Overvoltage Issues associated with De-energization of 345 kV Variable Shunt Reactors: Parametric Analysis and Mitigations

Jingxuan (Joanne) Hu, Ed McGann

***Abstract*-- This paper summarizes parametric sensitivity studies carried out to establish the range of chopping currents, chopping suppression overvoltages and reignition overvoltages that could occur during 345kV shunt reactor switching.**

The study shows that, if there were no surge arrester connected in parallel with shunt reactor, the reactor would be exposed to steep voltage wave surges with magnitudes close to the reactor design insulation level thus leading to accelerated insulation aging and potential reactor damage. Circuit breakers used in shunt reactor switching can reignite after current chopping depending on the breaker chopping number and circuit parameters. These re-ignitions not only expose the reactor to the steep wave magnitudes but also the transient recovery voltages observed across the circuit breaker contacts can reach or exceed the switching impulse rating of a general duty 362kV circuit breaker.

500kV breakers with controlled switching have been selected to eliminate breaker reignition and the associated over voltages.

***Keywords*: shunt reactor de-energization, current chopping, reignition overvoltage, controlled switching, parametric analysis, field measurement.**

I. INTRODUCTION

Three new 30-60 Mvar variable shunt reactors operated on a 345kV transmission system have been installed to facilitate voltage control within the 345kV system. De-energization of the shunt reactor could impose a severe duty on both the shunt reactor and its circuit breaker due to current chopping that occurs when interrupting small inductive currents. The severity of the switching duty increases when single or multiple re-ignition occur [1], [3]. Field measurements have been carried out during actual reactor switching as described in references [1] and [4]. These tests indicated that overvoltages as high as 2.3 pu could occur when de-energizing high voltage shunt reactors if no mitigation was provided to limit the chopping suppression overvoltages.

II. METHODOLOGY

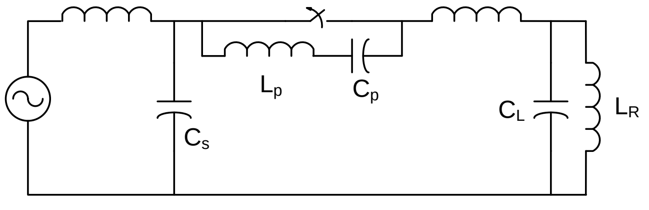
A parametric approach was adopted to establish the range of chopping currents, chopping suppression overvoltages and re-ignition overvoltages that could occur for 345kV shunt reactor switching. This approach is based on an expected range of stray shunt capacitance values and typical circuit breaker chopping characteristics using the conservative method presented in IEEE C37.012 [5] with the following assumptions:

- The magnetic coupling between different phase winding was ignored
- Typical chopping number of SF6 breakers were used for calculation of overvoltages
- Damping factor (β) was assumed to be 0.5

III. PARAMETRIC ANALYSIS RESULTS

Chopping current and overvoltages were estimated using the equations described in [5] with the following variables considered as shown in Table I.

TABLE I
VARIABLES FOR CALCULATING OVERVOLTAGES

Variable	Symbol	Unit	Value
Breaker Chopping Number	λ	$AF^{-0.5}$	$4x10^{4}$ - $19x10^{4}$
Source side inductance (SCC: 5-40kA)	L_s	H	0.01-0.1
Source side capacitance	C_s	pF	1000-30000
Circuit breaker parallel inductance	L_p	H	0.001-0.01
Circuit breaker parallel capacitance	C_p	pF	100-2000
Shunt Reactor Reactance (30-60Mvar at 345kV,) (µF)	L_R	H	10.52 - 5.26
Load side capacitance	C_L	pF	2000 - 5000
			

A. Chopping Current

The chopping current was calculated using equation (1) in [5]. Fig.1 shows the chopping current in Amperes as a

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function of chopping number and typical values for SF_6 puffer type breakers.

The chopping current is proportional to the chopping number and square root of the total capacitance across the circuit breaker. For the capacitance range considered for C_s, C_L and C_p, the total capacitance varies from 767 pF to 6286 pF which results in a chopping current varying from 1.11 A to 3.17 A, and 5.261 A to 15.1 A corresponding to chopping numbers of 0.4×10^5 and 1.9×10^5, respectively.

