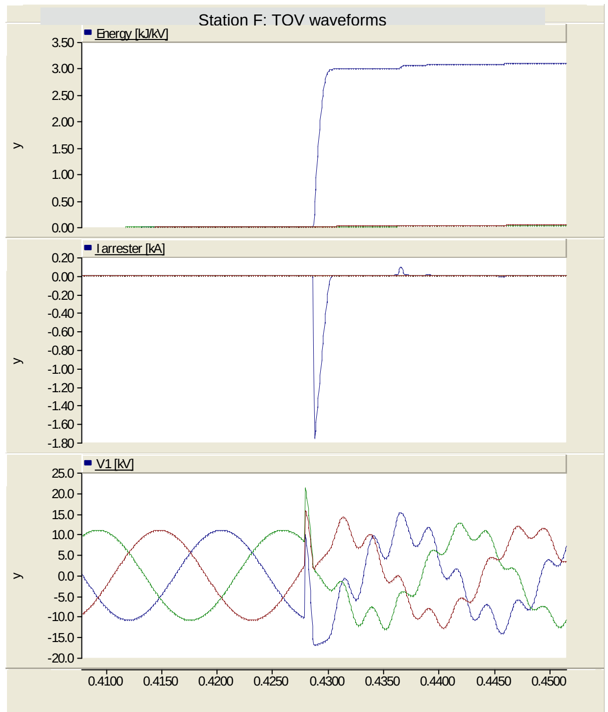

Fig. 5 Energy duty, over-voltage and current waveforms during breaker re-strike at station F

C. *Frequency Scan*

To identify possible harmonic voltage distortion issues, changes in impedance profiles with the PMC banks in service were investigated in frequency scan. In the simulation, impedance profiles were obtained using the detailed network model under different system conditions and contingencies.

The results indicated that addition of the PMC banks at one station does not have a significant effect on frequency profiles at other stations and buses. However, addition of the PMC bank does alter frequency responses near the installation buses. The main effects are seen in the 3rd to 8th harmonic range for the positive impedance. A typical impedance profile is shown in Fig. 6. This impedance change is not likely to cause much operating problems. However, if there is already harmonic voltage distortion issue at the same location, further corrective actions may be necessary.

TABLE 3 TYPICAL MOV ENERGY DUTIES

	Summer					Maximum Arrestor energy duty [kJ/kV]	Safety margin
	No. of Capacitors						
	1	**2**	**3**	**4**	**5**		
Station A	***2.25***					2.25	33.9%
Station B	2.33	***2.40***				2.40	29.4%
Station C	2.44	2.44	***2.48***			2.48	27.1%
Station D	2.45	2.50	2.65	***2.78***		2.78	18.1%
Station E	2.38	2.39	2.48	2.57	***2.59***	2.59	23.7%
Station F	2.99	3.22				3.22	***5.3%***

TABLE 4 IMPACT OF LOADING ON ENERGY DUTY AT STATION F

Percentage of Rated Load	Arrestor Energy Duty [kJ/kV]	Safety margin
0	3.22	5.40%
0.1	2.33	31.3%
0.2	1.76	48.3%
0.3	1.33	60.9%
0.4	1.00	70.5%
0.5	0.76	77.7%
0.6	0.57	83.3%
0.7	0.43	87.5%
0.8	0.31	90.8%
0.9	0.23	93.4%
1	0.23	93.4%
* Rated load is 28.2MVA		

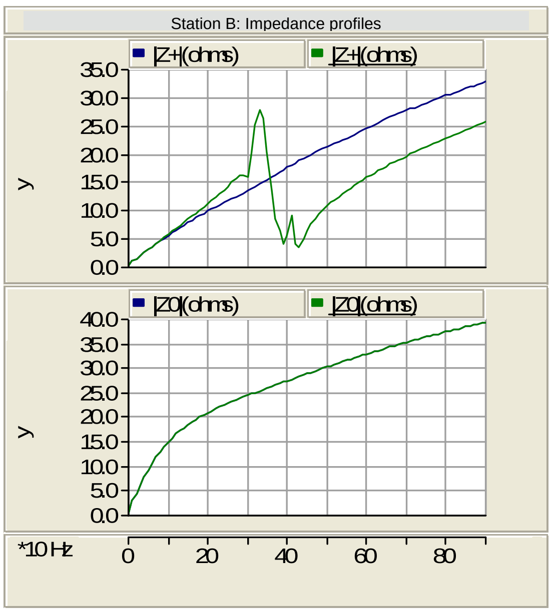

Fig. 6 Impedance profile comparison due to addition of PMC banks

D. Breaker TRV

The purpose of TRV investigation is to identify if the re-closer ratings for TRV are exceeded when the PMC banks are in service. The investigation was carried out by analyzing breaker TRV waveforms with detailed station configuration shown in Fig. 4. The simulated TRV waveforms were then compared with breaker rating specified by published standard [10].There are three types of re-closers existing in the system, and the re-closers with lower ratings were selected and evaluated for the TRV capability.

- Nominal voltage rating: 15.5kV
- Continuous current capability: 560A
- BIL: 110kV
- Maximum interrupting rating: 12kA

In the simulation, a three-phase ungrounded terminal fault was applied once the system reaches steady state, and the re-closer interrupts fault currents after three cycles. Then, TRV waveforms of the first open-pole contact were plotted against rated breaker TRV capability envelopes. Different load conditions and capacitor bank operation conditions were examined in this study.