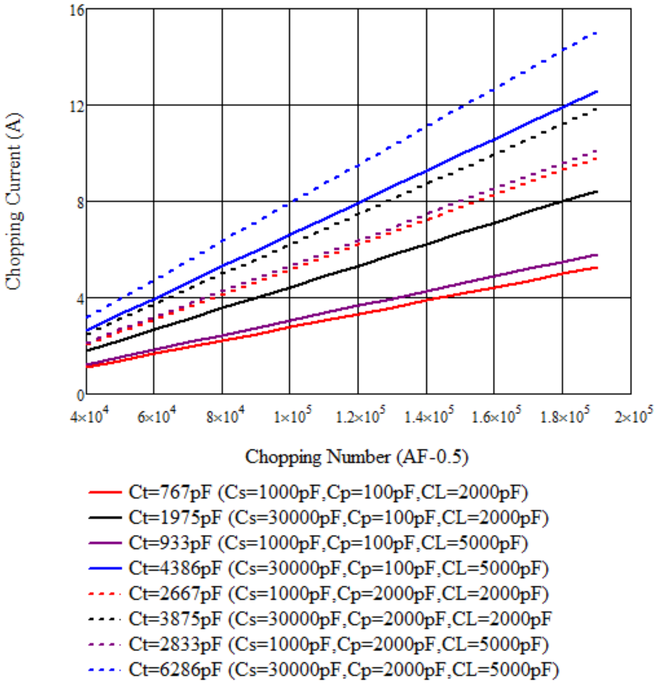


Fig.1 Calculated Chopping Current as a Function of Chopping Number

B. Chopping Overvoltage (Suppression Overvoltage)

The first peak of the oscillation has the same polarity as the system voltage at the time of interruption. This chopping voltage is referred as suppression overvoltage and can be calculated using equation (5) in [5] as repeated below.

$$k_a = \frac{V_{ma}}{V_0} = \sqrt{1 + \left(\frac{i_{ch}}{V_0}\right)^2 \frac{L_R}{C_L}}$$

where

i_{ch} is the chopped current level (A)
V_{ma} suppression peak overvoltage to ground (V)
V_o is the peak voltage (V) across shunt reactor at the instant of current interruption
L_R is the reactor inductance (H)
C_L is the load side effective capacitance to ground (F)

Suppression overvoltage is a function of chopping current (Capacitance and chopping number) and reactive power of reactor as shown in Fig.2. The suppression overvoltages can vary from 1 to 2.4 pu of V_o ($where\ V_o = \frac{345\times\sqrt{2}}{\sqrt{3}} = 287.1kV$). V_o is the peak voltage on the reactor prior to current interruption and its value is dependent on the actual circuit stray shunt capacitance, the breaker chopping number, and the reactance of the reactor. The highest overvoltage can be expected when the tap of the reactor is set at 30 Mvar (highest inductance).

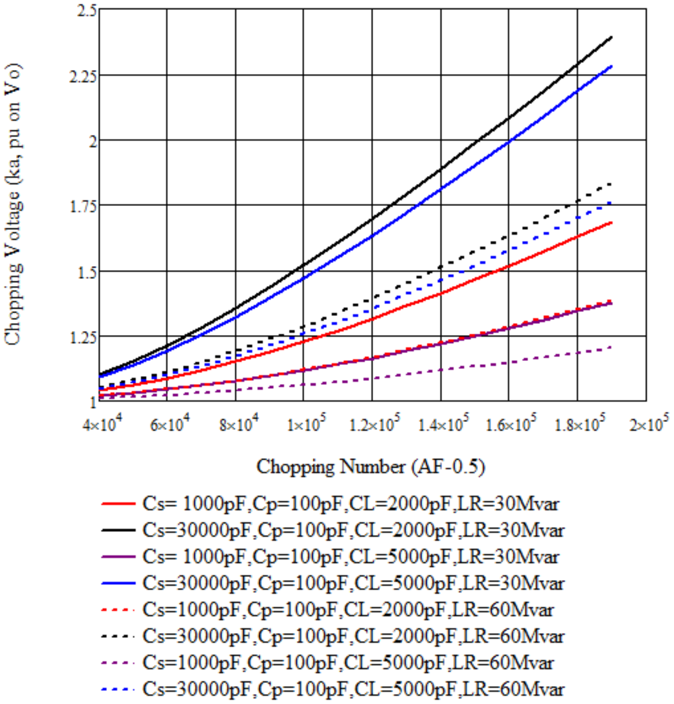


Fig.2 Calculated Chopping Voltage as a Function of Chopping Number

C. Overvoltage due to Re-ignition

If the breaker reignites, the magnitude of associated peak to ground overvoltage (k_p) could be as high as 2.4 pu as shown in Fig.3. Thus the shunt reactor would be exposed to these high overvoltages with a very steep rate of rise. The change of the overvoltages is normally within 1-2µs, and therefore rate of rise of re-ignition overvoltage could be 676kV/µs.

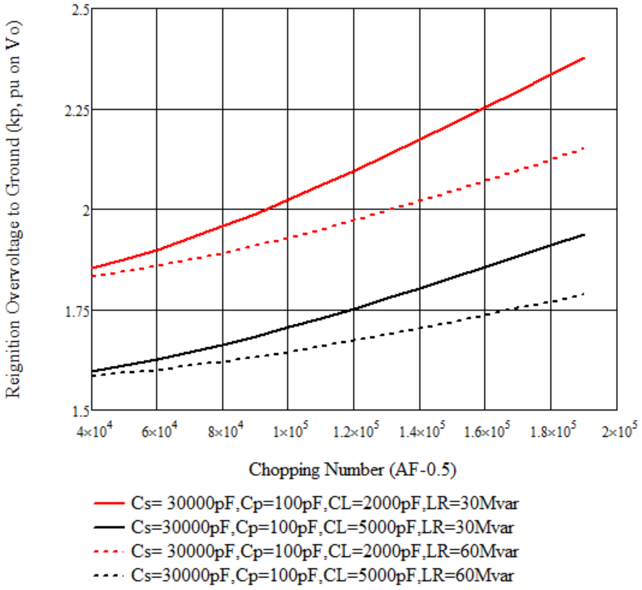


Fig.3 Calculated Reignition Voltage as a Function of Chopping Number

The peak to peak excursion voltages (k_s) are shown in Fig.4. In the worst case, a 4.8 pu on Vo could be expected if reactor tap is set for 30 Mvar output.

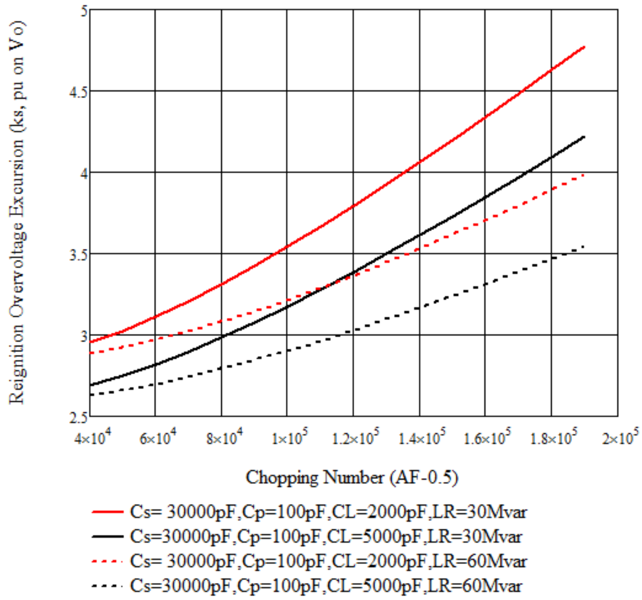


Fig.4. Calculated Reignition Voltage Excursion as a Function of Chopping Number

D. *Overvoltage across Circuit Breaker (TRV)*

The estimated overvoltages across the circuit breaker (krv) without the occurrence of reignition as a function of circuit breaker and circuit parameters are shown in Fig.5. High overvoltage of 2 to 3.4 pu on Vo voltage, which correspond to 563.4 kV and 957.8 kV, could be applied across the circuit breaker during the interruption.