A typical breaker TRV waveform and the governing voltage envelop defined by published standard are shown in Fig. 7. In this case, only one PMC bank was in service and the system was operating under typical winter load condition.

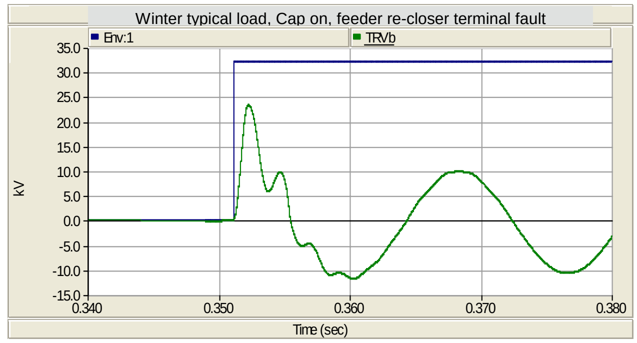

Fig. 7 Typical TRV waveform

The impact of loading, capacitor configuration and proposed limiting reactors are shown in Fig. 8. With the PMC banks in service, the TRV peak increases due to discharge of the PMC bank, but still well below the TRV capability value. In addition, the PMC banks in service improve re-closer TRV capability in initial rising profiles of the TRV. In all, there is no TRV stress observed with the PMC banks in service and use of recommended limiting reactors.

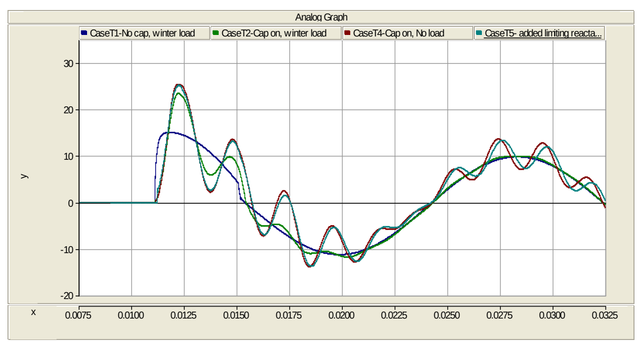

Fig. 8 TRV waveforms for different loading, capacitor configuration and limiting reactors

IV. CONCLUSIONS

PSCAD based transient analysis were employed to evaluate potential adversary impacts due to operations of PMC banks at MH distribution level, including calculation of inrush and out-rush transient currents, MOV arrester energy duty, frequency scans, and breaker TRV.

Both hand calculations based on published standards and transient simulations revealed that breakers at 11 stations could be overstressed in either inrush or out-rush situations. The addition of proper limiting reactance was required to mitigate this issue. Increased positive sequence harmonic impedances were also observed at some locations once the

PMC banks are in service. These changes are not significant and would be of concern only if there are harmonic voltage distortion issues already at these locations. The study of MOV energy duty indicates high energy absorption requirements during breaker re-strike when the feeder loads are disconnected. It was recommended that certain load (minimum 10%) is to be connected during PMC bank operations.

In conclusion, the electromagnetic transient analysis proves to be an effective tool for capacitor switching study at power system distribution level, and a complementary for the existing evaluation method based on published standards.

V. References

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VI. Biographies

Pei Wang was educated at Xi'an Jiaotong University and University of Manitoba. He has been with Manitoba HVDC Research Centre since 2000, and his main research interests are power electronics and power system simulation technology. He is a registered Professional Engineer with the Province of Manitoba.

Dharshana Muthumuni received his Ph.D. from the University of Manitoba in 2001. He now works as a Simulation Support and Research Engineer at the Manitoba HVDC Research Centre. His main research interests are in the areas of power system simulation, electrical machine and transformer modeling for transient simulation studies.

Zheng Zhou received her B.Sc. degree from Southeast University in 1988 and M. Sc. degree from the University of Manitoba in 2003. She is currently employed by Manitoba HVDC Research Centre. Her research interest is in power system, digital simulation and power electronics. She is a registered Professional Engineer with the Province of Manitoba.

J.C. Garcia Alonso obtained his B. Sc. from the Universidad Nacional de Colombia in 1996 and his M. Sc. from the University of Manitoba in 2005. He worked for four years designing large power transformers and currently works as a Research and Support Engineer at the Manitoba HVDC Research Centre.

Paul Wilson obtained his B.Sc. (EE) degree in 1987 from the University of Manitoba. Paul is currently employed by Manitoba Hydro as the Managing Director of Manitoba HVDC Research Centre. He is a registered Professional Engineer with the Province of Manitoba.

Randy Wachal obtained his B.Sc. (EE) degree in 1981 from the University of Manitoba. Randy is the Research Project Manager of the Manitoba HVDC Research Centre, a senior member of IEEE and a registered Professional Engineer in the Province of Manitoba.

Jared Waddell received a Bachelor of Science Degree in Electrical Engineering from the University of Manitoba, Canada in 1999. He has been with the Distribution Planning and Design Division at Manitoba Hydro since 1999, presently as the Distribution Performance Engineering Section Head. He is a registered Professional Engineer with the Province of Manitoba.