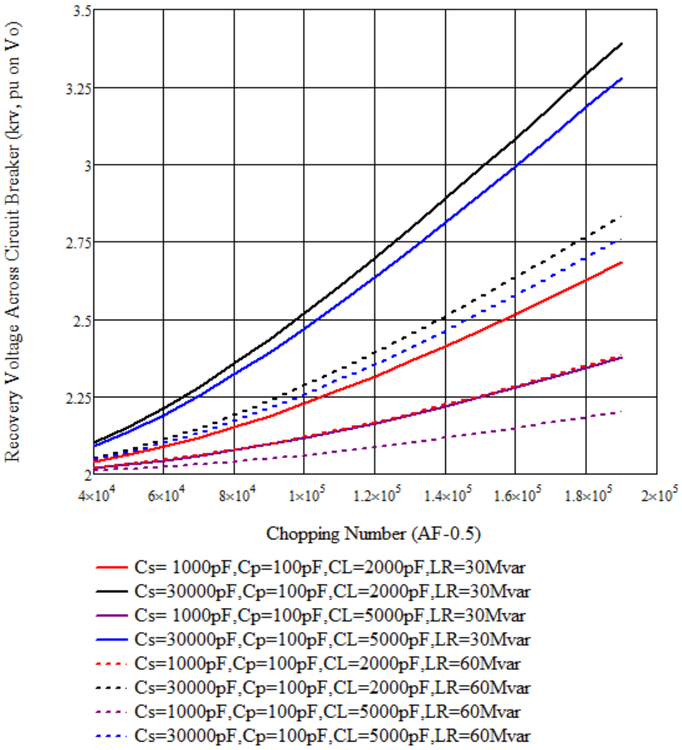
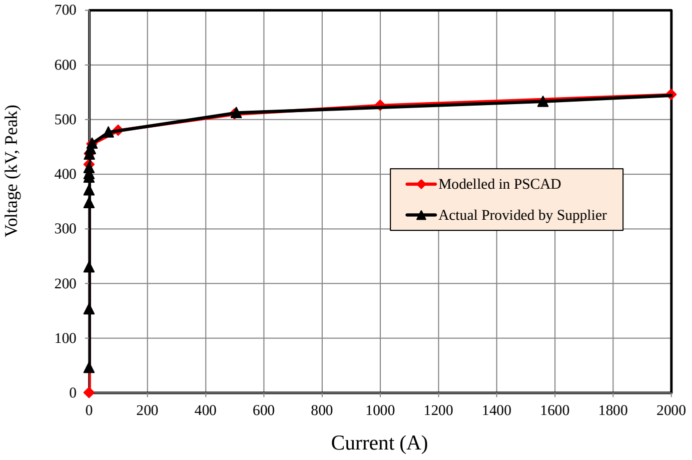


Fig.5 Calculated Breaker Recovery Voltage

The frequency of the overvoltage across the circuit breaker is normally within the range of a few hundred Hz to several kilo-Hz, similarly to switching surges. If assuming a 1.5 kHz oscillation frequency, the rate of rise of recovery voltage (RRRV) across circuit breaker is estimated to be 3.28 kV/μs.

E. *Effect of MOV in Parallel with Shunt Reactor*

The shunt reactor will be protected by surge arrester rated at 276 kV. The typical protective level of a 276 kV arrester is 1.93 pu, 2.25 pu and 2.48 pu on 281.7 kV for switching and lightning impulse and chopped wave, respectively. These correspond to protective ratios of 1.65, 2.03 and 2.4 for switching surge, lightning surge and chopped wave. Fig. 5 shows simulated 276 kV surge arrester VI characteristic as well as the actual characteristic provided by the supplier.



The effect of 276 kV surge arresters on the overvoltages assuming 12.6A chopping currents is demonstrated in Table II.

TABLE II
COMPARISON OF CALCULATED AND SIMULATED RESULTS SHOWING EFFECT OF SURGE ARRESTERS (ASSUMING 12.6A CHOPPING CURRENT)

	Calculated Using Equations as per IEEE C37.015	PSCAD Simulated Surge Arrester Disconnected	PSCAD Simulated Surge Arrester Connected
Chopping Current (A)	12.6	12.6	12.6
Suppression Voltage, V_{ma} (Peak, kV)	523.2	525	448
Recovery voltage peak to ground, V_c (Peak, kV)	523.2	505	416
Recovery voltage across breaker (Peak, kV)	819	793	701

The simulated voltage on both source side and load side (Reactor) of the circuit breaker, and recover voltage across the breaker are shown in Fig. 6.

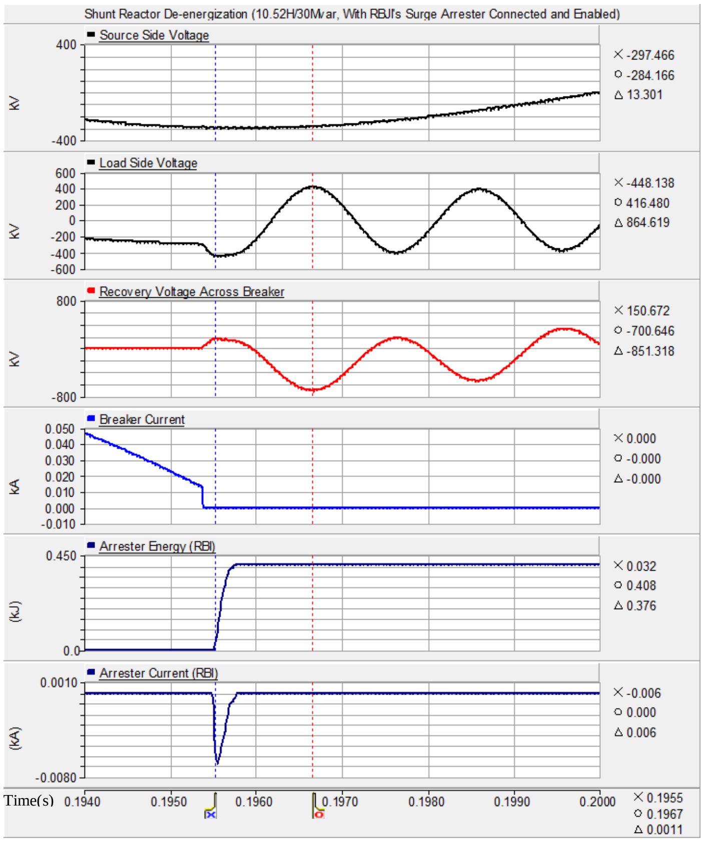


Fig. 6 PSCAD Simulated breaker recovery voltage due to de-energization of 30Mvar, 345kV shunt reactor with parallel 276kV surge arrester

F. Summary of Overvoltages

The overvoltages due to current chopping and reignition associated with 345 kV shunt reactor switching and their impact on the station equipment can be summarized as follows.

1) Overvoltages

The calculated maximum and minimum overvoltages are summarized in Table III.

TABLE III
SUMMARY OF CALCULATED OVERVOLTAGES[1,2,3]

Reactor Rating (Mvar)	Chopping Current (A)	Chopping Overvoltage (Suppression Voltage) (pu)	Re-ignition Overvoltage (pu)	Re-ignition Overvoltage Excursion (pu)	Overvoltage across Circuit Breaker (pu)
30	1.1-15.1	1.02-2. 40	1.00-2.40	2.00-4.80	2.00-3.40
60	1.1-15.1	1.00-1.83	1.00-2.15	2.00-3.98	2.00-2.84

1 The total capacitance across breaker varies from 767 pF to 6286 pF.
2 The breaker chopping number is varied 0.4x105 AF-0.5 to 1.9x10^{5} AF-0.5, chosen from IEEE C37.015.
3 Voltages are pu values on 345*sqrt(2)/sqrt(3)=281.7kV.

2) Insulation level and Surge Stress on Shunt Reactor and Circuit Breaker

Table IV summarizes the insulation level of shunt reactors and circuit breakers, and the highest surge overvoltages that could be imposed on shunt reactor and circuit breaker under the worst case scenario without surge arresters.

TABLE IV
SUMMARY OF INSULATION LEVEL AND SURGE STRESSES

Equipment	BIL (kV)	SIL (kV)	Calculated Chopping Overvoltage (Switching Surge) (kV)	Calculated Overvoltage across Circuit Breaker (Switching Surge) (kV)	Calculated Reignition Overvoltage (Lightning Surge) (kV)	Reignition Overvoltage Excursion (Lightning Surge) (kV)
Reactor	1300	900	676	-	676	**1352**
Breaker	1300	950 900	-	958	-	-

The overvoltage across the open circuit breaker contacts could reach 958 kV (3.4 pu on phase to ground voltage at 345 kV) if there is no limitation on these overvoltages.

Presently, there are no IEEE/IEC standards addressing breaker withstand capability of transient recovery overvoltage due to current chopping during shunt reactor de-energization. However, 80% of the terminal to terminal switching impulse withstand voltage across the breaker open contacts has been used to evaluate the breaker withstand capability [6]. Based on this non-standard criterion, the overvoltage across the circuit breaker shall not be higher than 760 kV and 720 kV, which are 80% of the terminal to terminal switching impulse withstand voltages of 950 kV and 900 kV (refer to Table IV) of 362 kV breakers at substations. Thus, the standard 345kV circuit breakers could reignite after current chopping depending on the breaker chopping number and circuit parameters.

The reactor could be exposed to the steep surges with magnitude as high as 1352kV which exceeds the 1300 kV design insulation level if not protected by the surge arresters.

Overvoltages resulting from the shunt reactor de-energization are unlikely to cause insulation breakdown of shunt reactors as they are protected by 276kV surge arresters connected at their terminals, but the repeated steep wave front overvoltages will stress the first few turns of the insulation thus accelerating aging of the insulation, and eventually leading to premature failure. Therefore some mitigation should be considered to reduce the chopping overvoltages and the risk of reignition of the circuit breakers

IV. MITIGATION

The number of mitigative means that can be used to reduce the duty on the circuit breaker and shunt reactor are as follows:

- controlled switching to maximize the arc duration during reactor switch de-energizing. This has two effects, firstly it introduces the arc resistance into the circuit and thus provides damping leading to lower values of chopping current, and secondly it allows the circuit breaker contacts to travel to a much wider opening thus increasing the possibility that the breaker can withstand the arc-suppression overvoltage without reigniting.
- circuit breakers with opening resistors. The additional resistance in the circuit provides damping leading to lower

values of chopping current and thus lower chopping suppression voltages.

- higher voltage circuit breakers (for example applying a 550 kV breaker at 345 kV). The greater withstand capability of the higher voltage breaker increases the likelihood that the breaker can withstand the chopping suppression overvoltage without reigniting
- Use of surge arresters across the heads of the circuit breakers.

Each mitigation option has pros and cons. Controlled switching has been proven to be a reliable technology on suppressing the switching transients and thus was selected for this application. To avoid the reignition during the de-energization of shunt reactor, the breaker contacts can be controlled to part in the reignition free window which is the difference between a half cycle time and the minimum arcing time without reignition if ignoring any tolerance. The breaker test report shows the breaker has minimum arcing time between 4.1 to 6.9 ms. In the worst case, the window for controlled switching device (CSD) to operate is only 1.43 ms. Thus, re-ignition may not be completely eliminated considering the tolerance of 2ms from the selected CSD. Therefore, a 550kV breaker with a capability to withstand the estimated recovery voltage during reactor de-energization was also specified. The 550kV breaker reduces the probability of a re-ignition even if the controlled switching does not fall within the reignition free window.

V. CONCLUSION

Overvoltages due to de-energization of 345 kV variable shunt reactors have been estimated using a sensitivity analysis approach. High overvoltages could be expected across the shunt reactor and its circuit breaker which could cause re-ignition of breaker and thus impose severe stress on the reactors. A 550kV breaker with a controlled switching device has been specified and installed for shunt reactor switching. Field measurements to validate the effectiveness of controlled switching on the elimination of re-ignition and overvoltages will be performed in the near future.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

Joanne Hu received her Bachelor’s degree in Electrical Engineering in 1995 (China) and her Master’s degree in Computer and Electrical engineering in 2001 (Canada). She has extensive experience in high voltage technologies and power equipment, power system stability and electromagnetic transient studies; HVDC system control and modeling; Equipment design studies;. She is a registered professional engineer in Manitoba (APEGM), and a senior member of IEEE. She is the Convenor of CIGRE WG B4.61-General Guidelines for HVDC Electrode Design**.**

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